European Commission

Study on clean energy R&I opportunities to ensure European energy security by targeting challenges of distinct energy value chains for 2030 and beyond

Final report

Independent Expert Report

Research and Innovation

Study on clean energy R&I opportunities to ensure European energy security by targeting challenges of distinct energy value chains for 2030 and beyond

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Manuscript completed in February 2024
First edition

PDF	ISBN 978-92-68-12862-6	doi: 10.2777/906828	KI-05-24-107-EN-N

Luxembourg: Publications Office of the European Union, 2024

EUROPEAN COMMISSION

Study on clean energy R&I opportunities to ensure European energy security by targeting challenges of distinct energy value chains for 2030 and beyond

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2024 Directorate-General for Research and Innovation

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ABBREVIATIONS

Acronym or abbreviation	Definition
AC	Alternating current
ACER	Agency for the Cooperation of Energy Regulators
ACT	Advanced control technologies
AI	Artificial intelligence
AEM	Anion-exchange membrane
AMI	Advanced metering infrastructure
BBSRC	Biotechnology and Biological Sciences Research Council
BECCS	Bioenergy with carbon capture and storage
BIPV	Building-integrated photovoltaics
CAES	Compressed air energy storage
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CCUS	Carbon capture, utilisation and storage
CdTe	Cadmium telluride
CENELEC	European Committee for Electrotechnical Standardization
CETO	Clean Energy Technology Observatory
CH_4	Methane
CHP	Combined heat and power
CIGS	Copper, indium, gallium, selenide
CIndECS	European Climate Neutral Industry Competitiveness Scoreboard
CINELDI	Centre for Intelligent Electricity Distribution [Norway]
CO_2	Carbon dioxide
CO_2 eq.	CO_2 equivalent

CONCAWE	Conservation of Clean Air and Water in Europe
COP	Conference of Parties
CRM	Critical raw material
CSA	Coordination and support action
CSH	Concentrated solar heating
CSP	Concentrated solar power
DAC	Direct air capture
DG RTD	Directorate-General Research and Innovation
DOE	Department of Energy [United States]
DTU	Danish Technical University
EC	European Commission
ECHA	European Chemicals Agency
EEA	European Environment Agency
EIC	European Innovation Council
EOL	End of life/end-of-life
ERA	European Research Area
ERC	European Research Council
EPSRC	Engineering and Physical Sciences Research Council [United Kingdom]
ETIP	European Technology & Innovation Platform
ETS	Emissions Trading System [EU]
ETSI	European Telecommunications Standards Institute
EU	European Union
eV	Electric vehicle
F-gas	Fluorine-gas
F&I	Forschung und Innovation
FME	Centres for Environment-Friendly Energy Research [Norway]

FPV	Floating photovoltaics
GBEP	Global Bioenergy Partnership
GHG	Greenhouse gas(ses)
gW	Gigawatt
H_2	Hydrogen
H_2S	Hydrogen sulfide
HDPE	High-density polyethylene
HEMS	Home energy management system
HVAC	Heating, ventilation and air conditioning
HVDC	High-voltage direct current
IA	Innovation action
IEA	International Energy Agency
ILUC	Indirect land use change
IPCEI	Important Projects of Common European Interest
IRA	Inflation Reduction Act [United States]
IRENA	International Renewable Energy
IT	Information technology
JU	Joint undertaking
LCOE	Levelised cost of electricity
LCOH	Levelised cost of heating
LFP	Lithium(-ion) iron phosphate (technology)
LULUCF	Land use, land use change and forestry
MFF	Multiannual Financial Framework
Mtoe	Million tonnes of oil equivalent
mW	megawatt
NDC	Nationally determined contribution
NZIA	Net-Zero Industry Act [EU]

OEM	Original equipment manufacturer(s)
OPEX	Operating expenditure
ORE	Offshore Renewable Energy (Catapult)
OTEC	Ocean thermal energy conversion
PCP	Pre-commercial procuremenet
PEM	Proton-exchange membrane
PESTLE	Political, economic, social, technological, legal and environmental (analysis)
PFA	Polyfluoroalkyl
PFAS	Perfluoroalkyl substances
PTFE	Polytetrafluoroethylene
PV	Photovoltaic(s)
PVC	Polyvinyl chloride
PVPS	Photovoltaic Power Systems Programme (IEA)
R&I	Research and innovation
RAG	Red–amber–green (rating)
RD&D	Research, development and demonstration
RDI	Research, development and innovation
RED	Renewable energy directive
RFNBO	Renewable fuel of non-biological origin
RIA	Research and innovation action
RHC	(ETIP) Renewable Heating and Cooling
RRF	Recovery and Resilience Facility
S3	Smart specialisation strategies
SAF	Sustainable aviation fuel
ScMI	System control and management interface (software)
SDG	Sustainable Development Goal [United Nations]

SET	Strategic energy technology (plan)
SHIP	Solar heat for district heating and for industrial processes
SME	Small to medium-sized enterprises
S–O	Strength–Oppportunity
S–T	Strength–Threat
STEM	Science, technology, engineering and mathematics
SWOT	Strength, weakness, opportunity, threat (analysis)
TCP	Technology Collaboration Programme
TEN-E	Trans-European Networks for Energy
TES	Thermal energy storage
TNO	Netherlands Organisation for Applied Scientific Research
TOR	Terms of reference
TRL	Technology readiness level
TÜV SÜD	Technischer Überwachungsverein [Germany]
UAE	United Arab Emirates
US	United States (of America)
UTES	Underground thermal energy storage
VC	Venture capital
VIPV	Vehicle-integrated photovoltaics
WASCOP	Water Saving for Solar Concentrated Power [EU project]
W–O	Weakness–Opportunity
WP	Work package
W–T	Weakness–Threat
ZEWT	Zero-Emission Waterborne Transport

ABSTRACT

In the coming decades, energy security will depend less on uninterrupted access to fossil energy sources and will be increasingly determined by the access to clean energy technologies, materials and components. This study, delivered by RAND Europe, CE Delft and E3-Modelling for the European Commission, assessed the energy security challenges of value chains across 17 clean energy technologies now and looking to 2050, and identified 30 research and innovation actions to address them. The bespoke methodology brought together futures methods and macroeconomic modelling, value chains analysis and strategic decision-making tools to set out priorities for action.

Key criticalities identified included such issues as the abundance, availability and security of supply of critical raw materials; supply chain complexity, location and resilience; the sustainability and environmental impacts of energy technologies; public opinion and acceptability; affordability; and digital vulnerabilities. Specific criticalities by technology value chain have been identified and prioritised and corresponding research and innovation (R&I) actions have been proposed tailored to those specific issues. The R&I action plan comprises 30 actions that can be implemented at European Union (EU) and national levels to address the criticalities identified, with the top 9 highest-priority R&I actions identified based on a SWOT (strengths, weaknesses, opportunities and threats) analysis.

EXECUTIVE SUMMARY

In the coming decades, energy security[1] will depend less on uninterrupted access to fossil energy sources and will be increasingly determined by the access to clean energy technologies, materials and components. This study, delivered by RAND Europe, CE Delft and E3-Modelling for the European Commission, aims to assess the energy security challenges of clean energy value chains now and looking to 2050, and to identify research and innovation (R&I) actions to address them.

Study approach. The methodology for this study brings together plausible future scenarios complemented with macroeconomic modelling from GEM-E3, with in-depth analysis of the energy security components of clean energy technology value chains. With this understanding of internal strengths and weaknesses for energy security and external opportunities and threats, R&I interventions were identified and strategically prioritised, with the aim to strengthen European energy security.

Future considerations for EU clean energy security. Three scenario narratives were developed to explore the context influencing EU clean energy security. Key drivers of change include the pace of EU and global decarbonisation, international relations and global trade, geopolitical uncertainty and conflict, digitalisation and cybersecurity, and climate adaptation.

Energy security criticalities of clean energy technology value chains. Analysis was conducted for 48 specific clean energy technology value chains across 17 technologies: advanced biofuels, bioenergy, concentrated solar energy, geothermal energy, hydropower, ocean energy, photovoltaics (PV), wind energy, direct solar fuels, carbon capture utilisation and storage, electricity and heat storage (including batteries, hydrogen and intermediate energy carriers), heat pumps, smart energy grid technologies, energy building and district heating technologies, off-grid energy systems, energy transmission and distribution technologies, and smart cities. For each technology, we identified energy security criticalities (points of failure in the value chain) based on the assessment of each value chain against 10 key indicators: geopolitical availability of critical raw materials (CRMs); natural abundance of CRMs and biomass; circularity of the value chain; supply chain complexity; supply chain location (with the assumption that value chains outside the EU are less secure); digital vulnerability; physical vulnerability; broader sustainability; affordability; and skills. We also holistically assessed these criticalities in the context of the wider technology clusters. The key energy security criticalities were then shortlisted for R&I intervention based on qualitative assessment and expert judgement, with consideration of the assessment against energy security indicators as described above and of the future scenarios and how they may interact with these indicators at two time points: 2030 and 2050. We also took into account the expected scale of the technology and its role in the energy system. This generated a list of criticalities against which we could generate potential R&I actions.

R&I action plan. R&I can help develop a greater understanding or solutions to challenges. This action plan was developed based on strengths, weaknesses, opportunities, and threats (SWOT) analysis of the EU R&I ecosystem; a review of existing R&I programmes; and expert input to ensure relevance, feasibility, potential impact and futureproofing. Actions were shortlisted and prioritised in the following steps:

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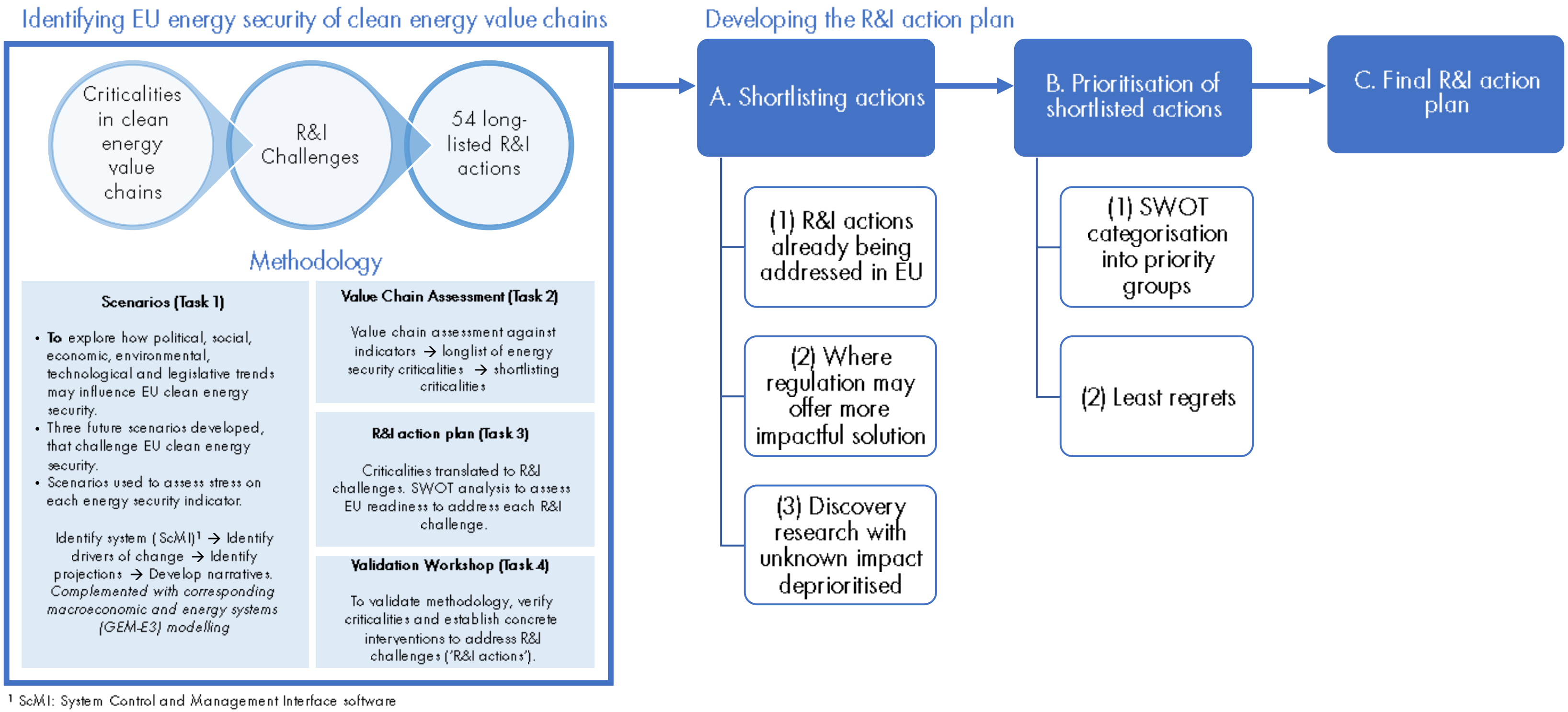
[1] Energy security is defined by the International Energy Agency as 'the uninterrupted availability of energy sources at an affordable price'.

Figure 1. Representation of the study methodology and steps towards identifying the final R&I action plan. ScMI = system control and management interface software.



In the table below, we present the top 9 highest-priority R&I actions, prioritised based on our SWOT analysis. Full details on all 30 actions are provided in Section 10, including criticalities covered, expected outcome and scope (which criticality and value chain the action addresses), suggested technology readiness level (TRL) by the end of the project, and potential funding programmes.

Highest-priority energy security criticalities	R&I actions	Relevant value chain
Batteries *Supply chain location*	**Improving the energy efficiency of battery manufacturing and recycling** *Improving the energy efficiency of these processes would provide a mechanism to increase competitiveness for an EU-based supply chain; address currently missing capabilities, such as raw materials processing; and develop skills and know-how for an EU battery supply chain.*	Lithium-based batteries
CRM *Security of supply of CRMs*	**Research and public engagement on mining of CRMs** *Research and public engagement on mining of CRMs would provide a better understanding of public concerns and mechanisms to address them (e.g. sustainable mining practices with minimal environmental impact, improved working conditions and operations). This will be important to enable domestic production to be increased, thereby de-risking a range of clean energy technologies, and would inform both technical approaches and policy and regulation in this area, as well as international production to ensure consistent supply and imports from countries outside of the EU. This is a shared, international challenge requiring cooperation.*	Mining of all CRM, in particular: cadmium telluride and perovskite PV (supply of cadmium, telluride, copper, lead); batteries (cobalt, lithium); semiconductors and microchips in smart technologies, where public opposition is a risk within and out of the EU due to mining practices and environmental impact
Energy transmission and distribution technologies *Availability and abundance of CRMs (copper and aluminium)*	**Increasing circular economy processes, recycling and reuse of electronics for smart energy technologies** *R&I programme to increase recycling and reuse in energy transmission and distribution and develop the sustainable production of aluminium and other alternatives. The call would take a two-pronged approach, looking at opportunities to replace copper with aluminium more energy efficiently, and considering how to incorporate sustainable aluminium.*	HVDC cabling
Geothermal energy *Availability and abundance of CRMs (aluminium, copper, nickel, titanium, chromium)*	**Implementing a 'design-to-recycling' scheme for geothermal energy** *This Horizon Europe call would aim to implement a 'design-to-recycling' scheme, including reducing and reusing CRMs in geothermal energy.*	Construction phase of geothermal plants (CRM use), end-of-life phase (all materials, including for casing and cementing)

Hydrogen *Supply chain resilience*	**A call for solutions to increase the resilience of hydrogen value chains** *With hydrogen technologies still in development, a call would support the development of solutions to increase the resilience of a future commercial value chain. This may include digital solutions, process efficiency improvements, reduced reliance on CRMs and water, design considerations for reduced complexity, and standard performance benchmarks.*	Solid oxide electrolysers (work at high temperature), electrodes and catalysts (CRM), and anion-exchange membranes (AEM) (membrane component, water use)
Compressed air energy storage (CAES) *Sustainability and environmental impacts*	**Developing a better understanding of the potential locations for underground CAES** *This research programme would aim to develop a better understanding of the potential locations for underground CAES. The extensive exploration for underground storage space adds considerable complexity to the construction and use of CAES, since CAES can only be deployed in areas where suitable underground cavities are available. The (environmental) risks of compressed air storage in depleted gas fields are relatively unknown and necessitate additional research. This could also reduce local social acceptance.*	Compressor and expansion system, above-ground storage tanks prior to injection, location of storage sites
PV *Supply chain location*	**Collaborative industry programme to increase the efficiency of PV manufacturing in the EU** *This Horizon Europe collaborative industry programme would support initial new supply chains focused on increasing the efficiency of solar PV manufacturing processes in the EU. This would support the development of solutions enabling onshoring and cost competitiveness of EU-based PV supply chains.*	Construction of silicon-based PV modules and CRMs within modules
Smart energy grid technologies and energy building and district technologies *Digital vulnerability*	**Addressing cybersecurity risks to smart energy grid, building and district heating technologies** *This intervention would develop solutions to address cybersecurity risks, including research to ensure cybersecurity can be maintained for legacy systems. Understanding of the landscape of threats will help inform regulation and standards.*	Advanced metering infrastructure, advanced control technologies and home energy management systems

Smart energy grids, smart cities, and energy building and district heating technologies *Availability and abundance of CRMs and location of advanced electronics supply chains (palladium, cobalt, gallium, germanium, silicon, rare-earth materials)*	**Increasing circular economy processes, recycling and reuse of electronics for smart energy technologies** *Recycling and reuse of electronics is currently low, and as early generation technologies reach end of life, there is an opportunity to support EU supply through recycling and reuse of these resources. This intervention would develop circular economy processes to increase the recycling and reuse of electronics for smart energy technologies. In particular, this should focus on the opportunities to reuse CRMs and will provide mechanisms to increase self-sufficiency within the EU.*	Construction and end-of-life phases in these technologies (less relevant for electric vehicle smart charging), including e-waste and cable waste and advanced metering infrastructure (which often incorporates semiconductors)

RÉSUMÉ ANALYTIQUE

Au cours des prochaines décennies, la sécurité énergétique[2] dépendra moins de l'accès ininterrompu aux sources d'énergie fossile et sera de plus en plus déterminée par l'accès aux technologies, matériaux et composants énergétiques propres. Cette étude, réalisée par RAND Europe, CE Delft et E3-Modelling pour la Commission européenne, vise à évaluer les défis des filières des énergies propres en matière de sécurité énergétique à l'heure actuelle, et à l'horizon 2050, et à identifier les actions à entreprendre en termes de recherche et d'innovation (R&I) pour y répondre.

Approche de l'étude. La méthodologie proposée pour cette étude rassemble des scénarios futurs plausibles complétés par la modélisation macroéconomique de GEM-E3, avec une analyse approfondie des composantes des filières des technologies de l'énergie propre en matière de sécurité énergétique. En comprenant les forces et les faiblesses intrinsèques en matière de sécurité énergétique, ainsi que les opportunités et les menaces externes, des interventions de recherche et d'innovation ont été identifiées et hiérarchisées stratégiquement dans le but de renforcer la sécurité énergétique à l'échelle européenne.

Considérations futures pour la sécurité énergétique en matière d'énergie propre. Trois scénarios ont été élaborés pour explorer le contexte qui influence la sécurité énergétique de l'UE en matière d'énergie propre. Les principaux facteurs de changement incluent le rythme de la décarbonisation au niveau européen et mondial, les relations internationales et le commerce mondial, l'incertitude et les conflits géopolitiques, la numérisation et la cybersécurité, ainsi que l'adaptation au climat.

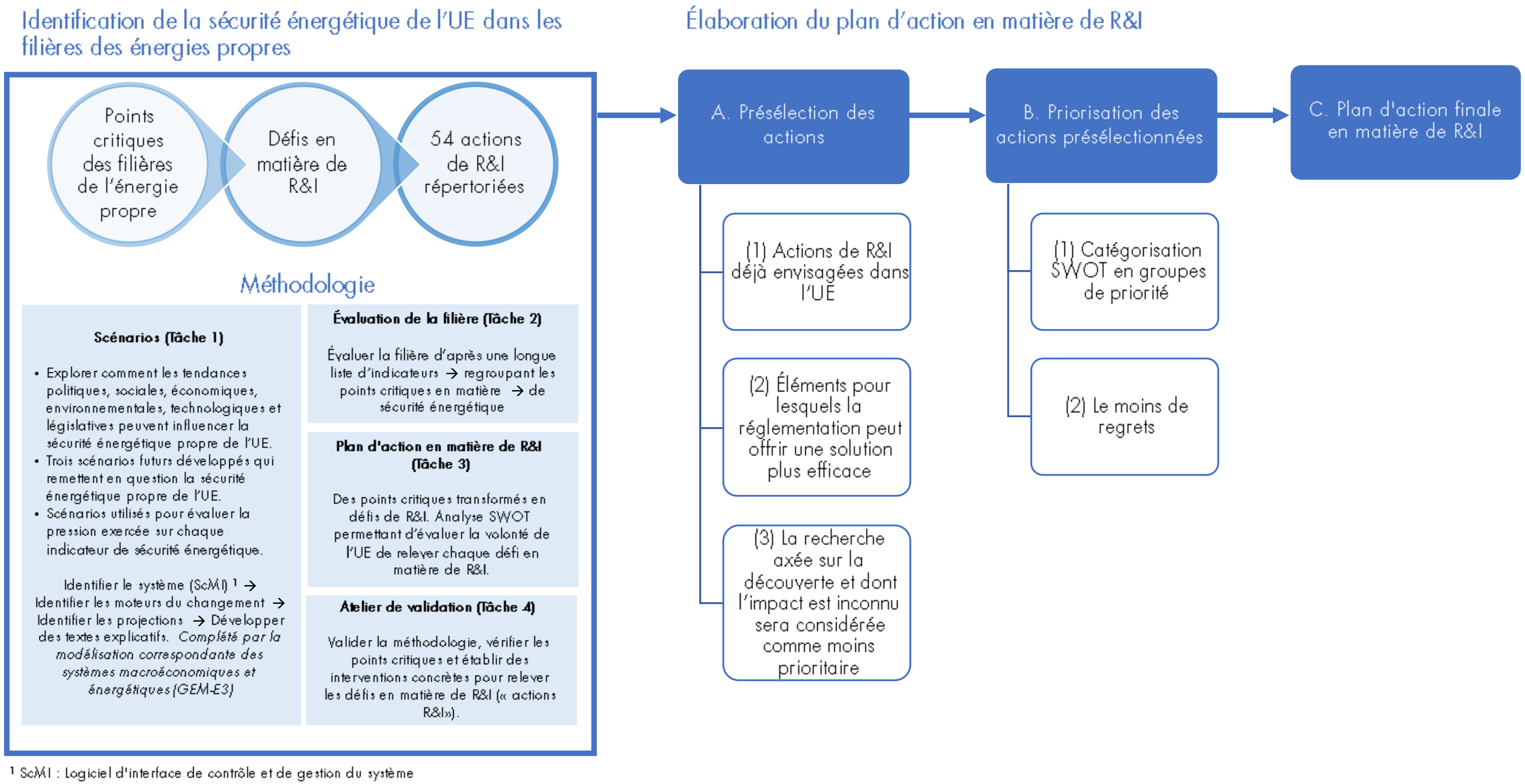
Aspects critiques en matière de sécurité énergétique dans les filières des technologies de l'énergie propre. L'analyse a été menée pour 48 filières spécifiques aux technologies de l'énergie propre dans 17 technologies : les biocarburants avancés, la bioénergie, l'énergie solaire concentrée, l'énergie géothermique, l'hydroélectricité, l'énergie océanique, le photovoltaïque (PV), l'énergie éolienne, les combustibles solaires directs, le captage, l'utilisation et le stockage du carbone, l'électricité et le stockage de la chaleur (y compris les batteries, l'hydrogène et les vecteurs énergétiques intermédiaires), les pompes à chaleur, les technologies des réseaux énergétiques intelligents, les technologies relatives aux bâtiments énergétiques et au chauffage urbain, les systèmes énergétiques hors réseau, les technologies de transmission et de distribution d'énergie et les villes intelligentes. Pour chaque technologie, nous avons identifié les points critiques en matière de sécurité énergétique (points faibles de la filière) sur la base de l'évaluation de chaque filière par rapport à 10 indicateurs clés : la disponibilité géopolitique des matières premières critiques (CRM); l'abondance naturelle des CRM et de la biomasse; la circularité de la filière; la complexité de la chaîne d'approvisionnement; la localisation de la chaîne d'approvisionnement (en partant du principe que les filières en dehors de l'UE sont moins sécurisées); la vulnérabilité numérique; la vulnérabilité physique; une perspective durable plus large; la viabilité financière et les compétences. Nous avons également évalué ces aspects critiques de manière globale dans le contexte de pôles technologiques plus larges. Les principaux aspects critiques en matière de sécurité énergétique ont ensuite été présélectionnés afin d'orienter la R&I sur ces éléments spécifiques, sur la base d'une évaluation qualitative et du jugement d'experts, en tenant compte de l'évaluation établie par rapport aux indicateurs de sécurité énergétique décrits ci-dessus, des scénarios futurs et de la manière dont ils peuvent interagir avec ces indicateurs à deux moments spécifiques : en 2030 et en 2050. Nous avons également pris en compte l'ampleur attendue de la technologie

[2] La sécurité énergétique est définie comme « la disponibilité ininterrompue de sources d'énergie à un prix abordable », d'après l'Agence internationale de l'énergie, Energy Security.

et son rôle dans le système énergétique. Une liste des points critiques face auxquels nous pourrions entreprendre des actions potentielles en matière de R&I a ainsi pu être établie.

Plan d'action en matière de R&I. La R&I peut améliorer notre compréhension et apporter des solutions aux défis qui s'imposent. Ce plan d'action a été élaboré sur la base d'une analyse des forces, des faiblesses, des opportunités et des menaces (SWOT) de l'écosystème R&I de l'UE, d'un examen des programmes de R&I existants et de la contribution d'experts pour garantir la pertinence, la faisabilité, l'impact potentiel et la pérennité des actions mises en place. Les actions ont été présélectionnées et hiérarchisées selon les étapes suivantes :

Image 2. Représentation de la méthodologie de l'étude et des étapes menant à l'identification du plan d'action final en matière de R&I. ScMI = Logiciel d'interface de contrôle et de gestion du système.



Dans le tableau ci-dessous, nous présentons les 9 actions de R&I les plus prioritaires, classées par ordre de priorité sur la base de notre analyse SWOT. Des détails complets sur les 30 actions sont disponibles dans la Section 10, y compris les éléments critiques couverts, les résultats attendus et la portée (à quelle criticité et filière l'action permet de répondre), le niveau de maturité technologique (TRL) suggéré d'ici la fin du projet et les programmes de financement potentiels.

Points critiques les plus prioritaires en matière de sécurité énergétique	Actions de R&I	Filière pertinente
Batteries *Emplacement de la chaîne d'approvisionnement*	**Amélioration de l'efficacité énergétique dans la fabrication et le recyclage des batteries** *L'amélioration de l'efficacité énergétique de ces processus fournirait un mécanisme permettant d'accroître la compétitivité d'une chaîne d'approvisionnement basée dans l'UE, de remédier aux compétences actuellement manquantes, telles que le traitement des matières premières, et de développer les compétences et le savoir-faire pour une chaîne d'approvisionnement européenne des batteries.*	Batteries au lithium
CRM *Sécurité d'approvisionnement des CRM*	**Recherche et engagement du public concernant l'exploitation minière des CRM** *La recherche et l'engagement du public concernant l'exploitation minière des CRM permettraient de mieux comprendre les préoccupations du public et les mécanismes permettant d'y répondre (par exemple, des pratiques minières durables avec un impact environnemental minimal, des conditions de travail et des opérations améliorées). Ce point sera important pour augmenter la production nationale, réduire les risques liés à certaines technologies énergétiques propres, et obtenir des informations essentielles sur les approches techniques, les politiques et la réglementation dans ce domaine, ainsi que sur la production internationale nécessaire pour garantir un approvisionnement et des importations constants en provenance de pays extérieurs à l'UE. Il s'agit d'un défi international partagé qui nécessite la coopération de tous.*	L'extraction de tous les CRM, notamment : le tellurure de cadmium et les cellules photovoltaïques à pérovskite (approvisionnement en cadmium, tellurure, cuivre, plomb); les batteries (cobalt, lithium); les semi-conducteurs et les puces électroniques dans les technologies intelligentes, où l'opposition du public représente un risque au sein et hors de l'UE en raison des pratiques minières et de l'impact environnemental
Technologies de transport et de distribution de l'énergie *Disponibilité et abondance des CRM (cuivre et aluminium)*	**Augmentation des processus d'économie circulaire, de recyclage et de réutilisation de l'électronique pour les technologies énergétiques intelligentes** *Programme de R&I visant à augmenter le recyclage et la réutilisation dans le transport et la distribution de l'énergie et à développer la production durable d'aluminium et d'autres alternatives. L'approche mise en place serait double : examiner les possibilités*	Câblage HVDC

	de remplacer le cuivre par de l'aluminium de manière plus efficace sur le plan énergétique et la manière d'incorporer de l'aluminium durable.	
Énergie géothermique *Disponibilité et abondance des CRM (aluminium, cuivre, nickel, titane, chrome)*	**Mise en œuvre d'un programme de « conception jusqu'au recyclage » pour l'énergie géothermique** *Cet appel d'Horizon Europe viserait à mettre en œuvre un programme de « conception jusqu'au recyclage », incluant la réduction et la réutilisation des CRM dans l'énergie géothermique.*	Phase de construction des centrales géothermiques (utilisation des CRM), phase de fin de vie (pour tous les matériaux, y compris pour le tubage et la cimentation)
Hydrogène *Résilience de la chaîne d'approvisionnement*	**Un appel à trouver des solutions pour accroître la résilience des filières de l'hydrogène** *Les technologies de l'hydrogène étant encore en développement, un appel soutiendrait le développement de solutions permettant d'accroître la résilience d'une future filière commerciale. Cet appel peut inclure des solutions numériques, des améliorations de l'efficacité des processus, une diminution de la dépendance aux CRM et à l'eau, des considérations en termes de conception visant à simplifier les processus et les indicateurs de performance.*	Électrolyseurs à oxyde solide (fonctionnant à haute température), électrodes et catalyseurs (CRM) et membranes échangeuses d'anions (AEM) (composant de membrane, consommation d'eau)
Stockage d'énergie par air comprimé (CAES) *Durabilité et impacts environnementaux*	**Développement d'une meilleure compréhension des emplacements potentiels pour les CAES souterrains** *Ce programme de recherche viserait à mieux comprendre les emplacements potentiels des CAES souterrains. L'exploration approfondie de l'espace de stockage souterrain ajoute une complexité considérable à la construction et à l'utilisation du CAES, puisque le CAES ne peut être déployé que dans des zones où des cavités souterraines appropriées sont disponibles. Les risques (environnementaux) associés au stockage de l'air comprimé dans des champs de gaz épuisés sont relativement inconnus et nécessitent des recherches approfondies. Ce programme pourrait également accroître l'acceptance sociale locale.*	Système de compression et de détente, réservoirs de stockage hors sol avant injection, emplacement des sites de stockage
PV *Emplacement de la chaîne d'approvisionnement*	**Programme industriel collaboratif visant à accroître l'efficacité de la fabrication de produits photovoltaïques dans l'UE** *Ce programme industriel collaboratif Horizon Europe soutiendrait les nouvelles chaînes d'approvisionnement initiales axées sur l'augmentation de l'efficacité des processus de fabrication de l'énergie solaire photovoltaïque dans l'UE. Il permettrait de soutenir le développement de solutions permettant la relocalisation et la compétitivité des coûts des chaînes d'approvisionnement photovoltaïques basées dans l'UE.*	Construction de modules PV à base de silicium et CRM dans les modules

Technologies de réseaux énergétiques intelligents et technologies de bâtiments et de quartiers énergétiques *Vulnérabilité numérique*	**Réponse aux risques de cybersécurité liés aux technologies de réseaux énergétiques intelligents, de bâtiments et de chauffage urbain** *Cette intervention permettrait de développer des solutions pour faire face aux risques associés à la cybersécurité, y compris des recherches visant à garantir que la cybersécurité puisse être maintenue pour les systèmes existants. La compréhension du paysage des menaces contribuera à éclairer la réglementation et les normes.*	Infrastructure de compteurs avancée, technologies de contrôle avancées et systèmes de gestion de l'énergie domestique
Réseaux énergétiques intelligents, villes intelligentes, bâtiments énergétiques et technologies de chauffage urbain *Disponibilité et abondance des CRM et localisation des chaînes d'approvisionnement en électronique avancée (palladium, cobalt, gallium, germanium, silicium, matériaux issus de terres rares)*	**Augmentation des processus d'économie circulaire, de recyclage et de réutilisation de l'électronique pour les technologies énergétiques intelligentes** *Le recyclage et la réutilisation des produits électroniques sont très limités pour le moment et, à mesure que les technologies de première génération arrivent en fin de vie, il existe une réelle opportunité de soutenir l'approvisionnement de l'UE en recyclant et en réutilisant ces ressources. Cette intervention permettrait de développer des processus d'économie circulaire pour accroître le recyclage et la réutilisation des appareils électroniques pour les technologies énergétiques intelligentes. Cette action devrait notamment se concentrer sur les possibilités de réutilisation des CRM et fournira des mécanismes permettant d'accroître l'autosuffisance au sein de l'UE.*	Phases de réalisation et de fin de vie de ces technologies (moins pertinentes pour la recharge intelligente des véhicules électriques), y compris les déchets électroniques et les déchets générés par les câbles, l’infrastructure de compteurs avancée (intégrant souvent des semi-conducteurs)

ZUSAMMENFASSUNG

In den kommenden Jahrzehnten wird die Energiesicherheit[3] weniger vom ununterbrochenen Zugang zu fossilen Energieträgern abhängen, sondern zunehmend durch den Zugang zu sauberen Energietechnologien, Materialien und Komponenten bestimmt werden. Die vorliegende Studie, die von RAND Europe, CE Delft und E3-Modelling für die Europäische Kommission durchgeführt wurde, zielt darauf ab, die Herausforderungen für die Energiesicherheit in Wertschöpfungsketten für saubere Energie jetzt und bis 2050 zu bewerten und Maßnahmen für Forschung und Innovation (F&I) zur Bewältigung dieser Herausforderungen zu identifizieren.

Studienansatz. Die für die vorliegende Studie vorgeschlagene Methodik kombiniert plausible Zukunftsszenarien, die durch makroökonomische Modellierung von GEM-E3 ergänzt werden, mit einer eingehenden Analyse der Energiesicherheitskomponenten von Wertschöpfungsketten für saubere Energietechnologien. Mit diesem Verständnis der internen Stärken und Schwächen der Energiesicherheit und der externen Chancen und Bedrohungen wurden Maßnahmen für Forschung und Innovation identifiziert und strategisch priorisiert, um die europäische Energiesicherheit zu stärken.

Künftige Überlegungen zur Sicherheit für saubere Energie in der EU. Es wurden drei Szenarien zur Untersuchung des Kontextes erarbeitet, der die Sicherheit für saubere Energie in der EU beeinflusst. Zu den wichtigsten Triebkräften des Wandels gehören das Tempo der Dekarbonisierung in der EU und weltweit, internationale Beziehungen und der Welthandel, geopolitische Unsicherheit und Konflikte, Digitalisierung und Cybersicherheit sowie die Anpassung an den Klimawandel.

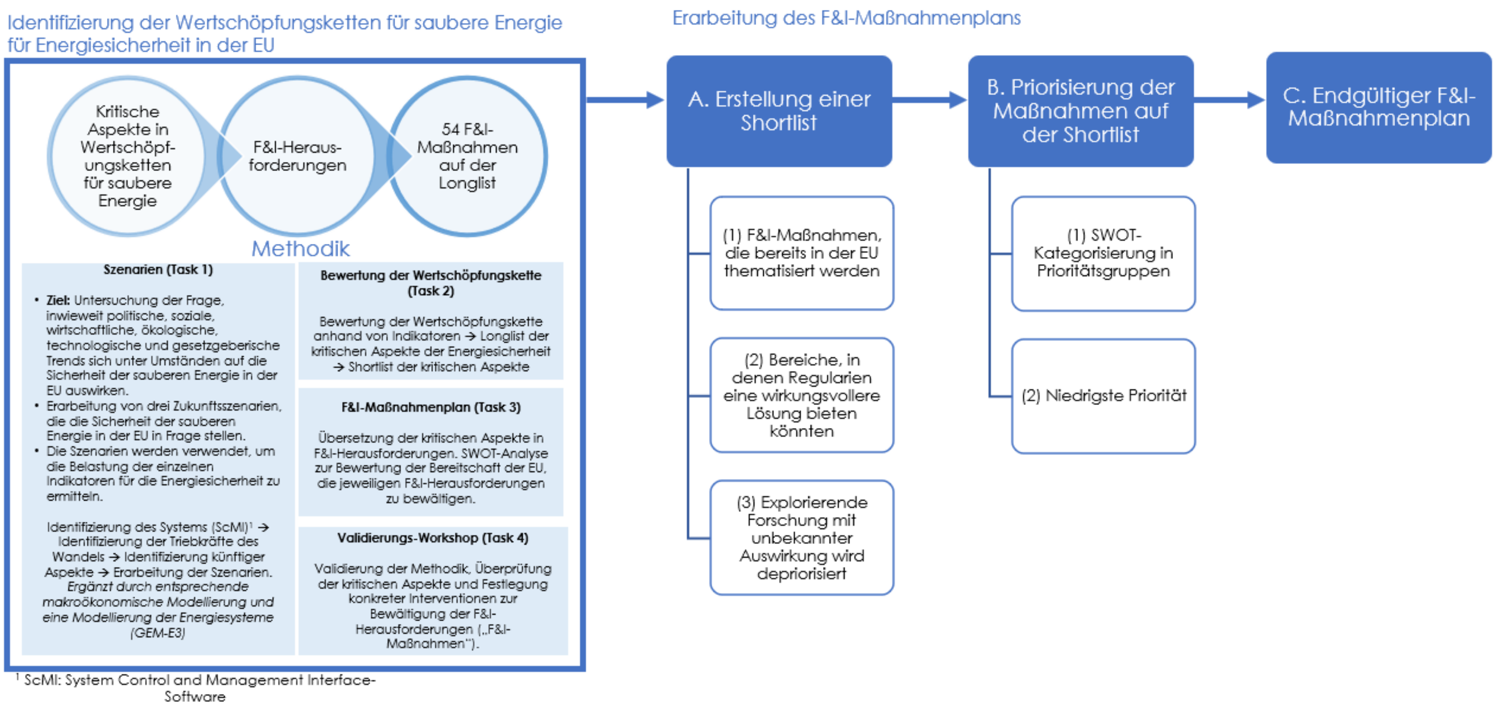
Kritische Aspekte der Energiesicherheit in Wertschöpfungsketten für saubere Energietechnologien. Die Analyse wurde für 48 spezifische Wertschöpfungsketten für saubere Energietechnologien in 17 Technologien durchgeführt: Fortschrittliche Biokraftstoffe, Bioenergie, konzentrierte Solarenergie, geothermische Energie, Wasserkraft, Meeresenergie, Photovoltaik (PV), Windenergie, direkte Solarkraftstoffe, Nutzung von Kohlenstoffabscheidung und Speicherung von Kohlenstoff, Strom- und Wärmespeicherung (einschließlich Batterien, Wasserstoff und Zwischenenergieträgern), Wärmepumpen, intelligente Energienetztechnologien, Energiegebäude- und Fernwärmetechnologien, netzunabhängige Energiesysteme, Technologien zur Energieübertragung und -verteilung und intelligente Städte. Wir identifizierten für jede Technologie die kritischen Aspekte der Energiesicherheit (Problemstellen in der Wertschöpfungskette), indem wir jede Wertschöpfungskette anhand von 10 Schlüsselindikatoren bewerteten: geopolitische Verfügbarkeit von kritischen Rohstoffen (critical raw materials, CRM), natürlicher Reichtum an kritischen Rohstoffen und Biomasse, Kreislauffähigkeit der Wertschöpfungskette, Komplexität der Lieferkette, Standort der Lieferkette (unter der Annahme, dass Wertschöpfungsketten außerhalb der EU weniger sicher sind), digitale Vulnerabilität, physische Vulnerabilität, allgemeine Nachhaltigkeit, Erschwinglichkeit und Fähigkeiten. Wir bewerteten diese kritischen Aspekte auch ganzheitlich im Kontext der größeren Technologiecluster. Die wichtigsten kritischen Aspekte der Energiesicherheit wurden dann auf der Grundlage einer qualitativen Bewertung und eines Urteils von Expert*innen in die engere Wahl für Maßnahmen für F&I einbezogen, wobei die Bewertung anhand der oben beschriebenen Indikatoren für die Energiesicherheit sowie der Zukunftsszenarien und deren möglicher Wechselwirkung mit diesen Indikatoren zu zwei Zeitpunkten berücksichtigt wurden: 2030 und 2050. Wir berücksichtigten auch den erwarteten Umfang der Technologie

[3] Energiesicherheit wird definiert als „die ununterbrochene Verfügbarkeit von Energiequellen zu einem erschwinglichen Preis, Internationale Energieagentur, Energiesicherheit.

und deren Rolle im Energiesystem. So entstand eine Liste kritischer Aspekte, anhand derer wir potenzielle F&I-Maßnahmen erarbeiten konnten.

F&I-Maßnahmenplan. F&I kann bei der Entwicklung eines besseren Verständnisses bzw. bei der Entwicklung von Lösungen für Herausforderungen helfen. Dieser Maßnahmenplan wurde auf der Grundlage einer Stärken-Schwächen-Chancen-Bedrohungen-Analyse (SWOT) des F&I-Ökosystems der EU, einer Überprüfung der bestehenden F&I-Programme und der Beiträge von Expert*innen erarbeitet, um Relevanz, Machbarkeit, potenzielle Auswirkungen und Zukunftssicherheit zu gewährleisten. Die Erstellung einer engeren Auswahl der Maßnahmen und ihre Einordnung nach Priorität geschah in den folgenden Schritten:

Abb. 3. Grafische Darstellung der Studienmethodik und der Schritte zur Ermittlung des endgültigen F&I-Maßnahmenplans. ScMI = Systemsteuerungs- und Verwaltungsschnittstellensoftware.



In der nachstehenden Tabelle präsentieren wir die 9 wichtigsten F&I-Maßnahmen, auf Grundlage unserer SWOT-Analyse nach Prioritäten geordnet. Vollständige Angaben zu allen 30 Maßnahmen finden Sie in Abschnitt 10, einschließlich der abgedeckten kritischen Aspekte, des erwarteten Ergebnisses und des Umfangs (auf welchen kritischen Aspekt und auf welche Wertschöpfungskette die Maßnahme abzielt), des vorgeschlagenen Technologie-Reifegrads (technology readiness level, TRL) am Ende des Projekts und der potenziellen Finanzierungsprogramme.

Kritische Aspekte der Energiesicherheit mit höchster Priorität	F&I-Maßnahmen	Relevante Wertschöpfungskette
Batterien *Standort der Lieferkette*	**Verbesserung der Energieeffizienz bei Herstellung und Recycling von Batterien** *Die Verbesserung der Energieeffizienz dieser Prozesse würde einen Mechanismus bereitstellen, der die Wettbewerbsfähigkeit einer EU-basierten Lieferkette erhöhen, die derzeit fehlenden Kapazitäten wie z. B. Rohstoffverarbeitung angehen und Fähigkeiten und Knowhow für eine Batterie-Lieferkette in der EU entwickeln würde.*	Lithium-Batterien
Kritische Rohstoffe (CRM) *Sicherheit der kritischen Rohstoffversorgung*	**Forschung und öffentliches Engagement für den Abbau kritischer Rohstoffe** *Forschung und Beteiligung der Öffentlichkeit im Bereich Abbau kritischer Rohstoffe würden zu einem besseren Verständnis der Bedenken der Öffentlichkeit und zu Mechanismen führen, mit denen diese Bedenken ausgeräumt werden könnten (z. B. nachhaltige Abbaupraktiken mit minimalen Umweltauswirkungen, verbesserte Arbeitsbedingungen und -abläufe). Dies ist wichtig, um die heimische Produktion zu steigern und so die Risiken einer Reihe sauberer Energietechnologien zu reduzieren. Dies würde auch die technischen Ansätze sowie die Politik und Regulatorik in diesem Bereich beeinflussen, ebenso wie die internationale Produktion, um eine konsistente Versorgung und Importe aus Ländern außerhalb der EU sicherzustellen. Dies ist eine gemeinsame, internationale Herausforderung, die Zusammenarbeit erfordert.*	Abbau aller kritischen Rohstoffe, insbesondere: Cadmiumtellurid und Perowskit-Photovoltaik (Lieferung von Cadmium, Tellurid, Kupfer, Blei), Batterien (Kobalt, Lithium), Halbleiter und Mikrochips in intelligenten Technologien, bei denen aufgrund der Abbaupraktiken und der Umweltauswirkungen öffentlicher Widerstand innerhalb und außerhalb der EU droht
Technologien zur Energieübertragung und -verteilung *Verfügbarkeit von/Reichtum an kritischen Rohstoffen (Kupfer und Aluminium)*	**Förderung von Kreislaufwirtschaftsprozessen, Recycling und Wiederverwendung von Elektronik für intelligente Energietechnologien** *F&I-Programm zur Steigerung des Recyclings und der Wiederverwendung bei der Energieübertragung und -verteilung sowie zur Entwicklung einer nachhaltigen Produktion von Aluminium und anderen Alternativen. Der Ausschreibung würde einen zweigleisigen Ansatz verfolgen, indem nach Möglichkeiten gesucht wird, Kupfer energieeffizienter durch Aluminium zu ersetzen, und indem überlegt wird, wie nachhaltiges Aluminium eingesetzt werden kann.*	HVDC-Kabel

Geothermische Energie *Verfügbarkeit von/Reichtum an kritischen Rohstoffen (Aluminium, Kupfer, Nickel, Titan, Chrom)*	**Umsetzung eines umfassenden Systems von der Konstruktion bis hin zum Recycling für geothermische Energie** *Dieser Ausschreibung von Horizont Europa würde darauf abzielen, ein vollumfassendes System von der Konstruktion bis zum Recycling umzusetzen, das auch die Reduzierung und Wiederverwendung von kritischen Rohstoffen in der Geothermie einschließt.*	Bauphase von geothermischen Anlagen (Nutzung kritischer Rohstoffe), End-of-Life-Phase (alle Materialien, auch für Gehäuse und Zementierung)
Wasserstoff *Stabilität der Lieferkette*	**Ein Ausschreibung zur Findung von Lösungen, um die Stabilität von Wertschöpfungsketten für Wasserstoff zu erhöhen** *Da sich Wasserstofftechnologien noch in der Entwicklung befinden, würde ein Ausschreibung die Entwicklung von Lösungen unterstützen, die die Stabilität einer zukünftigen kommerziellen Wertschöpfungskette erhöhen. Dazu können digitale Lösungen, Verbesserungen der Prozesseffizienz, eine geringere Abhängigkeit von kritischen Rohstoffen und Wasser, Designüberlegungen zur Verringerung der Komplexität und Standard-Leistungsbenchmarks gehören.*	Festoxid-Elektrolyseure (arbeiten bei hohen Temperaturen), Elektroden und Katalysatoren (kritische Rohstoffe) und Anionenaustauschmembranen (AEM) (Membrankomponente, Wasserverbrauch)
Druckluftenergiespeicher (CAES) *Nachhaltigkeit und Umweltauswirkungen*	**Entwicklung eines besseren Verständnisses der potenziellen Standorte für unterirdische Druckluftenergiespeicher (CAES)** *Dieses Forschungsprogramm würde darauf abzielen, ein besseres Verständnis der potenziellen Standorte für unterirdische Druckluftenergiespeicher (CAES) zu entwickeln. Die umfangreiche Suche nach unterirdischen Speicherräumen erhöht die Komplexität des Baus und der Nutzung von CAES erheblich, da CAES nur in Gebieten eingesetzt werden können, in denen geeignete unterirdische Kavernen vorhanden sind. Die (Umwelt-)Risiken einer Druckluftspeicherung in erschöpften Gasfeldern sind relativ unbekannt und bedürfen weiterer Forschung. Dies könnte auch die gesellschaftliche Akzeptanz erhöhen.*	Kompressor- und Expansionssystem, oberirdische Lagertanks vor der Injektion, Standort der Lagerstätten
Photovoltaik (PV) *Standort der Lieferkette*	**Gemeinsames Industrieprogramm zur Steigerung der Effizienz der PV-Herstellung in der EU** *Dieses gemeinsame Industrieprogramm von Horizon Europe würde erste neue Lieferketten unterstützen, die sich auf die Steigerung der Effizienz von Solar-PV-Herstellungsprozessen in der EU konzentrieren. Dies würde die Entwicklung von Lösungen unterstützen, die das Onshoring (die Inlandsverlagerung) und die Kostenwettbewerbsfähigkeit von PV-Lieferketten in der EU ermöglichen.*	Konstruktion von PV-Modulen auf Basis von Silizium und kritischen Rohstoffen in Modulen

Intelligente Energienetztechnologien und Energiegebäude- und Fernwärmetechnologien *Digitale Vulnerabilität*	**Bewältigung von Cybersicherheitsrisiken für intelligente Energienetz-, Gebäude- und Fernwärmetechnologien** *Im Rahmen dieser Intervention würden Lösungen zur Bewältigung von Cybersicherheitsrisiken entwickelt, einschließlich Forschung zur Sicherstellung, dass die Cybersicherheit für Altsysteme aufrechterhalten werden kann. Das Verständnis der Bedrohungslandschaft wird dazu beitragen, Regularien und Standards zu entwickeln.*	Moderne Zählerinfrastruktur, fortschrittliche Steuerungstechnologien und Energiemanagementsysteme für Privathaushalte
Intelligente Energienetze, intelligente Städte und Energiegebäude- und Fernwärmetechnologien *Verfügbarkeit von/Reichtum an kritischen Rohstoffen und Standort der Lieferketten für hochmoderne Elektronik (Palladium, Kobalt, Gallium, Germanium, Silizium, seltene Erden)*	**Förderung von Kreislaufwirtschaftsprozessen, Recycling und Wiederverwendung von Elektronik für intelligente Energietechnologien** *Derzeit wird Elektronik nur in geringen Anteilen recycelt und wiederverwendet, und mit Ende der Lebensdauer von Technologien der ersten Generation ergibt sich eine Gelegenheit, die Versorgung der EU durch Recycling und Wiederverwendung dieser Ressourcen zu unterstützen. Im Rahmen dieser Intervention würden Kreislaufwirtschaftsprozesse entwickelt, um das Recycling und die Wiederverwendung von Elektronik für intelligente Energietechnologien zu erhöhen. Der Fokus sollte hier insbesondere auf den Möglichkeiten der Wiederverwendung kritischer Rohstoffe liegen und wird Mechanismen zur Erhöhung der Selbstversorgung innerhalb der EU bereitstellen.*	Bau- und End-of-Life-Phasen dieser Technologien (weniger relevant für intelligentes Laden von Elektrofahrzeugen), einschließlich Elektroschrott, Kabelabfall und fortschrittlicher Zählerinfrastruktur (die oft Halbleiter enthält)

INTRODUCTION

Commissioned under specific contract RTD/2022/SC/023 – Study on clean energy R&I opportunities to ensure European energy security by targeting challenges of distinct energy value chains for 2030 and beyond, RAND Europe, with partners CE Delft and E3-Modelling, have delivered a timely study on clean energy R&I opportunities to ensure European energy security by targeting challenges of distinct energy value chains for 2030 and beyond. Recent events have brought Europe's vulnerabilities in energy security to the fore, with the energy crisis following Russia's invasion of Ukraine compounded by the lingering financial, supply chain and economic impact of the COVID-19 pandemic.[4] This study identified the energy security challenges of clean energy value chains now and in future and identify research and innovation (R&I) actions to address them.

With the urgency of the climate crisis, the EU has set out proposals in the Fit for 55 package to reduce net greenhouse gas (GHG) emissions by at least 55% by 2030 compared with the levels seen in 1990 and reduce net emissions by 2040.[5]

The clean energy transition is not free of its own energy security challenges. A number of clean energy technologies rely on rare earths, for example lithium and cobalt, that are available in limited supply or from a small number of exporting countries, creating vulnerability in the supply chain at a time of geopolitical uncertainty.[6] Other critical components for clean energy technologies, such as semiconductor chips, have also recently been a source of supply chain security challenges. The drop in demand with the COVID-19 pandemic and faster than expected recovery led to supply chain disruption and a global semiconductor chip shortage, with negative impacts on a wide range of economic sectors. This shortage was not the first and is not expected to be the last, with the semiconductor industry being vulnerable to droughts and other events and with production ramp-up relatively slow if demand changes quickly.[7,8,9] Internationally, a trend of nationalism is linked to policies introduced in certain countries and affecting global supply chains. For example, the tariffs and export controls imposed by China and the United States of America have resulted in supply chain disruption and reorganisation in key technology sectors, including semiconductors and telecoms.[10] The US Inflation Reduction Act is also expected to affect supply chains and competitiveness, with effects on the EU.[11] The EU announced its ambition to double its share of global production capacity of microchips to 20% by 2030 with the European Chips Act.[12]

As clean energy technologies are deployed at increasing scale and pace, it becomes ever more essential to consider the security of these value chains to prepare for, prevent and

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[4] Rabbi, M.F., Popp, J., Máté, D., Kovács, S. (2022), Energy Security and Energy Transition to Achieve Carbon Neutrality, *Energies* 15, 8126. https://doi.org/10.3390/en15218126

[5] European Council, Fit for 55 (accessed 2023); European Commission (2024), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Securing our future Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society.

[6] Chang, F. (2021), Beyond Oil: Lithium-Ion Battery Minerals and Energy Security (accessed 18/01/2023), Foreign Policy Research Institute.

[7] Bish, J., Stewart, D., Ramachandran, K., Lee. P., Beerlage, S. (2022), A new Dawn for European Chips (accessed 18/01/2023), Deloitte.

[8] Aboagye, A., Burkacky, O., Mahindroo, A., Wiseman, B. (2022), When the Chips are Down: How the Semiconductor Industry Is Dealing with a Worldwide Shortage (accessed 18/01/2023); World Economic Forum.

[9] Kamasa, J. (2022), Chip Shortages in the Light of Geopolitics and Climate Change (accessed January 2023), Center for Strategic & International Studies.

[10] Capri, A. (2020), *Semiconductors at the Heart of the US-China Tech War,* (accessed 2023), Hinrich Foundation.

[11] Kleimann, D., Poitiers, N., Sapir, A., Tagliapietra, S., Veron, N., Veugelers, R., Zettelmeyer, J. (2023), How Europe Should Answer the US Inflation Reduction Act (accessed 2023), Bruegel.

[12] European Commission, European Chips Act.

mitigate against the risk and possible impacts of disruption. With this in mind, to provide background context to this study, we will present a brief overview of EU energy policy and considerations for energy security, energy security of clean energy technology value chains, and R&I interventions and potential impacts to support energy security.

1. The EU energy policy context

Pursuant to Article 4 of the Treaty on the Functioning of the European Union, energy is a shared competence between the EU and Member States. The EU has the competence to enact energy policy, which aims to ensure the functioning of the energy market, ensure security of energy supply in the EU, promote energy efficiency and energy saving, promote the development of new and renewable forms of energy, and promote the interconnection of energy networks (Article 194 Treaty on the Functioning of the European Union).

Within the remit of these competences, the EU has rightly acknowledged the magnitude of the challenges affecting European energy security, putting in place various strategies, policies and initiatives aimed, directly and indirectly, at addressing energy security–related concerns:

- Presented by the European Commission (EC) in 2015, the European Energy Union has the ambition to provide EU consumers – households and businesses – with secure, sustainable, competitive and affordable energy. Energy security is one of the five mutually reinforcing dimensions of the Energy Union.[13]

- In order to translate the European Energy Union strategy into reality, the Clean Energy for All Europeans package was adopted over the course of 2018 and 2019. The package comprises a regulation and a directive on electricity, a regulation on risk preparedness, an overhaul of the Agency for the Cooperation of Energy Regulators (ACER), a revised directive on energy efficiency, a revised directive on renewables, a governance regulation, and a revised directive on energy efficiency of buildings. Of particular relevance is the risk preparedness regulation, which sets out rules for cooperation between Member States, with the aim of preventing, preparing for and managing electricity crises.[14] The Clean Energy for All Europeans package enhanced ACER's role in monitoring the security of the electricity supply. Pursuant to the ACER regulation, the agency monitors the performance of Member States in the area of security of electricity supply.[15] Additionally, the risk preparedness regulation mandates ACER to monitor the security of electricity supply measures on an ongoing basis.

- The European Green Deal aims to overcome the challenges of climate change and environmental degradation, and at the same time provide a sustainable growth strategy, reinforced by the objective of green recovery in a sustainable form, as highlighted, for example, in the EU Biodiversity Strategy. The European Green Deal includes a set of initiatives to reach these objectives, including the energy system integration strategy and the hydrogen strategy, which set out how to update the energy markets, including the decarbonisation of the production and consumption of hydrogen and methane. Building on these strategies, the Commission proposed the hydrogen and decarbonised gas market package, which includes a revision of the directive and regulation on gas and

[13] European Commission, Energy Union.

[14] Regulation (EU) 2019/941 of the European Parliament and of the Council of 5 June 2019 on risk-preparedness in the electricity sector and repealing Directive 2005/89/EC.

[15] Regulation (EU) 2019/942 of the European Parliament and of the Council of 5 June 2019 establishing a European Union Agency for the Cooperation of Energy Regulators.

hydrogen. The European Green Deal also includes policies likely to affect clean energy technology value chains, such as the circular economy action plan, with the *Report on Critical Raw Materials and the Circular Economy* and measures that will be introduced, including for such sectors as batteries.

- A number of initiatives that are part of the Fit for 55 package propose stimulating innovation. With this framework, the European Commission adopted a set of proposals to make the EU's climate, energy, transport and taxation policies fit for delivering on the European Green Deal and reducing net GHG emissions by at least 55% by 2030 compared with 1990 levels. Of particular relevance is the proposal for a regulation on methane emissions reduction in the energy sector, as well as an amendment of the renewable energy directive, setting the target of producing 40% of European energy from renewable sources by 2030. The Commission also proposed a revision of the energy-efficiency directive, raising the level of ambition of the EU energy-efficiency targets. The Commission further proposed a revision of the energy performance of buildings directive, raising the energy performance targets applicable to new and existing buildings. On 18 October 2023, the Council and Parliament revised the renewable energy directive (RED III), raising the share of renewable energy in overall EU energy consumption to 42.5% by 2030 within binding targets for certain technologies, for example a sub-target for hydrogen, advanced fuels and renewable fuels of non-biological origin (RFNBOs) in the transport sector.[16]

- The European Climate Law writes into law the goal set out in the European Green Deal for Europe's economy and society to become climate neutral by 2050.[17] The legislation also sets the intermediate target of reducing net GHG emissions by at least 55% by 2030 compared to 1990 levels. In November 2020, the Commission presented the EU strategy on offshore renewable energy, which aims to boost the capacity and use of offshore energy technologies.

- Launched in 2013, the Trans-European Networks for Energy (TEN-E) Policy supports cross-border projects to link Member States' energy networks and foster the integration of renewables. The revised TEN-E Regulation entered into force in June 2022. It contributes to the EU emissions reduction objectives by promoting integration of renewables and new clean energy technologies into the energy system.

- In spring 2022, the European Commission launched the REPowerEU plan to make Europe independent from Russian fossil fuels well before 2030. This initiative answers to the needs of drastically accelerating Europe's clean energy transition while increasing its energy independence from unreliable suppliers and volatile fossil fuel supply.

- In response to Russia's invasion of Ukraine, the European Member States established the EU Energy Platform, with the goal of securing the EU's energy supply at affordable prices in the current geopolitical context and phasing out the EU's dependency on Russian gas.[18]

- The global strategy, adopted in 2016, prominently covers energy security features and represents an integrated effort to work on the internal and external dimensions of

[16] Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652.

[17] Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law')

[18] European Commission (2024), EU Energy Platform (accessed 2023).

European energy security.[19] In response to Russia's invasion of Ukraine, the EU released a strategy on EU external energy engagement in a changing world, which focuses on international cooperation for increasing the speed of green energy innovation and roll-out.[20]

- The European Green Deal Industrial Plan[21] initiatives include the Critical Raw Materials Act (Critical Raw Materials Act),[22] proposed in March 2023, which sets out priorities for action with regards to raw materials identified as strategic for European green ambitions, among others, and where supply risks may emerge. The proposed regulation defines benchmarks for domestic capacity for EU annual consumption for the extraction, processing, recycling and diversification of supply from non-EU countries. The Act is concerned with creating secure and resilient EU critical raw material supply chains and considers innovation, including strengthening the uptake and deployment of breakthrough technologies in CRMs, of interest for clean energy value chains. Alongside, the Net-Zero Industry Act (NZIA) aims to strengthen the resilience and competitiveness of green technology manufacturing in the EU, including clean energy technologies, with a target 40% domestic production benchmark.[23] The NZIA aims to create enabling conditions for investment in Net-Zero technologies with mechanisms that include streamlined administrative and permitting processes, support innovation through sandboxes, and establishing a Net-Zero Europe Platform for coordination. A third initiative consists of reform of electricity market design. The Green Deal Industrial Plan centres around four pillars, namely regulatory design, funding access, skills development and enhancing supply chain resiliency.

- The European Chips Act entered into force on 21 September 2023, in an effort to prevent and reduce semiconductor shortages and to continue to support EU leadership in technology. The Act comprises initiatives to strengthen EU R&I, to improve the understanding of supply chains and to increase production capacity by 20% of the global market by 2030.[24]

- Resulting from REPowerEU, the EU Green Deal, the Critical Raw Materials Act and NZIA, a number of clean technology–specific strategies have also emerged in recent years, notably the EU hydrogen strategy (discussed above), the EU solar energy strategy (adopted May 2022),[25] the upcoming industrial carbon management strategy[26] and the wind power action plan (adopted October 2023).[27] The solar energy strategy aims to enable the deployment of approximately 600 gigawatt (gW) of solar PV by 2030 (increasing EU ambition by 43% compared to the Fit for 55 package solar ambition),

[19] European Commission (2016), *Shared Vision, Common Action: a stronger Europe* (accessed 2023).
[20] European Commission (2022), Joint communication to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions EU external energy engagement in a changing world.
[21] European Commission (February 2023), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, a Green Deal Industrial Plan for the Net-Zero Age.
[22] European Commission (16 March 2023), Critical Raw Materials: ensuring secure and sustainable supply chains for EU's green and digital future.
[23] European Commission (16 March 2023), Net-Zero Industry Act: making the EU the home of clean technologies manufacturing and green jobs.
[24] European Commission (2023), European Chips Act.
[25] European Commission (May 2022), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, EU Solar Energy Strategy.solar energy strategy.
[26] European Commission (February 2024), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Towards an ambitions Industrial Carbon Management for the EU.
[27] European Commission (October 2023), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, European wind power action plan.

facilitated through permitting, solar rooftop, and skills initiatives, as well as through establishing a Solar PV Industry Alliance. In June 2023, the EC released a call for evidence to feed into the industrial carbon management strategy. The strategy will focus on carbon capture, utilisation and storage (CCUS) used in hard-to-abate sectors in the EU, to support these in reaching climate neutrality and highlighting the needs of cross-border infrastructure. The wind power action plan aims to launch the Accele-RES initiative to facilitate and speed up permitting, improve auction design and access to finance and develop skills through partnerships. The action plan accompanies a strategy[28] and 'Communication on the EU's Offshore Energy'[29] (2020) and addresses challenges in achieving the 111 gW offshore renewable energy target set for 2030.- Most recently, the EC has set targets to reduce net emissions by 90% by 2040, building on a public consultation[30] and a detailed impact assessment.[31]

2. Energy security of clean energy value chains

The International Energy Agency defines energy security as 'the uninterrupted availability of energy sources at an affordable price'.[32] Energy security has a short-term and a long-term dimension. In the short term, it relates to the ability of the energy system to react promptly to sudden changes in the supply–demand balance, while in the long term it mainly relates to timely investments to supply energy in line with economic developments and environmental needs. The EU energy system brings together different technology value chains, and its energy security is not simply the sum of the energy security of each technology value, because interdependencies across the system and technology value chains can result in cascading effects and impact overall energy security.

In the coming decades, energy security will depend less on uninterrupted access to fossil energy sources and increasingly on access to energy technologies, as well as access to the materials required to produce equipment throughout the stages of the value chain (such as production, transformation and/or storage, distribution and end use). Clean energy technology value chains not only consist of hardware, in terms of accessibility and availability, but also are shaped by how the value chains are operated, both financially and organisationally, and by which types of stakeholders and entities are involved. At a more detailed level, these phases are embedded in and supported by other elements, such as the availability of skilled labour; financial resources; and material resources, such as raw materials, fuels and infrastructure.

One of the objectives of the European Energy Union, mentioned above, has been to ensure security of supply. The European Green Deal and the Fit for 55 package, although primarily directed towards achieving the EU's GHG emission reduction objectives, also contribute to the EU's energy security, by promoting energy efficiency and the further development of renewable energy production on European soil. However, the war in Ukraine and its

[28] European Commission (November 2020), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, An EU strategy to harness the potential of offshore renewable energy for a climate neutral future.

[29] European Commission (November 2020), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Delivering on the EU offshore renewable energy ambitions.

[30] European Commission (2023), EU Climate Target for 2040 (accessed 2023).

[31] European Commission (February 2024), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Securing our future: Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society. COM/2024/63 final.

[32] International Energy Agency (2024), Energy Security (accessed 2024).

repercussions all over Europe have shown that energy security is still far from guaranteed. Not only have energy prices sharply increased, but the damage inflicted on the Nord Stream pipelines in September 2022 has highlighted the physical vulnerability of energy supplies as a factor of importance not to be underestimated.

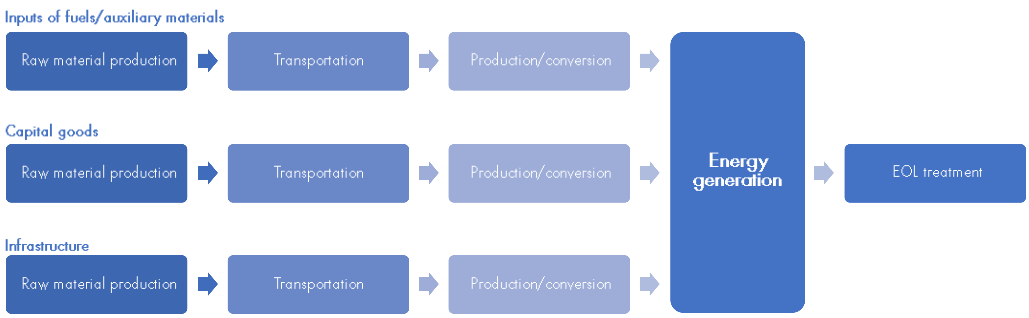
To be able to assess the energy security of technology value chains, we first need to discuss our understanding of both the concepts of clean technology value chains and energy security for the purpose of this study.

Clean technology value chains

In general terms, energy supply chains consist of the phases of production, transformation and/or storage, distribution and end use. At a secondary level, these phases are embedded in and supported by other elements, such as the availability of skilled labour, financial resources and material resources, including raw materials, fuels and infrastructure. Clean energy technologies can focus on different elements of the energy supply chain. This is often the phase where energy is produced, but it could also be, for example, the storage or distribution phases. Therefore, the exact value chain of a clean energy technology looks different for each type of technology. Nevertheless, such elements as fuels, raw materials, infrastructure and capital goods often play a key role in a clean energy technology value chain, besides the energy production itself. In Figure 2.1, a generic schematic overview is depicted of the main elements we consider in our understanding of clean technology value chains.

In our understanding, the requirement for the technology to be 'clean' refers not only to the absence of emissions of GHGs or other substances that potentially harm the environment, but also to the fact that the technology should be consistent with circular economy policies, including objectives aimed at the realisation of a bioeconomy. Therefore the 'end-of-life' (EOL) phase should explicitly be included in the assessment of the value chain.

Figure 2.1 Overview of clean energy technology value chains (generic). EOL = end of life



Energy security in low-carbon energy systems

In the 2016 study *Low-Carbon Energy Security from a European Perspective*, Lombardi and Gruenig describe the topic in detail.[33] As result of the complexity of the concept, definitions of the term energy security widely vary, but the authors have identified some common traits that many definitions and conceptualisations share. Although many definitions quoted are from

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[33] Lombardi, P. and Gruenig, M. eds. (2016), Low-Carbon Energy Security from a European Perspective, Elsevier, Amsterdam.

almost two decades ago, the definitions still seem relevant today. For example, one definition[34] states:

'Energy security as the ability of an economy to guarantee the availability of energy resource supply in a sustainable and timely manner with the energy price being at a level that will not adversely affect the economic performance of the economy … there are 3 fundamental elements of energy security …: (1) physical energy security; (2) economic energy security; and (3) environmental sustainability.'

Common traits regarding physical energy security provided by other definitions are the physical availability and accessibility of resources, in light of the spatial as well as the temporal dimension. Continuity, stability and predictability versus unforeseeable disruptions are traits commonly mentioned as well. Furthermore, policymakers frequently refer to the diversification of the energy mix, where the import of energy depends not on a single country, but on a range of countries all over the world. Besides geographically diversification of energy sources (decentralisation away from one main energy supply source), diversification in terms of the energy sources themselves (e.g. an energy system based on a mix of solar, wind, and so on) can also benefit energy security.

Almost all definitions include not only the physical aspects, but also economic characteristics. Overall, the often-used term adequacy refers to the ability of the system to supply customer requirements under normal operating conditions, whereas the term affordability specifies that this should be possible at affordable prices and with no adverse effects on economic performance. In terms of economic performance, the competitiveness of the European energy and innovation market is seen as an important prerequisite for the EU-wide economy.

Although many common traits are available to define the term energy security at different levels, the term energy security cannot be understood by only looking at the different sub-aspects. Energy security remains a multidimensional concept, which must be seen at a systemic level and wherein energy security in itself is a product of the interactions and interdependencies of a complex system.

3. R&I interventions and their potential to support energy security

R&I interventions have the potential to drive cost reduction and performance improvements in clean energy technologies to support affordability and increased deployment. Similarly, R&I interventions could be targeted to support the reduction of import dependencies for value chains, for example by developing alternative technological approaches or by enabling recycling and reuse of CRMs. Efficiency improvement from smart energy grid technologies could support the reduction of energy losses from distribution in the energy grid by between 2% and 14% in 2018, depending on the country.[35]

As clean energy technologies are deployed at increasing scale and pace, it becomes ever more essential to assess the energy security of clean energy technology value chains, and consider where R&I can help prepare, prevent and mitigate against the risk and possible impacts of disruption. With ambitious clean energy transition targets reflected in the European Green Deal and European Climate Law and embodied in Member State national energy and

[34] Intharak, N. et al. (2007), *A Quest for Energy Security in the 21st Century*, (accessed 2024), Asia Pacific Energy Research Centre.

[35] Council of European Energy Regulators (2020), *2nd CEER Report on Power Losses*, (accessed 2023).

climate plans, this study is a timely assessment to ensure R&I is leveraged to mitigate energy security risks associated with the clean energy transition.

As the Directorate-General for Research and Innovation has rightly noted in the invitation to tender, energy security will in future depend less on access to fossil energy sources and more on access to energy technology and materials to produce energy technology equipment. Energy technology includes the generation, conversion, storage and distribution of energy. It is a growing area in both interdisciplinary research and energy policy aimed at developing a secure and sustainable energy supply to meet the growing global energy demand in an increasingly strained global energy environment. As in other policy contexts, technological and non-technological R&I are essential tools in overcoming 'wicked problems', such as those presented by the growing global energy crisis. In this context, harnessing and successfully adopting and deploying innovative energy technologies is a crucial and indispensable step in the transition towards the sustainable energy systems necessary to provide affordable and lasting energy security in Europe. Research on the total net benefits of R&I interventions in the energy sector cite reduced electricity consumer bills, changes in generator profits and government revenue, health benefits from reduced air pollution, and climate benefits from reduced GHG emissions as some of the main quantifiable gains.[36] Beyond this, the more general benefits of R&I, including increased economic returns on R&I investment,[37] efficiency, efficacy, resilience, cost reduction and other gains that accrue from leveraging advanced technologies, are equally evident in the energy sector, making R&I interventions an indispensable and key tool in addressing the current energy security challenges and in assuring future energy security across Europe and beyond.

A solid financial base for R&I activities is available through the Multiannual Financial Framework (MFF), the Recovery and Resilience Facility (RRF) (foreseeing 37% of expenditure on climate actions), NextGenerationEU, Horizon Europe, and the Emissions Trading System (ETS) Innovation Fund. Furthermore, R&I activities received a notable stimulus through the European Research Area (ERA) process, launched in September 2020, and through the 'Communication on a Global Approach to Research and Innovation', adopted in May 2021. The new European innovation agenda endeavours to position Europe at the forefront of the new wave of deep-tech innovation and start-ups. The objective of the new agenda is to help Europe develop new technologies to address the most pressing societal challenges.

In Europe, R&I policy in energy and energy security is supported by the European Green Deal strategies,[38] which provides a novel policy context for research, innovation, and competitiveness and the strategic energy technology (SET) plan,[39] which is the core mechanism for the European Commission to engage on clean energy R&I activities with EU Member States, Associated Countries, industries and research institutes. EU R&I funding mechanisms that may be relevant or specific to clean energy research and innovation include Horizon Europe, the Cohesion Fund, the Connecting Europe Facility, the European Investment Bank, the European Regional Development Fund, Invest EU, the European Innovation Council, the Just Transition Mechanism, LIFE: Clean Energy Transition, the Recovery and Resilience Fund, the Innovation Fund, the European Energy Programme for Recovery, European Structural and Investment Funds, and European Cooperation in Science and Technology.[40]

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[36] Shawhan, D., Funke, C., Witkin, S. (2020), Resources for the Future, *Benefits of Energy Technology Innovation Part 1: Power sector modeling results* (accessed 2023), Resources for the Future.
[37] Guthrie, S., d'Angelo, C., Ioppolo, B., Shenderovich, Y., McInroy, G. R. (2018), *Measuring the Distribution of Benefits of Research and Innovation*, (accessed 2024), RAND Europe.
[38] European Commission, Energy and the Green Deal (accessed 2023).
[39] European Commission, Strategic Energy Technology Plan (accessed 2024).
[40] European Commission, Energy Research and Innovation Strategy (accessed 2023).

Public investment in energy R&I has increased globally, reaching nearly EUR 28 billion in 2019, including by the EU and EU Member States.[41] The United States and Japan invested the most in 2019, followed in the top 10 by the EU as a whole and a number of individual EU Member States. In 2020, Germany announced a recovery plan with around EUR 43 billion for sustainable investment, including renewable power and hydrogen.[42] The UN Sustainable Development Goal (SDG) 7 is focused on ensuring access to affordable, reliable, sustainable and modern energy. The Africa–EU Energy Partnership found that SDG 7 is possible in Africa, including with support from technological advancement and with existing partnerships to build upon.[43,44] Global appetite for developing and deploying innovative and new clean energy technologies must be regarded as an opportunity for collaboration with countries within and beyond the EU to find solutions to a global challenge.

The clean energy technologies to be considered in this study present promising R&I opportunities to address the various challenges related to energy security of the clean energy value chain, including expanding energy capacities and maintaining energy-related technological competencies and strategic autonomy within Europe. For example, R&I activities that drive cost reduction and performance improvement in the clean energy technology value chain can support energy affordability and increased deployment of technologies that reduce dependence on fossil fuel imports, such as wind and solar power. Similarly, R&I has the potential to support the reduction of import dependencies for those value chains, for example by developing alternatives and by recycling and reusing CRMs. Efficiency improvement from smart energy grid technologies could support the reduction of energy losses from distribution in the energy grid, between 2% and 14% of energy injected in 2018 depending on the country.[45]

With ambitious clean energy transition targets and upcoming legislation and regulation, this study is a timely assessment to ensure R&I is leveraged in anticipation of bottlenecks and risks, placing energy security as a core component of the clean energy transition and mitigating potential negative impacts.

4. Introducing the study and its objectives

The purpose of this study is to identify and strategically prioritise R&I opportunities to enhance European energy security with existing and novel clean energy technology value chains now and with a long-term horizon to 2030 and 2050 (in line with Net-Zero commitments). As such, the work consists of developing a methodology to deliver on the following aims:

- Assess the energy security components of European clean energy technology value chains now and looking to 2030 and 2050.
- Identify R&I opportunities and challenges to address critical elements of clean energy technology value chains to maintain, boost or mitigate risks to European energy security.

[41] International Energy Agency (2020), *World Energy Investment 2020: R&I and technology investment*, (accessed 2023).
[42] Harry Kretchmer (2020), Billions for Sustainable Investments – German's plan for a green recovery, World Economic Forum, July 2 (accessed 2023).
[43] IISD, Fiona D. Wollensack-Boult (2021), Achieving SDG 7 in Africa: New analysis shows where we stand, 7 September, International Institute for Sustainable Development (accessed 2023).
[44] Secretariat for the Africa-EU Partnership (2021), *European Financial Flows on SDG 7 to Africa*, (accessed 2023).
[45] Council of European Energy Regulators (2020), *2nd CEER Report on Power Losses*, (accessed 2023).

- Produce an action plan to enhance energy security across entire energy technology value chains over the next 10 years, prioritised based on an assessment of potential impact and strategic management tools.

This report sets out the methodology developed to deliver this study and the results of the study, including scenarios developed to explore future considerations for EU clean energy security, assessment of technology value chains and their energy security criticalities, analysis of the R&I landscape, and an R&I action plan to strengthen EU energy security. The study was conducted across four tasks. These tasks, and their alignment to the report content, are summarised in the table below.

Table 4.1 Alignment of tasks with chapters.

Study task	Report content
Task 1 – Developing a specific methodology for assessing clean energy technology value chains and their components for energy security and identifying promising R&I opportunities	The study methodology is summarised in Chapter 5 and set out in more detail in Annex A. As part of Task 1, we also developed scenarios which feed into the analyses for Tasks 2 and 3. These are set out in Chapter 6, with the underpinning political, economic, social, technological, legal and environmental (PESTLE) analysis provided in Annex B.
Task 2 – Detailed analysis of energy security parameters of clean energy technology value chains	The findings of the analysis are provided in Chapter 7. These are underpinned by detailed factsheets for each individual value chain, which are provided in Annex C. Annex D provides more detail and mapping of criticalities for the value chains.
Task 3 – Definition and impact evaluation of R&I opportunities to enhance energy security aspects of clean energy technology value chains and establishing a respective action plan	The findings of the R&I analysis are provided in Chapter 8, and the resulting R&I action plan is set out in Chapter 9. Some additional information about R&I actions which were not included in the shortlist – and our rationale for not including them – is provided in Annex F.
Task 4 – Validation workshop	A summary of the validation workshop is provided in Annex E. The findings have fed into the value chain analysis and development of the R&I challenges in Chapters 7 and 8.

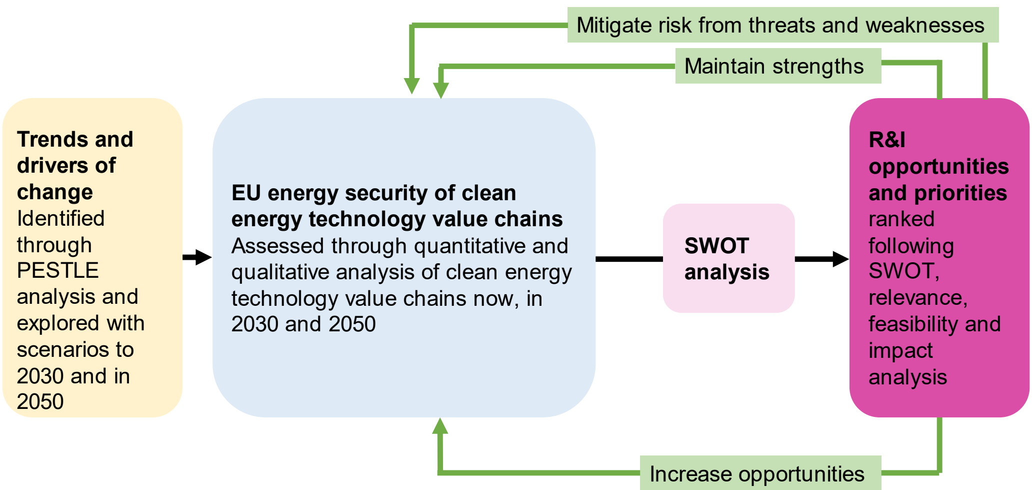
METHODOLOGY

This chapter provides a summary of the methodology for the study as developed in Task 1 of the study requirements. The full detail of the methodology is provided in Annex A.

5. Overview of methodologies used in the study

The methodology for this study brings together foresight- and futures-based methods, producing plausible scenarios to explore the trends and uncertainty on 2030 and 2050 time horizons, complemented with macroeconomic modelling from GEM-E3 and in-depth analysis of the energy security components of clean energy technology value chains. With this understanding of internal strengths and weaknesses for energy security, as well as of external opportunities and threats, potential R&I interventions were identified and strategically prioritised based on their relevance, feasibility and potential for impact to deliver the desired outcome of increased European energy security. SWOT and least-regrets analyses were used to identify those interventions that are required in all scenarios or across multiple technology value chains, making the intervention essential or potentially higher impact and a valid candidate for prioritisation. The conceptualisation of the study is presented in Figure 5.1.

Figure 5.1 Conceptualisation of the study



5.1. Summary of steps to identifying R&I action plan

The study was delivered as four tasks, as specified in the study terms of reference (TOR). In Task 1, the study team refined the overall methodology and developed the scenarios for use throughout the study. Task 2 consisted of in-depth analysis of the energy security of clean energy technology value chains as they stand now and with a 2030 and 2050 horizon, bringing together technology-specific analysis and the wider future context explored in the scenarios to assess energy security criticalities. Task 3 identified R&I interventions to maintain, boost or mitigate risks for energy security across entire technology value chains and drew on SWOT analysis to develop an action plan for the next 10 years. As part of Task

4, a validation workshop convened experts and key stakeholders from across the different technologies in scope to review and refine the study findings, feeding into final results and this report. The methods for each of these tasks are summarised below. Full details of the methodology can be found in Annex A.

A note on scope and definitions

This study used the International Energy Agency definition of the term energy security, as 'the uninterrupted availability of energy sources at an affordable price'.[1] For clean energy technology value chains, energy security depends not only on the source of energy, but to a greater extent on the availability of all relevant materials and components of the underlying technology value chain.

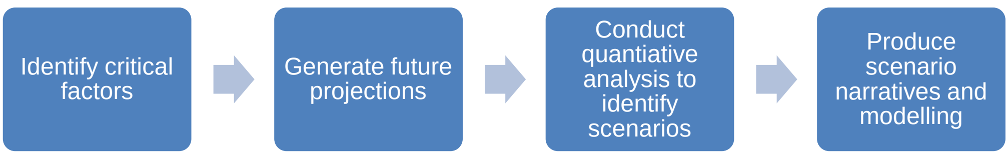
A set of 17 clean energy technologies were considered as in scope for this study as specified in the TOR: advanced biofuels, bioenergy, concentrated solar energy, geothermal energy, hydropower, ocean energy, photovoltaics, wind energy, direct solar fuels, CCUS, electricity and heat storage, including batteries, hydrogen and intermediate energy carriers, heat pumps, smart energy grid technologies, energy building and district heating technologies, off-grid energy systems, energy transmission and distribution technologies, and smart cities. Nuclear energy is out of scope.

R&I interventions are considered in scope of this study if they can be implemented or influenced by the European Commission and DG RTD. Education and skills interventions will generally not be directly in scope, but the study did consider them if they are a critical intervention for specific clean energy technology value chains.

- **Task 1: Scenario development (Annex A, Section 4)**

The overall approach to scenario development is summarised in Figure 5.2.

Figure 5.2 Operationalisation of the scenarios development



First, through a PESTLE[46] analysis based on interviews and desk research, we identified key drivers of change for the energy security of client energy value chains and shortlisted these to produce a set of critical factors. We then produced projections – potential directions of travel – for each of these factors and analysed how they could interact. Using our scenario analysis software, we then clustered these projections to identify potential scenarios, finding three scenario clusters. Each of these was written up as an illustrative narrative, presenting a 'snapshot' of three plausible futures to 2050 that can be used to stress test the value chains and, thereby, our R&I action plan. This qualitative narrative was supplemented by analysis of each scenario using the GEM-E3 model, producing estimates of the EU's dependence on imports and the necessary R&I investments across broad technology areas required to achieve the outcomes in each scenario.

Introducing the GEM-E3 model

[46] Political (P), economic (E), social (S), technological (T), legal (L), and environmental (E).

GEM-E3 is comprehensive, empirical, large, multi-regional and multi-sectoral. The technical basis for the model is a recursive dynamic computable general equilibrium model. The model provides detailed insights regarding the interactions of the macro-economy with the environment and the energy system. The following technology value chains are covered and of interest to this study: photovoltaic (PV) panels, wind turbines, batteries, electric vehicles, biofuels, and carbon capture and storage (CCS) technologies.

- **Task 2: Analysis of the energy security of clean energy value chains (Annex A, Section 6)**

Figure 5.3 Overview of process for analysis of value chains

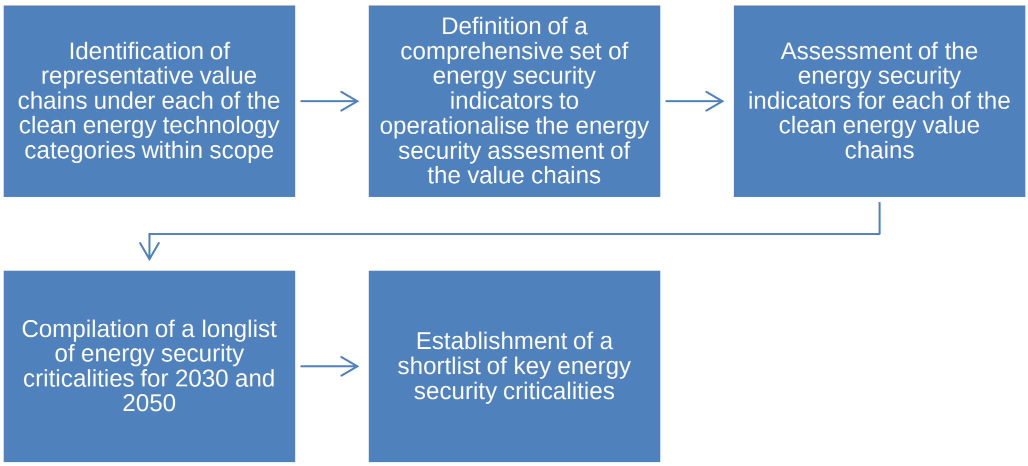


Figure provides a summary of the steps involved in Task 2. In this study, we assessed energy security risks associated with the 17 technology categories listed in the TOR for this study.[47] Each of these categories refers to broad technologies and may encompass several distinct energy value chains, so we identified a set of 48 value chains across these areas to allow us to explore energy security in detail. The selection was made by taking into consideration the extent to which the value chains are distinct (e.g. in terms of energy source, technological principles, deployment in the energy system, and material inputs) and ensuring a mix of value chains at different TRL levels. The energy security risks associated with these value chains were assessed by evaluating and scoring 10 energy security indicators, as set out in Table 5.1. These were identified based on the PESTLE analysis set out in Annex B. For each value chain, we produced a factsheet setting out information on the technology area and value chain and providing an assessment against the 10 indicators. These can be found in Annex C. Details on the indicators and how the assessments against these indicators were made can be found in Annex A, Section 6. We also produced summaries for the 17 technology categories, which are provided in Chapter 7, Section 7.4. The indicators are mapped against the value chain in Figure 5.4, below.

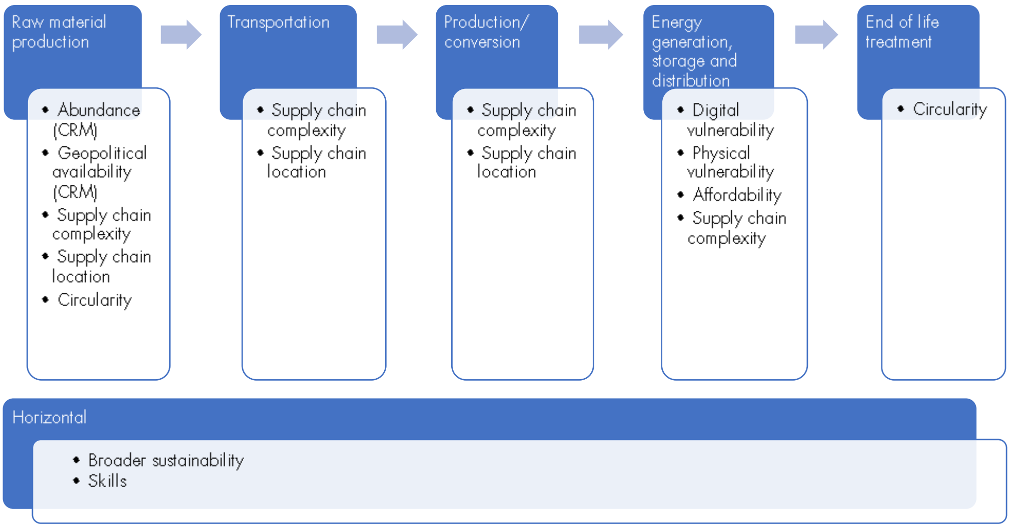
[47] Advanced biofuels, bioenergy, concentrated solar energy, geothermal energy, hydropower, ocean energy, photovoltaics, wind energy, direct solar fuels, CCUS, electricity and heat storage, including batteries, hydrogen and intermediate energy carriers, heat pumps, smart energy grid technologies, energy building and district heating technologies, off-grid energy systems, energy transmission and distribution technologies, smart cities.

Table 5.1 Indicator definitions

Indicator	Definition/relevance to energy security
Geopolitical availability (CRM)	Geopolitical availability of critical raw materials (as defined in the EU's list of critical raw materials) refers to the number of countries from which they are available, and the political risks associated with being dependent on those countries. The CRMs required to build and operate the technology are, ideally, available within (multiple countries in) the EU. Importing raw materials from outside the EU is a potential threat to energy security, especially if there are only a limited number of countries exporting the materials.
Abundance (CRM)	Critical raw materials are available in finite quantities, limited by the scale of mining and/or natural reserves. Sufficient raw materials required to operate the technology should be available. A high dependency on low-abundance materials poses a threat to energy security.
Circularity	Technologies can be recycled at end of life within the EU to supply resources for new products within the EU's economy. This reduces reliance on external suppliers and promotes resource autonomy and energy security. Also, EU legislation will increasingly require compliance with standards in terms of circularity and recycling, making non-recyclable technologies more vulnerable to future upscaling.
Supply chain complexity	Supply chain complexity refers to the number or length of the supply chain as well as the number of components required to produce a technology. Technologies that require highly specialised components or expert knowledge to build and operate can be disrupted more easily than technologies that are simpler. The same applies for long supply chains, which have a relatively large number of steps.
Supply chain location	As per the assumptions made by this study, if a large part of the supply chain exists outside of the EU, the energy value chain is considered more vulnerable.
Digital vulnerability	Technologies that are more reliant on digital infrastructure have the potential to be disrupted. This can be the case for technologies that are comparatively decentralised or technologies that are more reliant on continuous information inputs and have varying vulnerability to cyberattacks.
Physical vulnerability	Physical vulnerability refers to the physical infrastructure and circumstances of clean energy technologies and their value chains. Some value chains are vulnerable to physical disruptions, e.g. in the form of extreme weather events or deliberate sabotage. Additionally, decentralised value chains (e.g. solar PV) are less vulnerable to physical threats than centralised value chains (e.g. offshore wind turbines).
Broader sustainability	Broader sustainability is a horizontal value chain issue that has implications for energy security in terms of technology feasibility. Here, our assessment considers the wider aspects of the SDGs, where non-compliance is viewed as a risk. For example, social (e.g. poor working conditions) or environmental (e.g. threats to local water or food availability, biodiversity impacts, pollution) conditions may pose a risk

	to the ability of clean energy technology value chains to provide energy security, for instance because of increasingly strict legal requirements (compliance with which is assumed) or public opposition by EU inhabitants.
Affordability	Technologies with high costs (relative to technologies with a comparable role in the energy system) form a threat to energy security because higher societal costs limit the options to mitigate other energy security issues and may lead to the disruption of energy use for those consumers unable to afford energy.
Skills	If value chains require a large or specifically skilled workforce, this can become a limitation in their large-scale deployment.

Figure 5.4 Mapping of indicators against the value chain



We then produced a longlist of energy security criticalities by combining the assessment of the energy security indicators for each value chain with information from the three scenarios in order to add the time dimension to the energy security assessment. The longlist of energy security criticalities reflects any energy security risk that may materialise in 2030 and 2050, based on both the intrinsic energy security risks (the indicator scores from the value chain assessments) and the way the energy security indicators would be further stressed in the three scenarios. This was operationalised by first assigning a red–amber–green (RAG) rating to each energy security indicator for all three scenarios – each time both for 2030 and for 2050. The RAG ratings express to what extent the energy security indicator under consideration would be stressed compared to now in the three scenarios, adding a futures element to the energy security assessment. Second, using the matrix in Table 5.2, the longlist itself was established. This matrix shows for what combinations of indicator scores and scenario RAG ratings an indicator was longlisted as a potential energy security criticality.[48]

[48] The options were ‘longlisted’; ‘not longlisted’; and, for some combinations on the longlist, ‘up for discussion’. This was done to prevent the team overlooking important criticalities when drawing up the shortlist of key criticalities.

Table 5.2 Scoring approach for energy security indicators

Energy security indicator score/scenario RAG rating of energy security indicator	Green	Amber	Red
1	Not on longlist	Not on longlist	For discussion – to include on longlist
2	Not on longlist	For discussion – to include on longlist	Include on longlist
3	Include on longlist	Include on longlist	Include on longlist

Details on the shortlisting methodology can be found in Annex A, Section 6.4. The longlist itself is provided in Annex D.

We then undertook a shortlisting exercise, which consisted of a qualitative assessment involving a number of criteria, based on expert judgement.[49] Its aim was to select from the longlist those energy security criticalities that are most crucial to address in order to improve the EU's future energy security. This drew on the following key sources of evidence:

- The number of scenarios through which the energy security criticalities were included on the longlist was considered by making use of the 'heatmap' in Annex D. Although not a prediction of the future, the scenarios represent plausible ways the future may unfold. So, if an aspect of energy security appears to be a criticality in all three scenarios considered, it is more relevant to address than if it is considered a criticality in only one of the three scenarios.

- Aggregation of assessment results from value chain level to technology category level was also considered. Indeed, if a certain energy security indicator would be a criticality for all four value chains assessed under a particular technology category, this would strengthen the case for it to be considered a key criticality for energy security for that technology.

- Where this was inconclusive, other criteria were considered. These included development in time (e.g. was the criticality longlisted only in 2030, only in 2050, or in both years? Would the criticality only delay transformation or would it instead disrupt it?); expected scale of the technology in the future energy system; consideration of the nature of the criticality; and the expected role of the technology in the future energy system (e.g. are there potential replacements?). Also, a comparison across technologies was performed in order to ensure a consistent approach for criticalities that materialised in a similar way for several technologies.

- More detail on the shortlisting methodology can be found in Annex A, Section 6.5. The shortlist of key energy security criticalities itself is presented in Section 7.3 of this report.

- In order to be fully transparent about the way the shortlist was compiled, in Annex D (Table D.1), we present an overview of the longlisted criticalities that were not shortlisted,

[49] Carried out at a full-day internal consortium workshop, involving experts from both CE Delft and RAND Europe.

including the considerations that led to the decision not to shortlist them. In most cases, there are multiple reasons for not shortlisting a certain criticality, aligning with the criteria mentioned above. For instance, physical vulnerability of advanced biofuels was not shortlisted because 1) it was only longlisted for one of three value chains assessed and only through one scenario and 2) this particular value chain (algae-based biofuels) has a low TRL and the particular vulnerability is expected to be addressed while the technology is further developed, meaning it would at most slightly delay the technology, not prevent it from becoming commercially available. As another example, digital vulnerability was not shortlisted for CCS, as it was reasoned that the risk of cyberattacks is less pronounced for CCS than for technologies with other roles in the energy system, such as electricity generation or distribution, as attacks on the latter would have a much more disruptive impact.

- **Task 3: Identifying and prioritising R&I actions (Annex A, Section 7)**

This task consisted of two main steps. First, we conducted a review and mapping of the existing R&I landscape. Through a review of the literature, we identified existing relevant EU and national R&I programmes, focused on the top 10 largest funders so we can see where action is being taken, with a view to identifying any gaps with regards to criticalities for energy security and ensure any proposed R&I actions are complementary and additional. In addition to EU programmes, we also looked at non-EU countries with R&I programmes or interest in the relevant clean energy technology value chains, including Horizon Europe–associated countries; Mission Innovation countries; other, non-EU countries from the G7; and 5 additional G20 and African Union countries. This was relatively light touch and served to provide an understanding of this wider landscape help identify potential international collaborations.

Next, we used strategic management tools (SWOT and least-regrets) to analyse the clean energy value chains explored in Task 2 and develop corresponding R&I actions to form an R&I action plan. First, we converted the key energy criticalities identified into R&I challenges. For example, where the energy security criticality was ‘wider sustainability and environmental impacts’, the corresponding R&I challenge was ‘How can the environmental impacts be reduced or mitigated?’ During the definition of R&I challenges, some measures appeared to be outside of the scope of the study, including energy security criticalities for installation skills or security issues, such as sabotage, which were not immediately relevant to R&I. Discussions among validation workshop participants (Task 4) brought some of these measures back into consideration, as these could be influenced by R&I tangentially (e.g. skills for PV, sabotage for offshore wind). Criticalities and actions suggested by experts in the workshop were added to the final action R&I action plan, supplementing those identified through our analysis of the evidence.

A note on SWOT analysis

SWOT analysis is a management tool that looks at external opportunities and threats and internal strengths and weaknesses to identify key areas for strategic intervention and planning. SWOT analysis is an effective technique to examine performance, risks and potential for a strategy targeted towards a given outcome. It has the added benefit of bringing together different sources of evidence and building in futures analysis, looking ahead more than other management tools. Understanding overlaps and alignment between strengths and opportunities and weaknesses and threats provides a framework to discuss the prioritisation of actions and how they interlink.

SWOT analysis was carried out for the R&I ecosystem of each studied technology and the specific R&I challenges identified in the previous step. The SWOT analysis was used to assess internal strengths and weaknesses with regards to EU R&I capability for the challenges in question and existing opportunities for collaboration with external markets, solutions or threats, for example through increased competition with other countries with strong R&I and businesses. As the output of the SWOT analysis, each R&I challenge was assigned a 'SWOT category': Strength–Threat (S–T), Strength–Opportunity (S–O), Weakness–Threat (W–T), and Weakness–Opportunity (W–O). R&I challenges that were categorised as Weakness–Threat were prioritised for action as the highest potential risk to energy security, with associated strengths and opportunities used to help define the most appropriate R&I interventions (see Table 5.3). The SWOT analysis provided an evidence base for the initial definition of R&I interventions. With an understanding of the EU R&I landscape and international activities, the study team proposed R&I interventions to deliver solutions to the R&I challenges. The type of R&I intervention suggested was based on the state of the R&I ecosystem, whether existing solutions are in development, and whether public or private investment is needed. A least-regrets lens was applied as part of the review of the R&I action plan. Least-regrets analysis considers the relevance of the intervention across the different scenarios and considerations for futureproofing of R&I actions, as well as relevance to multiple R&I challenges and value chains. For example, where two possible R&I interventions may address the R&I challenges, if one provides wider applicability, through the least-regrets analysis it will be prioritised for final selection.

Table 5.3 Criteria for SWOT categorisation

SWOT category	Criteria for assignment
Strength–Threat: highest priority	The EU has a strong R&I ecosystem in the technology area, and is potentially already (but not necessarily directly) addressing the energy security criticality with R&I. The global context for R&I is highly competitive, with significant investment outside the EU especially in the private sector, where knowledge will not be shared. No technology solution is available or the trends influencing the energy security criticality are a threat (e.g. cyber threats are continuously evolving).
Strength–Opportunity: second-highest priority	The EU has a strong R&I ecosystem in the technology area, and is potentially already (but not necessarily directly) addressing the energy security criticality with R&I. The global context for R&I presents potential for collaboration, with shared challenges and public investment outside the EU. Potential solutions exist and are in development.
Weakness–Threat: third-highest priority	The EU R&I ecosystem is less globally competitive, with non-EU countries dominating publications, patents and/or investment. The global context for R&I is highly competitive, with significant investment outside the EU especially in the private sector, where knowledge will not be shared. No technology solution is available or the trends influencing the energy security criticality are a threat (e.g. cyber threats are continuously evolving).
Weakness–Opportunity: lowest priority	The EU R&I ecosystem is less globally competitive, with non-EU countries dominating publications, patents and/or investment.

	The global context for R&I presents potential for collaboration, with shared challenges and public investment outside the EU. Potential solutions exist and are in development.

- **Task 4: Validation workshop (Annex A, Section 8)**

The emerging study findings were presented in a validation workshop to expert stakeholders spanning relevant trade bodies; EU organisations (e.g. European Commission DGs and Executive Agencies) and partnerships (e.g. European Technology & Innovation Platforms (ETIPs), Joint Undertakings); research institutes; think tanks; and civil society organisations. Experts spanning all 17 technology areas were involved.

The workshop aimed to:

- Validate the methodology and findings so far, in particular on energy security criticalities;
- Refine the R&I action plan with consideration of feasibility, potential impact and futureproofing.

Inputs from participants were used to review and refine study findings, for example adding or removing energy security criticalities and refining R&I interventions for the action plan. Before the workshop, participants were sent a materials pack with the agenda, background to the study, and brief initial findings of the study, outlining shortlisted energy security criticalities and proposed R&I challenges, and were asked to review and provide input on the criticalities and proposed R&I challenges and corresponding actions. These were then explored in depth in a set of interactive sessions at the one-day workshop, which was held in a hybrid format, in December 2023. The workshop input, which is summarised in Annex E, fed directly into the finalised set of key criticalities and R&I challenges, and it informed the selection of R&I actions included in the action plan. Further details of how feedback was integrated into the study are provided in Annex A, Section 8.6.

5.2. Assumptions and limitations of the approach

5.2.1. **Assumptions**

The study made two key assumptions, presented here for transparency and clarity:

- As set out in the study TOR by DG RTD, domestic EU energy production is considered to be more secure than imported energy. For both the scenarios development and the assessment of energy security criticalities, the study assumed that current EU policies (for example environmental protections) and decarbonisation ambitions will be maintained or increase in ambition over the coming years and decades.
- This also translates into the assumption that where energy technologies require energy for the operation of their value chain, this energy is clean.

5.2.2. Limitations

While energy security is a systemic characteristic, the scope of this study is analysis at the value chain level, with the results aggregated at the level of the clean energy technology categories mentioned in Section 5. The study findings present energy security criticalities for individual value chains but do not consider how the value chains interact with each other within the energy system and how management of the system itself can mitigate risks to energy security. Energy system considerations or questions are highlighted throughout the findings of this study where relevant and appropriate. Further work, taking an Energy Systems view, would be valuable and complementary. In this study, it is the energy security of value chains that is the focus of the study, and not needs or considerations for deployment or measures to meet energy decarbonisation objectives.

The technology categories in scope of the study are broad and analysis was carried out by examining between one and four representative value chains per category. Analysis may not be applicable to every value chain in the technology category. Technology categories and applications are non-exhaustive.

The assessment was carried out at the level of the main value chain elements (e.g. for the element advanced electronics, not for specific types of chips). This pragmatic approach was taken with consideration of the feasibility of delivering the study; where specifics were identified by the study team or experts in the validation workshop, they are included in the findings.

A similar remark applies to the understanding of energy security for the assessment. A broad approach to the concept of energy security was deployed, distinguishing technical aspects as well as horizontal aspects, such as skills and sustainability issues. Due to feasibility considerations, the assessment of each of these aspects was focused at the level of main elements (e.g. 'installation skills' and 'research skills'; 'land use' and 'biodiversity'). Specifics suggested by the validation workshop participants were added where relevant.

In general, the energy security assessment should be understood primarily as a mapping exercise, creating an overview of where the main EU energy security risks arise within the landscape of clean energy technologies, rather than a detailed technological assessment of the value chains in scope.

More information was publicly available for some technology areas than for others, both in terms of the value chain analysis and in terms of the SWOT analysis. We have mitigated this where possible through expert consultation – particularly the validation workshop and PESTLE analysis interviews – to ensure our analysis of the available evidence is robust.

SCENARIOS

This chapter provides an overview of the scenarios and modelling developed for the study. This work was conducted as part of Task 1; however, it also provides a key input to the futures analysis and sensitivity testing supporting Tasks 2 and 3.

6. Results from the scenarios and GEM-E3 modelling

Chapter overview

Scenarios are plausible futures and useful tools to consider uncertainty and future developments, in particular to inform thinking and decision making towards a desired future outcome. We developed three scenarios (and one variant of Scenario 3) out to 2050, based on a structured analysis of trends and drivers, which can act as a stress test for our analysis of clean energy value chains to ensure the R&I action plan developed is 'future proofed' across a range of possible future landscapes. As such, these scenarios are intended not as predictions but as a test across a wide range of contrasting possible outcomes to provide a sensitivity analysis for the study. These three scenarios are as follows:

Scenario 1: The EU meets Net Zero amidst global challenges: In the year 2050, the EU has pursued Net Zero at any cost and just succeeded to meet its ambitions to decarbonise. The green transition is not a priority globally, with the EU isolated in its pursuit of Net Zero. Major powers have formed blocs with heightened internal cooperation, in stark contrast to the competition between them. With strained international relations, regional conflicts spread in scope and impact, disrupting supply chains, in particular those of CRMs-'-'s. Despite EU R&I investment, the cost of clean energy has not reduced, as disrupted CRMs supply takes its toll. Global temperatures are about to break 2 °C but are now stabilising, with projections suggesting the world is heading for 2.7 °C global warming by 2100.

Scenario 2: A digital EU meets Net Zero with global collaboration: In 2050 the world has fully decarbonised through extensive international collaboration and is on track to limit global temperature rise to below 2 °C. In Europe, the energy grid is entirely powered by renewables, with wind and solar dominating energy supply, and technologies, such as CCS, are employed to compensate for emissions from hard-to-decarbonise sectors. EU citizens support the transition, with many taking up new, green jobs and making significant changes to their lifestyle.

Scenario 3: Global conflict overshadows decarbonisations priorities: It is 2050, and highly tense international relations and spreading regional conflicts are disrupting global trade. Despite the EU maintaining its Net-Zero ambitions, the political and economic context has meant that decarbonisation targets cannot be met. Global collaboration is limited, and protectionist policies are in place. Investment in clean energy R&I has remained flat compared to the 2020s and technology costs are unchanged. Carbon emissions have continued to increase globally, with global temperature rises exceeding 2 °C by 2050 and well on track for 3 °C by the end of the century.

For each scenario, we have assessed the status of a set of 10 energy security indicators at two timepoints – 2030 and 2050 – using a RAG rating approach. This has directly informed the identification of key criticalities for which R&I actions should be developed, by allowing us to consider for different value chains how any existing weaknesses or concerns could be amplified as different futures play out (see Table 6.1). Similar assessments for 2030 have also been considered.

Table 6.1 Assessment of energy security indicators for each scenario in 2050. Each indicator assessed as red (R), amber (A) or green (G).

Energy security indicator	Scenario 1	Scenario 2	Scenario 3
Geopolitical availability	A	G	R
Abundance	A	G	R
Circularity	G	G	G
Supply chain complexity	A	A	G
Supply chain location	A	A	G
Digital vulnerability	A	R	R
Physical vulnerability	A	A	R
Broader sustainability	A	G	A
Affordability	A	G	A
Skills	R	G	G

These qualitative scenarios have been complemented by quantitative analysis using the GEM-E3 model, providing estimates for global production of clean energy technologies and market shares across the EU and other geographies. The modelling covers the three scenarios above, as well as a fourth scenario, in which the EU meets its decarbonisation targets but in the context of significant trade disruptions, to provide some insights into the challenges which the EU may face in pursuing decarbonisation and what would be needed to overcome these. This analysis shows that trade restrictions would require a significant amount of onshoring of production to the EU, which, in turn, would require significant R&I expenditure, particularly in the electric vehicles and batteries market. This would be a substantial increase, approximately USD 65-70 billion (ca. EUR 60-65 billion) compared to the scenario without trade restrictions over the period 2020 to 2050. Additionally, significant investment in the photovoltaic equipment sector, of close to USD 5-6 billion (ca. EUR 4.6-5.6 billion), would also be needed.

6.1. Introduction

Scenarios are plausible futures and useful tools to consider uncertainty and future developments, in particular to inform thinking and decision making towards a desired future outcome. Scenarios are not predictions.[50]

For the purpose of this study, the scenarios developed are intended to provide a stress-test mechanism to assess how different plausible futures may impact the energy security of clean energy value chains. The scenario narratives are also complemented by modelling with GEM-E3.

[50] European Foresight Platform, Scenario Method (accessed 2024).

Drivers of change for the system of interest to this study, which is EU clean energy value chains, were identified. For each driver, possible future projections presenting how the driver might evolve towards 2050 were developed. Following consistency and cluster analysis, three scenarios were developed, bringing together projections that might occur into a narrative describing a plausible future. It is important to bear in mind that the scope of these scenarios was limited to exploring the future of EU clean energy value chains and their energy security; the future of fossil fuels or details of pathways to decarbonisation are not in scope.

The scenarios all include the assumption that the EU maintains or increases the ambition of its current clean energy targets and associated legislation and regulation (including the EU Green Deal and Fit for 55), as well as overall policy direction with regards to environmental protections and compatibility with the SDGs. Where EU decarbonisation has not been fully achieved, this is due to potential drivers outside of policy, impeding progress with decarbonisation.

The scenario narratives present possible futures for EU energy security of clean energy value chains, in particular exploring the axes of international geopolitics and global efforts (or lack thereof) towards decarbonisation and the potential effects on EU energy security of clean energy value chains. In line with the purpose of the study, all scenarios highlight possibles challenge to energy security of clean energy value chains.

The narratives provide a mechanism for readers and the study team to imagine this plausible future and what it could look like. The narratives are a device to help bring to life plausible futures and help readers imagine them. As such, a balance between a short, engaging narrative and level of detail has to be found. Where a detail is included in one scenario and not in another, this does not mean it is not possible in another scenario, and we encourage readers to consider what would be compatible within these futures.

For each narrative, the study team has produced an assessment of how this plausible future might stress the different energy security indicators in 2030 and 2050 compared to now, exploring how intrinsic energy security vulnerabilities identified in the Task 2 value chain analysis may be brought to the fore in future. A RAG rating was used, with red corresponding to severely stressed compared to now, amber corresponding to an increase in stress compared to now, and green corresponding to no change in stress or decreased stress. The scenarios are a mechanism to explore how intrinsic energy security criticalities might be put under pressure in future; however, it is important to be clear that they are not a risk assessment with quantified likelihood and impact but, rather, a qualitative assessment of how risk associated with energy security criticalities may change in future.

As this study is focused on identifying R&I opportunities, technology and R&I are considered as part of the scenarios but not as a strong driver. Rather, this study will seek to identify where R&I can be used to reach the desired outcome of strengthened EU energy security and, to some extent, consider how R&I might affect or change possible futures.

The three scenario narratives are included in the next section, alongside their RAG rating for energy security indicators. The energy security indicator definitions are presented in Table 6.2.

Table 6.2 Energy security indicators

Indicator	Definition/relevance to energy security
Geopolitical availability (CRM)	Geopolitical availability of critical raw materials (as defined in the EU's list of critical raw materials) references the number of countries from which they are available and by the political risks associated with being

	dependent on those countries. The CRMs required to build and operate the technology are ideally available within (multiple countries in) the EU. Importing raw materials from outside the EU is a potential threat to energy security, especially if there are only a limited number of countries exporting the materials.
Abundance (CRM)	Critical raw materials are available in finite quantities, limited by the scale of mining and/or natural reserves. Sufficient raw materials required to operate the technology should be available. A high dependency on low-abundance materials poses a threat to energy security.
Circularity	Technologies can be recycled at end of life within the EU to supply resources for new products within the EU's economy. This reduces reliance on external suppliers and promotes resource autonomy and energy security. Also, EU legislation will increasingly require standards in terms of circularity and recycling, making non-recyclable technologies more vulnerable to future upscaling.
Supply chain complexity	Supply chain complexity is defined by the number or length of the supply chain as well as the number of components required to produce a technology. Technologies that require highly specialised components or expert knowledge to build and operate can be disrupted more easily than technologies that are simpler. The same applies for long supply chains, with a relatively large number of steps.
Supply chain location	As per the assumptions made by this study, if a large part of the supply chain exists outside of the EU, the energy value chain is considered more vulnerable.
Digital vulnerability	Technologies that are more reliant on digital infrastructure have the potential to be disrupted. This can be the case for technologies that are comparatively decentralised or technologies that are more reliant on continuous information inputs and the varying vulnerability to cyberattacks.
Physical vulnerability	Physical vulnerability refers to the physical infrastructure and circumstances of clean energy technologies and their value chains. Some value chains are vulnerable to physical disruptions, e.g. in the form of extreme weather events. Additionally, decentralised value chains (e.g. solar PV) are less vulnerable to physical threats than centralised value chains (e.g. offshore wind turbines).
Broader sustainability	Broader sustainability considers the wider aspects of the SDGs, where non-compliance is viewed as a risk. For example, social (e.g. poor working conditions) or environmental (e.g. threats to local water or food availability, biodiversity impacts, pollution) conditions may pose a risk to the ability of clean energy technology value chains to provide energy security, for instance because of increasingly stricter legal requirements (compliance with which is assumed) or public opposition by EU citizens.
Affordability	Technologies with high costs (relative to technologies with a comparable role in the energy system) form a threat to energy security because higher societal costs limit the options to mitigate other energy security issues and may lead to the disruption of energy use for those consumers unable to afford energy.

Skills	If value chains require a large or specifically skilled workforce, this can become a limitation in their large-scale deployment.

6.2. Development of the scenarios

The methodology for scenario development is described in detail in Annex A, Section 4. This section presents the inputs, key trends and projections that form the basis of the scenarios developed for the study.

The initial longlist of drivers of change was extensive and included the breadth of drivers that were found to be of interest to include in scenario development. Based on the PESTLE analysis and drawing on the RAND Europe driver database, the initial longlist consisted of 40 drivers of change of relevance to energy security of clean energy value chains. Some of the identified drivers of change overlapped or were a proxy for another driver (e.g. investment in clean energy technology can be used as a proxy for clean energy technology development. and some factors existed for which the future development is well understood. These were not used in the scenario analysis as they remained constant across scenarios (e.g. demographic trends). However, they may still be important as they provide constraints or contextual background for the scenario narratives and the SWOT analysis.

Following this initial down-selection by the study team, the first 23 drivers of change, highlighted in blue in Table 6.3, were considered in the cross-impact analysis.

Table 6.3 Longlist of drivers of change. Those highlighted in blue were included in the influence analysis; those highlighted in grey are overlaps or proxies for drivers of change and were not used in the influence analysis

Wider scope of regional instability
Increasingly multipolar world
Political fragmentation in EU Member States
International industry policy: global competition and collaboration
Economic growth
Economic inequality
Demand for clean energy technologies
Public investment in clean energy technologies
Private investment and foreign direct investment in clean energy technologies
Cost of energy
Climate change and extreme weather
Public perception and environmental awareness

Shortage of STEM (science, technology, engineering and mathematics) and digital skills
Just transition
Circular economy
Security of semiconductors supply
Digitalisation
Automation
Decarbonisation of transport
Pace of global decarbonisation
Pace of EU decarbonisation
Availability of critical raw materials
Global value chains
Pandemic emergencies and related risks
Technological development, including cybersecurity, biotechnology, advanced manufacturing, novel and advanced materials, blockchain systems, artificial intelligence
Deployment and adoption of innovation
Regulations and standards
Cyber crime, cyber warfare and cyber terrorism
Growth of smart cities
Advancement of Industry 4.0
Energy technology development
Global competition for talent
Ageing population in the EU
Mass migration of conflict or climate refugees
Growth in energy demand
Crisis-prone global economy
Fragile multilateralism
Fragile states

Redistribution of power across the economic G3: the United States, China and the EU
EU international relations with the United States and China

To shortlist the critical factors (Table 6.4), we undertook a cross-impact analysis of the 23 longlisted drivers of change to understand potential links between factors (how interlinked they are) and to identify which are the most important factors. Here we explored ‘active’ factors, which are those that have the most influence on other factors in the system, and ‘passive’ factors, which are those that are most influenced by others. The cross-impact analysis was undertaken by team members with scenarios and subject matter expertise. To mitigate against potential bias towards or against certain solutions, evidence was gathered from diverse sources, triangulated and iterated with internal analysis.

Table 6.4 Shortlisted drivers of change following cross-impact analysis

Availability of critical raw materials
Investment in clean energy technology R&I
International industry policy competition and collaboration
Cost of energy
Wider scope of regional instability
Global value chains
Pace of EU decarbonisation
Public perceptions
Economic growth
Increasingly multipolar world
Climate change
Pace of global decarbonisation
EU socio-economic inequality
EU policy and regulatory environment

Following shortlisting of critical factors, the study team generated three or four projections for each critical factor with the time horizons of 2030 and 2050, presented in Table 6.5.

Table 6.5 Critical factors and projections

Critical factor	Projections
EU socio-economic inequality	EU inequality increases compared to current levels.
	EU inequality stays the same compared to current levels.
	EU inequality decreases compared to current levels.
EU policy and regulatory environment	EU pursues Net Zero at any cost.
	EU pursues a just transition.
	Some regulations and policies are aligned with Net Zero but conflict with others.
	Regulations and policies do not incentivise Net Zero.
Availability of critical raw materials	CRMs are available, and supply is meeting demand.
	CRMs supply is disrupted, with short-lived shortages or delays in supply.
	CRMs supply is severely disrupted, with global shortages.
International industrial policy: competition and collaboration	International industrial policy is protectionist and competitive.
	International industrial policy is focused on collaboration between strategic allies and competition between blocs.
	International industrial policy is collaborative.
Cost of energy	Energy costs reduce for consumers.
	Energy costs remain relatively stable for consumers.
	Energy costs increase for consumers.
Investment in clean energy research, development and innovation (RDI)	Investment in clean energy increases but with no impact on the overall cost of clean energy.
	Investment in clean energy increases and reduces the cost of clean energy.
	Investment in clean energy does not change compared to current levels.
Wider scope of regional instability	Regional conflicts remain limited in their wider scope and impact.

	Regional instability results in spread of regional conflicts, with wider economic and trade disruption.
	Regional instability and conflict lead to major power conflict.
Global value chains and global trade	Global value chains dominate and continue to grow, with industry pursuing lower costs and efficiencies with offshoring. These value chains remain susceptible to disruption.
	Value chains have become more regionalised, with steady progress from multinationals to increase supply chain resilience.
	The growth in Asian markets becomes the driving force for global value chains, with multinationals focused on those markets at the expense of servicing EU needs and requirements.
Pace of EU decarbonisation	The EU has made significant progress with decarbonisation but has not achieved carbon neutrality in 2050.
	The EU decarbonises in line with current targets, achieving carbon neutrality in 2050.
	The EU accelerates its plans for decarbonisation, with carbon neutrality achieved ahead of 2050.
	The EU does not meet its decarbonisation targets by far.
Economic growth	Recession
	Slow growth
	Economic boom
International relations and global power	States are influential actors in the global order, and multilateral institutions and frameworks address global challenges and settle disputes (multilateralism).
	Major powers form blocks, with cooperation within blocks and competition between blocks (multipolarity).
	Power is shared among a variety of states and non-state actors, including corporations and megacities.
Climate change and extreme weather events	Climate change is limited to 1.5 °C warming. Extreme weather is more common.
	Climate change is limited to around 2 °C by 2100.
	Climate change is limited to around 3 °C by 2100.

	Climate change is on track for a global temperature rise above 4 °C by 2100.
Pace of global decarbonisation	Carbon emissions continue to increase across major economic actors, with limited global decarbonisation.
	The rate of global decarbonisation increases, with significant decarbonisation across major economies.
	Net Zero is achieved globally.
EU public perceptions of climate change, the energy transition and environmental awareness	Public sentiment is trending towards strongly opposing the energy transition.
	Public perceptions remain level and relatively neutral.
	Public sentiment is strongly in favour of the green energy transition, with increasing behaviour change and climate activism.
	Public sentiment is highly polarised, with variation and diversity in opinion.

The consistency analysis was then used to create our scenarios. The final step in the scenario process involved building concise narratives around the projections for each scenario. The narrative is told from the perspective of the future, building on the factor projections and, in a sense, bringing them to life. The scenarios present a description of different and plausible futures, designed to provide sufficient information for use through the study. The projections that make up each scenario are described in Tables 6.6-6.8, below.

A note on the scenario narratives

The scenario narratives are a representation of plausible futures with potential to challenge EU energy security of clean energy value chains. A key assumption is that the EU has maintained or accelerated its ambitions for decarbonisation and sustainability (in line with the EU Green New Deal, Fit for 55, and other existing or upcoming policies). Whether, and how, they are realised is influenced by non-policy drivers that differ across the scenarios. Details included in the narrative are intended to bring possible future developments to life for readers, but scenarios are not intended to be exhaustive, detailed descriptions of all contextual factors. Where some details are included in one scenario and not in another, we encourage readers to consider what may be plausible or compatible within these futures, as our analysis does in subsequent stages.

Table 6.6 Composition of Scenario 1

Key factors	Characteristic projections
Social inequality	EU inequality increases compared to current levels
EU policy and regulatory environment	EU pursues Net Zero at any cost
Availability of critical raw materials	CRMs supply is disrupted, with short-lived shortages or delays in supply
International industry policy competition and collaboration	International industrial policy is competitive and protectionist
Cost of energy	Consumer energy costs increase
Investment in clean energy RDI	Investment in clean energy increases but there is no impact on cost of clean energy
Wider scope of regional instability	Regional instability results in spread of regional conflicts, with wider economic and trade disruption
Global value chains and global trade	Value chains have become more regionalised, with steady progress from multinationals to increase supply chain resilience
Pace of EU decarbonisation	The EU has made significant progress with decarbonisation but has not achieved carbon neutrality in 2050
Economic growth	Recession
International relations and global power	Multipolarity – major powers form blocks, with cooperation within blocks and competition between blocks
Climate change and extreme weather	Climate change is limited to around 3 °C by 2100, global carbon emissions stabilise around current levels and start to fall after 2050, and carbon neutrality is not achieved by 2100
Pace of global decarbonisation	Carbon emissions continue to increase across major economies, and global decarbonisation is limited
Public perception and climate change awareness	Public sentiment is highly polarised, with variation and diversity in opinion

Table 6.7 Composition of Scenario 2

Key factors	Characteristic projections
Social inequality *	EU inequality decreases compared to current levels / EU inequality stays the same
EU policy and regulatory environment *	EU pursues a just transition / EU pursues Net Zero at any cost
Availability of critical raw materials	CRMs are available, and supply is meeting demand
International industry policy competition and collaboration	International industrial policy is collaborative
Cost of energy	Energy costs reduce for consumers
Investment in clean energy R&I	Investment in clean energy increases and reduces the cost of clean energy
Wider scope of regional instability	Regional conflicts remain limited in their wider scope and impact
Global value chains and global trade *	Global value chains dominate global trade and continue to grow, pursuing lower costs and efficiencies with manufacturing offshored to lower wage economies, and these value chains remain susceptible to disruption / Value chains have become more regionalised, with steady progress from multinationals to increase supply chain resilience
Pace of EU decarbonisation *	The EU accelerated its plans for decarbonisation, with carbon neutrality achieved ahead of 2050 / The EU decarbonises in line with current targets, with carbon neutrality achieved in 2050
Economic growth	Economic boom
International relations and global power	Multilateralism: states are influential actors in the global order, and multilateral institutions and frameworks address global challenges and settle disputes
Climate change and extreme weather *	Climate change it limited to 1.5 °C, in line with the ambitions of the Paris Agreement, global carbon emissions have been limited to Net Zero by 2050, and extreme weather is more common / Climate change is limited to around 2 °C by 2100, global carbon emissions are cut significantly but not as fast, and Net Zero is achieved in the 2070-2080s
Pace of global decarbonisation	Net-Zero carbon emissions are achieved globally
Public perception and climate change awareness	Public sentiment is strongly in favour of the green energy transition, with increasing behaviour change and climate activism

Table 6.8 Composition of Scenario 3

Key factors	Characteristic projections
Social inequality	EU inequality increases compared to current levels
EU policy and regulatory environment	Regulations and policies do not incentivise and are barriers to Net Zero
Availability of CRMs *	Critical raw material supply is severely disrupted, with global shortages / CRMs supply is disrupted, with short-lived shortages or delays in supply
International industry policy competition and collaboration	International industrial policy is competitive and protectionist
Cost of energy	Consumer energy costs increase
Investment in clean energy R&I	There is no change in clean energy investment and no impact on cost
Wider scope of regional instability *	Regional instability and conflict lead to major power conflict / Regional instability results in spread of regional conflicts, with wider economic and trade disruption
Global value chains and global trade	The growth in Asian markets becomes the driving force for global value chains, with multinationals focused on those markets at the expense of serving EU needs and requirements
Pace of EU decarbonisation	The EU does not meet its decarbonisation targets by far
Economic growth	Recession
International relations and global power *	Power is shared among a variety of states and non-state actors, including corporations and megacities / Multipolarity: major powers form blocks, with cooperation within blocks and competition between blocks
Climate change and extreme weather	Climate change is limited to around 3 °C by 2100, global carbon emissions stabilise around current levels and start to fall after 2050, and carbon neutrality is not achieved by 2100
Pace of global decarbonisation	Carbon emissions continue to increase across major economies, and global decarbonisation is limited
Public perception and climate change awareness	Public sentiment is highly polarised, with variation and diversity in opinion

6.2.1. Scenario 1: The EU meets Net Zero amidst global challenges

In the year 2050, the EU has pursued Net Zero at any cost and just succeeded in meeting its ambitions to decarbonise. The green transition is not a priority globally, and the EU is isolated in its pursuit of Net Zero. Major powers have formed blocs, with heightened internal cooperation, in stark contrast to the competition between them. With strained international relations, regional conflicts spread in scope and impact, disrupting supply chains, in particular those of CRMs. Despite EU R&I investment, the cost of clean energy has not reduced, as disruptions to CRM supply take their toll. Multinational companies have regionalised their supply chains in light of increasing protectionist policies and in search of resilience. With some countries meeting their emissions pledges and others pursuing Net Zero–incompatible policies, carbon emissions continued to increase but are now stabilising, with projections suggesting the world is heading for 2.7 °C global warming by 2100. In 2050, global temperature rises are about to break the 2 °C mark, with increased frequency of extreme weather, widespread impacts and the first ice-free summer in the Arctic. Russia maintains strict control of this new shipping route, limiting the opportunities for Asia–Europe trade to benefit.

Regional instability and supply chain disruptions

Europe is navigating the complexities of a multipolar world. The impacts of climate change are felt globally from the 2020s and contribute towards intensifying tensions between countries, especially those with water resource scarcity. Global demand for CRMs is high, driven by widespread adoption and development of digital technologies. The race to secure supply between power blocks in pursuit of strategic advantage has heightened local tensions in mineral-rich zones. One country experienced a military coup, with the new leadership blocking exports as a negotiating tactic to gain international recognition. Cobalt supply chains effectively collapsed for three months in the run-up to the 51st Conference of Parties, COP51, in 2046.

Europe is pursuing greater strategic autonomy in light of global instability and disruption. Multinationals serving the EU market have largely regionalised their value chains to service European markets, and although this has increased resilience, delays in production and delivery were introduced as supply chains were reorganised and new facilities set up. Circular economy policies are a notable success: laws to standardise production of components of key consumer goods, such as tablet and computer screens, reduce consumption and extend the lifespan of these goods, while the roll-out of major public incentive schemes for recycling and subsidies for industry circular economy partnerships are also a success. Despite these policies and increased European CRM production, the EU has not been able to achieve autonomy for all CRMs – particularly cobalt and nickel, for which the EU has limited reserves. The EU has looked to allied blocs and friend-shoring (manufacturing ties with allies) to form trade partnerships with key countries in North Africa and South America.

With ongoing geopolitical tensions and the pursuit of strategic advantages across major power blocks, international cooperation for the green transition is strained. Annual COP meetings continue to take place, but binding agreements are not reached during disucssions. Countries have pursued a diverging approach, with some meeting their green transition pledges and other pursuing policies set out in the 2020s, described by campaign groups as antiquated. The EU is one of the few groups of countries in the world that has actively pursued its ambitious Net-Zero targets. However, with supply chain disruptions affecting the cost of clean energy and timeliness of deployment, Member States have decarbonised at different rates, with some more able to pursue swift changes due to a range of factors, including structure of the economy and public acceptance.

Digital vulnerabilities have come to the surface. Renewable battery farms, onshore wind and energy storage are frequently located in regions where land and energy prices are relatively cheap. This includes disputed border regions where conflict sporadically flares up throughout the 2040s, and Member States where computing power is relatively cheap but security infrastructure is relatively less developed. This has caused ongoing issues through threats to digital and physical operations. Sophisticated cyberattacks have targeted battery farms in an attempt to disrupt the EU's energy grid.

A challenging economic context

The 2030s began with a promising economic outlook for clean energy industries, driven by significant investment and collaborations among Member States to achieve Net Zero at any cost. Protectionist industrial policies, however, hampered the EU's efforts, especially for those technology value chains dominated by non-EU countries. Protectionism and strained global trade laid the groundwork for a global recession, prompted by the collapse of Japanese banks. International R&I efforts have been unproductive and have limited the EU's ability to deliver on its ambitions of a cost-effective green transition, fuelling public debate and disagreement over the pursuit of Net Zero. With a disconnect between global efforts and EU decarbonisation ambitions, the EU has made additional efforts with regards to energy efficiency to reduce energy demand and therefore reduces the need for clean energy technologies to match current energy production trends.

The North Sea is now a vast offshore wind farm and tidal energy hub, building on those industries where the EU had strengths and opportunities for collaboration. Further, subsea cables in the North Sea are crucial in enabling cross-border electricity trading to help deal with the variability of renewables. The sizeable workforce of oceanographers, maintenance workers, engineers and workers in many more disciplines is now a substantial contributor to gross domestic product across Europe. Some Member States invested heavily in geothermal resources, further reducing dependence on external clean energy imports. The EU continues to pursue innovative solutions, for example deploying blockchain-type technologies to increase the efficiency of the decentralised clean energy grid. To encourage adoption, those connecting their domestic solar panels to the grid are provided with financial incentives.

The cost burden of the energy transition has become one of the top three issues for EU citizens. In what is already a challenging economic context for households, the cost of clean energy for consumers is not reducing as promised, with volatile raw material prices and the mismatch between workforce skills and demand resulting in high installation and maintenance costs. The EU's push towards Net Zero, however, speeds up the decline in the use of traditional oil and gas, removing subsidies and stranding industry assets, meaning renewables are not substantially more expensive than the alternatives.

Social rifts over the energy transition

Inequalities across the EU are further highlighted by the recession and unequal impacts of the clean energy transition. In 2050, while some regions celebrate strides towards decarbonisation, others continue to face challenges and have not been able to reach the Net-Zero target. Polarised public opinion is split across committed supporters of the green transition, who are willing to make extensive lifestyle changes for a sustainable future, and those who think investment should be focused on solving other challenges – healthcare and immigration in particular. The transition is not viewed as just, and protests in major European cities are frequent, with the latest delaying the implementation of energy-efficiency measures. Offshore wind becomes a lightning rod for this debate after a maritime terrorism incident in 2044, which leads to substantial debate around whether taxpayers or private companies owning wind farms should pay for enhanced ocean security measures. A hostile occupation of cement plants by former employees displaced following the rapid introduction of emissions taxes on the sector is also emblematic.

Environmental challenges and missed targets

In 2050, Europe and the world are confronted with the impacts of a 2 °C increase and the latest Intergovernmental Panel on Climate Change modelling puts the world on track for 2.6 °C by 2100. Northern Europe experiences prolonged rainfall, in contrast to southern Europe, which experiences intensified heatwaves, with significant knock-on effects on agriculture and natural habitats. The impact of rising sea levels, including intense storms leading to flash floods and coastal erosion along the North Sea coastline, is an important area of concern at the moment. In pursuit of Net Zero at any cost, environmental concerns were sidelined to open new mines and repurpose land for biofuel production.

Table 6.9 presents the corresponding RAG rating[51] for Scenario 1 across energy security indicators for 2030 and 2050, together with a brief explanation of the rationale for the RAG assessment.

Table 6.9 Scenario 1 energy security indicator RAG rating

Energy security indicator	2030	2050	Scenario factors influencing RAG ratings
Geopolitical availability			The development and entrenchment of major power blocs creates clear geopolitical tensions, which reduces the availability of materials to the EU. Despite this, a semblance of order – exemplified by the ongoing COP negotiations and occasional partnerships between blocs – means there is availability of CRMs from a range of other regions.
Abundance			Increased or alternative sources of CRMs have not resolved challenges around abundance. Successes with circularity and new EU mines have increased sources of raw materials; however, this has not been possible for all CRMs, and as the rest of the world's priorities are not focused on decarbonisation, insufficient market pull is available to increase supply.
Circularity			The successful implementation of the EU's ambitious circular economy policies throughout the 2030s as part of the sustained push towards Net Zero means circularity is resilient. These policies are embodied by laws to standardise production of key consumer goods components, the roll-out of major public incentive schemes for recycling, and subsidies for industry circular economy partnerships in high-waste sectors.
Supply chain complexity			With a multipolar world and the pursuit of friend-shoring, supply chains have shortened to increase their resilience. However, for some technologies, highly specialised components or knowledge are still required for construction and operation, carrying

[51] Red = most risk, green = least risk.

			a degree of vulnerability. For much of the 2020s and 30s, the EU continues to prioritise the pursuit of innovative solutions, which reach maturity in the subsequent decade. The deployment of blockchain-type technologies to increase the efficiency of the decentralised clean energy grid is an exemplar, but such technologies come with complicated governance and decentralised infrastructure, adding substantial complexity to the system. GEM-E3: The EU is dependent on battery imports both for its electric vehicle industry and storage and for PV for power generation. However, it remains strong in the production of wind turbines, leading global production. The value chain complexity in each case is influenced by different factors. The battery supply chain is characterised by its technical complexity in manufacturing, sensitive raw material sourcing, and evolving recycling needs. The wind turbine supply chain, on the other hand, deals more with large-scale industrial manufacturing, logistical challenges due to the size of components, and issues related to EOL management.
Supply chain location			Multinationals serving the EU market have largely regionalised their value chains to service European markets, and the continued success of North Sea wind farms and, in some areas, geothermal energy means a substantial proportion of energy supply chains are located within the EU. GEM-E3: Ongoing geopolitical tensions combined with basic lack of CRM deposits in the EU mean some parts remain outside of the EU, resulting in a moderate supply chain location risk. The moderate global engagement in adopting and producing clean energy technologies does not favour the diversification of production capacities across countries. EU suppliers remain mostly Asian economies.
Digital vulnerability			The widespread adoption and development of digital technologies among consumers and throughout the energy grid increases dependency on technology and extends the attack surface for malicious actors. A spate of damaging cyberattacks follows.
Physical vulnerability			Renewable wind and battery farms, which are key to the EU's electric vehicle (eV) market and to energy storage, are in regions that have historically been subject to border disputes, while the growth and success of North Sea wind farms raise the risk of maritime terrorism.

			As global temperatures increase, physical infrastructure is subject to more frequent extreme weather events.
Broader sustainability			In pursuit of Net Zero at any cost, environmental concerns were sidelined to open new mines and repurpose land for biofuel production. Social Sustainable Development Goals are also negatively impacted in places, as across Europe, major public disturbances frequently occur as protestors contest high domestic energy prices and the impact on labour markets associated with high-emissions industries, such as cement production.
Affordability			High global demand for CRMs and high installation and maintenance costs raises prices for renewable energy. A recession – prompted by protectionism, strained global trade and the subsequent collapse of Japanese banks – makes the cost burden a substantial issue. The EU's push towards Net Zero, however, speeds up the decline in use of traditional oil and gas, removing subsidies and stranding industry assets, meaning renewables are not substantially more expensive than the alternatives. GEM-E3: Decarbonisation increases the production and investments in clean energy technologies, and as a result, the production costs are declining due to learning-by-doing and learning-by-research effects. The single market of the EU is sufficiently sizeable to allow most of the technologies to reach maturity in 2050; economies of scale and R&I driven by the EU market drive cost reductions across all technologies, including batteries.
Skills			Substantial labour demands in now-dominant renewables sectors, such as offshore wind, and a shortage of technical experts who support the implementation of more novel energy system technologies, such as blockchain-enabled consumer energy incentives, mean that the energy system requires large amounts of skilled labour. The onshoring and friend-shoring of supply chains also puts pressure on the limited supply of highly skilled executive-level workers.

6.2.2. Scenario 2: A digital EU meets Net Zero with global collaboration

The scenario narratives are a representation of plausible futures with potential to challenge EU energy security of clean energy value chains. A key assumption is that the EU has maintained or accelerated its ambitions for decarbonisation and sustainability (in line with the EU Green New Deal, Fit for 55, and other existing or upcoming policies). Whether, and how, they are realised is influenced by non-policy drivers that differ across the scenarios. Details included in the narrative are intended to bring possible future developments to life for readers, but scenarios are not intended to be exhaustive, detailed descriptions of all contextual factors. Where some details are included in one scenario and not in another, we encourage readers to consider what may be plausible or compatible within these futures, as our analysis does in subsequent stages.

It is 2050, and the world has fully decarbonised, with extensive international collaboration, on track to limit global temperature rises to below 2 °C. In Europe, the energy grid is entirely powered by renewable energy technologies, with wind and solar dominating energy supply alongside the stop-gap technologies, such as CCS, deployed to compensate for the emissions from hard-to-decarbonise sectors. EU citizens are supportive of the transition, with many taking up new, green jobs and making significant changes to their lifestyles to reduce energy demand.

Global collaboration addressing the climate emergency

Following warnings from the Intergovernmental Panel on Climate Change and impacts of extreme weather events across the world, the COP agreed legally binding targets to deliver ambitious, nationally determined contributions, with financing structures, to enable the transition across all countries. In Europe and elsewhere, limiting warming to 2 °C requires putting the economy on a wartime footing in the 2020s and 30s, with the other policy priorities subservient to the green transition. This global policy consensus strengthens multilateralism, which in turn incentivises countries to keep the peace; conflicts emerge at a regional level but are limited in scope and spread.

The EU leverages this multilateralism to build strategic partnerships and a cooperative approach across international industrial policies to pursue Net-Zero emissions and the Sustainable Development Goals. In the earlier decades of the transition, the need for urgent and substantial action necessitates a rigid focus on state-mandated green innovation missions. These massive investments range from ‘moonshots’ (i.e. large investments into big technological advancements) including such developments as scaling of direct air capture of carbon dioxide (CO_2), wind-assisted shipping, and the automated detection and flaring of methane emissions) to investment in public green infrastructure, such as carbon transport, carbon sequestration installations and domestic heat pump networks.

Effective carbon markets are in operation, with avoidance and removal credits, and are designed to ensure that they are less susceptible to gaming than historic precedents, negating the potential for developed countries to ‘outsource’ to the producing countries the emissions for carbon-intensive goods consumed.

Initially, as countries raced to decarbonise, international policies created unintended and unconstructive competition with domestic incentives that resulted in supply chain reorganisations as businesses responded to subsidies and market opportunities. However, with close collaboration for energy R&I and policy coordination, unintended consequences of domestic policies are minimal now and collaboration supports clean energy innovation uptake globally.

Rapid deployment of clean energy technologies

In Europe, decarbonisation has met the European Commission's targets. This involved rapid deployment of mature clean energy technologies, in particular solar and wind power, in the 2020s and 2030s, and increasing deployment of carbon capture technologies – aided by substantial public investment in carbon transport and storage infrastructure – to compensate for heavy industry sectors where solutions are yet to be developed. As clean energy policy missions and investments progress rapidly, with some succeeding while others fail, markets and supply chains are initially characterised by volatility and turbulence throughout these decades. With relative global stability and to enable the pace of the transition, the EU still relies on complex global value chains for clean energy technologies. To reduce reliance on these supply chains, the EU launched an extensive CRMs exploration mission, with several new lithium mines opening in Portugal, France and Sweden.

By 2050, systems and markets have stabilised, supply chain efficiencies are realised, and parts of the value chain are localised within the EU to ensure supply meets demand but extensive digitisation of the grid and other parts of the energy system, alongside the ongoing need for importing some CRMs from outside the EU, means there is still inherent complexity in the system. Technology failures, and the associated demand for ongoing maintenance, pose substantial challenges. Some suspect that due diligence and quality checks were not pursued systematically across complex technology value chains. Reports of earlier-than-expected failures and complex protracted legal battles between suppliers and purchasers across renewable energy systems populate the news cycle.

A Net-Zero digital society

A European citizens' assembly is in continuous operation as a just transition governance mechanism and provides legitimacy to the EU's policies and decision making.

EU citizens feel engaged in the transition, with substantial, ring-fenced subsidies persuading many to take a direct stake in the transition as electricity market participants, including through deployment of residential solar panels, demand-response initiatives, and the dynamic sending and drawing of electricity to and from the artificial intelligence (AI)–managed grid by electric vehicles. The push towards a circular economy was a gateway to low-carbon lifestyle changes, and high streets are now a hub for repair shops and low-carbon food stalls, following a concerted push towards localising agriculture and food production by the EU Commission and developing low-carbon alternatives, such as lab-grown meat.

With the pace of transition, by 2030, access to a skilled workforce rapidly became a bottleneck to clean energy technology deployment. The EU and Member States launched a series of training programmes supporting workers from fossil fuel–based sectors to join the green workforce, and young people take part in a year-long 'green public service' that equips them with skills needed to join renewable energy value chains in future. Digitisation and automation further support the transition, with the EU leveraging its Digital Decade plan to deliver decarbonisation targets.

Smart European cities make it easy for people to move around and carry out their day-to-day activities. Sophisticated 'mobility-as-a-service' offerings give citizens access to a diverse range of semi-autonomous electric vehicles, zero-emissions buses, trains and elevated cycle lane networks that get them from A to B efficiently and with a minimised carbon footprint. Following dramatic improvements to virtual and augmented reality and haptic sensors, 'virtual vacations' and 'staycations' are the norm, and demand for commercial flights has reduced significantly.

On track for 2 °C warming

Despite best efforts, 1.5 °C of global warming was reached in the 2030s. However, the global temperature rise is stabilising and on track to stay below 2 °C by 2100. The climate is changed, affecting crops and water resources: southern Europe is 10-20% drier compared to the 2000s, experiencing severe drought events and flash floods. Northern Europe is wetter and flooding more frequently. Extreme weather events are the main cause of electricity grid failure and disruption in Europe. The record-breaking heatwave in 2046 caused major disruptions as wind turbines came to a standstill due to reduced wind conditions and as widespread wildfires damaged power transmission lines and their smoke prevented solar panel operation.

Table 6.10 presents the corresponding RAG rating for Scenario 2 across energy security indicators for 2030 and 2050, together with a brief explanation of the rationale for the RAG assessment.

Table 6.10 Scenario 2 energy security indicator RAG rating

Energy security indicator	2030	2050	Scenario factors influencing RAG ratings
Geopolitical availability			The EU leverages the consensus around the rapid Net-Zero transition to form cooperative strategic partnerships across the energy value chain. Multilateralism also offers clear economic incentives for countries to maintain peaceful relations, and conflicts are limited. The nature of some green policies also promotes geopolitical calm: for example, effective carbon markets minimise potential geopolitical disputes that would have likely arisen from developed western nations' carbon 'outsourcing' – importing emission-intensive goods from the countries and attributing the emissions to the country that produced them.
Abundance			Limiting warming to 2 °C requires a wartime footing in the 2020s and 30s, with the other policy priorities subservient to the green transition. During these decades, the massive demand for raw materials places substantial pressure on supply chains, resulting in acute shortages and months-long periods where supply is severely disrupted. In response, the EU makes CRM availability and autonomy a core pillar of its industrial policy, with several new mines opening in Portugal, France and Sweden in the late 2030s, after extensive exploration. By 2050, CRMs supply is stable relative to demand.
Circularity			The push towards a circular economy was a gateway to low-carbon lifestyle changes, and high streets are now a hub for repair shops and low-carbon food stalls.
Supply chain complexity			In the earlier decades of the transition, the need for urgent and substantial action necessitates a rigid focus on state-mandated green innovation missions. These massive investments range from moonshots to

			investment in public green infrastructure, such as carbon transport and sequestration networks and domestic heat pump systems. As these missions progress rapidly and some succeed while others fail, markets and supply chains are characterised by volatility and turbulence. By 2050, supply chains and markets have stabilised. However, the EU is left reliant on complex globalised value chains and acutely vulnerable to disruption. GEM-E3: Massive adoption of clean energy technologies has lowered costs through economies of scale and R&I, but no new technologies with less complex value chains are expected to deploy. Hence the EU is still dependent on certain complex technologies.
Supply chain location			The EU has relied on global value chains to meet the pace of decarbonisation in a collaborative global context. In 2030, the pace of action globally introduced challenge and unintended consequences with regards to competition and supply chain reorganisations to benefit from incentives introduced in individual countries. As a constructive and coordinated approach developed, markets have stabilised by 2050; however, supply chains very much remain global and subject to local disruption, as onshoring has not been achieved. GEM-E3: The global deployment of clean energy technologies has accelerated the pace of emerging firms and regional markets, but the economies that have managed to be at the technological frontier maintain their comparative advantage and retain their market leadership. The EU is largely autonomous in key energy technologies but highly dependent on imports from Asia.
Digital vulnerability			Digitisation and automation further support the transition, with the EU leveraging its Digital Decade plan to deliver decarbonisation targets. Smart European cities make it easy for people to move around and carry out their day-to-day activities as efficiently as possible, with fleets of autonomous electric vehicles servicing transport demand alongside comprehensive clean public transport networks. This means the transition is highly dependent on digital technologies. A new challenge in 2050 is technology failures and the associated demand for maintenance. Some suspect that due diligence and quality checks were not pursued systematically across complex technology value chains, especially considering the pace and scale of deployment. Reports of earlier-than-expected failures and product recalls, especially for batteries, are appearing on news-sharing platforms.
Physical vulnerability			Extreme weather events are the main cause of electricity grid failure and disruption in Europe. The

			record-breaking heatwave in 2046 caused major disruptions as wind turbines came to a standstill due to reduced wind conditions and as widespread wildfires damaged power transmission lines and their smoke prevented solar panel operation.
Broader sustainability			The scale of change needed for the Net-Zero transition requires some early sacrifices in the lead-up to 2030, with specific sectors and policy areas coming second place, resulting in some public challenge. As mines are opened to meet demand for CRMs, sustainable mining techniques are not widely developed. The situation improves moving forward towards 2050. A European citizens' assembly is in continuous operation as a just transition governance mechanism and provides legitimacy to the EU's policies and decision making. EU citizens feel engaged in the transition and have adopted low-carbon lifestyles.
Affordability			The wartime footing of clean energy policy, coupled with a need to take investment risks in a range of unproven and unscaled clean energy technologies, necessitates unprecedented levels of investment throughout the 2020s, 30s and 40s. Despite effective efforts from the EU to minimise the economic impacts of these investments for consumers and companies – for example, through job transition schemes and protected subsidies – some of these costs unavoidably trickle through to energy prices. By 2050, the need for intensive capital investments has subsided and cheap renewable energy dominates.
Skills			Access to a skilled workforce is a bottleneck to clean energy technology deployment in the earlier stages of the transition. The EU and Member States launched a series of training programmes supporting workers from carbon-intensive sectors to transition to greener ones, and young people take part in a 'green public service' that equips them with skills needed to join renewable energy value chains in future.

6.2.3. Scenario 3: Global conflict overshadows decarbonisations priorities

The scenario narratives are a representation of plausible futures with potential to challenge EU energy security of clean energy value chains. A key assumption made is that the EU has maintained or accelerated its ambitions for decarbonisation and sustainability (in line with the EU Green New Deal, Fit for 55, and other existing or upcoming policies). Whether, and how, they are realised is influenced by non-policy drivers that differ across the scenarios. Details included in the narrative are intended to bring possible future developments to life for readers, but scenarios are not intended to be exhaustive detailed descriptions of all contextual factors. Where some details are included in one scenario and not in another, we encourage readers to consider what may be plausible or compatible within these futures, as our analysis does in subsequent stages.

It is 2050, and highly tense international relations and spreading regional conflicts are disrupting global trade. Despite the EU maintaining its overall ambitions for Net Zero, the political and economic context has brought challenge after challenge, and decarbonisation targets are largely unmet. Global collaboration is limited, with protectionist policies in place. Investment in clean energy R&I has remained flat compared to the 2020s, and technology costs are unchanged. Carbon emissions have continued to increase globally, with global temperature rises exceeding 2 °C by 2050 and on track for 3 °C by the end of the century.

Geopolitical and global trade instability

Volatile and unstable international relations have led to major power conflicts and proxy wars in strategically important regions. Implications for global trade are significant, with major disruption in particular for CRMs supply. Cyberattacks targeting critical infrastructure, including transport and energy, are a constant concern, with periodic black outs. Recession and protectionist industrial policies have contributed to a complex environment for multinationals to operate in. The main drivers for global markets are increased military spending and the growing Asian market, now the world's largest consumer population, with huge demand from development and rapid smart urbanisation. Multinationals have pivoted to focus on these business opportunities, resulting in a lack of private sector interest in clean energy, at the expense of meeting EU needs and requirements.

For many countries, including EU Member States, geopolitical instability has led to prioritisation of defence investment, autonomy and efforts to maintain strategic alliances. The public also prioritises safety and affordable living costs as their daily lives become more disrupted by the ongoing conflicts. The EU has, for example, led significant initiatives to onshore previously globalised value chains, reducing the impact of shocks and disruptions.

For countries with 2050 decarbonisation targets, policies from the 2020s were continued and achievement of more ambitious pledges was slowed down by disruption. Some CRMs become effectively completely unavailable due to the geographic location of resources. Despite significant efforts to pursue the development of alternative materials with AI-led materials discovery, insufficient progress has been made and materials discovery and supply remains a significant barrier to achieving decarbonisation. Regulations and policies have not worked in synergy with decarbonisation targets, introducing multiple challenges and trade-offs for achieving Net Zero when competing priorities were pursued.

A hindered EU green transition

Recession and lack of global research collaboration has hindered EU decarbonisation progress. Knowledge-exchange activities have significantly reduced between blocs, leaving the EU alone in its efforts around energy R&I. Global capital is concentrated in Asia, and Member States are struggling to attract foreign investment into Europe for clean energy deployment. Recognising the difficulties of the context, the EU was not able to continue increasing investment in energy R&I and was unable to deliver cost reductions as it had hoped. Compounded by shortages of CRMs caused by extreme weather events and conflict, the consumer cost of clean energy is increased, with knock-on effects for public support for the transition.

EU citizens have conflicting attitudes towards the green transition. Ambitious policies in the 2020s were viewed as unjust, and changes required to roll out low-carbon transport were perceived as enforced rather than desirable. As a result of the economic situation, unemployment, and increasing inequality, public discontent is high, with significant resistance to clean energy deployment. Some believe that continuing decarbonisation is necessary to prevent the most serious consequences of climate change. At the same time, conspiracy theories and apocalypticism have gained ground and prompted vandalism against clean energy infrastructure. After the dramatic cyber-attack of 2043, when the European grid was taken down, the risk of cyberattacks is front-of-mind. Even those people who describe themselves as neutral are reluctant to adopt smart technologies despite the promise of energy-efficiency gains.

Worsening impacts of climate change

Carbon emissions have continued to increase in major economies, with the main limiting factor being the ongoing recession, and are on track to reach 3 °C rise before 2100. In the 2040s, 2 °C warming was exceeded, and in 2050, the global temperature is 2.1 °C above pre-industrial temperatures. The implications are severe, with extreme heat and sea level events more than five times more frequent, leading to crop failure and casualties. Increased rainfall and flooding in northern Europe are disrupting productivity and mobility. The Netherlands and Belgium are deeply concerned by sea level rise and are exploring options to reclaim land and evacuate affected populations. A digital twin of Venice was created in an effort to digitally preserve this endangered global heritage site. The physical vulnerability of energy infrastructure and offshore assets is exploited by malicious cyberattacks, in attempts to compound risks and increase impacts.

Table 6.11 presents the corresponding RAG rating for Scenario 3 across energy security indicators for 2030 and 2050, together with a brief explanation of the rationale for the RAG assessment.

Table 6.11 Scenario 3 energy security indicator RAG rating

Energy security indicator	2030	2050	Scenario factors influencing RAG ratings
Geopolitical availability			The geopolitical situation grows increasingly tense, and in 2030, there is severe disruption to supply chains as conflict and geopolitical events impact the availability of CRMs. By 2050, the situation has somewhat improved as supply chains have reorganised to reduce their vulnerability to geopolitical events. However, for those materials with only one or a small number of supplier countries due to the location of reserves, supply continues to be severely disrupted and vulnerable to shocks.
Abundance			Decarbonisation is overshadowed by other priorities in this conflicted world, and therefore further exploration and resource exploitation does not happen. Supply volumes remain strained, with recycling only offering minor relief.
Circularity			The EU pursues circularity at an accelerated pace to increase its autonomy and resilience amidst global conflict and disruption.
Supply chain complexity			Policy interventions in the pursuit of autonomy and market incentives take time to shorten supply chains, but by 2050, significant proportions of EU value chains are located within the EU or in countries that are close allies.

			GEM-E3: The EU becomes autonomous in key and complex supply chains; hence its exposure in this scenario is limited.
Supply chain location			As conflicts escalate in scope in the 2020s, supply chains become severely disrupted when operations are in or near conflict zones. The shift to cyber warfare has a much stronger impact on countries with less advanced cybersecurity infrastructures and requirements. Reactive measures to increase resilience result in supply chains predominantly based in the EU or allied countries by 2050. GEM-E3: EU has very low dependency on primary and secondary imports in clean energy technologies, due to trade restrictions.
Digital vulnerability			Increased digitisation has prompted a move towards cyberattacks and cyber warfare as the primary form of threat during conflicts. Cybersecurity measures improve; however, hackers continue to search for vulnerabilities with sufficient success to ensure cyber threats remain a major concern.
Physical vulnerability			Physical vulnerability continues to increase from the physical threats from conflict, from cyberattacks causing physical damage and from global temperature rise.
Broader sustainability			The public views other issues as more important than decarbonisation and grows increasingly polarised and opposed to the green energy transition in 2030. Conspiracy theories spread, leading to attacks against energy infrastructure. As the pace of decarbonisation reduces, public opinion remains opposed, but there are no major protest or disruptions in 2050.
Affordability			Spiralling costs of materials and components caused by supply chain disruption results in rising costs of energy in 2030 and serious affordability challenges for consumers. The situation improves as value chains adapt to mitigate risks of disruptions; however, costs remain high in 2050, especially compared to 2023-2024. GEM-E3: Trade restrictions in clean energy technologies increase their production and investments. Technology improvements and learning-by-doing effects reduce the production costs. However, this scenario increases in total the costs for the EU economy, because the

			technologies produced are more expensive than any other scenario considered.
Skills			With the slowed progress to decarbonise, demand on skills does not increase rapidly and pressure on skills requirements is limited.

6.3. Current status of clean energy technologies market

6.3.1. Current status of market share and demand–supply trade

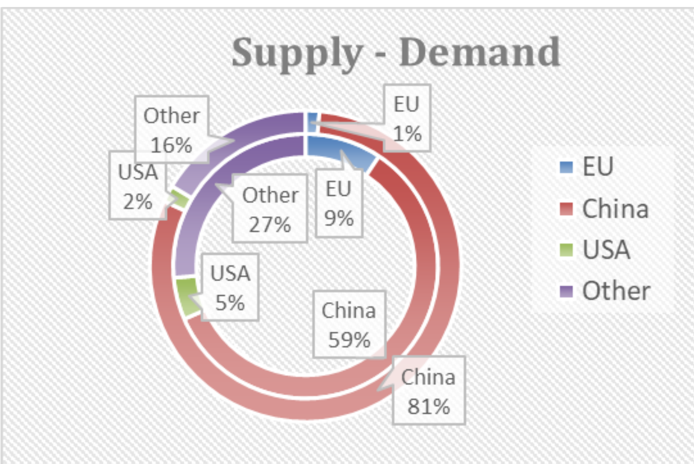
Before presenting the results of the GEM-E3 model for the scenarios, we present an overview of the current market status for key clean energy technologies, including PV panels, wind turbines, batteries, electric vehicles, biofuels and CCS technologies. The aim is to provide a comprehensive understanding of the characteristics and dynamics that define each market.

Photovoltaic panels

The PV panel market has witnessed remarkable growth in recent years, driven by advancements in technology and increasing awareness of renewable energy. Key characteristics include declining costs, improved efficiency, and a growing global installed capacity. Government incentives and supportive policies have played a crucial role in fostering market expansion.

The global production of PV panels has reached approximately EUR 37 billion, with China establishing a dominant position by commanding a market share of 70-80%. China's leadership in the market is notable, representing a substantial majority of the total production value. Following behind is Vietnam, emerging as a significant player in the industry, albeit with a comparatively smaller market share. This concentration underscores the pivotal role that China plays in the global landscape, with Vietnam making noteworthy contributions to the industry's overall production. In Figure 6.1, a doughnut graph is utilised to depict the proportions of the entire market. The outer circle represents the supply, while the inner circle represents the demand. The difference between these two circles visually communicates the net exports of the country, for the respective technology.

Figure 6.1 PV panel supply (domestic production – outside circle) and demand (domestic demand – inside circle) for 2020.

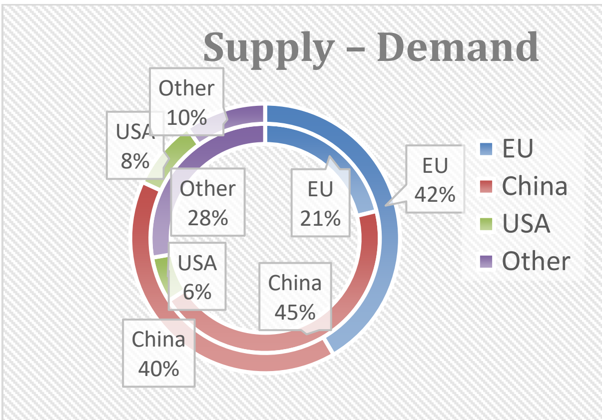


Wind turbines

The wind turbine market has evolved into a mature and competitive industry. Large-scale onshore and offshore wind projects are contributing significantly to global energy production. Notable characteristics include increasing turbine size, enhanced efficiency, and a trend towards incorporating smart grid technologies. Market growth is influenced by both environmental considerations and economic factors.

The EU and China jointly hold the position of the largest producers in the wind turbines industry, contributing significantly to the global production, which is estimated to be around USD 100 billion (ca. EUR 93 billion[52]). This dominance emphasises their pivotal roles in shaping the dynamics and scale of the overall industry, with each having an impact on the substantial global production value. The category 'other' holds a significant share. For the wind equipment industry, 'other' refers mainly to Brazil, India and Canada.

Figure 6.2 Wind equipment supply (domestic production – outside circle) and demand (domestic demand – inside circle) for 2020



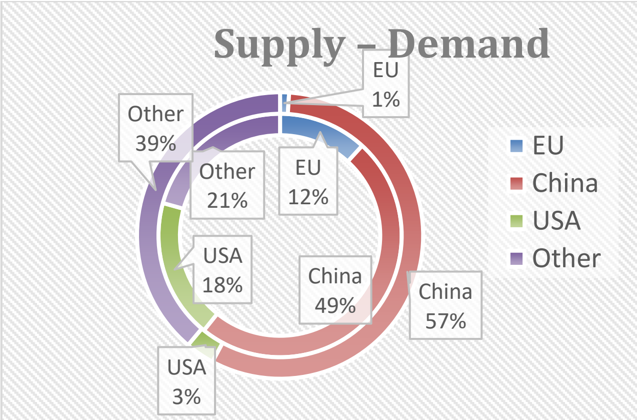
Batteries

The battery market is experiencing significant changes, driven by the surge in demand for electric vehicles and energy storage solutions. Advancements in lithium-ion technology dominate the landscape, with a focus on higher energy density and longer life cycles. The market is characterised by ongoing research and development, increased manufacturing capacities, and a growing emphasis on sustainable battery recycling.

The global production in this sector amounts to approximately USD 54 billion (ca. EUR 50 billion). China leads the market, commanding a dominant share of around 55%. Following China, other key players include Korea, holding a substantial, 20% market share; Japan, with 10%; and India, with 5%. This distribution highlights China's significant influence in the global market, with Korea, Japan and India also playing notable roles in shaping the industry landscape.

[52] Exchange rates used throughout the report are from the European Central Bank, as of 29 February 2024. ECB, Euro Foreign Exchange Reference Rates (accessed 29/03/2024).

Figure 6.3 Batteries supply (domestic production – outside circle) and demand (domestic demand – inside circle) for 2020

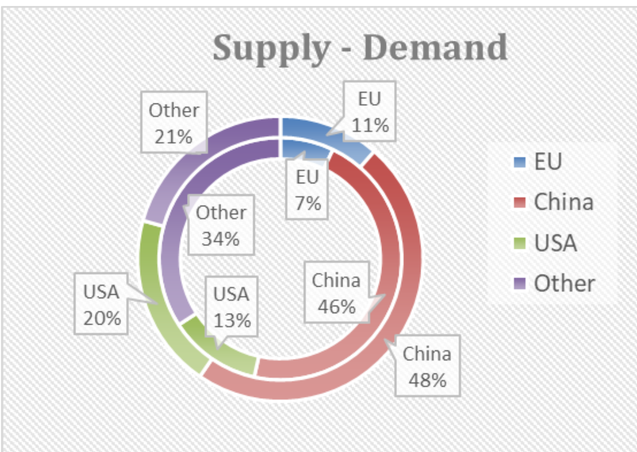


Electric vehicles

The electric vehicle market is experiencing robust growth, with increasing adoption globally. Key characteristics include rising sales figures, expanding market share and a growing consumer awareness of the benefits of electric mobility. Government incentives, emission reduction targets and changing consumer attitudes contribute to this momentum.

The global market for electric vehicles is valued at approximately USD 250 billion (ca. EUR 231 billion). China holds the position of the largest producer in this market, with the United States and the EU following closely behind. This distribution underscores China's significant role as a major contributor to the industry's global market value, with the United States and EU also making substantial contributions to the overall market dynamics. Korea and Japan, included in ‘other’, also make a significant contribution to the supply of electric vehicles.

Figure 6.4 Electric vehicles supply (domestic production – outside circle) and demand (domestic demand – inside circle) for 2020

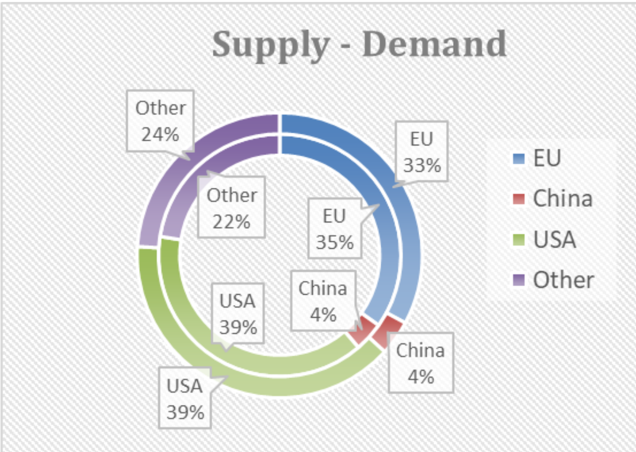


Biofuels

The biofuels market is shaped by a quest for sustainable alternatives to traditional fossil fuels. Key characteristics include a diverse range of feedstocks, such as corn, sugarcane and algae, contributing to bioethanol and biodiesel production. Government mandates and incentives, along with the focus on reducing carbon emissions, drive market dynamics. Challenges include competition with food production and the need for advanced biofuel technologies.

The global production in this sector amounts to approximately USD 132 billion (ca. EUR 124 billion), with the United States and the European Union emerging as the leading forces in the market. This indicates a substantial combined influence, with both the United States and the EU playing pivotal roles in shaping the industry's global production landscape. Brazil also makes significant contribution to the production of biofuels and holds a market share of around 10%.

Figure 6.5 Biofuels supply (domestic production – outside circle) and demand (domestic demand – inside circle) for 2020



Carbon capture and storage technologies

CCS technologies play a critical role in mitigating industrial emissions. The market is characterised by ongoing research to enhance capture efficiency and reduce costs. Key developments include the integration of CCS with industrial processes and power generation. Government incentives, carbon pricing mechanisms, and corporate sustainability goals are shaping the adoption of CCS technologies. As the market is very small in 2020, and data for 2020 are not available.

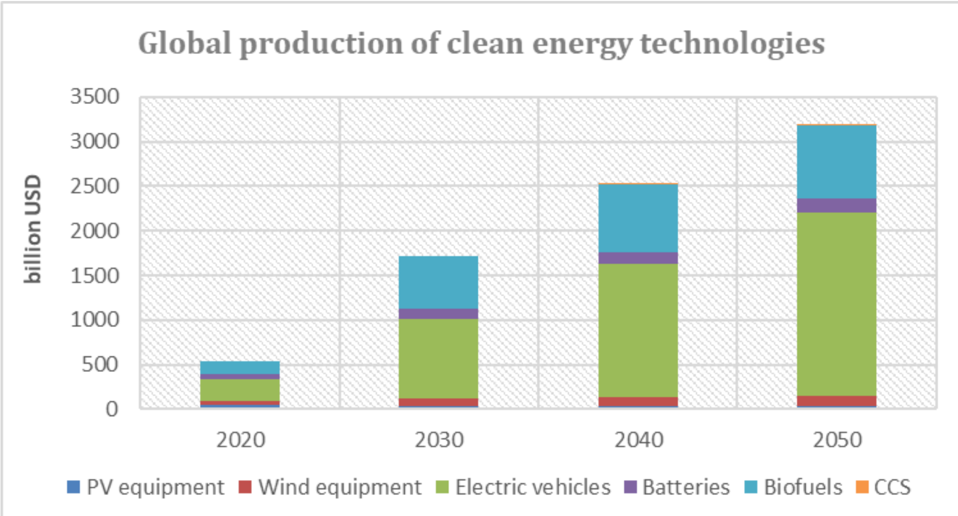
6.4. GEM-E3 modelling for the scenarios

6.4.1. Scenario 1

In GEM-E3, the quantification of Scenario 1 implies that the EU eventually reaches its target (55%) by 2030 and Net Zero until 2050 but does not benefit from significant global cost reduction in clean energy technologies because non-EU countries do not engage in significant decarbonisation efforts; they achieve their nationally determined contribution (NDC) in 2030 and have similar carbon prices for the 2030-2050 period.

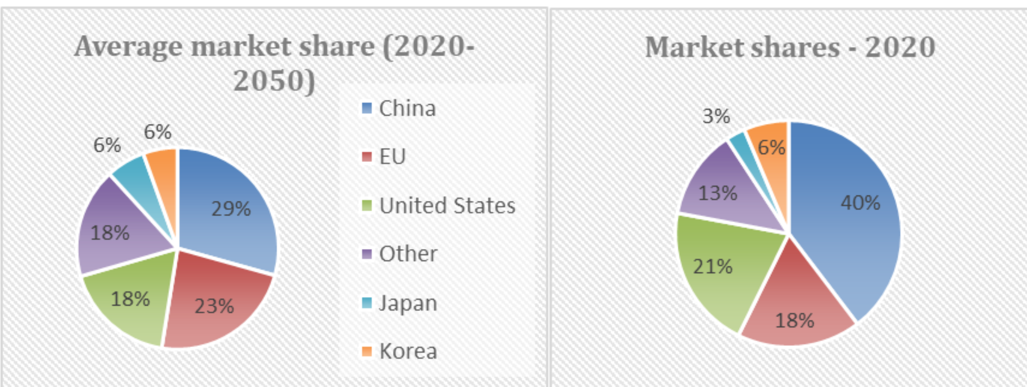
In the long term, by the year 2050, the global production of clean energy technologies is anticipated to experience a substantial increase, reaching an estimated value of around USD 3.2 trillion (ca. EUR 3 trillion). This projection signifies a remarkable, sixfold rise compared to the production levels observed in the year 2020 (Figure 6.6). The production growth in the EU is projected to outpace that of non-EU countries, with a substantial, 7.6 times increase compared to the production levels recorded in the year 2020. This indicates that the EU is on a faster trajectory in advancing its clean energy technology production compared with non-EU countries, emphasising its commitment to sustainable and environmentally friendly initiatives in comparison to non-EU nations.

Figure 6.6 Market size per clean energy technology – Scenario 1



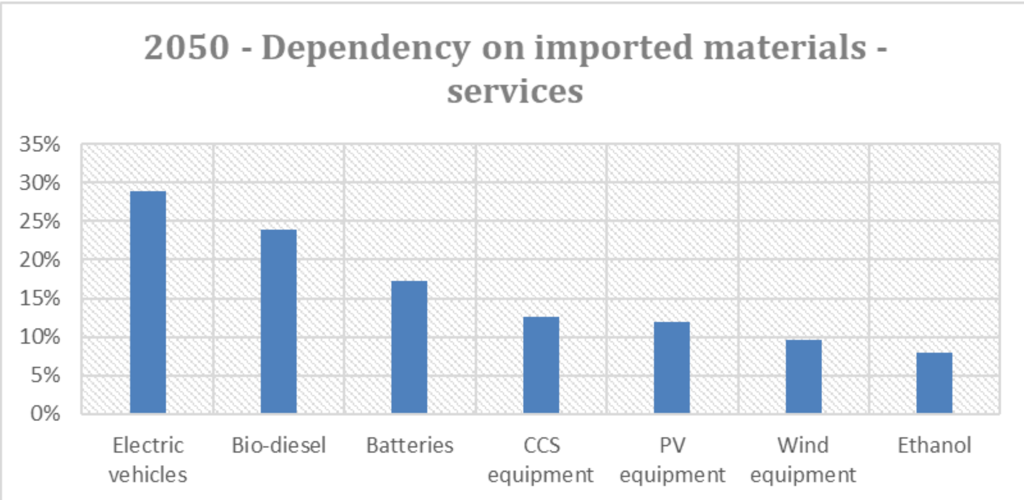
From 2020 to 2050, the EU maintains an average market share of 23% in global clean energy technology production and China leads, at 29%. Within the EU's production portfolio, there are significant market shares in wind and biofuels. However, there is notable lag in the production of PV panels and batteries. In the electric vehicles market, characterised by its substantial size, China, the EU, and the United States emerge as dominant players in terms of production.

Figure 6.7 Market shares of clean energy technologies by country – Scenario 1. Average market share shows overall trends relative to 2020 over the period of interest (e.g. reduced market share for China)



Throughout the simulation period, the EU relies on imports from China for batteries and photovoltaic panels (PV equipment, batteries), as well as from Korea for batteries. In the EU's value chain for electric vehicles, there is a notable dependency on imported materials and services, accounting for approximately 29% in 2050. This indicates significant reliance on external sources for various components and services crucial to the production of electric vehicles. In contrast, the wind equipment and ethanol value chains exhibit lower dependency on imports, ranging around 8-10%. This suggests a relatively higher degree of self-sufficiency or reliance on regional sources for materials and services in these specific clean energy technology sectors.

Figure 6.8 EU Dependency on imported materials and services by clean energy technology – Scenario 1

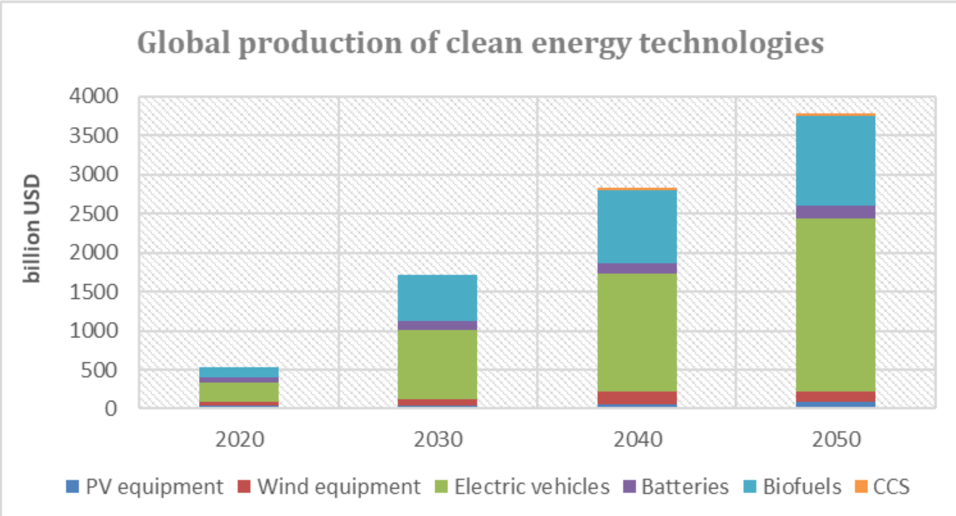


6.4.2. Scenario 2

The GEM-E3 quantification of Scenario 2 implies that EU and non-EU countries reach their NDC target by 2030 and Net Zero by 2050 (based on the Net-Zero pledges from COP26).

A collective effort to reduce GHG emissions sends a consistent signal to investors, prompting an acceleration of investments and R&I expenditures. This heightened commitment results in a peak in demand for clean energy technologies. By the year 2050, in this scenario, the global production of clean energy technologies surges to nearly USD 3.8 trillion (ca. EUR 3.5 trillion), marking a substantial, sevenfold increase from the levels observed in 2020. This scenario underscores the profound impact of coordinated efforts in driving substantial growth and innovation within the clean energy technology sector.

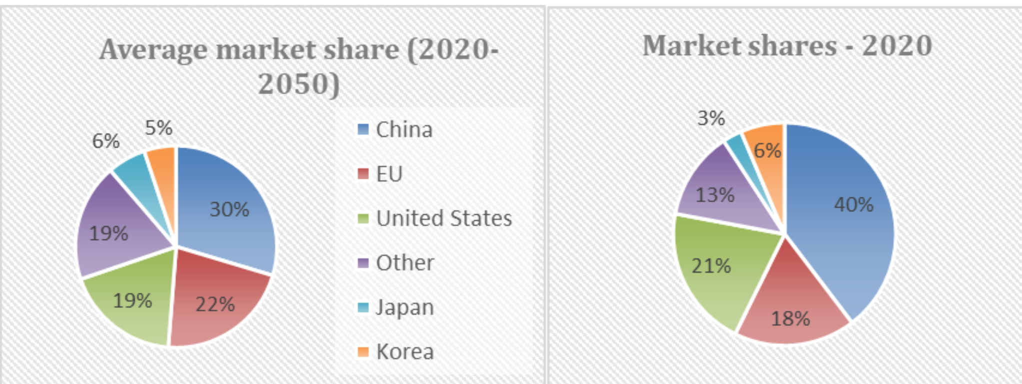
Figure 6.9 Market size per clean energy technology – Scenario 2



From 2020 to 2050, the EU maintains a substantial average market share, of around 22%, in global clean energy production, and China leads, at approximately 30%.

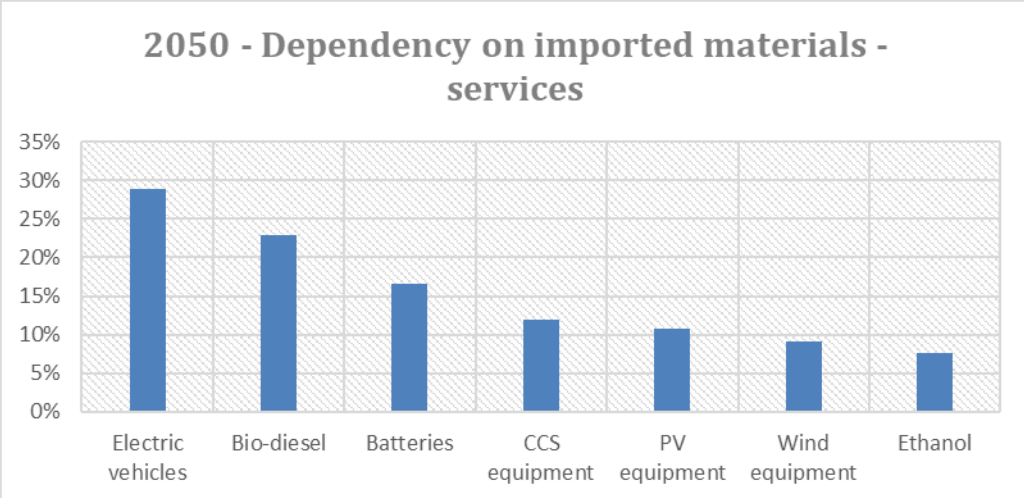
In this scenario, the EU benefits from access to low-cost technologies, facilitated by a global effort that further reduces the cost of these technologies. Additionally, the EU gains access to external markets, allowing it to direct its competitive clean energy products to a broader audience.

Figure 6.10 Market shares of clean energy technologies by country – Scenario 2. Average market share shows overall trends relative to 2020 over the period of interest (e.g. reduced market share for China)



As in Scenario 1, the EU relies on imports from China for batteries and photovoltaic panels (PV equipment, batteries), as well as from Korea for batteries. In the EU's value chain for electric vehicles, there is still a significant reliance on imported materials, highlighting the highest dependency in this sector. Conversely, in the value chains for wind equipment and ethanol, the dependency on imported materials is comparatively lower, showcasing the lowest levels of reliance on external sources for these specific clean energy technology sectors.

Figure 6.11 Dependency on imported materials and services by clean energy technology – Scenario 2

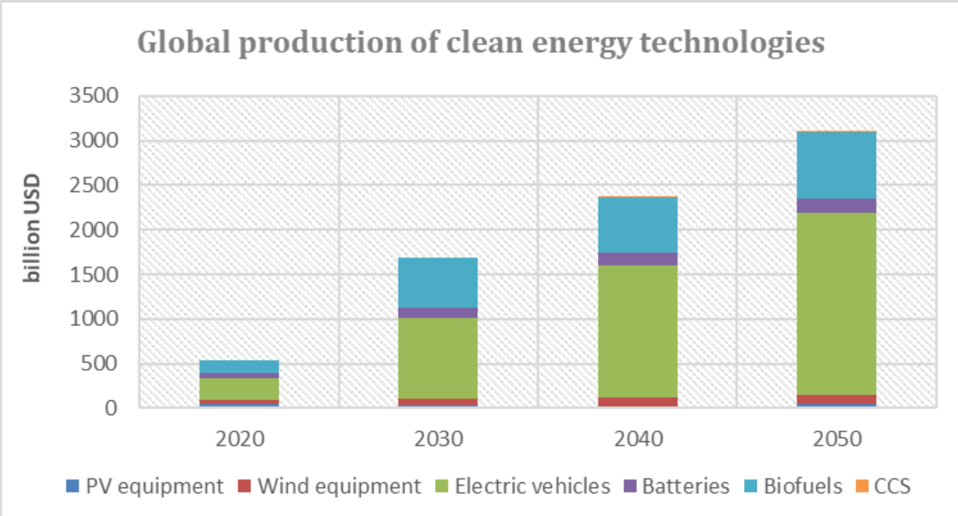


6.4.3. Scenario 3

The GEM-E3 quantification of Scenario 3 implies that the EU achieves a GHG emission reduction target of 40% until 2030 and 65% until 2050 compared to 1990 levels, while non-EU countries reach their NDC target by 2030 and do not pursue significant decarbonisation afterwards. Global trade restrictions have been assumed; in particular, the EU is modelled to meet almost in full its demand for industry, ethanol and agriculture. This has resulted in a significant increase in the EU market share in clean energy technologies.

In this scenario, the global production of clean energy technologies is notably lower than in any other considered scenario, reaching almost USD 3.1 trillion (ca. EUR 2.9 trillion), which represents a 5.8-times increase from 2020 levels. Despite this overall decrease, the EU maintains a sizeable market share in clean energy technologies. Despite having lower ambition regarding GHG emission reduction, the EU strategically increases its domestic capacity, aiming to achieve self-sufficiency. This signifies a deliberate effort by the EU to enhance its resilience and autonomy in the clean energy technology sector, even in the context of a lower global clean energy technology production scenario.

Figure 6.12 Market size per clean energy technology – Scenario 3



Throughout the period 2020 to 2050, the EU maintains a market share of approximately 25% in global clean energy production. While the market shares are similar to those in Scenario 1, two distinct channels influence these shares differently compared to Scenario 1.

- **Lower ambition in GHG emission reduction:** Scenario 3 features a lower ambition in GHG emission reduction, resulting in decreased demand for clean energy technologies. This reduction in demand contributes to a lower market share for the EU in clean energy technologies compared to Scenario 1.

- **Trade restriction impact:** The imposition of trade restrictions in Scenario 3 increases EU production of clean energy technologies, leading to a higher market share. The trade restriction effect slightly dominates, contributing to an overall higher market share for the EU in clean energy technologies compared to Scenario 1.

In summary, the interplay of these two factors results in a nuanced market dynamic, with trade restrictions exerting a slightly stronger influence on increasing the EU's market share, despite the lower demand stemming from reduced GHG emission reduction ambition.

Figure 6.13 Market shares of clean energy technologies by country – Scenario 3. Average market share shows overall trends relative to 2020 over the period of interest (e.g. reduced market share for China)

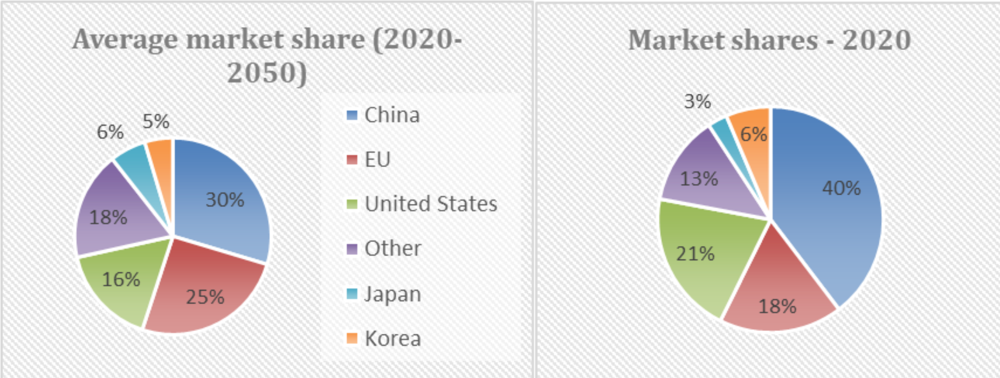
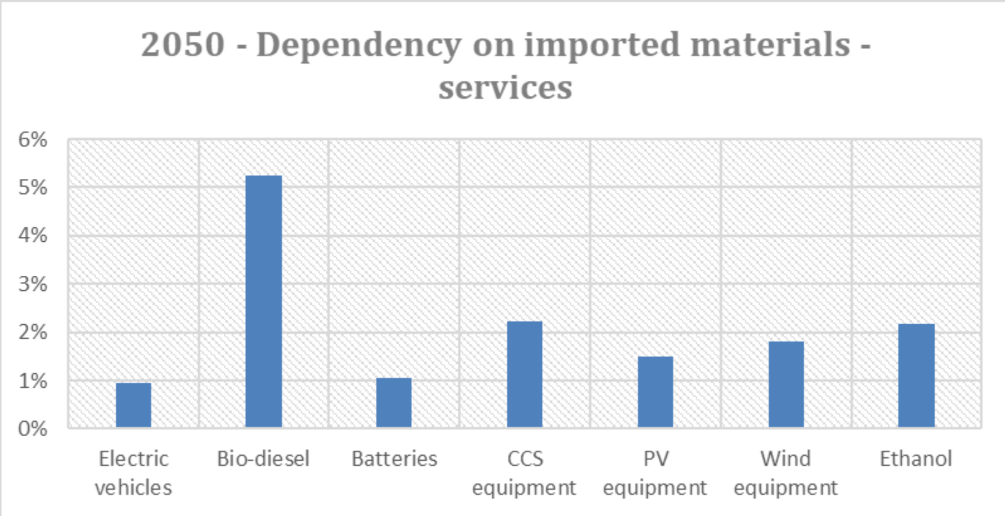


Figure 6.13 illustrates the dependency on imported materials and services. In contrast to Scenarios 1 and 2, in Scenario 3 the EU achieves autonomy in all clean energy technologies. This indicates that, in Scenario3, the EU has successfully reduced or eliminated its reliance on external sources for materials and services across various clean energy sectors. This achievement underscores the EU's strategic efforts to enhance self-sufficiency and minimise dependencies on imported components, contributing to a more autonomous and resilient clean energy landscape.

In the electric vehicle sector, characterised by a substantial market size, production is predominantly dominated by China, the EU, and the United States. Notably, due to the scenario's assumption of trade restrictions in clean energy technologies, the EU has strategically shifted to covering its demand for clean energy technologies through domestic production. As a result of this strategic shift, the dependency of the EU's electric vehicle value chain on imported materials and services has significantly declined in comparison to previous scenarios. It now stands at approximately 1%, marking a notable decrease from the previous level, where it stood at around 29%. This reduction reflects the EU's efforts to enhance self-sufficiency and reduce reliance on external sources for crucial components in the electric vehicle manufacturing process.

Figure 6.14 Dependency on imported materials and services by clean energy technology – Scenario 3



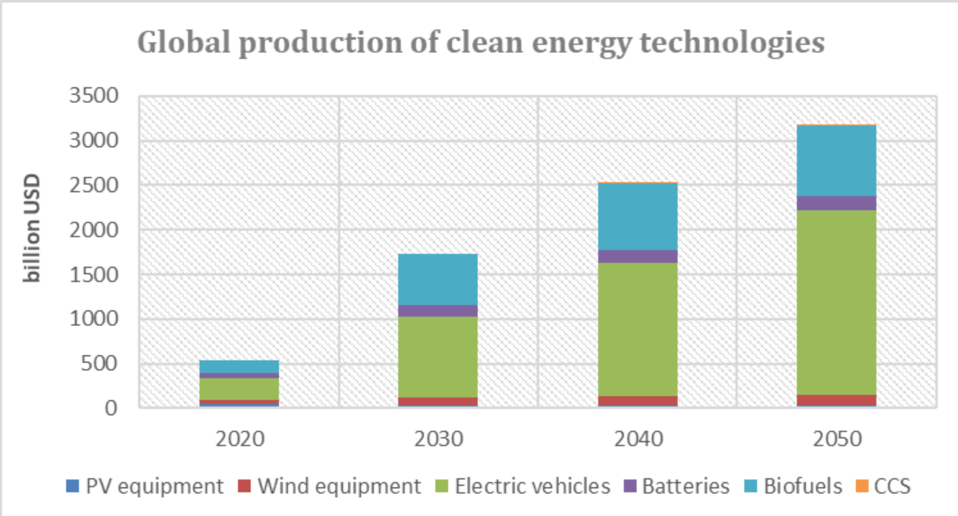
6.4.4. Scenario 3B (high EU ambition)

An additional scenario was modelled with GEM-E3 to provide an understanding of what the EU might need to do to achieve Net Zero and autonomy for clean energy technology value chains. This scenario is a sensitivity analysis of Scenario 3. In this sensitivity analysis, the EU increases its GHG emissions reduction targets. It is assumed that highly tense international relations and spreading regional conflicts are disrupting global trade. Despite the political and economic challenges, the EU maintains its Net-Zero ambitions and achieves its decarbonisation targets (attains GHG emission reduction target of 55% by 2030 and Net-Zero emissions by 2050 compared to 1990 levels). The EU meets nearly all of its demand for industry, ethanol, and agriculture products through domestic production and achieves the goal of achieving greater self-sufficiency and reducing external dependencies in key economic sectors. This scenario emphasises the EU's commitment to fostering innovation and research while achieving autonomy in the clean energy sector. This scenario shows that EU internal capacity and market size are sufficient large to support the deployment and associated cost reductions of clean energy technologies. However, this comes at a cost, as technologies may not reach full cost reduction potential as they would in an international, concerted climate action (without trade restrictions).

The GEM-E3 quantification of Scenario 3B (high EU ambition) indicates that the EU successfully achieves a GHG emission reduction target of 55% by 2030 and attains Net-Zero emissions by 2050 compared to 1990 levels. In contrast, non-EU countries achieve their NDC target until 2030 but do not actively pursue significant decarbonisation thereafter. Global trade restrictions are assumed in this scenario. Specifically, the EU is modelled to satisfy nearly all of its demand for industry, ethanol and agriculture through domestic production. This trade strategy aligns with the EU's goal of achieving greater self-sufficiency and reducing external dependencies in key economic sectors.

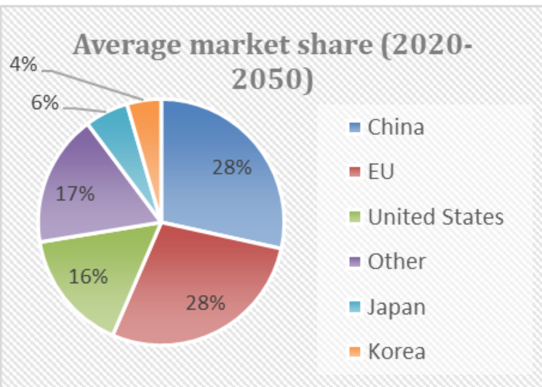
In this scenario, the global production of clean energy technologies remains at levels similar to Scenario 1, where the GHG emissions mitigation ambitions are consistent. However, the implementation of trade restrictions has led to the relocation of some global production into the EU, differing from the dynamics observed in Scenario 1.

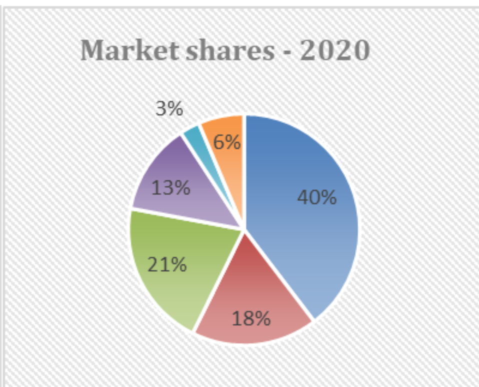
Figure 6.15 Market size per clean energy technology – Scenario 3B (high EU ambition)



Throughout the period 2020 to 2050, the EU achieves its highest average market share in Scenario 3B (high EU ambition), reaching 28%. This represents a peak compared to other scenarios considered. The ambitious GHG emission reduction targets, attainment of Net-Zero emissions, and trade restrictions in Scenario 3B (high EU ambition) contribute to the EU's enhanced market position in the global clean energy technology landscape.

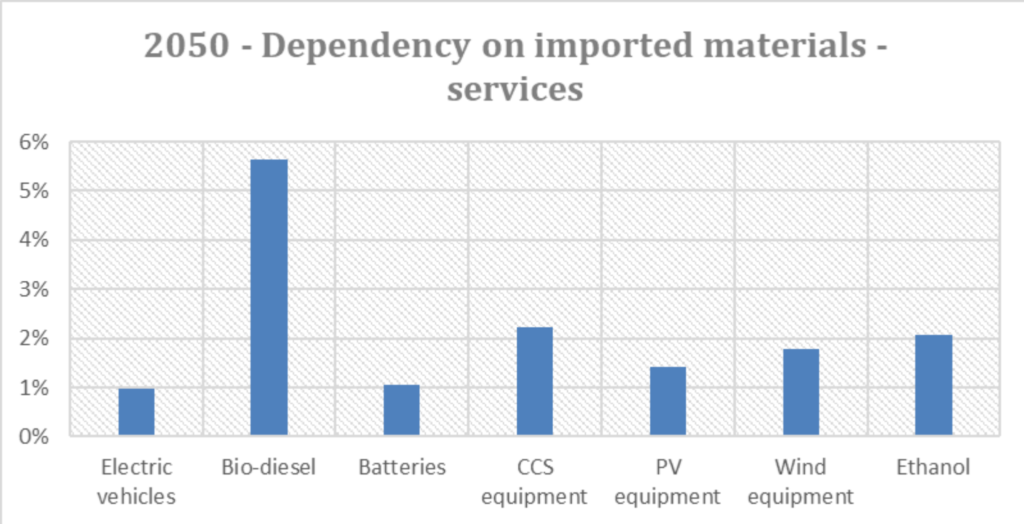
Figure 6.16 Market shares of clean energy technologies by country – Scenario 3B (high EU ambition). Average market share shows overall trends relative to 2020 over the period of interest (e.g. reduced market share for China)





Like in Scenario 3, in Scenario 3B (high EU ambition), the EU attains autonomy in all clean energy technologies. This signifies that the EU has effectively decreased or eliminated its dependence on external sources for materials and services across a range of clean energy sectors. The strategic initiatives and policies implemented in Scenario 3B (high EU ambition) contribute to the EU's self-sufficiency, reducing vulnerabilities associated with external dependencies in the clean energy technology landscape.

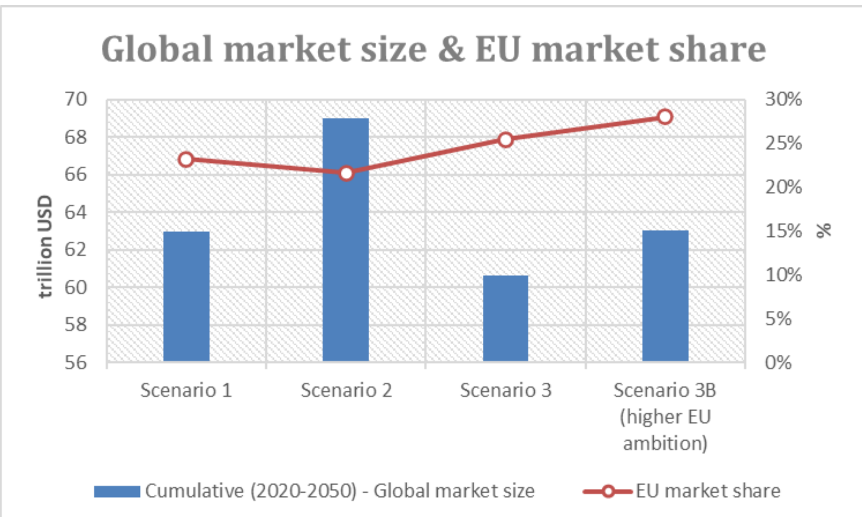
Figure 6.17 Dependency on imported materials and services by clean energy technology – Scenario 3B (high EU ambition)



6.5. Synthesis of the scenario results, comparisons and model caveats

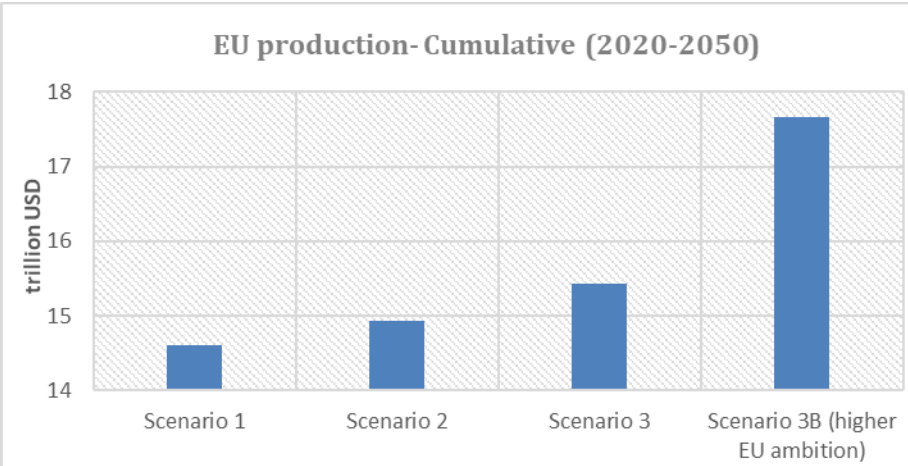
In Scenario 2, characterised by a concerted and decisive action towards reducing GHG emissions, a consistent and clear signal to investors accelerates investments and R&I expenditures. This robust commitment results in a peak in demand for clean energy technologies. Over the period 2020 to 2050, the market size of clean energy technologies in Scenario 2 reaches USD 69 trillion (ca. EUR 64 trillion). On the other hand, Scenario 3, with its lower ambition in GHG emission reduction, experiences the lowest production of clean energy technologies among the considered scenarios. This showcases the pivotal role of ambitious emission reduction goals in stimulating investment, innovation, and, ultimately, the demand for clean energy technologies.

Figure 6.18 Global clean energy technology production – cumulative (2020-2050)



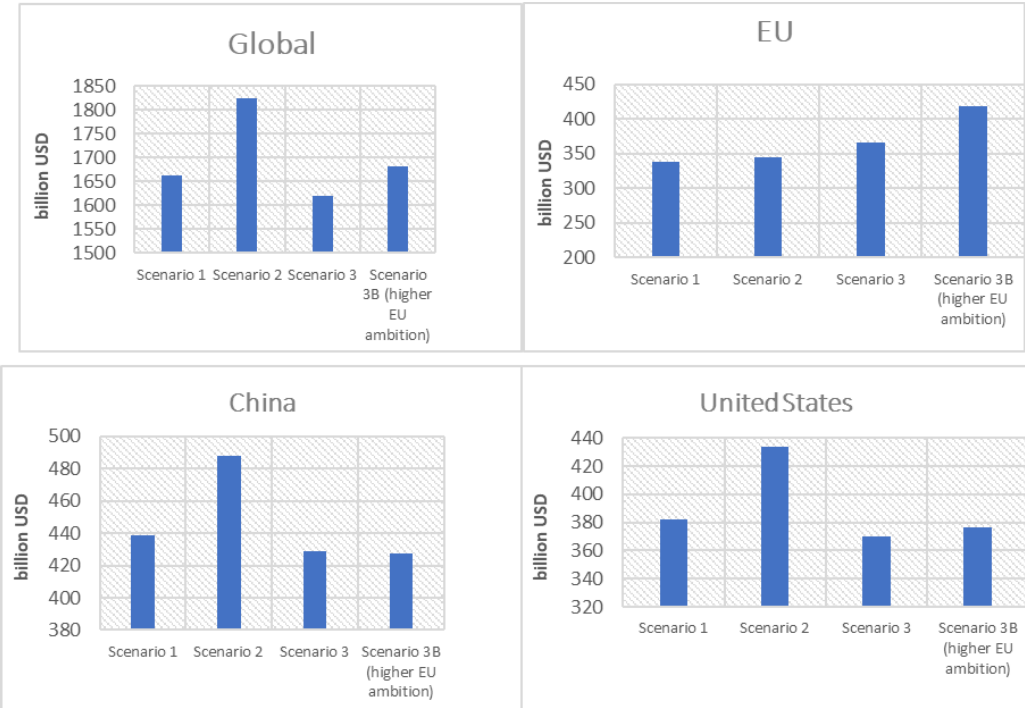
When focusing solely on the EU, Scenario 3B (high EU ambition) stands out in terms of clean energy production. The implementation of trade restrictions and the increased GHG emissions reductions goals are the primary contributors to this outcome. In contrast, Scenario 1, characterised by the absence of trade restrictions, results in the lowest clean energy production within the EU. This underscores the significant impact that trade policies can have on the EU's domestic clean energy production levels, highlighting the importance of trade dynamics in shaping the outcomes of the clean energy sector.

Figure 6.19 EU clean energy technology production – cumulative (2020-2050)



In Scenario 2, characterised by a global effort to mitigate GHG emissions, there is a peak in global R&I expenditures. This scenario reflects a heightened collective commitment to addressing environmental challenges, stimulating increased R&I activities on a global scale. In contrast, Scenario 3, despite having lower ambitions in reducing GHG emissions, sees higher EU R&I expenditures compared to Scenarios 1 and 2. This increase is attributed to the implementation of trade restrictions, reflecting the EU's strategic focus on self-sufficiency and technological advancements. In Scenario 3B (high EU ambition), EU R&I expenditures reach their peak, driven by the fact that the EU covers nearly all domestic demand for clean energy technologies, with the goals of achieving the GHG emission reduction. This scenario emphasises the EU's commitment to fostering innovation and research while achieving autonomy in the clean energy sector.

Figure 6.20 R&I expenditures by region and global – Cumulative (2020-2050)



Upon closer examination of R&I expenditures in the EU by technology, a notable contributor to the rise in expenditures resulting from trade restrictions is evident in the eV and batteries market. There is a substantial increase, approximately USD 65-70 billion (ca. EUR 60-65 billion), compared to the scenario without trade restrictions over the cumulative period 2020 to 2050. Additionally, a discernible uptick is observed in the photovoltaic equipment sector, reflecting a nearly USD 5-6 billion (ca. EUR 4.6-5.5 billion) increase.

Figure 6.21 EU R&I expenditures by technology – Cumulative (2020-2050)

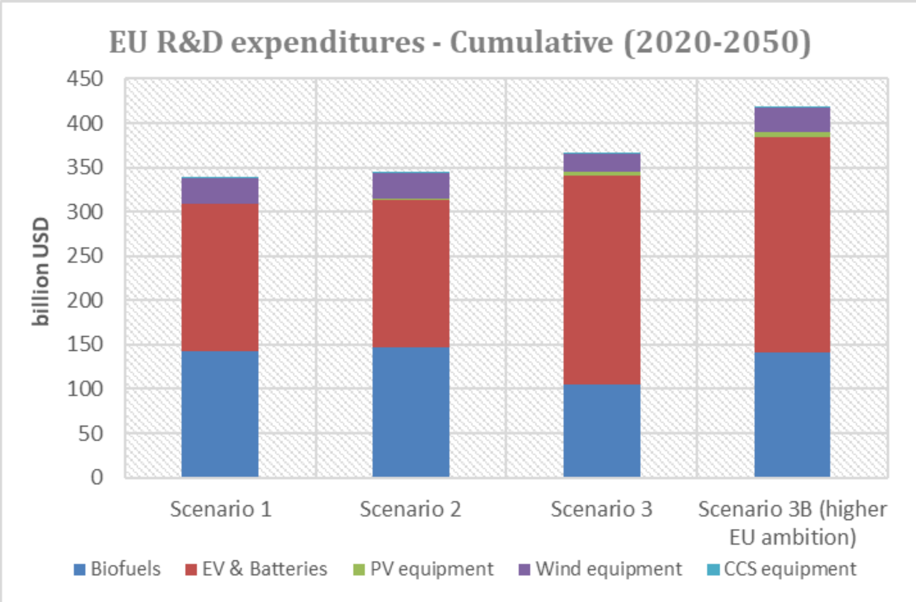
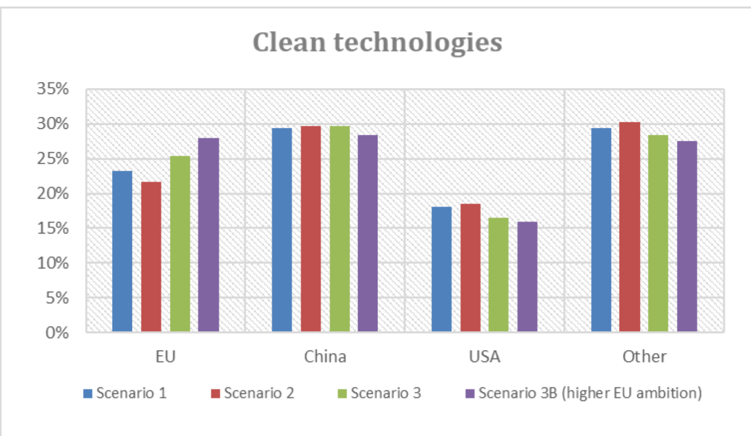


Figure 6.22 illustrates the average market share by country and scenario in the clean energy technology market. In Scenario 3B (high EU ambition), the EU claims the highest market share compared to other scenarios. This is attributed to the EU's ambitious climate targets and a strategic emphasis on self-sufficiency in clean energy technologies, which contribute to its leading market position. Conversely, Scenario 2 exhibits the lowest market share for the EU, driven by the global effort to mitigate GHG emissions, resulting in a substantial increase in clean energy production in non-EU countries and diminishing the EU's relative market share. It is difficult for countries that have established a comparative advantage in certain technologies to lose market share, as they have already accumulated a significant stock of knowledge.

Figure 6.22 Market shares in clean energy technologies by country – average in the period 2020-2050



The most significant change in EU market shares occurs in photovoltaic equipment and batteries where these sectors are heavily reliant on imports (Figure 6.23). In Scenarios 3 and

3B (high EU ambition), where trade restrictions are implemented, the EU experiences a substantial increase in market share for PV equipment and batteries.

Figure 6.23 EU market share to global production by scenario – average in the period 2020-2050

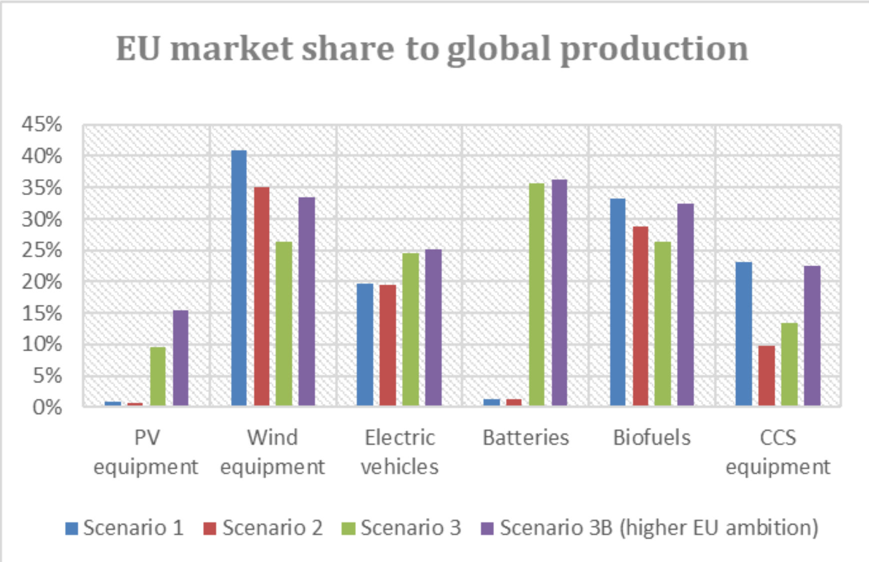
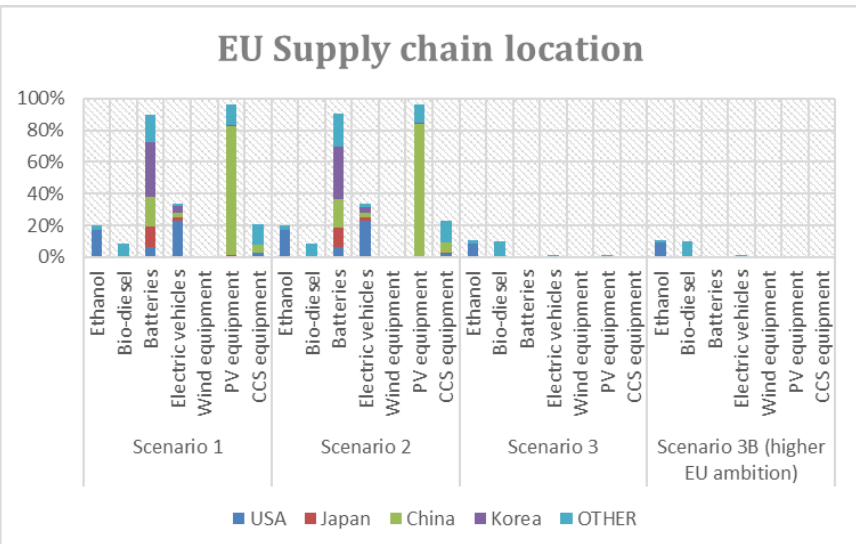


Figure 6.24 illustrates the EU's dependency on imports by location. In Scenarios 3 and 3B (high EU ambition), there is a notably low dependency on imports. In Scenarios 1 and 2, PV equipment is primarily imported from China, showcasing a concentrated import dependency. Conversely, the import dependency for batteries is more diversified, with imports sourced from various countries rather than being concentrated in one particular region. This visual representation underscores the impact of different scenarios on the EU's import dependencies, with trade restrictions in Scenarios 3 and 3B (high EU ambition) contributing to a reduction in overall import dependency.

Figure 6.24 EU dependency on imports by origin of country (2050)



The GEM-E3 model incorporates CRMs, such as cobalt, into broader sectors, such as 'cobalt in non-metallic minerals', due to limitations in data granularity. This poses limitations for a more in-depth exploration of the intricate supply chains associated with clean energy technologies, as the grouping hinders the ability to delve into specific details of the supply chains for essential materials, such as cobalt.

In February 2024, the European Commission published its impact assessment outlining potential routes to achieve the objective of attaining climate neutrality in the EU by 2050.[53] In light of this assessment, the Commission suggests a 90% net reduction in GHG emissions by 2040 relative to the levels recorded in 1990. In the scenarios implemented in this study, GHG emissions reduction by 2040 is lower (5%) than the target of the impact assessment. Therefore, stresses to value chains – due to the increased demand in light of the increased GHG reduction ambitions – will generally be slightly more significant than what we have forecast in this study. Table 6.12 presents the GHG emissions reductions achieved in our study compared to 1990 levels in 2040, where the EU achieves 85% GHG emissions reductions compared to 1990 levels.

Table 6.12 Per cent change in EU greenhouse gas emissions compared to 1990 levels

Scenario	2040
1	−85%
2	−85%
3	−54%
3B (higher EU ambition)	−83%

[53] European Commission (2024), 2040 Climate Target (accessed 2024).

ENERGY SECURITY ANALYSIS OF CLEAN ENERGY TECHNOLOGY VALUE CHAINS

This chapter provides the findings of Task 2 of the study, on the analysis of clean energy technology value chains.

7. Results from value chain analysis

Chapter overview

Purpose and contents

In this chapter, the main results of the energy security analysis of the clean energy technologies are presented.

The energy security assessment was carried out through a three-step approach. First, the 48 selected clean energy value chains were assessed for energy security, using 10 energy security indicators. Then, a longlist of energy security criticalities was compiled by combining the value chain assessments with the scenarios presented in Chapter 6. Finally, a shortlist of key energy security criticalities was established by selecting the most urgent criticalities from the longlist, based on several criteria (see Section 7.2-7.3).

At the start of the chapter, the shortlist of key criticalities for energy security is presented. This shortlist formed the basis for the identification of R&I challenges, which in turn are addressed in the R&I action plan.

In the remainder of the chapter, the following results are described briefly for each clean energy technology category:

- Description of the technology
- Shortlisted key criticalities
- Summary of the value chain assessments

The full value chain assessments (factsheets) can be found in Annex C. The longlist of energy security criticalities can be found in Annexes D and F.

The shortlisted criticalities for each technology were validated during the workshop on 7 December 2023. Key remarks from workshop participants have been included in the relevant technology sections.

Main outcomes

Overall, the geopolitical availability and abundance of CRMs, digital vulnerability and skills came out as the main energy security risks across the clean energy technology landscape. In several cases, digital vulnerability and skills were originally not shortlisted as key criticalities, but validation workshop participants indicated that the sector perceived them as significant risks.

Identified risks related to the supply chain complexity or supply chain location often were linked to geopolitical availability and abundance of CRMs. Also several risks identified as issues of broader sustainability were linked to CRMs, for instance their mining or their EOL disposal.

For most clean energy technologies, the listed CRMs are ‘generic’ ones that are needed throughout the energy system, such as copper, aluminium and nickel. Therefore, potential supply risks for these materials should not be linked to a specific technology but, rather, to the clean energy system as such. In the R&I action plan, this systemic risk related to the availability of the generic CRMs is addressed separately.

In addition to advanced electronics for 'smart' technologies, the availability of which was identified as a key criticality by the initial assessment, validation workshop participants pointed at the importance of 'standard', low-technology electronics as well. Supply chains for this type of electronics have been disrupted recently and are projected to remain under pressure in future.

As for digital connectivity, 'smart' technologies are especially vulnerable, but so are technologies wherein cyberattacks may cause significant physical damage, such as wind turbines. To this, validation workshop participants added digital vulnerabilities arising from interconnectivity between several devices in a single household or industrial facility, such as heat pumps, solar panels and charging devices.

For skills, it was noted that there is a general shortage of 'installation skills', arising from competing clean energy technologies all struggling to reel in sufficient installation capacity. However, the current situation is not necessarily an accurate prediction of skills availability in the longer term, when clean energy technologies will have had the opportunity to establish themselves more strongly.

Next steps

The shortlisted criticalities (Section 7.3) formed the basis of the next stage of the study. A SWOT analysis extracted evidence on the EU's readiness to address the corresponding R&I challenge for each energy security criticality. This is detailed further in Section 8.

The validation workshop provided feedback on the criticalities and identified missing criticalities, which were incorporated into this stage.

7.1. Introduction

In this chapter, the main results of the energy security assessment of the clean energy technologies in scope of this study are presented. The chapter starts with the results of the selection of value chains (Section 7.2), presenting the assessed value chains for all technology categories. Then, the shortlist of key criticalities for energy security is presented (Section 7.3). Finally, a section presenting the main results of the energy security assessment for each technology category follows (7.4).

The results were obtained in different steps, as described in the methodology (Annex A, Section 6). First, an energy security assessment at value chain level was carried out. For each value chain, a standardised assessment format was filled out, first describing some key characteristics of the value chain and then assessing and scoring the 10 energy security indicators. This resulted in a factsheet for each value chain. All factsheets are presented in Annex C.

In a second step, a longlist of criticalities was established at value chain level, combining the indicator scores and the RAG ratings of the three scenarios. The longlist is presented in Annex D in the form of a 'heatmap', showing the number of scenarios that longlisted a criticality.

Next, from the longlist, a shortlist of key energy security criticalities was derived, showing the criticalities that are most crucial to address in order to increase the EU's energy security. The shortlist is included at the end of this chapter. It forms the basis for the identification of R&I challenges and interventions in the next chapter.

In order to present the results of these consecutive steps in a useful and comprehensive way, this chapter is organised along the clean energy technology categories assessed in the study. Each technology category is assigned a separate section, including:

- A brief **description of the technology and its role in the energy system**. This is based on the 'Characteristics' sections from the factsheets and includes remarks on the TRL level of the value chains and key features that are important to note in order to understand the way the value chains are applied within the energy system and what specific needs or natural limitations exist for their deployment.

- The **key criticalities for energy security** that were shortlisted for the technology category, following the methodology presented in Annex A, Section 6.[54] Annex D includes a brief explanation on why the other longlisted[55] criticalities were not shortlisted, with reference to the criteria presented in the methodology.

- Finally, a summary of the **main findings of the detailed assessments at value chain level** (as presented in the factsheets in Annex C). For ease of reference, the indicator scores of all value chains of the technology category are given in a table,[56] and where applicable, a brief explanation is included detailing the energy security risk. For instance, if the 'physical vulnerability' energy security indicator was assigned a score of 2 or 3, the specific physical vulnerability is described. If relevant, significant differences between the scores of two or more value chains are also explained. This part of the section is not exhaustive; it highlights the most relevant energy security risks identified, including those that were not selected for the shortlist as a key criticality. For the complete value chain assessments, we refer to Annex C, which includes all literature sources supporting the assessments (these assessments are not repeated in the sections below).

7.2. Selection of clean energy value chains for assessment

Following the methodology explained in Annex A, Section 6.1, below we present the value chains selected for assessment for all clean energy technology categories within scope of this study.[57] As explained in more detail in Annex A, we split the category electricity and heat storage into three categories – batteries, hydrogen and other storage – and we added the category RFNBOs to cover carbon capture and utilisation (CCU). Thus, we considered 20 distinct clean energy technology categories in our analysis,

Advanced biofuels

The category advanced biofuels represents technologies that convert biomass into fuels. From a technological point of view, the production of several types of advanced biofuels is (highly) intertwined, in the sense that many different combinations of biomass feedstocks and production technologies exist. In order to select a representative but limited number of value chains and focusing on potential energy security risks, we considered the origin of the biomass used to produce a certain biofuel to be a key criterion (principle 4) due to risks associated with the biomass supply. Based on this reasoning and considering taking into

[54] As both indicators, 'geopolitical availability' and 'abundance', refer to CRMs, we took these two together for inclusion on the shortlist as a key criticality by referring to them as 'critical raw materials'. Abundance can also refer to sustainable biomass. See also Section 7.3, which presents the shortlist.

[55] For at least one value chain and one projection year. Not including the items on the to-be-discussed lists.

[56] 1 = low risk, 2 = moderate risk, 3 = high risk. The colour codes in these tables refer to the energy security scores (1 = green, 2 = amber, 3 = red); they should not be confused with the RAG ratings of the scenarios.

[57] In particular principles 1-4, used for the selection and referred to below, are explained in this Annex.

account different TRLs, we outlined value chains based on three types of biomass origin: algae-based, primary crop–based and waste-related biofuels.

Bioenergy

The category bioenergy represents technologies that convert biomass directly into heat or electricity or into energy carriers, such as biogas. Based on the origin of the biomass (principle 4) used as an input for producing bioenergy, we distinguished two energy value chains: primary crop–based/forest-based bioenergy and waste-based bioenergy. We reason is that primary crop–based/forest-based bioenergy may compete for other land use, while waste-based bioenergy does not have this challenge. We considered this issue significant to such an extent that we should assess these two value chains separately.

Concentrated solar energy

Concentrated solar energy (CSE) utilises the heat from sunlight to produce heat or generate electricity. Typically, a power plant consists of mirrors that focus sunlight on a tank that contains a molten salt. The molten salt is then used to power a heat engine. Despite slight differences in designs, we consider the majority of the CSE value chains to be similar (principle 2). Therefore, we selected a concentrated solar power plant as a single value chain representing this technology category.

Geothermal energy

Geothermal energy extracted from Earth's crust can be directly used in the form of heat or used to generate electricity. Geothermal energy plants have different designs or principles in the way they extract the geothermal energy, and the type is often determined by the quality of the geothermal source. We considered the differences in designs to be insignificant from an energy security perspective (principle 2), and as a consequence, we assessed a geothermal energy plant as a single energy value chain representing this technology category.

Hydropower

Hydropower uses the gravitational energy stored in water flows to generate electricity. We focused on hydropower for the generation of electricity in the form of a hydropower dam, as this is the main current application of hydropower in the EU (principle 3). It may also be used to store energy (pumped storage) or in more local or small-scale applications. Hydropower plants may differ in dam and turbines designs. Yet, we considered these differences insignificant for the purpose of this study (principle 2), and as a consequence, we considered hydropower dam as a single energy value chain representing this technology category.

Ocean energy

Ocean energy includes four types of energy generation: tidal energy, wave energy, thermal energy and salinity gradient energy. Tidal energy and wave energy are generally harvested by using mechanical structures that convert kinetic/potential energy into electricity. Thermal energy, on the other hand, can be harvested by converting temperature differences between warm surface water and cold deep ocean water. Salinity gradient energy is harnessed from the chemical potential energy difference between two types of water supply with different salt concentrations. Following these four working mechanisms, we distinguished four different ocean energy value chains based on the primary source of (ocean) energy they use (principle 1), namely: tidal energy, wave energy, thermal energy and salinity gradient energy. Note that for most of the value chains, the deployment location is also different (principle 3). Despite the existence of different structural designs for wave and tidal energy, we considered these differences to be rather insignificant from the energy security point of view, and hence did not deploy a further subdivision (principle 2).

Photovoltaics (solar PV)

PV value chains convert solar light into electricity via semiconductor materials. Depending on the material used as semiconductor, we can distinguish crystalline silicon technologies, thin-film technologies – e.g. copper, indium, gallium, selenide (CIGS); cadmium telluride (CdTe); and perovskites – and multi-junction technologies. In order to limit the number of value chains, and since applying different combinations of layers in multi-junction technologies is mainly done to increase efficiency but does not entail new energy security issues, we did not include multi-junction technologies in our assessment. Mainly based on the distinction in used input materials (principle 4), but also based on the different TRLs, we selected the following four energy value chains for further assessment: silicon-based photovoltaics, CIGS photovoltaics, CdTe photovoltaics and perovskite photovoltaics.

Wind energy

The category wind energy represents technologies that convert wind into electricity. We distinguished four different wind energy value chains, namely: Onshore wind turbines, offshore wind turbines, airborne wind system and downwind rotor. From a technological point of view, the value chains for an offshore – and an onshore wind turbine are similar. Yet, we considered potential risks associated with the transportation and deployment location (principle 3) to be distinct such that these two value chains should be analysed separately. Downwind rotor wind turbines and airborne wind systems are technologically distinct (principle 2) from the other wind energy value chains.

Direct solar fuels

Direct solar fuels or sunlight-to-X technologies convert solar energy directly into chemical energy in the form of liquid or gaseous fuel. We considered two distinct energy value chains for this category: Photochemical/photobiological direct solar fuels and thermochemical direct solar fuels. The main difference between the photochemical route and the thermochemical route is that thermochemical processes use concentrated solar heat to drive chemical reactions, while photochemical processes utilise light-absorbing materials to directly convert solar energy into chemical fuels. Based on this technological difference (principle 2) we decided to evaluate these two value chains separately.

Carbon capture, utilisation and storage

CCUS entails many different principles and processes, many of which are only indirectly linked to the energy system as such. CCS involves capturing CO_2 emissions generated from industrial processes and power generation, transporting the captured CO_2 to storage sites, and securely storing it underground to prevent its release into the atmosphere. Despite the existence of several techniques for capturing, extracting and storing CO_2, CCS was analysed as a single energy value chain in the energy security assessment (principle 2). Note that CCU was discussed in the section on RFNBOs.

Batteries

This category encompasses many different types of value chains for energy storage. For example, lithium-based batteries come in many different compositions. However, there are also batteries that do not use lithium as their main energy carrier material, e.g. lead acid or alkaline batteries. Despite variations in composition, we consider the inclusion of CRMs in batteries to be a major security risk due to supply risk associated with CRMs. For this reason, we distinguished batteries that do use or do not use CRMs in their design (principle 4) as different value chains for assessment, considering that even though this is not a distinction commonly used in literature, it is a useful one in order to clearly isolate the role of CRMs in the energy security of batteries. Besides differences in chemical composition, battery energy value chains also differ from a technological perspective and in how they are deployed in the energy infrastructure (principles 2 and 3). For example, redox-flow batteries use pumps and are relatively heavy, and they are therefore used mainly for large-scale energy storage. Similarly, molten salt batteries operate at high temperatures, making them suitable for a limited number of applications. Based on principles 2, 3 and 4, we distinguish four different battery energy value chains: batteries containing CRMs, batteries containing no CRMs, redox-flow batteries and molten salt batteries.

Hydrogen

As this study concerns clean energy technologies, we only considered renewable hydrogen. Renewable hydrogen is produced from electrolysing water. Based on principles 2 and 4, we found four separate main electrolysis value chains: alkaline electrolysis, proton-exchange membrane (PEM) electrolysis, solid oxide electrolysis, and AEM electrolysis. All these electrolysis value chains use different materials for their design (principle 4), and they differ in technological properties (principle 2), such as the purity of the produced hydrogen, efficiency, maintenance, and the magnitude of the operational electrical currents.

Renewable fuels of non-biological origin

RFNBOs is a group of fuels that are produced chemically from CO_2, nitrogen and hydrogen. Based on these inputs, and using several chemical steps, different types of RFNBOs can be produced.[58] Additionally, the three inputs (CO_2, nitrogen and hydrogen) are shared across all RFNBOs. Due to this overlap, we considered the evaluation of a single type of RFNBO to be representative of all other RFNBOs with respect to energy security. We chose synthetic kerosene (e-kerosene) as the energy value chain used for the energy security assessment (noting that this term can also refer to kerosene produced from components of biological origin, but use of such components is not applicable for RFNBOs by definition). Note that the production of renewable hydrogen, an essential input for RFNBOs, was assessed as a separate energy value chain (under the heading hydrogen).

Heat pumps

Heat pumps transfer heat from inside a building to outside or vice versa, with the purpose of heating or cooling. For the energy security assessment, we considered two distinct energy value chains: industrial heat pumps and domestic heat pumps. From an energy security perspective, energy risks related to heat pumps may have different implications for industry than for households (principle 3). Additionally, industrial and domestic heat pumps differ in their technical properties (principle 2), especially their typical temperature range.

Smart energy grid technologies

Smart energy grid technologies represent a group of digital technologies that have the aim to optimise the transfer and use of electricity on the grid. Three distinct energy value chains were identified: eV smart charging, advanced metering infrastructure and home energy management systems. eV smart charging refers to technologies that are used to reduce the load on the grid and costs related to the charging of eVs. Advanced metering infrastructure refers to digital devices that measure and communicate with each other in order to optimise the transmission/distribution of energy. Home energy management systems refer to technologies that monitor and control the energy use within households in order to improve energy efficiency and reduce energy costs. Although all three value chains use electronics and (smart) software, the application of each value chain is rather distinct and is associated with different parts of the energy system (principle 3).

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[58] Global Alliance Powerfuels, Powerfuels – Global Alliance Powerfuels (accessed 2024).

Energy building and district heating technologies

This category represents energy technologies that are used in the context of district heating and buildings. We found three distinct energy value chains: advanced control technologies, thermal energy storage, and combined heat and power. The term advanced control technologies (ACT) refers to technologies that use data-driven and automated strategies in order to optimise the generation, distribution, consumption, and management of energy. Thermal energy storage technologies store energy in the form of heat in a storage medium such that it can be used at a later moment in time. Combined heat and power is a technology that generates electricity and useful thermal energy (heat) from a single (renewable) energy source. All three energy value chains are used in the context of district heating, but they are distinct in terms of technology (principle 2), application (principle 3) and material input (principle 4).

Off-grid energy systems

Off-grid energy systems represent a group of technologies that provide heat or electricity locally, while not being connected to the wider (e.g. national) electricity grid. Instead, off-grid energy systems can either supply energy to a single end user (e.g. a thermal collector providing energy for one household, without further connections) or form a micro-grid, consisting of multiple local end users who are mutually interconnected. In terms of the CRMs needed, micro-grids do not differ from large-scale grids, but they are less vulnerable to digital and some types of physical threats (such as sabotage) due to the lower potential fallout, which is why off-grid energy systems are treated separately in this study.

Three distinct energy value chains were identified for off-grid energy systems: heating based on renewable gas, heating based on solid biomass, and solar heating using a thermal collector. Note that solar heating uses solar energy directly for heating, while the other two value chains use an intermediate energy carrier (principle 1). Although heating based on gas or on solid biomass are rather similar from a technological point of view, their origin and the supply chain of their input material (i.e. gas or solid biomass) are rather distinct (principle 4) and may be associated with different energy security risks. These considerations led us to distinguish among these three value chains. Off-grid solar PV was not included as a separate value chain under off-grid systems, since solar PV is treated separately in this study (see above). All energy security risks related to the production and supply chain of solar panels are treated under the photovoltaics (solar PV) category, while the risks related to the fact that the system is off-grid, as touched upon above, are covered by the category off-grid energy systems (as they are the same for off-grid solar PV and other off-grid value chains).

Energy transmission and distribution technologies

This category represents technologies that relate to the transmission and distribution of energy. We identified two distinct energy value chains within this category that may play a key role in the future energy system: hydrogen storage and transportation and high-voltage direct current (HVDC) transmission. HVDC transmission is used to transport electric power more efficiently over long distances. Hydrogen storage and transportation technologies refer to the storage and transportation of (renewable) hydrogen. Hydrogen needs to be stored, for instance, when it is produced as a flexibility mechanism for the electricity system, in cases of surplus renewable electricity generation. Obviously, these two energy value chains are distinct in terms of technology, application and material input (principles 2, 3 and 4). Note that the production of renewable hydrogen was assessed as a separate energy value chain (under the heading hydrogen).

Smart cities

The category smart cities represents a group of digital technologies that focuses on optimising logistics and energy use in an urban environment. This category encompasses a large number of technologies and applications, some of which have only an indirect link with the energy system as such, which makes this technology category different from most others assessed in this study. Therefore, the identification of distinct clean energy value chains within this category was challenging. Autonomous driving was selected as a representative value chain, since it relies on smart technology in order to optimise the energy efficiency of transport. Also, many researchers and companies have been focusing on the development and implementation of this technology in the past decade. It was considered that other value chains within this category may share the same energy security risks, in as far as they are clean energy technologies related to the availability of advanced electronics and digital vulnerabilities.

Other electricity and heat storage (compressed air energy storage and flywheels)

There are many different technologies that can store electricity or heat. Thermal energy storage is already considered in the category energy building and district heating technologies. We identified two other distinct technologies: CAES and flywheels. CAES and flywheels are distinct from a technological point of view (principle 2) as well as in how they may fulfil a role in the electricity system (principle 3). For example, fly wheels can typically store energy for a short period of time, while CAES can store energy long term.

7.3. Shortlist of key criticalities for energy security

In Table 7.1, all shortlisted key criticalities are summarised. The brief descriptions of the key criticalities as shown in this table were sent to the validation workshop participants as pre-workshop material. In Section 7.4, below, more detail is offered on the key criticalities.

Validation workshop participants stressed that CRMs form an overarching issue for all clean energy technologies. Key CRMs are aluminium, copper, manganese and nickel. Copper is a key CRM for all electric devices, manganese, for steel, and nickel, for stainless steel. Aluminium is appropriate for various structures where steel is not used. Also, almost all value chains need electronics of some kind, including several CRMs, such as silicon metal, germanium, gallium and arsenic.

Table 7.1 Summary of all shortlisted key criticalities

Technology category	Shortlisted key criticalities[59]	Brief description of key criticalities
Advanced biofuels	Abundance	The availability of feedstock presents the main energy security risk to advanced biofuels value chains. Abundance, supply chain complexity and broader sustainability are all factors, in particular potential competition for land use or waste use and the increased sustainability and complexity risk introduced if feedstock is imported from outside the EU.
Bioenergy	Abundance	The availability of biomass feedstock presents the main energy security risk to bioenergy value chains. The availability of biomass feedstock is limited by competition for land use and availability of sustainably produced biomass, and there are EU criteria in place.
Concentrated solar energy	Broader sustainability	Relatively high water and land use are required for CSE, introducing the risk of competition for other uses. The heat transfer fluid may also pose risks to the environment due to its toxicity. Ecosystem risks related to the concentrated beam of light are uncertain in a context of increasing environmental protections.

[59] CRM = geopolitical availability and/or abundance of CRMs.

	Affordability	The levelised cost of electricity (LCOE) of CSE is approximately three times higher than of silicon-based PV. It is uncertain whether CSE costs will decrease significantly, whereas the cost of solar PV and other clean energy technologies are predicted to decrease further.
Geothermal energy	CRM	Geothermal energy technologies rely on the use of CRMs. The materials are available from one to four EU countries. However, global demand is expected to rise significantly, and the market is increasingly competitive, introducing a risk of scarcity and price increases that would affect the energy security of geothermal energy value chains.
Hydropower	Broader sustainability	Hydropower can have very high ecological impact and has prompted negative responses from local communities. This may limit the possibility of further development of hydropower in the EU or pf other initiatives to extend the life and use of existing infrastructure.
	Physical vulnerability	Climate impacts, including loss of glaciers, droughts and flooding, may significantly impact the ability of hydropower to operate in future, because of changing water levels in reservoirs.
	CRM	Hydropower technologies use critical raw materials in permanent magnets for turbines. The materials are available from up to four EU countries; in the case of permanent magnets, production is concentrated in one non-EU country. Global demand is expected to rise, and the market is increasingly competitive, introducing a risk of scarcity and price increases that would affect the energy security of hydropower value chains.
Ocean energy	Broader sustainability	The environmental impacts of ocean energy are uncertain and could present a risk to the deployment of ocean energy in a context of increasing environmental protection regulation and public concern. For example, the risk of disturbance to marine animals is not well understood, and salinity gradient inlet volumes could pose a risk of entrainment to fish and other organisms. Sustainability concerns may contribute to shaping public opinion, which will be important for successful deployment.
	Affordability	The cost estimates (LCOE) for ocean energy are currently high, in part due to the level of innovation and resulting high capital costs.

	CRM	Ocean energy technologies rely on the use of critical raw materials. The materials are available from up to four EU countries; in the case of permanent magnets, production is concentrated in one non-EU country. Global demand is expected to rise significantly, and the market is increasingly competitive, introducing a risk of scarcity and price increases that would affect the energy security of ocean energy.
Photovoltaics	CRM	The production of solar PV requires a number of critical raw materials that are in limited supply within the EU or globally or that are concentrated in a limited number of non-EU countries.
	Supply chain location	Over 90% of the PV value chain is located outside the EU. The location of supply may change in future, but not without significant political and economic efforts. One of the assumptions of the study is that supply chains outside the EU introduce a risk to energy security.
	Digital vulnerability	Inverters needed for solar panels to operate flexibly within the smart grid carry a cyber security risk.
	Skills	For silicon-based solar cells, installation skills are required and already scarce in some areas of the EU. The availability of a significant and distributed workforce can introduce a risk to the deployment and pace of deployment of solar panels across the EU. In the case of perovskites, research and development skills are needed for further development and EU advantage.
Wind energy	CRM	Most wind energy technologies rely on the use of critical raw materials that are sourced outside the EU and in some cases from only one or a few countries, with the potential for disruption and limited supply.
	Physical vulnerability	The performance of wind energy is dependent on weather patterns and may be negatively affected by changing patterns caused by climate change. Extreme weather events may also cause physical damage to wind turbines, although this was noted to be a fairly low risk in the validation workshop.
Direct solar fuels	CRM	The production of direct solar fuels requires a number of critical raw materials used as catalysts or in the electrodes. Bismuth supply is dominated by one non-EU country, and natural abundance is limited.

	Supply chain complexity	The components for direct solar fuels are highly specialised and, as a technology still in development, its components are not finalised. The uncertainty and potential for future complexity in the supply chain introduces a potential risk, as complex supply chain may be more vulnerable to disruption or only as resilient as the weakest link.
	Skills	As the technology for the production of direct solar fuels is still in development, highly skilled and specialised labour is needed. This is viewed as a major criticality for further development of the technology in the EU.
	Affordability	With high cost of materials and equipment, as well as highly specialised pathways, direct solar technologies face challenges to be competitive now and in the longer term. High costs are a threat to the energy security of the value chain.
Carbon capture, utilisation and storage (utilisation covered under renewable fuels of non-biological origin)	Broader sustainability	CCUS is faced with a number of sustainability issues contributing towards an overall risk to the security of the value chain, in particular with regards to deployment. Concerns and environmental risks linked to CCUS include fossil fuel lock-in, additional emissions from enhanced oil recovery for injection of carbon dioxide, leakage and seismic activity linked to carbon storage and potential negative public opinion, as well as impacts on local biodiversity of large infrastructure projects and carbon leakages.
	Affordability	CCUS has high capital costs, with requirements for significant infrastructure; however, financial revenues are dependent on carbon markets and are currently limited.
Batteries	CRM	Batteries used today are heavily dependent on critical raw materials, with significant risk around future availability and risk to disruption of supply. Many of these materials are mined and processed outside the EU, and the supply is dominated by a small number of countries. Global demand is also expected to significantly increase, with a risk of scarcity of resources if supply does not increase to meet demand.
	Supply chain location	In addition to supply chains for raw materials being located in a small number of non-EU countries, the supply chain for lithium-ion batteries, including the supply chain for manufacturing equipment, is predominantly outside the EU, and it would require significant investment for an EU-based supply to become price-competitive.
Hydrogen	CRM	Hydrogen technology is dependent on critical raw materials for key components, with significant risk around future availability and risk to disruption of supply. Many of these materials are mined and processed outside the EU and the supply is dominated by a small number of countries. Global

		demand is also expected to significantly increase, with risk of scarcity of resources if supply does not increase to meet demand.
	Physical vulnerability	Large amounts of renewable energy are needed to produce hydrogen with electrolysing technologies, which can be subject to intermittencies. The electricity grid can also be subject to disruption, introducing a potential risk of the energy security of hydrogen value chains.
	Broader sustainability	Large amounts of pure water are needed to produce hydrogen. While perfluoroalkyl substances (PFAS) are also required for certain hydrogen value chains, the EU has a commitment to phase out use of PFAS.
	Affordability	The cost of producing hydrogen, in particular with alkaline and PEM electrolysers, are currently high for some technologies, and uncertain for others. Costs of electrolysers and the hydrogen are expected to decline in future; however, they are currently an important barrier in commercial implementation of the technology and its energy security.
	Supply chain complexity	The supply chains for PEM are complex and are vulnerable to disruption. With regards to solid oxide and AEM, the supply chains are not yet established, and there is uncertainty over future complexity and vulnerability.
Renewable fuels of non-biological origin	Supply chain complexity	The supply chain for synthetic kerosene and its complexity is uncertain. In particular, complexity will be linked to the scale-up and availability of sustainable CO_2 from direct air capture, which is a supply chain that is still in development.
	Physical vulnerability	Large amounts of renewable energy or hydrogen are needed to produce RFNBOs. The electricity grid can be subject to disruption, introducing a potential risk to the energy security of RFNBO value chains.
	Affordability	The costs of synthetic kerosene are linked to the cost of CO_2. In the case of synthetic kerosene produced through carbon capture from air, costs are expected to be high. We note that direct air capture is not the only source of carbon but has the potential to become the main source of carbon in future as other sectors decarbonise.
Heat pumps	CRM	Heat pumps require a significant amount of low-technology critical raw materials for semiconductor chips to operate, and disruption to global semiconductor value chains has resulted in delivery delays for heat pumps. The materials are available from up to four EU countries. However, global

		demand is expected to rise significantly, and the market is increasingly competitive, introducing a risk of scarcity and price increases that would affect the energy security of heat pump value chains.
	Physical vulnerability	Renewable energy is needed to operate heat pumps. The electricity grid can be subject to disruption, introducing a potential risk of the energy security of heat pumps, with, for example, loss of heating during an electricity black-out.
Smart energy grid technologies	CRM	Smart grid technologies require a number of critical raw materials, in some cases only available from one or a small number of non-EU countries. Linked to this, the supply chains for advanced electronics are predominantly outside the EU, introducing potential risk to the energy security of these value chains. These criticalities are less relevant for eV smart charging.
	Digital vulnerability	Smart energy grid technologies are very digital dependent and inherently vulnerable to cyberattacks or disruption of digital networks, with potential negative impacts on the operation of the energy grid. Advanced metering infrastructure and home energy management systems are vulnerable to data theft as well.
Energy building and district technologies	CRM	Smart grid technologies require a number of critical raw materials, in some cases only available from one or a small number of non-EU countries. Linked to this, the supply chains for advanced electronics are predominantly outside the EU, introducing potential risk to the security of these value chains.
	Digital vulnerability	Energy building and district technologies are very digital dependent and inherently vulnerable to cyberattacks or disruption of digital networks, with potential negative impacts on the operation of the technologies.
Off-grid energy systems	CRM	Off-grid energy systems rely on certain CRMs. In particular, copper presents a potential challenge, with limited resources and increasing demand.
	Broader sustainability	The feedstock used for production of biogas for biogas tanks is sometimes illegally polluted by prohibited biowaste (for instance slaughterhouse waste) or fossil waste (for instance chemical waste). This could end up in the food chain, through the digestate produced in addition to biogas. For pellet stoves, local air pollution is a broader sustainability issue. With an increasing trend toward environmental protection and regulation, if these risks are not managed, the security of the value chain may be at risk.
	CRM	Energy transmission and distribution technologies rely on certain CRMs. In particular, copper presents a potential challenge, with limited resources and increasing demand. EU aluminium

Energy transmission and distribution technologies		production has also reduced in recent years due to increasing costs, with increasing EU dependence on imports from a small number of countries.
	Digital vulnerability	Cyberattacks on power grids in general and HVDC links in particular pose a significant and growing threat to the stability, reliability and security of the power system.
Smart cities	CRM	Smart cities require a number of critical raw materials, in some cases only available from one or a small number of non-EU countries. Linked to this, the supply chains for advanced electronics are predominantly outside the EU, introducing potential risk to the security of these value chains.
	Digital vulnerability	Smart cities are very digital dependent and inherently vulnerable to cyberattacks or disruption of digital networks, with potential negative impacts on the operation of the energy grid.
Other storage (compressed air energy storage and flywheels)	CRM	These technologies rely on certain CRMs. In particular, copper presents a potential challenge, with limited resources and increasing demand, and EU aluminium production has reduced in recent years due to increasing costs, with increasing EU dependence on imports from a small number of countries.
	Broader sustainability	The use of compressed air storage can lead to ground subsidence and seismic activity. While the risks associated with underground activities related to natural gas storage are well understood, the risks associated with compressed air storage are relatively unknown and require further research to resolve uncertainty.
	Supply chain complexity	Compressed air storage is only suited to certain areas. Extensive research and underground exploration are necessary and may involve considerable complexity for the construction and use of compressed air storage. Complexity introduces an increased risk of disruption and delay, affecting the security of the value chain.

7.4. Description of criticality shortlisting per technology area

Below, the main results of our energy security assessment are presented for all clean energy technologies in scope. In each instance, a brief description of the technology is given and the shortlisted criticalities for the technology are described. Also, a brief overview of the main findings of the underlying value chain assessments is presented – the full assessments (factsheets) can be found in Annex C. A summary of longlisted criticalities, together with a brief explanation why they were not shortlisted, is found in Annex D, Table D.1.

7.4.1. Advanced biofuels

General description and role in the energy system

Advanced biofuels are energy carriers that can be used in transport and that are produced using sustainable biomass as feedstock. The sustainability criteria for the feedstocks are regulated by the land use, land-use change and forestry (LULUCF) directive and the RED. In this project, for the energy security assessment, a distinction was made between three types of advanced biofuels: algae-based, crop-based and biomass waste–based fuels. The former has a TRL of 4-5, whereas the latter two have a TRL of 9.

Energy security: key criticalities for the technology category

For advanced biofuels, the main criticalities are: **abundance** of biomass feedstock (linked to **supply chain complexity**), and **broader sustainability**.

All three types of biomass feedstocks used for the advanced biofuel value chains assessed face different types of energy security risks, which are related to a combination of abundance, supply chain complexity and broader sustainability.

For *algae-based advanced biofuels*, the low TRL means that the supply chain has not yet been established. In addition, the production of algae may have negative environmental effects on (sea) water and existing ecosystems. For *crop-based advanced biofuels*, there may be competition for land with other land uses, such as agriculture. In addition, demand for crops for material applications may increase which introduces competition with crops for energy use.

For *waste-based advanced biofuels*, there is a limit to the amount of biomass waste available and suitable for use, there will possibly be competition with other applications of the feedstock (for instance in chemistry), and, with a high feedstock demand, there is risk of greenwashing by adding illegal (fossil/biomass) feedstocks, although a new EU database for biofuels that is being established will mitigate possible fraud risks. For all three, supply chain complexity increases when feedstocks need to be imported from outside the EU. This also increases sustainability risks as monitoring the value chain becomes more complex.

Validation workshop participants added that, apart from biomass availability, the availability of (proprietary) catalysts may also become an issue in future. However, catalysts can be made of a range of materials, including natural or uncritical materials. Validation workshop participants noted that policy uncertainty is a significant risk for the development of advanced biofuels.

Energy security: overview of findings from the value chain assessments

In Table 7.2, the energy security indicator scores for the three value chains assessed are presented.

Table 7.2 Energy security indicator scores for advanced biofuels[60]

Value chain/ indicator	Geopolitical availability	Abundance	Circularity	Supply chain complexity	Supply chain location	Digital vulnerability	Physical vulnerability	Broader sustainability	Affordability	Skills
Algae-based	1	1	1	3	1	1	2	2	2	1
Crop-based	1	1	1	2	1	1	1	1	1	1
Waste-based	1	2	1	2	1	1	1	1	2	1

Affordability may be an energy security risk for algae- and waste-based advanced biofuels but was not longlisted. For algae, affordability is one of the research development topics, and there is still uncertainty around this topic. In addition, physical vulnerability is a potential energy security risk for algae-based advanced biofuels, as predatory organisms and environmental influences may negatively impact harvests. Validation workshop participants further noted that biomass abundance may be a medium risk in certain cases, also for crop and algae-based biofuels.

7.4.2. Bioenergy

General description and role in the energy system

Bioenergy refers to the use of biomass to produce electricity or heat. Two value chains are distinguished: primary crop– and forest-based bioenergy and waste-based bioenergy. The former includes woody biomass that is primarily cultivated for bioenergy and woody biomass generated as secondary product from the forest industry or from maintenance of forests (such as saw dust, pruning waste and residual wood).

Woody biomass can be directly used for bioenergy in a stove, boiler or fireplace, mostly by households, or it can be compressed into pellets, briquettes or chips and used by households or industrial applications, including electricity generation.

Waste-based biomass consists of waste from households, agricultural residues, paper and pulp residues and sewage treatment residues.

Bioenergy is already a well-established energy source in the EU. Bioenergy feedstock supply was around 150 million tonnes of oil equivalent (Mtoe) in the EU in 2015 but is expected to increase to 250 to 300 Mtoe in 2050, depending on the scenario.

[60] The numbers are the indicator scores from the value chain assessments, denoting intrinsic energy security risks (1 = least risk, 3 = most risk).

Energy security: key criticalities for the technology category

For bioenergy, the main criticality is: **abundance.**

The availability of biomass feedstocks for bioenergy is limited by the availability of land and forests (primary crop–based) and by how much biomass waste is generated from consumption (waste-based). Although woody biomass is abundant, sustainably produced woody biomass is not necessarily abundant. Within the EU's RED policy, biomass sources need to meet strict sustainability criteria, meaning that primary forest, highly biodiverse forests or grasslands, nature-protected areas, and land with high carbon stocks, including wetlands, are excluded.

Validation workshop participants noted that biomass cascading (prioritising the biomass applications with more economic and ecological added value over applications which less added value) is not yet an integral part of policies in general (in the RED III, it is included as a general principle). The nature of competition for biomass as a feedstock and for energy remains unclear, and discussions are currently taking place on a theoretical level. The way in which this competition will play out in practice could affect how much biomass is actually available for energy generation, i.e. its abundance in the context of energy.

Energy security: overview of findings from the value chain assessments

In Table 7.3, the energy security indicator scores for the value chains assessed are presented.

Table 7.3 Energy security indicator scores for bioenergy

Value chain/ indicator	Geopolitical availability	Abundance	Circularity	Supply chain complexity	Supply chain location	Digital vulnerability	Physical vulnerability	Broader sustainability	Affordability	Skills
Primary crop–based	1	2	1	2	1	1	1	2	1	1
Waste-based	1	2	1	1	1	1	1	1	1	1

The availability (abundance) of bioenergy is linked to other energy security risks. The RED sustainability criteria (which limit the availability) are in place due to broader sustainability concerns, e.g. linked to biodiversity impacts and reduction in carbon stocks.

Similarly, because compliance with the sustainability criteria needs to be proven, monitoring, verification and certification of the biomass feedstock make the supply chains more complex and can introduce risks of irregularity and fraud, especially when the biomass is imported from non-EU countries.

7.4.3. Concentrated solar energy

General description and role in the energy system

CSE is a technology that can be used for both *electricity* and *heat generation*. Like solar PV, its energy source is sunlight, but the technology is dependent on direct sunlight and a high radiation intensity, as opposed to ambient daylight for solar PV. Therefore, CSE is less suitable for areas at higher latitudes. It is better suited to higher temperatures than solar PV, which suffers from efficiency losses when temperatures increase.

The technology uses mirrors to reflect and concentrate solar energy on a specific point (known as the receiver). In most cases the mirrors and receiver are placed on a tall tower. During the process, the solar energy from the sunlight is converted to thermal energy (heat). The heat is then transferred into a working liquid and travels through a sealed heat exchanger, heating water in order to bring it to the boil. Steam from the boiling water spins a turbine to generate electricity.

The same working principle can also be applied to concentrating solar heat for district heating and for industrial processes (SHIP). A temperature of 100℃ to 400℃ is required for SHIP.

The scale of application of CSE is currently relatively limited (2.4 gW, almost entirely in Spain). Scaling up seems possible, but the technology remains bound to geographical areas that receive direct sunlight for a high number of hours per year. This is mostly related to the latitude of the location and the associated climate zone. Although climate zones may slowly shift due to climate change, large-scale application in northwestern Europe is not plausible within the timescale of this study (up to 2050).

Energy security: key criticalities for the technology category

For CSE, the key criticalities identified for energy security are: **broader sustainability** and **affordability.**

Broader sustainability. The main sustainability issues related to this value chain concern the relatively high land and water use. Land use mainly concerns the spatial area needed for the receiver tower and the mirrors. Water use is high because the system needs wet cooling and the turbine requires relatively large amounts of water, in a landscape that is typically very dry. Also, the toxicity of the heat transfer fluid may pose risks to the environment. Risks to the ecosystem (related to the concentrated beam of light involved) are less clear.

Validation workshop participants considered broader sustainability, in particular with respect to environmental impact, a low risk.

Affordability.[61] The costs of CSE (LCOE) are about three times higher than those of standard Si-based solar PV, and it is unclear whether these will decrease significantly in future as a result of autonomous developments (while costs of solar PV are predicted to decrease further). As the energy security risks are evaluated relatively to other, comparable value chains, this means a risk for CSE.

Energy security: overview of findings from the value chain assessments

In Table 7.4, the energy security indicator scores for the value chain assessed are presented.

[61] Shortlisted as an item on the to-be-discussed list for 2030 and 2050.

Table 7.4 Energy security indicator scores for the concentrated solar value chain assessed

Value chain/ indicator	Geopolitical availability	Abundance	Circularity	Supply chain complexity	Supply chain location	Digital vulnerability	Physical vulnerability	Broader sustainability	Affordability	Skills
Concentrated solar energy plant for heat and electricity generation	1	1	2	1	2	1	2	2	2	1

There are some circularity risks, but these are not related to CRMs and the indicator was not longlisted. The use of heat transfer fluids has a circularity aspect (water use) but is also related to environmental risks, as not handling them well can lead to environmental damage (as mentioned above).

In terms of supply of the necessary components of the value chain, there is a limited dependency on non-EU countries, as manufacturing is centred in Spain. However, the relatively small potential for upscaling could mean that the number of suppliers or manufacturers will remain (very) limited, which poses a risk to the robustness of the supply chain.

As for physical vulnerability, there is no single main risk, but, rather, a combination of distinctive risks, such as high temperatures impacting the efficiency of the technology and the excessive dependence on one single component (the receiver).

7.4.4. Geothermal energy

General description and role in the energy system

Geothermal energy technology harnesses heat from Earth's interior. This heat is then used either indirectly, to generate electricity or directly, to heat buildings or, increasingly, in industrial processes. The potential for geothermal energy depends on the geographical location and the depth of the well. Geothermal energy technologies are considered mature (TRL 9), though additional technologies are still under development. Geothermal energy technologies are already used in the European energy system. Their importance is expected to increase as the energy landscape moves further towards sustainability and carbon neutrality.

Some technologies, such as ground-source heat pump systems and geothermal district heating systems, are experiencing stable growth. Although the expansion of large-scale geothermal projects for heat and electricity generation has been gradual, the rate is expected to pick up pace as oil and gas companies are increasingly involved in such projects. Moreover, new developments in geothermal energy are enhancing its appeal. Advances include the development of large, high-temperature heat installations. This innovation extends the usability of lower temperature (easier to access) geothermal sources, making them suitable for applications beyond residential heating, including district heating networks and industrial processes. Additionally, efforts are successfully targeting and developing 'medium-deep' geothermal resources, with temperatures ranging from 30-60°C. Previously deemed unattractive, these resources are now viable with modern building insulation and potent heat pumps. Deep geothermal projects, however, still encounter challenges, including high upfront costs, complex licensing processes, and limited, costly and time-consuming acquisition of subsurface data.

Energy security: key criticalities for the technology category

For geothermal energy, the key criticalities identified for energy security are: **CRMs** (specifically aluminium, copper, nickel).

CRMs. Equipment used to extract heat from Earth's interior relies on CRMs, in particular aluminium, copper, nickel and titanium. Aluminium is used in buildings, pipelines, platforms and equipment, such as compressors. Copper and nickel are used in turbines and alternators that generate electricity. Copper is also used in cooling towers and other accessories. Titanium is a catalyst in the gas treatment system for removal of odorous H_2S. All these CRMs are available in one to four EU countries, though China increasingly dominates the aluminium market. Aluminium and titanium have low risks related to their abundance. However, as global demands are rising, more scarcity and higher prices could be expected. Copper and nickel have a medium abundance risk, with rising demands for these raw materials.

Validation workshop participants indicated that skills within regulatory and permitting agencies are considered an important criticality by the sector. In particular, geological knowledge and expertise seems to be lacking for the permitting of geothermal energy.

Energy security: overview of findings from the value chain assessments

In Table 7.5, the energy security indicator scores for the value chain assessed are presented.

Table 7.5 Energy security indicator scores for geothermal energy

Value chain/ indicator	Geopolitical availability	Abundance	Circularity	Supply chain complexity	Supply chain location	Digital vulnerability	Physical vulnerability	Broader sustainability	Affordability	Skills
Geothermal plant	1	2	1	1	2	1	1	2	1	2

In addition to the key criticalities related to the energy security of geothermal energy technologies, the following energy security indictors pose risks for the value chain assessed within this technology category: supply chain location, broader sustainability and skills.

Supply chain location is a moderate risk for the deployment of geothermal power generation, as the major manufacturers of equipment are located outside of the EU, in particular in Japan (Toshiba, Fuji and Mitsubishi) and the United States (Ormat). For geothermal heat applications, the oil and gas industry is the main supplier, and there are also European suppliers. Overall, the risk of availability of equipment produced outside of Europe is moderate.

Broader sustainability issues are a moderate risk for geothermal energy. Issues are pollutants and GHGs that are emitted from geothermal wells. Gases, such as carbon dioxide, hydrogen sulphide, hydrogen, ammonia, and methane (CO_2, H_2S, H_2, NH_3 and CH_4), could be emitted during drilling or operation. In addition, contaminants, such as radon, silicates, carbonates, metal sulphides and sulphates, mercury, arsenic, antimony, selenium and chromium, could be emitted into the water. To mitigate emissions, both into air and into water, appropriate containment of both gases and effluents is necessary. The emission of pollutants and GHGs linked to geothermal power plants may pose a challenge to their operations due to environmental regulations and public acceptance concerns. This poses a moderate risk for the technology.

Skills are a moderate risk for the deployment of geothermal energy, as it requires a well-trained, specialised workforce. The sector already faces shortages of skilled labour: increased demand for ground-source heat pump systems could recently not be met due to, among others, lack of skilled workers. These shortages are expected to continue to thwart the deployment of geothermal energy technologies in future.

7.4.5. Hydropower

General description and role in the energy system

Hydropower generates electricity by using the potential energy of water at a high elevation. As water flows downward from higher altitudes, this mechanical force is used to drive turbines and generators to produce power. Hydropower dams are well established and are very energy efficient. However, they are the most cost effective in areas of high elevation, where large energy potentials exist and large reservoirs can be built.

Most of the suitable locations for large reservoirs have already been exploited in the central and northern EU. This limits the future expansion of hydropower in the EU's energy mix. However, there is still substantial potential for increased pumped hydropower (where hydropower fulfils the function of energy storage), modernisation of hydropower, and use of hydropower in smaller-scale installations, such as in water treatment facilities and other water network infrastructures**.**

The ageing of large dams is an emerging global development issue of water storage infrastructure. Decommissioning or refurbishment of ageing dams is essential to address public safety concerns and broader sustainability issues. Through refurbishing, installing more efficient installations and improving digital connectivity, it is possible to prolong the facility's lifetime and increase production at the same time. Refurbishment projects come with substantial costs and can easily take up to 10 years to complete, dependent on the dam's properties, but their advantage is that the lifetime of the hydropower installation is prolonged, while decommissioning means putting an end to the energy production of the installation.

Energy security: key criticalities for the technology category

For hydropower energy, the key criticalities identified for energy security are: **CRMs**, **broader sustainability**, and **physical vulnerability**.

CRMs. Risks mainly relate to copper and permanent magnets.

Broader sustainability. In many cases, dams serve multiple functions beyond energy generation, such as irrigation, hydropower, water supply, flood control and recreation, benefiting local communities and serving broader purposes. However, hydropower dams have a potentially high ecological impact due to dam and reservoir installation, including modification of hydrological regimes and aquatic habitats, water quality, barriers to fish migration, introduction of pest species and impact on sedimentation, impoundment and methane emissions. Further, there is a possible negative social impact of large-scale dams because the building of dams may involve resettlement of local communities, impact the few remaining pristine waterways in Europe, increase the risk of waterborne diseases and influence cultural heritage sites. These risks are less pronounced for smaller-scale hydropower facilities or installations in existing structures. Lastly, there is also a public safety risk as dams become older.

Validation workshop participants stressed that public opposition to hydropower is the biggest risk to further development of the technology. Participants suggested that the public is not well aware of hydropower benefits and impacts and that opposition to hydropower is not based on evidence. Moreover, participants noted that solutions for some of the environmental impacts do exist (e.g. modernisation of existing hydropower, developing hidden hydro in existing infrastructures, new pumped hydro using existing reservoirs, and abandoned mine closed-loop hydropower). However, broader sustainability challenges go beyond environmental impacts.

Physical vulnerabilities. Climate change can affect the capabilities of hydropower dams to continuously supply electricity. Loss of glaciers and droughts can lower their future capacity. In addition, due to the large potential damage of dams breaking, hydropower infrastructure can be a target of attacks.

Validation workshop participants noted that climate change will indeed affect the timing of inflow to the reservoirs, since it will lead to more snow melt in spring and decreasing glacier melt in summer. They added that glacier retreat could result in an opportunity for new, multipurpose reservoirs at new glacier lakes. Several projects in the Alps have been identified[62] that could yield new, multipurpose reservoirs for energy supply and water management. Similarly, multipurpose hydropower reservoirs could be used to mitigate the effects of floods and droughts in increasingly arid zones in Europe. Validation workshop participants further stressed that physical vulnerability to climate change is a key issue for hydropower. They referenced an European Environment Agency (EEA) study on climate adaptation and impacts on various technologies (2019).[63] According to the findings, hydropower is highly sensitive to climate impacts.

Validation workshop participants added that existing plants need to be prepared to serve a storage function; this may add to supply chain complexity and costs. The participants also highlighted costs and market conditions as a general issue for hydropower. There are large upfront investment costs, and lead times are long, which increases investor risks. Financial incentives for additional services of reservoirs are insufficient, and solutions to environmental impacts exist but are expensive. Regulatory and permitting challenges were also mentioned as a risk (with low preparedness).

Energy security: overview of findings from the value chain assessments

In Table 7.6, the energy security indicator scores for the value chain assessed are presented.

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[62] Validation workshop input.

[63] European Environment Agency (2019), Adaptation Challenges and Opportunities for the European Energy System, European Environment Agency, Copenhagen.

Table 7.6 Energy security indicator scores for hydropower

Value chain/ indicator	Geopolitical availability	Abundance	Circularity	Supply chain complexity	Supply chain location	Digital vulnerability	Physical vulnerability	Broader sustainability	Affordability	Skills
Hydropower plant	2	2	2	2	1	1	3	3	1	1

Some additional remarks are in order here. Turbines and generators require some materials (copper, permanent magnets) that are moderately scarce. In addition, permanent magnets are not available within the EU, with production mostly concentrated in China.

Furthermore, it can be noted that most hydropower dams in Europe are reaching an old age, and there are arguments in favour of decommissioning these dams, including protection of public safety, growing maintenance costs, progressing sedimentation of the reservoir, and environmental restoration. The decommissioning of dams can be complex compared to other technologies, which translates in a moderate risk score for both circularity and supply chain complexity. Alternatively, dams may be refurbished, which is associated with higher costs and long lead times but retains or even increases the energy-generation capacity of the dam, which is an important advantage from the perspective of energy security.

7.4.6. Ocean energy

General description and role in the energy system

Ocean energy uses different properties of the seas to generate electricity: kinetic energy of waves and tides, temperature differences, and salinity differences creating chemical potentials. Four value chains are assessed here:

- Tidal energy, using the kinetic energy created by tidal currents in coastal regions;
- Wave energy, using the energy of waves created by wind;
- Ocean thermal energy conversion (OTEC), based on temperature differences between ocean layers; and
- Salinity gradient power, utilising differences in the chemical potential between two bodies of water with different salinity.

At the moment, all ocean energy technologies are in development, and they do not yet generate substantial amounts of electricity for the EU. Tidal energy and wave energy are the furthest developed (TRL 7-9), although their current capacity is very limited. OTEC is at a lower level of development (TRL 5). It also requires high surface water temperatures (25 °C) and is therefore only relevant for overseas territories for the EU. Salinity gradient power needs to be developed further (TRL 7) but has a substantial estimated technical potential (about 49 gW for the EU).

Energy security: key criticalities for the technology category

For ocean energy, the key criticalities identified for energy security are: **CRMs, broader sustainability** and **affordability**.

CRMs. Risks mainly relate to the availability of copper, aluminium and permanent magnets, which make up roughly 10% of the total weight of a tidal or wave energy system.

Broader sustainability. The risk here is based on uncertainties regarding their ecological impacts. For example, wave and tidal energy generation create underwater noise, which may disturb marine animals. However, this effect is not yet well understood, at least for larger-scale installations, which are not yet deployed. Similarly, salinity gradient inlet volumes can pose a risk to the entrainment of fish and other organisms.

During the validation workshop, there were mixed opinions on the risks posed by broader sustainability. Some participants stressed that environmental impacts have been limited, while others indicated that ocean energy is not yet applied at large scale, so impacts of large-scale installations are not known yet.

Affordability. The LCOE estimates for ocean energy technologies are >0.1 EUR/kWh, which is linked to technological complexity and economy of scale of the technologies and therefore high capital expenditures (CAPEX) cost (e.g. membranes for salinity gradient energy). Validation workshop participants considered affordability a medium risk.

Energy security: overview of findings from the value chain assessments

In Table 7.7, the energy security indicator scores for the four value chains assessed are presented.

Table 7.7 Energy security indicator scores for ocean energy

Value chain/ indicator	Geopolitical availability	Abundance	Circularity	Supply chain complexity	Supply chain location	Digital vulnerability	Physical vulnerability	Broader sustainability	Affordability	Skills
Tidal	2	2	2	2	2	2	1	3	3	2
Wave	2	2	2	3	2	2	1	3	3	2
Thermal	1	1	2	3	3	2	3	3	3	2
Salinity gradient	2	2	1	2	2	1	2	2	3	3

In addition to the key criticalities (discussed above), for some specific value chains additional energy security risks have been identified. Since there are many moderate risks, we only mention the highest risks here.

For wave and thermal ocean energy, the supply chains are considered complex due to the challenges of offshore installation.

For OTEC in particular, several parts are complex from an engineering point of view, as the materials are required to withstand corrosion and hard sea conditions. For example, the cold-water inlet pipe is hard to engineer as it is affected by a variety of forces. For the operations, the supply chain is complex, as the locations to operate and maintain these systems are far out at sea for offshore OTEC, requiring deep-sea divers. The supply chain location is also considered a risk, since almost the entire supply chain is located outside the EU and only very limited geographic locations are suitable for OTEC. Finally, OTEC is physically vulnerable to damage and climate change.

Finally, for salinity gradient energy, the relative level of R&I required and the specialised skills required have been identified as key issues.

7.4.7. Photovoltaics (solar photovoltaics)

Role in the energy system and general description of the technology

Solar PV is a technology that is widely used for renewable electricity generation and is predicted to play a significant role in the future EU energy system. It is based on the conversion of sunlight into electricity through the application of specific semiconductor materials. In 2022, 69.5 gW of solar power capacity was installed in the EU. In the coming years, further growth is expected. The EU's REPowerEU plan includes the ambition of 320 gW of solar PV newly installed by 2025, more than twice today's level, and almost 600 gW by 2030. According to SolarPower Europe, the total solar fleet in the EU is projected to reach 920 gW under a Medium Scenario and 1 184 gW under a High Scenario, both numbers surpassing the REPowerEU plan's objective.

Three types of solar PV can be distinguished: crystalline silicon technologies, thin-film technologies (CIGS[64], CdTe[65], perovskites) and multi-junction technologies. The latter category, which involves many possible combinations of semiconductor layers to improve efficiency, is not discussed here (see Section 7.2, Value chain selection). We instead focused on crystalline silicon solar panels, which is the dominant technology, currently accounting for about 95% of global installed PV capacity, and thin-film technologies, which have advantages, such as lower weight and higher flexibility and may become increasingly relevant for future energy generation. Thin-film solar cells can be produced by simple and scalable methods and therefore have the potential to be more cost effective than crystalline silicon technologies. However, thin-film technologies are not widely commercially available yet, and further research and development on, for example, operational lifetime, degradation and manufacturing processes is needed.

As solar PV works in ambient daylight and is not dependent on direct sunlight, its area of application includes most of Europe, in contrast to CSE (see Section 7.4.3). In general, the application of solar PV is strongly localised, in the sense that it is applied to many different, small-scale locations (mostly roofs of houses and other buildings). In the EU, almost all generation capacity is connected to the main electricity grid. Larger-scale applications, such as parking lot roofs, 'solar farms' in fields and floating solar farms, are becoming more widely used. Floating solar panels, especially at sea, are more complex, and it is more expensive to establish a connection to the mainland. However, as the efficiency of solar PV decreases at higher temperatures, the natural cooling provided at sea is a specific advantage.

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[64] Copper indium gallium selenide.
[65] Cadmium telluride.

Energy security: key criticalities for the technology category

For photovoltaics, the key criticalities identified for energy security are: **CRMs**, **supply chain location**, **digital vulnerability** and **skills**.

CRMs. The production of solar PV requires various CRMs that are in limited supply within the EU and/or concentrated in a limited number of non-EU countries and/or not abundantly available. These most notably include silicon, boron and gallium. These materials are needed for the solar cells and are essential for the conversion of sunlight into electricity.

Supply chain location. In all cases, the value chain is almost entirely located outside the EU. China dominates nearly all aspects of solar PV manufacturing – supply of raw materials (53%) and components (89%), as well as production (70%). Russia is the second-largest producer of silicon, followed by Brazil and Norway (in 2022). The EU supplies 6% of the raw materials used in PV systems. European firms' investments account for less than 5% of the total investment volume, while Chinese companies account for around 65-70% of the investment volume.[66] Entering to the market with EU cells and modules is difficult due to lower production cost in Asia.

The location of supply may change in future, but not without strong political and economic efforts, and therefore we consider supply chain location to be a key criticality. It is important to note, however, that the potential for the establishment of a perovskite supply chain within the EU is much higher than for the other value chains considered, since this technique is not yet commercially available and therefore global production locations have not yet been established. Besides, R&D for perovskite PV is needed to improve the stability of the solar cells, in order for this technology to be broadly implemented. Part of this R&D work is currently done by academia and research institutes within the EU, which can lead to potential advantages in the development of this new technique.

Digital vulnerability. The risks of digital vulnerability are mostly related to the inverters needed for solar panels. It is expected that the future renewable electricity system will need more flexibility, including flexible renewable generation. This means that it should be possible to externally switch off or on solar panels when necessary given weather conditions, including domestic solar panels. This poses a risk to all owners of solar panels, which has not been well addressed as yet. Validation workshop participants confirmed that cybersecurity for PV inverters is a topic of focus for the sector.

Skills. For the established value chain of Si-based solar panels, availability of individuals with installation skills is the main potential limiting factor for the further uptake of solar PV. For the other value chains assessed, especially perovskites, availability of people with the necessary research skills is also critical, as further R&D is needed to mature the technologies.

Validation workshop participants noted that, besides the CRMs mentioned above, low-technology semiconductor chips are also essential for PV value chains, in particular for the inverters. Recent events have shown how vulnerable to disruptions the supply chain for this type of chip is. The EU Chips Act focuses on high-end chips and therefore does not address this issue.

Energy security: overview of findings from the value chain assessments

In Table 7.8, the energy security indicator scores for the four value chains assessed are presented.

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[66] Support to Assessment and Monitoring of Industrial Research, Innovation and Technologies (RTD/2021/OP/0004).

Table 7.8 Energy security indicator scores for the four photovoltaic value chains assessed

Value chain/ indicator	Geopolitical availability	Abundance	Circularity	Supply chain complexity	Supply chain location	Digital vulnerability	Physical vulnerability	Broader sustainability	Affordability	Skills
Silicon-based	3	2	2	2	3	2	1	2	1	2
Copper, indium, gallium, selenide	2	2	2	2	3	2	1	2	1	3
Cadmium telluride	1	2	2	2	3	2	1	2	1	3
Perovskite	1	1	2	2	3	2	1	2	1	3

In terms of geopolitical availability and abundance of CRMs, there is an interesting difference between perovskite and the other value chains that were assessed. Perovskite is not dependent on materials that are low in abundance or concentrated in specific non-EU countries, while the other three value chains are, with pure silicon, indium and gallium being the specific CRMs that may pose a risk for large-scale application in the EU. Copper and nickel are also key materials for solar PV technology, and for many other clean energy technologies as well; however, in general, their abundance is higher.

As perovskite solar cells are still in development and not yet available at a commercial scale, they will not be able to replace other types of solar cells in the short term. However, the potential to establish a perovskite supply chain within the EU is (much) higher than for the other value chains considered. As perovskite is a relatively new technology, the EU could be the first mover in this field.

Although solar panels, especially those that are silicon based, are vulnerable to damage and resulting defects from weather events (such as hail or broken tree branches), as well as a loss of efficiency due to higher temperatures, these negative impacts will in general be localised: They will affect a relatively small area at once, over a short timeframe. Because solar panels can and will be deployed in almost the entire EU, the risk associated with physical vulnerability is considered to be low.

Large-scale solar farms require significant land area or, in the case of floating PV, water area. This can lead to local opposition or biodiversity risks. Concerns about agriculture competition, disruption of the local environment or aesthetical concerns can arise. However, involving local citizens, such as allowing them to participate in construction plans or purchase a fair share, and planting shrubs and plants that promote biodiversity can help mitigate this to some extent. The EU biodiversity strategy specifically mentions solar panel farms providing diversity-friendly soil cover as a win–win solution for energy and biodiversity. Another broader sustainability risk concerns EOL waste management. Since solar PV will be used to such large extent, proper disposal and recycling of PV modules are essential to prevent environmental contamination and enable the reuse of valuable and rare materials.

7.4.8. Wind energy

General description and role in the energy system

Technologies for electricity generation include wind energy. Wind energy already plays an important role in the European clean energy transition, and its share in energy generation is expected to grow in the coming decades, with the European wind power action plan[67] of the European Commission envisaging the EU expanding total wind generation capacity to over 500 gW in 2030, from 204 gW in 2022. Currently, onshore and offshore wind turbines are most commonly used. Wind energy facilities can be placed in groups called 'farms' but can also stand alone. The facilities are connected to the electricity grid and could be directly linked to electrolysers, to produce hydrogen.

The following four wind energy values chains were assessed for this study: onshore wind turbines (commercially deployed, some innovations between TRL 1 and 9), offshore wind turbines (commercially deployed, some innovations between TRL 4 and 9), airborne wind energy systems (e.g. kites, autonomous aircraft) (TRL 3-5), and downwind wind turbines (TRL7-8).

The main distinction between the four value chains assessed is the design, which determines the way in which wind is converted into electricity. This influences the material use of the technologies: for instance, airborne wind systems require less material than wind turbines. The design of wind energy technologies also determines where the technology can be placed: airborne wind energy systems can, for instance, be placed at higher altitudes than wind turbines can. Lastly, the LCOE depends on the design: increasing rotor diameters of upwind turbines (which are most commonly deployed) reduce LCOE; however, this complicates the systems. Downwind turbines – another value chain assessed in this study – may present a solution for this challenge. In addition, the lower material use of airborne wind systems also increases their affordability.

The location where the technology is placed is also a factor for energy security issues and one of the reasons for distinguishing between onshore and offshore wind turbines.

Energy security: key criticalities for the technology category

For wind energy, the key criticalities identified for energy security are: **CRMs** and **physical vulnerability.**

CRMs. The use of CRMs in all of the wind energy technologies poses risks in terms of energy security, especially as wind energy is expected to play a major role in the European and global transition towards clean energy technologies. The CRMs used in on- and offshore wind turbines with highest risk according to the EU are copper, boron/borate, nickel and light and heavy rare-earth materials. Copper, boron and light and heavy rare-earth materials are used in turbines that generate electricity. Nickel is required for manufacturing the alloy steels used in e.g. the gearbox and the turbine. Airborne wind energy systems additionally use lithium and titanium. Lithium is found in the battery that is required to maintain the flight trajectories of the kites or aircrafts. Titanium is used in the structure of the aircrafts.

Copper, nickel and titanium are CRMs that are available in one or more EU countries. Titanium has low risks related to overall abundance. However, as global demands are rising,

[67] European Commission (October 2023), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, European wind power action plan.

more scarcity and higher prices could be expected. Copper and nickel have a medium abundance risk, with rising demands for these raw materials. Supply risks for lithium and heavy rare-earth elements are considered high, since there are no EU suppliers and since the market is dominated by one country (China).

Physical vulnerability. Climate change is expected to influence and change wind speed patterns, thus lowering the energy-generation potential of wind energy technologies. In addition, wind energy technologies are relatively vulnerable to extreme weather events, which are expected to occur more often in future. For instance, lighting may strike more often, storms may lead to a temporary shutdown of (onshore) wind turbines, and airborne wind energy systems are relatively vulnerable to hail. Finally, offshore wind energy technologies can be sabotaged by cable cutting.

Validation workshop participants noted that CRMs are a far more pressing energy security issue for wind energy than is physical vulnerability to climate change. Participants added regulatory and permitting challenges as a high risk (with low preparedness). These challenges are linked to opposition by local communities due to visual and auditory impact of wind farms.

Energy security: overview of findings from the value chain assessments

In Table 7.9, the energy security indicator scores for the four wind energy technology value chains are presented.

Table 7.9 Energy security indicator scores for wind energy

Value chain/ indicator	Geopolitical availability	Abundance	Circularity	Supply chain complexity	Supply chain location	Digital vulnerability	Physical vulnerability	Broader sustainability	Affordability	Skills
Onshore	2	2	1	1	1	2	2	2	1	2
Offshore	2	2	1	2	1	2	3	2	2	2
Airborne wind system	2	2	2	1	1	2	3	1	1	2
Downwind rotor	2	2	1	1	1	2	3	2	2	2

In addition to the key criticalities, the following energy security criticalities were identified as posing risks for some or all of the value chains assessed within this technology category: digital vulnerability, broader sustainability and skills.

Digital vulnerability risks for wind energy technologies are related to cyberattacks, which can cause substantial damage to wind turbines, threatening the reliable electricity generation of these systems. We expect this digital vulnerability to apply to all wind energy value chains assessed.

Wind turbines (either onshore, offshore or downwind rotor) are related to several broader sustainability issues. These are mostly caused by their location, depending on whether they are onshore or offshore (downwind rotor systems can be located both on- and offshore). The most important broader sustainability issues related to offshore turbines are their (negative) impact on wildlife, both during the development and the deployment phase, and potential negative impact on such sectors as fishing, defence and tourism. Onshore wind turbines can also negatively affect wildlife and may face public acceptance issues. Finally, balsa wood, which is used in onshore wind turbines, is over-logged in the Amazon rainforest, causing environmental issues. Airborne wind energy systems might have benefits in comparison with some of the more stringent sustainability issues related to the other three value chains (all turbines). Therefore, this energy security indicator is less critical for this particular value chain.

As wind energy technologies are expected to play a major role in the European energy transition, a large workforce is needed, mainly in their construction phase. In particular, offshore wind technologies require specific skills, which may be partly drawn from decreasing offshore fossil fuel exploration.

7.4.9. Direct solar fuels

General description and role in the energy system

Direct solar fuels or sunlight-to-X technologies convert solar energy directly into chemical energy in the form of liquid or gaseous fuel. This creates storable and transportable fuels without the intermediate step of electricity generation. Direct solar fuels are thus attractive because they overcome two main challenges with solar power generation: intermittency and electrons as energy carrier. Intermittency is an issue because generated power needs to be either used simultaneously or stored for later use, which entails conversion losses. The energy carrier can be an issue for some types of energy use, such as heavy industry or transportation, as this type of energy demand is difficult to electrify. Gaseous or liquid solar fuels solve both issues.

Two different routes exist for the generation of direct solar fuels: a photochemical and a thermochemical route. The main difference between the photochemical route and the thermochemical route is that thermochemical processes use concentrated solar heat to drive chemical reactions, while photochemical processes use light-absorbing materials or artificial photosynthesis to directly convert solar energy into chemical fuels. When direct solar fuels are produced through these processes on the basis of non-biological feedstock, they count as RFNBOs (see also Section 7.4.13).

The development of direct solar fuels is still in its early phases. The technology for the photochemical route is not yet commercialised and is in the R&I phase (TLR 1-3). For the thermochemical route, there is a first commercial demonstration by Synhelion, i.e. a TRL of 4-5.

Energy security: key criticalities for the technology category

For direct solar fuels, the main criticalities that were identified for the shortlist are: **CRMs**, **supply chain complexity** and **skills.**

CRMs. The CRMs bismuth and titanium are used as catalysts or in other critical parts of the technology, such as electrodes. Both are on the CRMs list of the EU. China dominates bismuth mining, while multiple countries mine titanium. Bismuth has a high abundance risk, while titanium has a low-abundance risk. Carrier materials needed for direct solar fuels may contain critical raw materials, such as titanium dioxide, but carrier materials not based on CRMs are also available (see also factsheet on photovoltaics in Annex C).

Supply chain complexity. The components required for direct solar fuels are highly specialised. The technology is also still in the development phase, meaning that components and materials are still being researched. The specialised character and ongoing research are the main supply chain complexities for this technology.

Skills. As the technology for the production of direct solar fuels is still in the development phase, highly skilled and specialised labour is needed. The particular skillset and academic level are a major criticality for further development of the technology.

Energy security: overview of findings from the value chain assessments

In Table 7.10, the energy security indicator scores for the two value chains assessed are presented.

Table 7.10 Energy security indicator scores for direct solar fuels

Value chain/ indicator	Geopolitical availability	Abundance	Circularity	Supply chain complexity	Supply chain location	Digital vulnerability	Physical vulnerability	Broader sustainability	Affordability	Skills
Photochemical/ photobiological	1	2	1	3	2	1	1	2	3	3
Thermochemical	1	1	1	2	2	1	1	2	3	3

In addition to the key criticalities related to the energy security of direct solar fuel technologies, the following energy security indictors pose risks for some or all of the value chains assessed within this technology category: supply chain location, broader sustainability, and affordability.

For supply chain location, the main factor is the geographical area where research is conducted. Although EU research organisations have a strong track record, they do not have a leading role in solar fuel research. This poses a moderate risk for the European development and deployment of the direct solar fuel technology.

Broader sustainability is a moderate risk for thermochemical generation of direct solar fuels, as this technology uses concentrated solar power, which has high land and water requirements and therefore could impact local environments. The risks are, however, relatively limited compared to other technologies; therefore, this indicator is considered a moderate risk. As the photochemical route does not rely on concentrated solar power (for heat) but on semiconductor solar cells (for the photochemical reaction), these considerations apply in a less pronounced way.

The affordability of the direct solar fuels technologies is a major risk. Given the high costs of materials and equipment and the highly specialised pathways, the direct solar technologies struggle to be competitive, even in the long term (2050-2100). The high costs could be a major hurdle for this technology to be of practical importance in the future energy system.

7.4.10. Carbon capture and storage

General description and role in the energy system

To mitigate the effects of climate change and avoid worst-case outcomes, a combination of technologies will be necessary. While the transition to renewable carbon-free energy sources is a condition sine qua non, fossil fuels are expected to continue to play a role in the transition period. CCS can be used in this period to mitigate the effects of the CO_2 emissions that arise from burning these fuels.

CCS was long considered a last-resort option as a carbon mitigation technology. Although CCS is a mature technology (TRL 9), it has therefore not yet been widely applied in practice. However, a considerable part of the know-how and skills for deploying this technology is based on skills transferrable from the oil and gas industries. Currently the projects are in early stages. In 2022, 73 CCS facilities were being developed in Europe and the UK.

It is not entirely clear yet what the exact role of CCS will be in the energy system. CCS can be of importance during the transition period for sectors that are challenging to decarbonise, such as heavy industry and fossil fuel–based power generation. For heavy industry, e.g. steel making, CCS can be a solution for scope 1 and 2 emissions (the latter if CCS is applied in the power sector). Scope 3 emissions are out of scope here. CCS could have a role in the transition towards a fossil-free system because gas-fired power plants are necessary to balance the power system while other technologies are being developed and deployed.

Energy security: key criticalities for the technology category

For CCS, the main criticality is **broader sustainability**. Several issues with CCS technology are linked to broader sustainability topics:

- Fossil lock-in. The first issue is the concern that the use of CCS diminishes the incentives and pace to transition to fossil-free energy sources. It thus creates a lock-in for fossil technologies and leads to more GHG emissions.

- Additional emissions. The second concern is the enhanced oil recovery used for injection of CO_2, leading to increased extraction of oil hence additional CO_2 emissions.

- Leakage and seismic activity. Carbon storage has an inherent, albeit very small, risk of leakage and seismic activity. In addition, the existence of this risk, and its possible real-life occurrence, can negatively impact public opinion.

- Impacts on local biodiversity. CCS projects are large infrastructure projects. Their construction impacts local environments and thus biodiversity. Reuse of existing natural gas infrastructure can help mitigate the effects. In addition, leakages, albeit unlikely, of CO_2 into the marine environment increase the acidity of the water and thus disrupt the local ecosystem by decreasing calcification of marine organism shells and by lowering nutrient availability. Leakages should be prevented through thorough inspection and maintenance of pipelines.

Energy security: overview of findings from the value chain assessments

In Table 7.11, the energy security indicator scores for the value chain assessed are presented.

Table 7.11 Energy security indicator scores for carbon capture and storage

Value chain/ indicator	Geopolitical availability	Abundance	Circularity	Supply chain complexity	Supply chain location	Digital vulnerability	Physical vulnerability	Broader sustainability	Affordability	Skills
Capture and storage infrastructure	1	1	1	1	1	2	2	3	3	2

In addition to the key criticalities related to the energy security of CCS, the following energy security indictors pose risks for the value chain assessed within this technology category: digital and physical vulnerability, affordability and skills.

Both digital and physical vulnerabilities are considered moderate risks for CCS. Both are related to possible sabotage of offshore infrastructure. CCS infrastructure is vulnerable to cyberattacks because a considerable part is controlled remotely. Physical sabotage could include attacks on the pipelines and platforms. In addition, unintentional damage to pipelines could have the same effects. The CCS infrastructure is, however, less likely to be the target of attack than the power, gas or internet infrastructure, as disruption of the latter three results in more immediate impacts. Hence, the risk is moderate.

Affordability is a high risk for CCS because the technology has high capital costs (due to the required extensive infrastructure) yet has limited financial revenues. The revenues are dependent on the carbon market, in particular EU-ETS. As the cost for emissions via the EU-ETS rises, CCS can become financially more attractive. However, in general CCS projects are not lucrative, cash-generating endeavours, and hence subsidy is required.

Skills are a moderate risk for CCS because its deployment requires skilled technical personnel. Given the general shortages in the technically skilled workforce, sufficient people with the additional offshore skills could be difficult to find. This is a moderate risk.

7.4.11. Batteries

General description and role in the energy system

Batteries serve a variety of purposes across numerous applications. They are used as a portable source of power for devices, such as electronics, and increasingly for electrical vehicles. In the energy system, batteries serve as back-up power, storage for fluctuating renewable power, and for power-balancing needs and grid services, such as stability and resolving network congestion.

Given the broad range of applications and the ubiquity of batteries, different technologies exist. An important distinction is whether batteries are used for mobile or stationary applications. Mobile applications require batteries of small size and weight, i.e. high energy densities. Lithium-ion batteries perform best on these characteristics and are therefore currently widely used in mobile applications, such as appliances and electrical vehicles. Li-ion batteries have a TRL of 9.

Batteries used in the energy system are stationary batteries. They have less strict requirements for energy density. In these cases, important characteristics are timescales for energy storage and response times. Li-ion, redox-flow and molten salt batteries can be applied for storage on a timescale of hours. Redox-flow battery systems could be used for up to half a day to potentially multiple days in future. Both redox-flow and molten salt batteries have a TRL of 9. For energy storage of days or weeks and for seasonal storage, other technologies are more applicable and cost effective. These technologies include Na-ion saltwater, Zn-ion, Na-S room temperature and Zn-air batteries. All are relatively low-cost technologies with high energy storage potential and do not depend on CRMs. Na-ion and Na-ion saltwater have a TRL of 8 to 9, whereas other technologies are in development (TRL from 2 to 4).

Energy security: key criticalities for the technology category

For batteries, the key criticalities identified for energy security are: **CRMs, supply chain location** and **broader sustainability**.

CRMs. Batteries used today, in particular the ubiquitous Li-ion batteries heavily depend on CRMs. Access to CRMs today and in the future is increasingly at risk. For Li-ion batteries, lithium is the essential material used for energy storage. Cobalt is used as cathode material and is of importance for battery safety and lifetime extension. Nickel and aluminium are also used for cathodes. Graphite makes up the anode and up to half the weight of Li-ion batteries. Other battery technologies also depend on CRMs. For redox-flow batteries, vanadium is a key material, and it is sourced from outside of Europe. For technologies under development, such as Li-based solid-state batteries and magnesium-ion batteries, the CRMs include magnesium and rare-earth metals. The abundance and supply chain location (see also next point) are a key risk for the use of these technologies in future. On the other hand, molten salt, Na-ion, Na-ion saltwater, Zn-ion, Na-S and Zn-air batteries do not contain CRMs and are therefore of particular interest for future use in the European energy system. Such elements as Na, S and Zn are already produced on considerable scales in Europe, and there are significant known reserves.

Validation workshop participants added that the number of recycling facilities is currently the limiting factor with regards to recycling of CRMs. In 2050, a recycling ability need of 40-60% of battery materials is projected, but with the current number of recycling facilities, this recycling rate will not be achievable.

Supply chain location. Many CRMs present in batteries, such as lithium, cobalt, magnesium and graphite, are mined and produced outside the EU, which poses a high supply risk. China, other Asian countries and some African countries play a major role on a global scale. China is the world's largest supplier of lithium and lithium batteries. The Democratic Republic of Congo is the world's largest supplier of cobalt. Nickel is predominantly produced in Indonesia, while China increasingly controls the aluminium market. China also dominates the graphite market. Europe is dependent on China, Russia and South Africa for its vanadium supply. The elements for alternative battery chemistries, such as Zn- and Na-based batteries, are more readily available in Europe but still in early technological development.

Broader sustainability. CRMs are mined, and mining activities pose severe social and environmental hazards. Mining conditions are often very poor, with Democratic Republic of Congo an infamous example. Mining is associated with environmentally harmful effects, such as accelerated droughts, pollution and contamination of water and soil. The low cost of such resources as Zn, Na and saltwater could lead to a trend where it is economically uninteresting to recycle these materials. However, from a circularity and sustainability aspect, recycling/reuse should always be prioritised over the use of primary resources from mining or other extraction methods. In addition, processing of CRMs is energy intensive. This is expressed as global warming potential (equivalent CO_2 emissions per kWh of battery produced). The global warming potential of Li-ion batteries is 30-200 kg CO_2 equivalent (eq.)

per kWh. For redox-flow batteries, the production of V_2O_5 has a global warming potential of 180 kg CO_2 eq. per kWh.

Validation workshop participants added that public opinion is indeed a risk for battery production, as the social acceptability of mining for battery production is being challenged.

Energy security: overview of findings from the value chain assessments

In Table 7.12, the energy security indicator scores for the four value chains assessed are presented.

Table 7.12 Energy security indicator scores for batteries

Value chain/ indicator	Geopolitical availability	Abundance	Circularity	Supply chain complexity	Supply chain location	Digital vulnerability	Physical vulnerability	Broader sustainability	Affordability	Skills
Containing critical raw materials	3	2	2	2	3	2	1	3	1	2
Not containing critical raw materials	1	1	2	2	1	2	1	1	2	2
Redox-flow	2	1	1	2	3	2	1	1	2	2
Molten salt	1	1	1	1	1	1	1	1	2	2

In addition to the key criticalities related to the energy security of batteries, the following energy security indictors pose risks for some or all of the value chains assessed within this technology category: circularity, supply chain complexity, digital vulnerability, affordability and skills.

In terms of circularity, the EU has taken steps to increase the capacity for recycling of batteries containing CRMs, in particular Li-ion batteries. Recycling existing materials is crucial to decrease the risks associated with materials in these batteries. However, as the demand for batteries is expected to increase exponentially in the coming years and decades, the amount of new materials necessary will continue to exceed the amount available for recycling in the near and medium future. For other battery technologies, such as molten salt, Zn-air and Na-S, the materials can be relatively easily recycled. For technologies under development, recycling still needs to be set up.

Supply chain complexity is considered a moderate risk for most battery technologies. The exception is molten salt batteries. The underlying reasons for complexity differ per technology. For Li-ion batteries, the main complexity is economical and lies in the low prices of batteries produced in China, resulting in the difficult competitive position of Europe and its dependence on China. For vanadium redox-flow batteries, the complexity is related to the supply chain location and thus to Europe's dependence on possibly geopolitically challenging supply countries. For batteries not containing CRMs, the main complexity lies in the scaling up of manufacturing processes and securing supply chains, as these technologies are relatively young.

Digital vulnerability is an issue for all battery technologies associated with the use of batteries in the power system. Stationary batteries provide grid services and react on digital signals, such as market prices or grid status. In case of a cyber-attack on batteries, a sudden, simultaneous charge or discharge spike in a large number of batteries could destabilise the power system, resulting in possible loss of power or damage to key power system components.

Physical vulnerability is limited for all battery technologies. Any natural damage or sabotage has limited effects on the larger energy system. For Li-ion batteries, the physical risk is moderate due to fire hazard, in particular the difficulties of extinguishing a fire in Li-ion batteries.

Affordability risks mirror the other risk indicators evaluated in this project. Li-ion batteries are currently the cheapest available technology. This is the reason for their broad application. Other technologies have other advantages yet are more expensive than Li-ion batteries; hence the higher risk associated with their affordability.

Skills are a moderate risk for all battery technologies. The increasing demand for labour in the energy sector and energy transition is expected to be a limiting factor for the adoption of this technology. This is the case regardless of the specifics of the technology. For technologies under development, additional risks exist for availability of an expert workforce to conduct the research and development at a sufficient pace.

7.4.12. Hydrogen

General description and role in the energy system

Hydrogen can play an energy storage role in a clean energy system. In that case, hydrogen is produced using renewable electricity generated by, for instance, wind farms or solar PV. These technologies generate electricity intermittently and therefore do not always supply energy when there is demand. Hydrogen produced using electrolysis can store the energy from these electricity technologies when there is no demand. Electrolysers could be either directly coupled to a large-scale wind parks or solar farms (this is typically the case for larger electrolysers) or be connected to the grid. The hydrogen can be used as a fuel in either set-up.

In this project, four different electrolysers technologies have been assessed for energy security risks: alkaline (TRL 8-9), PEM (TRL 8-9), solid oxide (TRL 3-5) and AEM (TRL 3-5).

Energy security: key criticalities for the technology category

Across the board, for hydrogen produced using electrolysing technologies, the technology faces some specific energy security issues. These are being addressed by developing new electrolysing technologies, but up until now this has, in turn, introduced new energy security issues. For the production of renewable hydrogen, the key criticalities identified for energy security are: **CRMs**, **physical vulnerability**, **broader sustainability**, **affordability** and **supply chain complexity**.

CRMs. Especially PEM and solid oxide electrolysers pose risks related to CRMs need (respectively platinum, titanium and iridium, and scandium). Also nickel is essential for many electrolysers.

Physical vulnerability.[68] As large amounts of renewable electricity are needed to produce hydrogen with electrolysing technologies, this technology category is vulnerable to physical disruptions of the electricity grid. It is also vulnerable because electrolysis requires stable operating conditions.

Broader sustainability. To produce hydrogen using electrolysing technologies, large amounts of pure water are needed. In addition, specifically for PEM, PFAS are needed. Currently no viable alternatives are available; therefore a blanket ban on PFAS would strongly impact the possibilities for hydrogen production through electrolysis.

Affordability. Especially the costs of producing hydrogen using alkaline and PEM electrolysers are currently high. Costs of hydrogen produced using the other two electrolysing technologies are still uncertain, due to their low TRL. The costs of electrolysers and hydrogen are expected to decline in future; however, these costs are currently an important barrier in commercial implementation of the technology.

Energy security: overview of findings from the value chain assessments

In Table 7.13, the energy security indicator scores for the four value chains assessed are presented.

Table 7.13 Energy security indicator scores for hydrogen

Value chain/ indicator	Geopolitical availability	Abundance	Circularity	Supply chain complexity	Supply chain location	Digital vulnerability	Physical vulnerability	Broader sustainability	Affordability	Skills
Alkaline electrolysis	1	2	1	1	1	2	1	2	3	2
Proton-exchange membrane electrolysis	2	3	1	2	2	2	1	2	3	2
Solid oxide electrolysis	3	2	1	2	1	2	1	2	2	2
Anion-exchange membrane electrolysis	1	2	1	2	1	1	1	2	2	2

For PEM, solid oxide and AEM electrolysers, the supply chain complexity is an additional energy security risk to be highlighted. PEM has a vulnerable and complex chain, and solid oxide (SO) and AEM are still at a low level of technology readiness; hence the value chains have not been established yet.

[68] Through to-be-discussed list for 2030 and 2050.

7.4.13. Renewable fuels of non-biological origin

General description and role in the energy system

RFNBOs are energy carriers based on renewable feedstocks other than biomass that can be used in transport. RFNBOs by definition are required to be based on sustainably sourced feedstocks, e.g. hydrogen or CO_2, entailing strong requirements on value chain transparency and enforcement. Examples are hydrogen produced via electrolysis and synthetic fuels. For this technology category, the value chain of synthetic kerosene has been assessed. Furthermore, if direct solar fuels are produced based on non-biogenic feedstock, these fuels are also considered RFNBOs (see Section 7.4.9, Direct solar fuels).

Synthetic kerosene is produced using green hydrogen (from electrolysis) and CO_2 (from direct air capture (DAC) or point source capture) through the reverse water gas-shift reaction and the Fischer-Tropsch process. Use of fossil point sources of CO_2 will be prohibited as per 2041, following the Delegated Act on Recycled Carbon Fuels. At the same time, DAC is still low TRL and very energy intensive due to the relatively low concentration of CO_2 in the air and the high temperatures needed. The TRL of the entire value chain is 4-8. The route of synthetic kerosene production via methanol synthesis was not assessed, due to its low TRL.

Energy security: key criticalities for the technology category

For the technology category RFNBOs, the key criticalities identified for energy security are: **affordability**, **supply chain complexity** and **physical vulnerability**.

Affordability. Hydrogen from electrolysis with renewable electricity is expected to be remain more expensive than hydrogen from natural gas. CO_2 from DAC has high costs. A lot of energy and heat is needed to capture CO_2 from air due to the low atmospheric concentration. This translates into expected high costs of synthetic kerosene.

Supply chain complexity. The scale-up and related availability of sustainable CO_2 from DAC is uncertain. In addition, this supply chain still needs to be set up.

Physical vulnerability. s large amounts of renewable electricity are needed to produce RFNBOs, this technology category is vulnerable to physical disruptions of the electricity grid.

Energy security: overview of findings from the value chain assessments

In Table 7.14, the energy security indicator scores for the value chain assessed are presented.

Table 7.14 Energy security indicator scores for renewable fuels of non-biological origin

Value chain/ indicator	Geopolitical availability	Abundance	Circularity	Supply chain complexity	Supply chain location	Digital vulnerability	Physical vulnerability	Broader sustainability	Affordability	Skills
Synthetic kerosene	1	1	1	2	1	2	2	2	3	2

In addition to the key energy security criticalities, there are some energy security risks related to the broader sustainability of both renewable electricity production chains (e.g. wind and solar PV) and hydrogen via electrolysis. These are further discussed in other sections; however, they are indirectly also relevant for this technology category. This also goes for digital vulnerability of the energy system, which is related to the high use of electricity of the value chain.

As parts of the value chain need further development, specific R&D skills are important for the large-scale availability of RFNBOs to the EU's energy system.

7.4.14. Heat pumps

General description and role in the energy system

Heat pumps are a widely used technology for *energy conversion*: electricity is used to convert heat that is at a low temperature level (from a source such as the surrounding air, energy stored in subsurface aquifers, or nearby sources, such as water or waste heat from a factory) to heat that is at a higher temperature level that fits demand. As long as the electricity deployed is from a renewable source, a heat pump can be considered a renewable ('clean') energy technology.

Heat pumps are deployed for different applications, depending on the output temperature range required. In our analysis, we assessed two types of value chains: industrial heat pumps and domestic heat pumps.

In industrial applications, heat pumps supply the heat that is needed for specific industrial processes, mostly related to manufacturing or processing goods or food products, that take place at low or moderate temperature levels. Different required output temperatures are possible depending on the type of process. Industrial heat pumps are mainly used for low-temperature processes, below 100° C. Output temperatures of 150° C can be achieved if waste heat at about 100 °C is available for input. The TRL of heat pumps up to 140 °C is high (8 or higher). For the temperature range of 140-200 °C, the TRL is 4-9 depending on the scale of application. For temperatures of > 200 °C, heat pumps are only available in prototype phase (TRL 4), but it is expected that high-temperature heat pumps will also become available for industry to replace fossil-based heating over the next decades.

In residential applications, heat pumps serve to supply the heat needed for heating the house and hot water use (sometimes the heat pump can supply cooling as well). A temperature well below 100° C is sufficient for these purposes, and the TRL of domestic heat pumps is 9.

A condition for large-scale application of heat pumps, both for industrial and domestic purposes, is the availability of a sufficient electricity network connection. Network congestion, for instance due to increasing deployment of heat pumps and parallel electrification of other sectors, such as mobility, could hamper the roll-out of heat pumps in the short term.

Energy security: key criticalities for the technology category

For heat pumps, the key criticalities identified for energy security are: **CRMs**, **physical vulnerability** and **skills**.

CRMs. This concerns the CRMs copper, aluminium and nickel, which are essential for many other clean energy value chains as well. Copper, aluminium and nickel are mainly used in the piping components. Copper is further used in the evaporator components as well as in electrical wiring. Although recycling initiatives for CRMs are being developed and deployed, the demand is expected to exceed the available recycled materials.

Physical vulnerability. As large amounts of renewable electricity are needed to deploy heat pumps, this technology category is vulnerable to physical disruptions of the electricity grid.

Skills. The risk of a shortage of skilled workers is elevated compared to other value chains for a couple of reasons. Heat pumps are a decentralised value chain, with a need for installation of every single device at a different location (either a house or an industrial site). Especially for industrial heat pumps, the design often needs to be customised to the specific criteria of the end user. This implies a higher need of installation skills than for standard devices, such as solar panels. Also, a shortage of skilled workers is currently already creating bottlenecks in the deployment of heat pumps, and the expected increase of their application both for industrial and for domestic purposes will further increase this pressure.

Validation workshop participants stressed that, although the training for installation is relatively quick, there is a strong competition for workers across clean energy technology sectors, due to overall shortages and the United States attracting workers away from the EU.

Validation workshop participants noted that, besides the CRMs mentioned above, also low-technology semiconductor chips are essential for the operation of heat pumps, and recent events have shown how vulnerable to disruptions the supply chains for this type of chip are. As the European Chips Act focuses on high-end chips, it does not address this issue. Participants also noted that digital vulnerability does increase when several devices, such as heat pumps, solar panels and charging devices for eV, are coupled in future in order to allow for flexibility in the electricity system.

Energy security: overview of findings from the value chain assessments

In Table 7.15, the energy security indicator scores for both value chains assessed are presented.

Table 7.15 Energy security indicator scores for the heat pump value chains assessed

Value chain/ indicator	Geopolitical availability	Abundance	Circularity	Supply chain complexity	Supply chain location	Digital vulnerability	Physical vulnerability	Broader sustainability	Affordability	Skills
Industrial heat pumps	1	2	1	2	2	2	2	2	2	3
Domestic heat pumps	1	2	1	2	2	2	2	2	1	3

From Table 7.15, it follows that the energy security assessment of both types of value chains has a similar outcome, which is expected because the technology is essentially the same for both applications that were assessed. Only the scores for affordability differ. This difference is related to the larger scale, higher temperature range and (partly) lower TRL of industrial heat pumps compared to domestic heat pumps, leading to higher costs per kWh in the case of industrial heat pumps. Especially in the higher temperature range, industrial heat pumps are not yet competing for costs with existing fossil fuel–based heating solutions.[69]

Regarding the supply chain, several types of risks have been identified in the assessment. Its complexity is relatively elevated, as each heat pump needs to be installed (and maintained) separately at a specific location (qn industrial facility or a home), which means, especially for industrial applications, that tailored adjustments may be needed. Also, as industrial heat pumps are designed for specific temperature ranges and processes, opportunities for mass production are limited. For domestic heat pumps, this barrier is less pronounced.

Another aspect that leads to a relatively challenging value chain is the fact that the production of several key elements, mainly compressors, electronic components and refrigerant, is dominated by a relatively small number of suppliers in a few countries. This does include European countries, however, meaning that the value chains are not completely dependent on non-EU countries.

Digital vulnerability is considered to be elevated because of the risk of cyberattacks on the electricity system, as with other value chains that require relatively high amounts of (renewable) electricity.

The risk in the area of broader sustainability is moderately high because of recently revised EU legislation on the deployment of F-gases (fluorinated gases), which are used in heat pumps as refrigerants. This may slow down the application of heat pumps, at least temporarily.

Affordability of industrial heat pumps may form a risk as well, but this is mainly an issue for higher temperature range heat pumps, and we expect costs to decrease over time due to current R&I efforts as well as political and economic incentives to decarbonise industrial processes.

7.4.15. Smart energy grid technologies

General description and role in the energy system

The technology category smart energy grid technologies represents a group of technologies that in some way help regulate the supply of and demand for energy, increasing energy efficiency. This can reduce energy costs, help reduce overloading of the electricity grid, and, as it leads to more efficient use of energy and thus resources, increase sustainable energy use. In this project, the following smart energy grid value chains were assessed for energy security: eV smart charging, advanced metering infrastructure (AMI) and home energy management systems (HEMS). All three technologies are at TRL 9; however, electric vehicle smart charging is not applied at big scale.

Energy security: key criticalities for the technology category

For smart energy grid technologies, the key criticalities identified for energy security are: **CRMs** (linked to complexity and location of advanced electronics sub-value chain and circularity), **digital vulnerability** and **skills**.

[69] CE Delft performed a study on this, but the publication on it is written in the Dutch language only. De Vries, M., Jongsma, C., Voulis, N., Groenewegen, H. (2023), Kosteneffectieve Alternatieven voor CCS: Uitwerking van de 'zeef' ten bate van de SDE++-subsidieronde voor 2023, CE Delft, Delft.

CRMs. Smart energy grid technologies are based on advanced electronics, which contain such CRMs as palladium, cobalt, gallium, germanium, silicon and rare-earth materials. In addition, the semiconductors and chips needed for these electronics are mainly manufactured in a limited number of countries outside the EU. These criticalities are less relevant for eV smart charging. In addition, CRM availability and abundance also relate to circularity, so the recycling rate of CRMs must improve for the EU to be able to be more self-sufficient in the supply of these materials.

Digital vulnerability. Smart energy grid technologies are very digital dependent, which inherently makes them vulnerable to cyberattacks or disruptions of the digital network. This could negatively impact the functioning of the energy grid. AMI and HEMSs are vulnerable to data theft as well.

Skills. For all assessed smart energy grid technologies, specialised skills are needed for widespread implementation and successful integration with existing energy infrastructure. This involves professionals with various skills and expertise, for whom the demand is increasing. Labour shortage has an effect on the pace of adoption of these technologies and is expected to be a limiting factor.

Validation workshop participants mentioned resilience to solar storms as a potential physical vulnerability for this technology.

Energy security: overview of findings from the value chain assessments

In Table 7.16, the energy security indicator scores for the three value chains assessed are presented.

Table 7.16 Energy security indicator scores for smart energy grid technologies

Value chain/ indicator	Geopolitical availability	Abundance	Circularity	Supply chain complexity	Supply chain location	Digital vulnerability	Physical vulnerability	Broader sustainability	Affordability	Skills
Electric vehicles smart charging	1	1	2	1	1	3	1	1	1	2
Advanced metering infrastructure	2	2	2	2	2	3	1	2	1	2
Home energy management systems	2	2	2	2	2	3	1	2	1	2

In addition to the key criticalities, broader sustainability can pose energy security risks for AMI and HEMS. These are related to the use of CRMs, the mining of which often has a negative environmental impact and is related to human rights violations.

7.4.16. Energy building and district heating technologies

General description and role in the energy system

The technology category energy building and district heating technologies represents a collection of multi-building heating and cooling systems. In this project, the following value chains have been assessed within this category: ACT, thermal energy storage (TES) and combined heat and power (CHP). All technologies can be used to optimise energy generation, distribution and/or consumption. This is, for instance, done by utilising waste heat and connecting and balancing demand and supply. The technologies assessed within each value chain all are at TRL 9. However, ACT are not widely commercially utilised yet.

Energy security: key criticalities for the technology category

For energy building and district heating technologies, the most critical value chain in terms of energy security is ACT. Both TES and CHP are not very vulnerable to energy security risks. Therefore, the key criticalities identified for energy security are: **CRMs** (linked to complexity and location of advanced electronics sub-value chain) and **digital vulnerability**.

CRMs. ACT depend on complex electronics, which contain such CRMs as palladium, cobalt, gallium, germanium, silicon and rare-earth materials. In addition, the semiconductors and chips needed for these electronics are mainly manufactured in a limited number of countries outside the EU.

Digital vulnerability. As ACT are all about digital connection, they are vulnerable to cyberattacks, which compromise the operation of these technologies. In addition, data gathered by the technologies are vulnerable to theft.

Energy security: overview of findings from the value chain assessments

In Table 7.17, the energy security indicator scores for the three value chains assessed are presented.

Table 7.17 Energy security indicator scores for energy building and district heating technologies

Value chain/ indicator	Geopolitical availability	Abundance	Circularity	Supply chain complexity	Supply chain location	Digital vulnerability	Physical vulnerability	Broader sustainability	Affordability	Skills
Advanced control technologies	2	2	2	2	2	3	1	1	1	2
Thermal energy storage	1	1	2	1	1	1	1	1	1	1
Combined heat and power	1	2	1	1	1	2	1	1	1	1

The table shows that in addition to the key criticalities mentioned for advanced control technologies above, also skills (for ACT), circularity (for TES) and abundance of CRMs other than advanced electronics (for CHP) can lead to potential energy security risks. For ACT, successful integration into the existing energy infrastructure requires a multidisciplinary approach, involving professionals with various skills and expertise, in a sector which already has a high demand for such workers. Therefore, the skills gap poses an energy security risk. For TES, circularity is an issue as the EOL treatment of borehole components of underground TES (UTES; one example of possible TES solutions) could be cumbersome. For CHP, the use of copper poses abundance risks.

7.4.17. Off-grid energy systems

General description and role in the energy system

Some remote locations in Europe are disconnected from energy grids. Off-grid energy systems can provide energy for these locations. The following clean off-grid energy systems have been assessed in this project, all providing off-grid heat: biogas tank, pellet stove and thermal collector (solar heat). All technologies are at TRL 9. Solar PV was not assessed as a separate value chain under off-grid energy systems but is treated as a separate technology in Section 7.4.7.

Energy security: key criticalities for the technology category

For off-grid energy systems, the key criticalities identified for energy security are: **CRMs** and **broader sustainability**.

Critical raw materials. The CRMs needed for the production of the off-grid energy systems assessed are copper and aluminium. Especially for thermal collectors, the use of copper might present some abundance issues. Thermal collectors also need a magnesium or aluminium anode rod to protect against erosion, and they require several non-CRMs, such as fibreglass and foam for insulation and high-density polyethylene (HDPE) for pipes.

Broader sustainability. The feedstock used for production of biogas for biogas tanks is sometimes illegally polluted by prohibited biowaste (for instance slaughterhouse waste) or fossil waste (for instance chemical waste). This could end up in the food chain, through the digestate produced in addition to biogas. For pellet stoves, local air pollution is a broader sustainability issue. For thermal collectors, the heat transfer fluid may pose environmental risks if not properly managed.

Energy security: overview of findings from the value chain assessments

In Table 7.18, the energy security indicator scores for the three value chains assessed are presented.

Table 7.18 Energy security indicator scores for off-grid energy systems

Value chain/ indicator	Geopolitical availability	Abundance	Circularity	Supply chain complexity	Supply chain location	Digital vulnerability	Physical vulnerability	Broader sustainability	Affordability	Skills
Biogas tank	1	1	1	1	1	1	1	2	1	1
Pellet stove	1	1	1	1	1	1	1	2	1	1
Solar heat: thermal collector	1	2	2	1	1	1	1	1	2	1

Apart from the key criticalities, circularity may pose a moderate risk for thermal collectors as recycling of metallic components is mostly possible but not yet well established.

Affordability was also assessed to be a moderate risk for thermal collectors, based on relative cost levels. Levelised cost of heat (LCOH) for thermal collectors is estimated at 8-11 eurocents per kWh,[70] which is higher than the estimated LCOH for geothermal energy (see Section 7.4.4).

7.4.18. Energy transmission & distribution technologies

General description and role in the energy system

Energy transmission and distribution technologies play a crucial role in the overall energy system by facilitating the delivery of energy carriers – electricity and hydrogen in the cases of the value chains considered here – from energy-generation sources to end users. The electricity transmission and distribution technologies essentially consist of *cables* and supporting equipment. The hydrogen transmission and distribution technologies consist of *pipelines* and supporting equipment. HVDC transmission technology is a particular subset of electricity transmission technology used for the transport of electrical energy over long distances.

Both hydrogen storage and transportation, as well as HVDC transmission, already exist and are already part of the European energy system. While most portions of the power system are an alternating current (AC) system, some portions of the systems are connected through HVDC cables, called HVDC links. HVDC links are used when long distances, such as undersea crossings, need to be bridged, due to lower energy losses in long-distance HVDC transmission cables. Hydrogen and thus hydrogen storage and transportation technologies are expected to play an increasingly important role in the energy system: as an energy carrier instead of natural gas, in sector coupling providing a link between electricity and industrial sectors, and as a flexible source for the electricity system. HVDC is expected to become

[70] Schiebler, B., Giovanetti, F., and Fischer, F. (2018), Levelized Cost of Heat for Solar Thermal Systems with Overheating Prevention, Solar Heating & Cooling Programme, International Energy Agency.

increasingly important as large quantities of renewable electricity will be transported over long distances across Europe.

Energy security: key criticalities for the technology category

For energy transmission and distribution technologies, the key criticalities identified for energy security are: **CRMs**, **physical vulnerability** and **digital vulnerability**.

CRMs. Both copper and aluminium are indispensable for HVDC cables, as the metal conductors are made of one of these two materials. Copper has better electro-physical performance, though aluminium is often preferred over copper for very long distances due to its lighter weight. The European production of aluminium has been decreasing in the past half decade due to increasing energy prices (aluminium smelting is energy intensive). China's production has in the meantime been increasing. Therefore, although the raw material itself is available from different sources, Europe is increasingly dependent on China for the processed product.[71] Copper is on the CRMs list due to its strategic importance.

Although these polymers are not CRMs according to the EU's definition, it is worth noticing that HVDC cables are also dependent on specific polymers, such as are cross-linked polyethylene (shortened to XLPE), which offers electrical insulation, thermal resistance and mechanical strength to the cable. Alternative polymers with the same function are ethylene propylene rubber, polyethylene and polyvinyl chloride (commonly known as PVC). These polymers are derived from petrochemical feedstocks. This introduces a dependence on petroleum and natural gas and is therefore associated with the supply risks of petroleum and natural gas.

Physical vulnerability. Many of the existing HVDC cables are underwater links connecting different parts of Europe, in particular connections across the North Sea, the Baltic Sea and in the Mediterranean. Protecting these cables at their full length against physical sabotage is in practice exceedingly difficult. The real-life threat of sabotage is moreover increasing, and in June 2023 NATO set up a taskforce to protect undersea infrastructure.[72] The consequences of physical sabotage on the power system are similar to the consequences of cyberattacks, described below.

Validation workshop participants mentioned resilience to solar storms as a potential physical vulnerability for this technology.

Digital vulnerability. Cyberattacks on power grids in general and HVDC links in particular pose a significant and growing threat to the stability, reliability and security of the power system. At least three types of attacks (timing attack, replay attack and false data injection attack) on an AC–HVDC system can result in large oscillations or unstable conditions. Moreover, because the European power grid is an interconnected system, a successful cyber-attack on an HVDC link can have severe consequences, which can propagate through the entire European system. In principle, the system should be able to overcome the outage of any single piece of infrastructure, e.g. an HVDC link. However, the loss of a key power transmission component, such as an HVDC link, makes the system considerably more vulnerable. An attack on two or more HVDC links or a situation where an attack on an HVDC link coincides with another outage could have severe effects throughout the system. The potential results include power outages and thus loss of power supply to vital infrastructure (hospitals, water treatment plants, etc.) and loss of productivity through business disruption.

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[71] Reuters (May 2023), Aluminium Is the West's Critical Minerals Blind Spot.
[72] AP News (June 2023), NATO Moves to Protect Undersea Pipelines, Cables as Concern Mounts over Russian Sabotage Threat.

In Table 7.19, the energy security indicator scores for the two value chains assessed are presented.

Table 7.19 Energy security indicator scores for energy transmission and distribution technologies

Value chain/ indicator	Geopolitical availability	Abundance	Circularity	Supply chain complexity	Supply chain location	Digital vulnerability	Physical vulnerability	Broader sustainability	Affordability	Skills
Hydrogen storage and transportation	1	1	1	2	1	1	1	1	1	1
High-voltage direct current transmission	1	2	2	1	1	2	2	2	1	2

In addition to the key criticalities related to the energy security of energy transmission and distribution technologies, the following energy security indicators pose risks for some or all of the value chains assessed within this technology category: supply chain complexity, broader sustainability and skills.

Hydrogen storage and transportation does have a moderate risk for supply chain complexity. This is particularly the case when hydrogen infrastructure needs to be constructed de novo, without the ability to repurpose former natural gas infrastructure. This is less of a concern with HVDC or the power grid in general, since the grid is ubiquitous throughout Europe.

HVDC transmission has additional moderate risks for broader sustainability and skills, which are all related to the construction of this infrastructure in primarily marine environments. The construction of HVDC links involves potential disturbance on large areas of seabed, with possible environmental consequences which need to be mitigated to decrease the broader sustainability risk. Working in marine environments requires specific skills and training. Given the shortages in technically skilled workforce, sufficient people with these additional skills could be difficult to find. Both issues are less relevant for hydrogen storage and transportation because most of this infrastructure is expected to be constructed on land.

7.4.19. Smart cities

General description and role in the energy system

Smart cities entail many different technologies, which are all somehow related to the energy system. For this project, we have assessed the value chain 'autonomous driving'.

Autonomous driving is defined as the capability of a vehicle to navigate and operate on its own without human intervention. There are various levels of automation, from basic assistance (TRL 9) to human drivers to fully driverless vehicles (TRL 3). Its role in the energy system is that it may reduce the energy consumption of vehicles. This is attributed to the potential of improving traffic flows and a reduction in excessive acceleration/braking, i.e. making vehicles drive as efficient as possible. Autonomous vehicles require many additional electronics, such as sensors, in comparison to non-autonomous vehicles. In addition, they are much more dependent on digital connection.

Energy security: key criticalities for the technology category

For smart cities (autonomous driving), the key criticalities identified for energy security are: **CRMs** (linked to complexity and location of advanced electronics sub-value chain), **digital vulnerability** and **skills**.

CRMs. Autonomous driving technology requires devices, such as sensors, light detection and ranging (usually shortened to LiDAR) and central processing units (usually shortened to CPUs). For these devices, copper aluminium and regular electronics are needed. In particular, the technology heavily depends on advanced electronics, which contain CRMs, such as palladium, cobalt, gallium, germanium, silicon and rare-earth materials. In addition, the electronics needed to make a vehicle perform autonomously are mainly manufactured in a limited number of countries outside the EU. The same goes for semiconductors needed for these electronics. Therefore, the indicators abundance (related to CRMs), supply chain complexity and supply chain location are very connected for this value chain and are all related to high energy security risks.

Digital vulnerability. As autonomous driving is a very digital-dependent technology, it is vulnerable to cyberattacks, which potentially have very serious safety-related consequences. Potential risks are availability attacks (rendering the vehicle's information technology (IT) system inaccessible), integrity or confidentiality attacks (compromising integrity and confidentiality of personal data) and authenticity attacks (potentially leading to theft of the vehicle).

Skills. Autonomous driving technology requires specialised knowledge on both the hardware and the software of the electronics involved. The automotive industry is already known to often face labour shortages across most segments, and autonomous driving would increase the demand for these specific skills, which are also in high demand in other sectors.

Validation workshop participants mentioned resilience to solar storms as a potential physical vulnerability for this technology.

Energy security: overview of findings from the value chain assessments

In Table 7.20, the energy security indicator scores for the value chain assessed are presented.

Table 7.20 Energy security indicator scores for smart cities

Value chain/ indicator	Geopolitical availability	Abundance	Circularity	Supply chain complexity	Supply chain location	Digital vulnerability	Physical vulnerability	Broader sustainability	Affordability	Skills
Autonomous driving	2	3	2	3	3	3	2	2	2	3

In addition to the key criticalities, some other potential energy security risks of autonomous driving are physical vulnerability, broader sustainability and affordability. The value chain is physically vulnerable as the technology relies on cameras and sensors. These can be negatively affected by certain weather conditions, such as rain. These effects are local, but they could have severe consequences. While autonomous driving might reduce costs of driving, its safety depends on, for instance, the quality or amount of sensors, which may increase the costs of autonomous vehicles. Finally, public acceptance of autonomous driving might be difficult, as ethical dilemmas are involved in the programming of the vehicles. These issues all influence the potential of successful implementation of autonomous driving and hence its contribution to decreasing energy demand.

7.4.20. Other energy storage

General description and role in the energy system

Energy storage is becoming increasingly important in future power grids due to the growing integration of renewable energy sources. The intermittent nature of renewable sources, such as solar and wind, creates challenges in matching energy supply with demand in real time. Energy storage technologies play a pivotal role in addressing these challenges by storing excess energy when it is available and releasing it when needed. This balancing needs to be done on different time scales – from seconds to seasons. To achieve this, different types of storage technologies exist. Battery technologies (Section 7.4.11) and storage of hydrogen (Section 7.4.18) are discussed separately. Pumped hydroelectric energy storage (pumped hydropower) is also increasingly used for balancing the power grid – see also Section 7.4.5. In this section, we describe two types of technologies relying on physical principles: CAES and flywheels. These two technologies have very different roles in the power system, as their time scales of action differ.

CAES can be used for electricity storage of several hours to a day, since this timeframe has a profitable business case in the current energy markets. In this process, electricity drives a compressor to compress air, which is then injected at high pressure into substantial underground areas, such as salt caverns, or potentially into depleted gas fields and aquifers. When electrical power is needed, the stored compressed air is heated and expanded through a turbine to drive a generator.

Flywheels can be used for short-term balancing of the power system, on a time scale of seconds to minutes. A flywheel is a large mass that stores energy in rotational energy. The flywheel is driven by an electric motor (during surplus of energy). The electric motor brings the wheel to high speed. The rotational energy in the flywheel can later be converted into electricity by slowing down the wheel with the electric motor, which can also work as a generator. Flywheels are a relatively straightforward technology. Due to their short time scales of action, the applications of flywheels in the EU energy system are mainly in short-term balancing of the power system.

Energy security: key criticalities for the technology category

For other forms of energy storage, the key criticalities identified for energy security are: **CRMs**, **broader sustainability** and **supply chain complexity**.

CRMs. The CRMs for CAES are aluminium and copper. These materials are used in the above-ground critical parts, such as the compressor, generator and motor. For flywheels, the CRMs are copper and silicon, although in relatively limited amounts as flywheels mainly consist of steel. Copper is used in the motor, and a fraction of silicon is used in the propulsion. Western production of aluminium has been decreasing in the past half decade due to increasing energy prices (aluminium smelting is energy intensive). China's production has in the meantime been increasing. Therefore, although the raw material itself is available from different sources, Europe is increasingly dependent on China for the processed product. Copper is on the European CRMs Act due to its strategic importance, and it has a medium abundance risk. Silicon has a low risk associated with abundance but is predominantly sourced from China.

Broader sustainability. The use of CAES has broader sustainability risks because pumping compressed air in and out of underground cavities can lead to ground subsidence and seismic activity. While the risks associated with underground activities related to natural gas storage are well understood, the risks of compressed air storage are relatively unknown and necessitate additional research. Furthermore, the extraction of salt and underground activities frequently receive limited support from the local community, primarily due to concerns regarding subsidence and seismic events.

Storage areas intended for CAES can serve the purpose of storing hydrogen as well. As it is uncertain whether there will be enough suitable storage space for hydrogen, it is most likely that storage space for CAES is in competition with underground storage of hydrogen. It is expected that hydrogen will have a more predominant role in the energy system and therefore might be prioritised over CAES.

Supply chain complexity. CAES can only be deployed in areas where suitable underground cavities are available. To determine whether this is the case, extensive research is necessary. This extensive exploration for underground storage space adds considerable complexity to the construction and use of CAES, and therefore to the total supply chain.

Energy security: overview of findings from the value chain assessments

In Table 7.21, the energy security indicator scores for the value chains assessed are presented.

Table 7.21 Energy security indicator scores for other forms of energy storage

Value chain/ indicator	Geopolitical availability	Abundance	Circularity	Supply chain complexity	Supply chain location	Digital vulnerability	Physical vulnerability	Broader sustainability	Affordability	Skills
Compressed air storage	1	2	1	2	2	1	2	3	2	2
Flywheels	1	1	1	1	1	1	1	1	2	1

In addition to the key criticalities related to the energy security of other forms of energy storage technologies, the following energy security indictors pose risks for some or all of the value chains assessed within this technology category: supply chain location, physical vulnerability, affordability and skills.

The supply chain location for CAES has a high risk due to the specific requirement for locations for underground storage. Salt caverns and depleted gas field are unevenly distributed throughout Europe. Moreover, not all salt caverns or gas fields are suitable for CAES. Therefore, every potential site needs to undergo an exploration phase. It is uncertain at the moment how many locations would qualify for CAES, and finding suitable locations can be a lengthy and complex process. Flywheels, however, can be easily placed at sites of choice throughout the system.

The physical vulnerability of CAES is scored as a moderate risk. CAES itself is not inherently physically vulnerable, but in the unlikely event of earthquakes or landslides, the underground storage facility is vulnerable. The geological stability should be monitored to maintain safe and reliable operation and prevent cracks or leaks.

Both CAES and flywheels are relatively expensive technologies compared to other types of storage, and therefore affordability is a moderate risk.

7.5. Comparative assessment

In Table 7.22, an overview of all indicator scores is presented. This table is a compilation of Tables 7.2 to 7.21, above. It does not include new information, but it enables an easy comparison of the energy security indicator scores of all the value chains assessed. Note that these are the scores associated with the separate value chain assessments, so before the longlisting was performed by combining the indicator scores with the scenarios.

Table 7.22 Overview of energy security indicator scores for all 48 value chains assessed.

Technology category	Value chain	Geopolitical availability	Abundance	Circularity	Supply chain complexity	Supply chain location	Digital vulnerability	Physical vulnerability	Broader sustainability	Affordability	Skills
Advanced biofuels	Algae-based	1	1	1	3	1	1	2	2	2	1
	Crop-based	1	1	1	2	1	1	1	1	1	1
	Waste-based	1	2	1	2	1	1	1	1	2	1
Bioenergy	Primary crop–based	1	2	1	2	1	1	1	2	1	1
	Waste-based	1	2	1	1	1	1	1	1	1	1
Concentrated solar energy	Concentrated solar energy plant	1	1	2	1	2	1	2	2	2	1
Geothermal energy	Geothermal plant	1	2	1	1	2	1	1	2	1	2
Hydropower	Hydropower plant	2	2	2	2	1	1	3	3	1	1
Ocean energy	Tidal	2	2	2	2	2	2	1	2	3	2
	Wave	2	2	2	3	2	2	1	2	3	2
	Thermal	1	1	2	3	3	2	3	2	3	2

	Salinity gradient	2	2	1	2	2	1	2	2	3	3
Photovoltaics	Silicon-based	3	2	2	2	3	2	1	2	1	2
	Copper, indium, gallium, selenide	2	2	2	2	3	2	1	2	1	3
	Cadmium telluride	1	2	2	2	3	2	1	2	1	3
	Perovskite	1	1	2	2	3	2	1	2	1	3
Wind energy	Onshore	2	2	1	1	1	2	2	2	1	2
	Offshore	2	2	1	2	1	2	3	2	2	2
	Airborne wind system	2	2	2	1	1	2	3	1	1	2
	Downwind rotor	2	2	1	1	1	2	3	2	2	2
Direct solar fuels	Photochemical/photobiological	1	2	1	3	2	1	1	2	3	3
	Thermochemical	1	1	1	2	2	1	1	2	3	3
Carbon capture, utilisation and storage	Capture and storage infrastructure	1	1	1	1	1	2	2	3	3	2
Batteries	Containing critical raw materials	3	2	2	2	3	2	1	3	1	2
	Not containing critical raw materials	1	1	2	2	1	2	1	1	2	2
	Redox-flow	2	1	1	2	3	2	1	1	2	2

	Molten salt	1	1	1	1	1	1	1	1	2	2
Hydrogen	Alkaline electrolysis	1	2	1	1	1	2	1	2	3	2
	Proton-exchange membrane electrolysis	2	3	1	2	2	2	1	2	3	2
	Solid oxide electrolysis	3	2	1	2	1	2	1	2	2	2
	Anion-exchange membrane electrolysis	1	2	1	2	1	1	1	2	2	2
Renewable fuels of non-biological origin	Synthetic kerosene	1	1	1	2	1	2	2	2	3	2
Heat pumps	Industrial	1	2	1	2	2	2	2	2	2	3
	Domestic	1	2	1	2	2	2	2	2	1	3
Smart energy grid technologies	Electric vehicles smart charging	1	1	2	1	1	3	1	1	1	2
	Advanced metering infrastructure	2	2	2	2	2	3	1	2	1	2
	Home energy management systems	2	2	2	2	2	3	1	2	1	2
Energy building and district technologies	Advanced control technologies	2	2	2	2	2	3	1	1	1	2
	Thermal energy storage	1	1	2	1	1	1	1	1	1	1
	Combined heat and power	1	2	1	1	1	2	1	1	1	1

Off-grid energy systems	Biogas tank	1	1	1	1	1	1	1	2	1	1
	Pellet stove	1	1	1	1	1	1	1	2	1	1
	Solar heat: thermal collector	1	2	2	1	1	1	1	1	2	1
Energy transmission and distribution technologies	Hydrogen storage and transportation	1	1	1	2	1	1	1	1	1	1
	High-voltage direct current transmission	1	2	2	1	1	2	2	2	1	2
Smart cities	Autonomous driving	2	3	2	3	3	3	2	2	2	3
Other electricity and heat storage	Compressed air storage	1	2	1	2	2	1	2	3	2	2
	Fly wheels	1	1	1	1	1	1	1	1	2	1

From this table, it follows that some of the value chains have relatively low total scores and therefore low energy security risks associated with them. This for instance applies to all off-grid energy systems, flywheels, geothermal energy and TES, hydrogen storage and transportation, CHP, molten salt batteries, bioenergy and advanced biofuels. Value chains that are associated with relatively high energy security risks are, among others, ‘smart’ technologies, such as autonomous driving and smart energy grid technologies; direct solar fuels; photovoltaics; ocean energy technologies; and hydrogen production.

Another way of comparing across technologies and value chains is by looking at the criticalities that were longlisted. These can be presented by means of a ‘heatmap’: it shows through how many scenarios a criticality was longlisted (see methodology in Annex A, Section 6). In Table 7.23 and 7.24, for each value chain and each energy security indicator, it is indicated whether it was longlisted as a criticality through 1, 2 or 3 scenarios (or 0, which means it was not longlisted as a criticality), for 2030 and 2050, respectively.

Table 7.23 Heatmap of longlisted energy security criticalities, showing the number of scenarios through which they were longlisted, for 2030

Technology category	Value chain	Geopolitical availability	Abundance	Circularity	Digital vulnerability	Physical vulnerability	Supply chain complexity	Supply chain location	Broader sustainability	Affordability	Skills
Wind energy	Onshore	0	2	0	1	1	0	0	1	0	0
	Offshore	0	2	0	1	3	1	0	1	0	0
	Airborne wind system	0	2	0	1	3	0	0	0	0	0
	Downwind rotor	0	2	0	1	3	0	0	1	0	0
Advanced biofuels	Algae-based	0	0	0	0	1	3	0	1	0	0
	Crop-based	0	0	0	0	0	1	0	0	0	0
	Waste-based	0	2	0	0	0	1	0	0	0	0
Photovoltaics	Silicon-based	3	2	0	1	0	1	3	1	0	0
	Copper, indium, gallium, selenide	0	2	0	1	0	1	3	1	0	3
	Cadmium telluride	0	2	0	1	0	1	3	1	0	3
	Perovskite	0	0	0	1	0	1	3	1	0	3

Ocean energy	Tidal	0	2	0	1	0	1	1	1	3	0
	Wave	0	2	0	1	0	3	1	1	3	0
	Thermal	0	0	0	1	3	3	3	1	3	0
	Salinity gradient	0	2	0	0	1	1	1	1	3	3
Geothermal energy	Geothermal plant	0	2	0	0	0	0	1	1	0	0
Hydropower	Hydropower plant	0	2	0	0	3	1	0	3	0	0
Hydrogen	Alkaline electrolysis	0	2	0	1	0	0	0	1	3	0
	Proton-exchange membrane electrolysis	0	3	0	1	0	1	1	1	3	0
	Solid oxide electrolysis	3	2	0	1	0	1	0	1	0	0
	Anion-exchange membrane electrolysis	0	2	0	0	0	1	0	1	0	0
Batteries	Containing critical raw materials	3	2	0	1	0	1	3	3	0	0

	Not containing critical raw materials	0	0	0	1	0	1	0	0	0	0
	Redox-flow	0	0	0	1	0	1	3	0	0	0
	Molten salt	0	0	0	0	0	0	0	0	0	0
Other electricity and heat storage	Compressed air storage	0	2	0	0	1	1	1	3	0	0
	Fly wheels	0	0	0	0	0	0	0	0	0	0
Bioenergy	Primary crop–based	0	2	0	0	0	1	0	1	0	0
	Waste-based	0	2	0	0	0	0	0	0	0	0
Concentrated solar energy	Concentrated solar energy plant	0	0	0	0	1	0	1	1	0	0
Renewable fuels of non-biological origin	Synthetic kerosene	0	0	0	1	1	1	0	1	3	0
Carbon capture, utilisation and storage	Capture and storage infrastructure	0	0	0	1	1	0	0	3	3	0
Heat pumps	Industrial	0	2	0	1	1	1	1	1	0	3

	Domestic	0	2	0	1	1	1	1	1	0	3
Smart energy grid technologies	Electric vehicles smart charging	0	0	0	3	0	0	0	0	0	0
	Advanced metering infrastructure	0	2	0	3	0	1	1	1	0	0
	Home energy management systems	0	2	0	3	0	1	1	1	0	0
Energy building and district technologies	Advanced control technologies	0	2	0	3	0	1	1	0	0	0
	Thermal energy storage	0	0	0	0	0	0	0	0	0	0
	Combined heat and power	0	2	0	1	0	0	0	0	0	0
Off-grid energy systems	Biogas tank	0	0	0	0	0	0	0	1	0	0
	Pellet stove	0	0	0	0	0	0	0	1	0	0
	Solar heat: thermal collector	0	2	0	0	0	0	0	0	0	0
Energy transmission and	Hydrogen storage and transportation	0	0	0	0	0	1	0	0	0	0

distribution technologies	High-voltage direct current transmission	0	2	0	1	1	0	0	1	0	0
Smart Cities	Autonomous driving	0	3	0	3	1	3	3	1	0	3
Direct solar fuels	Photochemical/ photobiological	0	2	0	0	0	3	1	0	3	3
	Thermochemical	0	0	0	0	0	1	1	1	3	3

Table 7.24 Heatmap of longlisted energy security criticalities, showing the number of scenarios through which they were longlisted, for 2050

Technology category	Value chain	Geopolitical availability	Abundance	Circularity	Digital vulnerability	Physical vulnerability	Supply chain complexity	Supply chain location	Broader sustainability	Affordability	Skills
Wind energy	Onshore	1	1	0	2	1	0	0	0	0	1
	Offshore	1	1	0	2	3	0	0	0	0	1
	Airborne wind system	1	1	0	2	3	0	0	0	0	1
	Downwind rotor	1	1	0	2	3	0	0	0	0	1

Advanced biofuels	Algae-based	0	0	0	0	1	3	0	0	0	0
	Crop-based	0	0	0	0	0	0	0	0	0	0
	Waste-based	0	1	0	0	0	0	0	0	0	0
Photovoltaics	Silicon-based	3	1	0	2	0	0	3	0	0	1
	Copper, indium, gallium, selenide	1	1	0	2	0	0	3	0	0	3
	Cadmium telluride	0	1	0	2	0	0	3	0	0	3
	Perovskite	0	0	0	2	0	0	3	0	0	3
Ocean energy	Tidal	1	1	0	2	0	0	0	0	3	1
	Wave	1	1	0	2	0	3	0	0	3	1
	Thermal	0	0	0	2	3	3	3	0	3	1
	Salinity gradient	1	1	0	0	1	0	0	0	3	3
Geothermal energy	Geothermal plant	0	1	0	0	0	0	0	0	0	1
Hydropower	Hydropower plant	1	1	0	0	3	0	0	3	0	0
Hydrogen	Alkaline electrolysis	0	1	0	2	0	0	0	0	3	1

	Proton-exchange membrane electrolysis	1	3	0	2	0	0	0	0	3	1
	Solid oxide electrolysis	3	1	0	2	0	0	0	0	0	1
	Anion-exchange membrane electrolysis	0	1	0	0	0	0	0	0	0	1
Batteries	Containing critical raw materials	3	1	0	2	0	0	3	3	0	1
	Not containing critical raw materials	0	0	0	2	0	0	0	0	0	1
	Redox-flow	1	0	0	2	0	0	3	0	0	1
	Molten salt	0	0	0	0	0	0	0	0	0	1
Other electricity and heat storage	Compressed air storage	0	1	0	0	1	0	0	3	0	1
	Fly wheels	0	0	0	0	0	0	0	0	0	0
Bioenergy	Primary crop–based	0	1	0	0	0	0	0	0	0	0
	Waste-based	0	1	0	0	0	0	0	0	0	0

Concentrated solar energy	Concentrated solar energy plant	0	0	0	0	1	0	0	0	0	0
Renewable fuels of non-biological origin	Synthetic kerosene	0	0	0	2	1	0	0	0	3	0
Carbon capture, utilisation and storage	Capture and storage infrastructure	0	0	0	2	1	0	0	3	3	1
Heat pumps	Industrial	0	1	0	2	1	0	0	0	0	3
	Domestic	0	1	0	2	1	0	0	0	0	3
Smart energy grid technologies	Electric vehicles smart charging	0	0	0	3	0	0	0	0	0	1
	Advanced metering infrastructure	1	1	0	3	0	0	0	0	0	1
	Home energy management systems	1	1	0	3	0	0	0	0	0	1
Energy building and	Advanced control technologies	1	1	0	3	0	0	0	0	0	1

district technologies	Thermal energy storage	0	0	0	0	0	0	0	0	0	0
	Combined heat and power	0	1	0	2	0	0	0	0	0	0
Off-grid energy systems	Biogas tank	0	0	0	0	0	0	0	0	0	0
	Pellet stove	0	0	0	0	0	0	0	0	0	0
	Solar heat: thermal collector	0	1	0	0	0	0	0	0	0	0
Energy transmission and distribution technologies	Hydrogen storage and transportation	0	0	0	0	0	0	0	0	0	0
	High-voltage direct current transmission	0	1	0	2	1	0	0	0	0	1
Smart Cities	Autonomous driving	1	3	0	3	1	3	3	1	0	3
Direct solar fuels	Photochemical/photobiological	0	1	0	0	0	3	1	0	3	3
	Thermochemical	0	0	0	0	0	0	1	1	3	3

STRATEGIC ANALYSIS OF R&I CHALLENGES INTERVENTIONS TO STRENGTHEN EU ENERGY SECURITY OF CLEAN ENERGY TECHNOLOGY VALUE CHAINS

This chapter comprises the findings from Task 3 of the study, analysing R&I challenges to develop an R&I action plan. The chapter also includes input from Task 4, the validation workshop, although the findings of that task are summarised in Annex E and details of how feedback was integrated into the study are provided in Annex A, Section 8.6.

Chapter overview

To develop an R&I action plan, the shortlisted criticalities, identified in the value chain analysis and presented in Section 7, were evaluated to identify the EU's readiness to address the corresponding R&I challenge for each energy security criticality.

The SWOT analysis consists of an evidence review of existing and past EU and international R&I programmes and R&I ecosystem characteristics to inform the assessment of strengths, weaknesses, opportunities and threats for each energy security criticality and corresponding R&I challenge.

The assessment of each criticality considered the corresponding R&I challenge that resulted for a criticality. For example, the criticality for geothermal energy was *availability and abundance of CRM*, which resulted in the question 'How can the reliance and use of CRMs be reduced in geothermal energy?' To determine the SWOT rating, the analysis considers whether existing R&I programmes are addressing the energy security criticality, to what extent the EU is globally competitive for R&I in that technology area, what are the opportunities for international collaboration, whether solutions to the criticality are already in development and where, and what are the potential threats.

The SWOT assessments of each criticality were used in prioritising potential R&I actions and determining if additional or new action was necessary to address the criticality.

- **Strength–Threat:** There is evidence of a strong EU R&I ecosystem and ongoing EU R&I activities in the technology area, but activities outside the EU pose a threat to the EU's leadership in the technology (e.g. increased competitiveness and investment in non-EU companies). Alternative threats include no known solution to the criticality (e.g. no alternative materials to substitute CRM).
- **Strength–Opportunity:** There is evidence of a strong EU R&I ecosystem and ongoing EU R&I activities in the technology area, and there is scope to collaborate with countries with existing research into the criticality (including Associated Countries to Horizon Europe) or across shared challenges.
- **Weakness–Opportunity:** The EU R&I ecosystem is less globally competitive, but there is scope to collaborate with countries with existing research into the criticality (including Associated Countries to Horizon Europe) or across shared challenges.
- **Weakness–Threat:** The EU R&I ecosystem is less globally competitive, and activities outside the EU pose a threat to the EU's leadership in the technology.

The prioritisation process is described further in Chapter 9. Final SWOT categorisations for these criticalities are listed below.

Weakness–Threat	Strength–Threat
Geothermal energy – availability and abundance of CRM	**Bioenergy** – abundance of feedstock

Direct solar fuels – availability and abundance of CRM **RFNBOs** – availability and abundance of CRM **Smart grids** – availability and abundance of CRM **Building/district heating technologies** – availability and abundance of CRM **Off-grid systems** – availability and abundance of CRM **Transmission/distribution technologies** – availability and abundance of CRM **Smart cities** – availability and abundance of CRM **Other storage (CAES)** – availability and abundance of CRM **PV** – supply chain location **Batteries** – supply chain location **Hydrogen** – supply chain resilience **Smart grids** – digital vulnerability **Other storage (CAES)** – sustainability and environmental impact	**Heat pumps** – availability and abundance of CRM **CSE** – affordability **CCUS** – affordability **PV** – digital vulnerability **Building/district heating technologies** – digital vulnerability **Transmission/distribution technologies** – digital vulnerability **Smart cities** – digital vulnerability **Hydrogen** – broader sustainability and environment impact **Direct solar fuels** – skills **RFNBOs** – skills
Strength–Opportunity	**Weakness–Opportunity**
Advanced biofuels – abundance of feedstock **PV** – abundance and availability of CRM **Wind energy** – availability and abundance of CRM **Batteries** – availability of CRM **Hydrogen** – availability and abundance of CRM **CCUS** – broader sustainability and environment impact **CSE** – sustainability and environmental impacts **Off-grid systems** – sustainability and environmental impacts **Ocean energy** – sustainability and environmental impacts **Hydropower** – environmental impacts **Hydropower** – physical vulnerabilities and impacts of climate change **Wind energy** – physical vulnerability to climate change	**Hydropower** – abundance and availability of CRM **Ocean energy** – abundance and availability of CRM **Ocean energy** – public opinion **PV** – skills

Ocean energy – affordability

Hydrogen – affordability

Direct solar fuels – affordability

RFNBOs – affordability

Direct solar fuels – supply chain complexity

RFNBOs – supply chain complexity

Hydrogen – vulnerability to wider energy system dependence

Heat pumps – vulnerability to wider energy system dependence

CCUS – public opinion

R&I interventions to address each challenge are also proposed, based on the study team's expertise and the validation workshop drawing on the expertise of energy technology stakeholders.

An additional section is included on the energy system. System-level R&I interventions (which address the interconnectedness of different technologies, as opposed to an intervention which impacts multiple technologies that are independent of each other, e.g. CRM mining) may be the solution to some energy technology value chain R&I challenges. These have been highlighted where relevant. Due to the scope of the study, the research team did not carry out extensive analysis of energy system–level R&I and potential intervention.

A note on the chapter structure

The chapter is broken down by technology, and each section comprises three parts, described below:

In each technology, criticalities are first presented (outlined in boxes), with a short description of the challenge they pose to the technology value chain. The corresponding R&I action – which was used to carry out the SWOT analysis – is noted, as well as the final SWOT rating for the criticality.

A summary of the SWOT analysis follows (schematic below), describing key evidence from the analysis. This is done for clarity, so the reader can get a rapid overview of the assessment of the evidence. R&I interventions are then suggested following this assessment.

The analysis itself is presented as a table at the end of each technology section, with citations, for reference.

Part 1: Criticality		
Description	Corresoponding R&I challenge	SWOT assessment

Part 2: How SWOT was assigned	
Summary of SWOT analysis	Proposed R&I intervention

Part 3: SWOT analysis data	
Analysis (presented as a table)	Citations

Next steps

Following the shortlisting of criticalities, and the initial proposal of corresponding R&I challenges and interventions (actions) to address these, the findings were presented to experts in the validation workshop. Inputs from the workshop highlighted missing criticalities (e.g. wind energy – digital vulnerability), validated the suggested R&I interventions and proposed alternative/modified interventions to address the criticalities (participant inputs are summarised in Annex E). These inputs are denoted where relevant throughout this section.

The final longlist of R&I actions was then taken forward into a shortlisting and prioritisation stage, described in Section 9.

8. Results from SWOT analysis

This section presents an overview of the evidence and analysis for the development of R&I interventions for each clean energy technology value chain in scope. The evidence includes a review of existing and past EU and international R&I programmes and R&I ecosystem characteristics to inform the assessment of SWOT for each energy security criticality and corresponding R&I challenge. A short summary of the SWOT analysis precedes the SWOT tables; all references are included in the tables.

The analysis considers whether existing R&I programmes are addressing the energy security criticality, to what extent the EU is globally competitive for R&I in that technology area, opportunities for international collaboration (shared challenge or public R&I investment in non-EU countries), whether solutions to the criticality are already in development and where, and potential threats (private sector R&I investment in non-EU countries). This analysis informed the SWOT category setting out the EU's position to address the corresponding R&I challenge for each energy security criticality. The methodology for the SWOT assessment carried out for each criticality is detailed in Annex A (Section 7.2.2.) and here, in summary:

- **Strength–Threat:** There is evidence of a strong EU R&I ecosystem and ongoing EU R&I activities in the technology area, but activities outside the EU pose a threat to the EU's leadership in the technology (e.g. increased competitiveness and investment in non-EU companies). Alternative threats include no known solution to the criticality (e.g. no alternative materials to substitute CRM).

- **Strength–Opportunity:** There is evidence of a strong EU R&I ecosystem and ongoing EU R&I activities in the technology area, and there is scope to collaborate with countries with existing research into the criticality (including Associated Countries to Horizon Europe) or across shared challenges.

- **Weakness–Opportunity:** The EU R&I ecosystem is less globally competitive, but there is scope to collaborate with countries with existing research into the criticality (including Associated Countries to Horizon Europe) or across shared challenges.

- **Weakness–Threat:** The EU R&I ecosystem is less globally competitive, and activities outside the EU pose a threat to the EU's leadership in the technology.

R&I interventions to address each challenge are also proposed, based on the study team's expertise and the validation workshop drawing on the expertise of energy technology stakeholders.

It is worth noting that the extent and detail of this analysis varied depending on the level of publicly available information for each technology area. We have endeavoured to conduct a comprehensive review of all publicly available material, but the extent of this availability differed for different technology areas. We have, where possible, mitigated any gaps in the evidence through expert consultation, particularly through the validation workshop. However, it remains the case that, of necessity, we have more detailed information for some technologies as a result of our efforts to retain and use details and nuance in our analysis wherever possible.

The study scope looked at individual technologies and their criticalities, to identify particular interventions to address these. However, feedback from the workshop and our research highlighted the interconnectedness of the energy system (e.g. potential competition arising from feedstock use among bioenergy, advanced biofuels, RFNBOs, and heating technologies and CRM use between technologies), how the energy grid needs to change to accommodate technologies, and how system-level R&I interventions may be the solution to some energy technology value chain R&I challenges. Therefore, an additional action is included on the energy system.

8.1. Advanced biofuels

8.1.1. Key criticality: abundance of feedstock, with links to the complexity of the supply chain and broader environmental sustainability considerations

Description of criticality: The availability of feedstock presents the main energy security risk to advanced biofuels value chains. Abundance, supply chain complexity and broader sustainability are all factors, in particular potential competition for land use or waste use and the increased sustainability and complexity risk that is introduced if feedstock is imported from outside the EU.

- ➔ **R&I challenge**: How can the security and availability of sustainable feedstocks be improved for advanced biofuels?

EU R&I SWOT assessment: Strength–Opportunity

Summary of SWOT assessment. The EU has significant strengths in R&I, performing well in terms of high-value patents and inventions and multiple investment, including through Cluster 5 of the Horizon Europe work programme. The Circular Bio-based Europe Joint Undertaking (CBE JU) supports research on biomass, and the R&I challenge is specifically in scope. The ETIP and SET Plan Implementation Working Group 8 have highlighted opportunities and challenges for broadening biomass feedstock from non-food-related sources, as well as the need for cost-efficient, sustainable biomass and conversion techniques. The main weaknesses for the EU are low private sector investment and policy uncertainty (in terms of future EU and global policy developments and regulation).

With regards to external threats, other countries are investing in developing their domestic supply chains and these attract more private investment than the EU. However, technological solutions, such as prediction algorithms and existing collaborations, present convincing *opportunities* to resolve this criticality (e.g. shared challenge that can be tackled collaboratively with non-EU countries).

Proposed R&I intervention. The EU (and national programmes – highlighted in the SWOT analysis where relevant) is already supporting R&I that specifically addresses this challenge.[73] Complementary areas for R&I identified during the validation workshop were focused on sustainability initiatives, co-benefits of feedstock solutions for other priorities, such as supporting biodiversity and carbon sequestration, efficiency improvements of production processes and initiatives to develop circular value chains. Specific suggestions from the validation workshop include: R&I on the types of crops that can be grown in specific conditions (e.g. marginal, abandoned land areas) and potential co-benefits, such as improvement of soil conditions; establishment of credible sustainable governance systems to manage local risks; optimising supply chains and how to connect local dispersed resources with production facilities; feedstock flexibility to broaden the feedstock base; planning for circular waste management and future biofuel, biochemical and biomaterial production; use of complex feedstock such as from food factories; development of technology for biomass pre-treatment for purification and drying supporting biofuels, biomaterials and biochemical supply chains; growth of biomass crops outside current fertile cropland; efficiency improvements with development of biorefineries and improvement of conversion efficiencies to reduce costs and de-risk value chains; and research on the synergies of biomass production, biodiversity and climate change adaptation.

The potential impacts of climate change were highlighted in the validation workshop as a key future consideration. Uncertainty in the future policy landscape was mentioned as a significant risk to the criticality, which would impact R&I.

In terms of impact and feasibility, policy and regulatory action to increase certainty and resolve risks around the abundance of feedstock was identified by participants as high impact and high feasibility. Policy intervention was viewed as crucial, with R&I intervention playing an important complementary role.

Proposed R&I intervention. Based on the above analysis, the following options for intervention are proposed:

- **Non-R&I action**: Policy and regulatory action should be taken in order to provide certainty on feedstocks for advanced biofuels.

- **R&I action 1**: A Horizon Europe research programme focused on understanding crop growth conditions, and potential biodiversity and carbon sequestration co-benefits, would provide further assessment and evidence, complementing existing work, to inform policy development and coordination across different EU policy priorities. This R&I intervention would support evidence-based decision making and develop a deep understanding of potential trade-offs or benefits to consider for synergy across EU energy security, decarbonisation and biodiversity policy.

- **R&I action 2**: A collaborative industry R&I programme or local funds could create incentives to increase business investment in the EU or EU regions, including through support for demonstration of technologies, cost reductions for biofuels processes, and development of an EU circular value chain and hubs for feedstocks and advanced biofuels.

Table 8.1 SWOT – evidence overview for EU advanced biofuels R&I

Strengths (internal – EU)	**Opportunities** (external)
A strong R&I ecosystem: The EU had a 65% share of high-value patents in 2017-2019 and a leading position for publications. EU countries are part of the top 10 countries for high-value inventions.[74] In 2022, the EU was top for inventions granted and scientific publications.[75]	Potential collaborators: The United States, ,-etc Japan, China, Korea and the UK are part of the top 10 countries for high-value inventions in the period 2009-2019.[90] Collaborations on publications were strong between the EU, the United States, and rest-of-the-world countries excluding including

The EU is also a world leader in this area, with 19 of 24 operational commercial advanced biofuels plants (of which 12 are in Sweden and Finland).[76]

Public/EU investment: The Horizon Europe 2023-2024 Work Programme includes up to EUR 57 million for targeted R&I on advanced biofuels R&I (and an additional EUR 58.5 million through Zero-Emission Waterborne Transport (ZEWT) Partnership calls).[77] The Horizon Europe 2021-2022 work programme included up to EUR 64 million on advanced biofuels R&I.[78] Germany is providing EUR 1.9 billion for the further development and production of advanced biofuels until 2026.

Horizon 2020 projects, such as BIKE, S2BIOM and MAGIC, have investigated suitability of non-food crops for biofuels and are described as needing further assessment.[79]

Advanced biofuels studied in Horizon 2020 projects showed the potential for biofuels to contribute to the EU's soil strategy and biodiversity strategy, with demonstration of high sustainability levels.[80] Biofuels also have the potential to contribute to the use of sustainable fertilisers as part of innovative crop rotation systems and carbon sequestration initiatives.[81]

Existing EU networks include the Circular Bio-based Industries Joint Undertaking (BBI JU) from 2014 to 2020 and now Circular Bio-based Europe Joint Undertaking (CBE JU).[82] The BBI JU had a funding call in 2020 for enabling technologies (such as 'big data', geographic information systems, sensors, AI, the internet of things, and prediction algorithms) to improve availability and sustainability for the bio-based industry. The TRL at the end of the project will be 4-5.[83] CBE JU has a funding call in 2023 for aquatic biomass waste and residues. One of the objectives is to address the bottlenecks regarding the availability, sourcing, logistics and associated infrastructure in biomass feedstock supply systems.[84]

The bioenergy ETIP lists several EU-funded projects on availability assessment and biomass mapping.[85] An ETIP working group has published a report on opportunities and challenges for broadening biomass feedstock from non-food related sources, recommending R&I actions (such as big data and automation for optimal harvest and storage, and calculation of yields).[86] The SET Plan Implementation Working Group 8 highlights the technical, economic and infrastructure needs of advanced biofuels to China, India, South Korea, the UK, Japan and Switzerland.[91]

Horizon Europe–associated countries: Norway granted funding in 2016 to establish a new research centre for sustainable biofuels (Bio4Fuels), focused on the conversion of biomass to biofuels, not the availability of biomass itself.[92] The UK has a GBP 36 million (ca. EUR 42 million) Biomass Feedstocks Innovation Programme to increase domestic production of biomass, running from 2021 to 2025.[93]

Existing international collaborations include the Integrated Biorefineries Mission (led by India and the Netherlands, and also involving Brazil, Canada and the UK)[94] and the Zero-Emission Shipping Mission (led by Denmark, Norway, South Africa and two industry partners).[95] Japan is collaborating with the EU on breakthrough research on advanced biofuels. In 2021, it provided EUR 1.2 million to a total EUR 10.7 million joint investment for three projects.[96]

Potential R&I solutions to this challenge in development include the use of emerging technologies, such as AI and big data, to monitor and predict feedstock availability, agriculture and sustainability.

Technologies for biofuels production are fully mature and commercial (e.g. gasification, fermentation, fast pyrolysis). Support for full-scale and demonstration projects aimed at continuous production of advanced biofuels integrated into a circular system would be beneficial to develop the value chain.[97]

reduce feedstock and conversion technique costs and the opportunity to use biomethane as a feedstock.[87] Imperial College Consultants conducted a study at the request of CONCAWE on future sustainable biomass availability in the EU. The report finds significant potential for advanced biofuel production with sustainable biomass feedstocks in the EU; however, this is dependent on developing and deploying biomass conversion technologies.[88] A number of sustainability certification schemes have been developed and recognised by the European Commission to ensure sustainability of biofuels.[89]	
Weaknesses (internal – EU) The EU share of venture capital (VC) investments only accounted for 6% of global deals in 2016-2021.[98] The EU's share of early-stage investment decreased between 2016-2021 compared to 2010-2015. Policy uncertainty is identified as a potential risk in the EU, including with regards to balancing biomass production and biodiversity.[99] The RED II list is very restrictive and still under development, creating uncertainty for the biofuels industry. The RED III made some progress on categorising feedstocks as having a high indirect land use change (ILUC) – land clearance to allow for the expansion of overall agricultural area to meet additional demand for land for energy. However, the standard is subject to change, and there is still uncertainty around whether and how to phase out certain crops (e.g. soy) that can cause deforestation.[100] Sustainable and suitable feedstock is not clearly defined in current policy and legislative documents; this includes the lack of definition for degraded land, non-food crops suitable for biofuels.[101] Feedstock categories are also further fragmented at the Member State level with national registers also in need of harmonisation to support transnational EU trade.[102] The *Horizon Europe Strategic Plan 2025-2027 Analysis* report identified a potential gap: 'the use of R&I to improve and upscale technologies using advanced biofuels and synthetic renewable fuels for made-in-Europe industrial manufacturing to avoid creating a new dependency on outside supply'.[103]	**Threats** (external) The United States and Canada received the largest share of early-stage investment since 2010, and the EU's share of investment has decreased. VC biofuels investment was on average EUR 250 million per year. [104] Canada, China and the United States have announced significant investment in research and deployment of biofuels, combined with targets for biofuel production.[105] The US Inflation Reduction Act allocates USD 500 million (ca. EUR 462 milion) for grants to cover up to 75% of the cost of biofuel infrastructure projects in the United States.[106] Biomass resources are abundant in many exporting countries, such as the United States, Brazil, Canada and China, and the International Energy Agency (IEA) highlights potential for 20 billion litres of biodiesel to come from India, while Brazil could account for 40% of all biofuel exports in 2028.[107]

73 Specific examples are outlined in SWOT Table 15.1.

74 European Commission (2022), Clean Energy Technology Observatory, Advanced Biofuels in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg.

75 European Commission (2022), *Clean Energy Technology Observatory, Advanced Biofuels in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets*, Publications Office of the European Union, Luxembourg.

76 European Commission (November 2022), Report from the Commission to the European Parliament and the Council, Progress on Competitiveness of Clean Energy Technologies, COM/2022/643.

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8.2. Bioenergy

8.2.1. Key criticality: abundance of feedstock, linked to environmental sustainability considerations

Description of criticality: The availability of biomass feedstock presents the main energy security risk to bioenergy value chains. The availability of biomass feedstock is limited by competition for land use and availability of sustainably produced biomass, and there are strict EU criteria in place.

➔ **R&I challenge**: How can the security and availability of sustainable biomass be improved for bioenergy?

EU R&I SWOT assessment: Strength–Threat

Summary of SWOT assessment. The EU has significant strengths in R&I, performing well in terms of high-value patents and inventions and multiple investments, including through Horizon Europe Cluster 5, while ETIP Bioenergy and ETIP Renewable Heating and Cooling (RHC) include this topic in their strategic R&I agendas. Externally, technological solutions, such as prediction algorithms and existing collaborations, present opportunities to resolve this criticality. However, global investment has recently fallen, and the EU has been overtaken by China in number of publications. Compared to that of advanced biofuels, the global context for bioenergy presents more threats to the EU than opportunities.

Proposed R&I intervention. The EU is already supporting R&I specifically addressing this challenge. Additional areas for R&I identified during the validation workshop are sustainability initiatives; co-benefits of feedstock solutions for other priorities, such as supporting biodiversity and carbon sequestration; efficiency improvements of production processes; and initiatives to develop circular value chains. Specific suggestions from the validation workshop include: R&I on the types of crops that can be grown in specific conditions (e.g. marginal, abandoned land areas) and potential co-benefits, such as improvement of soil conditions; establishment of credible sustainable governance systems to manage local risks; optimising supply chains and how to connect local, dispersed resources with production facilities; feedstock flexibility to broaden the feedstock base; increasing understanding of policymakers, NGOs and the public of forest management and market-based cascading use of wood with bioenergy as a potential pathway for the valorisation of low-value by-products and wastes that cannot be used otherwise; growing biomass crops outside of current fertile cropland; and research on the synergies of biomass production, biodiversity and climate change adaptation.

Another suggestion from the validation workshop was to carry out a research programme on replacing old and inefficient bioenergy devices with more efficient ones to free up biomass resources for other sectors. However, due to limited further information found on this suggestion, it was not included in the proposed list for R&I actions.

The potential impacts of climate change, as well as potential trade-offs needed in biomass availability, were highlighted in the validation workshop as a key future consideration.

In terms of impact and feasibility, policy and regulatory action to increase certainty and resolve risks around the abundance of feedstock was identified by participants as high impact and high feasibility. Policy intervention was viewed as crucial, with R&I intervention playing an important complementary role.

- **Non-R&I action 1**: Policy and regulatory action should be taken to provide certainty on feedstocks for bioenergy, including consideration of resource efficiency, in alignment with RED III.

- **R&I action 1**: Research and public engagement should be carried out to support knowledge sharing and public acceptance around opportunities and co-benefits for biomass production and the bioeconomy, to make better use of existing or unused resources, forests, land and crops.

- **R&I action 2**: A research programme should be set up to develop pathways for the sustainable exploitation of unused biomass volumes and potential biodiversity, forest management and carbon storage co-benefits.

Table 8.2 SWOT – evidence overview for EU bioenergy R&I

Strengths (internal – EU)	**Opportunities** (external)
The EU is a global leader in high-value inventions of bioenergy technology.[108] Existing networks are contributing to connectivity across the R&I ecosystem. The Bioenergy Partnership is an interregional partnership between regions in Finland, Spain, Estonia and Romania.[109] ETIP Bioenergy convenes more than 600 stakeholders to guide R&I and deployment activities and policy, and the ETIP RHC includes the biomass technology panel overseeing bioenergy in heating and cooling technologies[110] The Horizon Europe 2023-2024 Work Programme includes EUR 92 million for bioenergy projects.[111] RED III highlights the need to consider cascading use of biomass in bioenergy policies, to support resource efficiency.[112] The funding calls by the JU are targeted towards bio-based industries and relevant to the criticality. BBI JU had a funding call in 2020 for enabling technologies (such as big data, geographic information systems, sensors, AI, the internet of things, and prediction algorithms) to improve availability and sustainability for the bio-based industry. The TRL at the end of the project will be 4-5.[113] The CBE JU has a funding call in 2023 for aquatic biomass waste and residues, with an objective to address the bottlenecks regarding the availability, sourcing, logistics and associated infrastructure in biomass feedstock supply systems.[114] The EU is a strong competitor for early-stage VC investments, with 29.5% of global investment in 2017-2022 and with the proportion of early-stage investment increasing relative to late stage.[115]	Horizon Europe–associated countries: Through the Engineering and Physical Sciences Research Council (EPSRC) and Biotechnology and Biological Sciences Research Council (BBSRC), the UK funded the Supergen Bioenergy Hub, which is devoted to research on bioenergy.[118] Existing collaborations include the Global Bioenergy Partnership (GBEP), with the United States, the UK, and Canada[119]; the IEA Bioenergy Technology Partnership[120]; and the Clean Energy Ministerial (CEM) Biofuture Platform (partners include the IEA Bioenergy Technology Collaboration Programme (TCP) and GBEP).[121] Potential R&I solutions to this challenge in development include the use of emerging technologies, such as AI and big data, to monitor and predict feedstock availability, agriculture and sustainability. A targeted intervention to replace residential use of woody biomass with more efficient fuels would free up biomass resources for other sectors.[122] Numerous biomass-to-energy pathways with high technology readiness levels are available and deployed. Others, at lower technology readiness levels, are not yet extensively tested with a range of feedstock.[123] The availability of marginal and degraded land can reduce the supply risk of sustainable biomass and competition for land and other uses, with potential co-benefits, such as restoration of land and carbon storage.[124] Sustainability certification schemes, developed for biofuels and bioenergy, can

Significant volumes of biomass resources in Europe remain unexploited.[116] Over the course of Horizon 2020, EUR 769 million was awarded to bioenergy projects.[117]	ensure compliance with sustainability criteria. For example, negative impacts of forestry operations are attributed to the use of biomass (ex-forestry residues) for bioenergy, but in most cases these impacts should be attributed to the use of biomass for other uses.[125]
Weaknesses (internal – EU) The Horizon Europe *Strategic Plan 2025-2027 Analysis* report identifies cost reductions as an area for further R&I for bioenergy technologies.[126] The EU's share of global VC investment was 20% in 2017-2022.[127] Late-stage investment decreased in the EU in 2022. There is policy uncertainty around balancing biomass production and biodiversity and food security.[128] For the first time, RED II imposed EU-wide sustainability criteria, but discussions for RED III had already started before many Member States had fully implemented the requirements of RED II. These different timescales between implementation and policy are not allowing for full evaluation of criteria before changes to RED were made.[129] The EU's share of global VC investment decreased in 2016-2021 (from 9% to 6%).[130]	**Threats** (external) China outranked the EU in terms of publications relating to biomass feedstock for heat and power.[131] Globally, VC investment in bioenergy had significantly decreased since 2013 but jumped to EUR 752.1 million in 2022. The United States receive almost half of global VC investment between 2017-2022. [132] Some countries, such as Japan, are allocating subsidies to infrastructure upgrades, providing support to local industry.[133]

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[124] Pre-workshop exercise submission.
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[131] European Commission (2023), Clean Energy Technology Observatory, Bioenergy in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg.
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8.3. Concentrated solar energy

In this study's scope, CSE comprises concentrated solar power (CSP) and SHIP.

8.3.1. Key criticality 1: sustainability and environmental impacts of concentrated solar energy

Description of criticality: Relatively high water and land use are required for CSE, introducing the risk of competition for other uses. The heat transfer fluid may also pose risks to the environment due to its toxicity, and ecosystem risks related to the concentrated beam of light are uncertain in a context of increasing environmental protections.

➔ **R&I challenge**: How can environmental requirements and impacts of CSE be reduced or mitigated?

EU R&I SWOT assessment: Strength–Opportunity

Summary of SWOT assessment. The EU is a leader in R&I and already funding a number of Horizon Europe projects specifically targeting the criticality. International researchers are also working on this challenge and are likely to publish new knowledge and findings, with the potential for international collaboration to solve this shared challenge.

Proposed R&I intervention. The EU is supporting targeted R&I for this R&I challenge. An additional R&I intervention is not proposed at this stage, and a follow-up call to existing R&I programmes may be valuable if gaps are identified or further research is needed. Workshop participants validated this proposal.

8.3.2. Key criticality 2: affordability

Description of criticality: The costs of CSE in LCOE are approximately three times higher than those of silicon-based PV. It is uncertain whether CSE costs will decrease significantly, whereas the costs of solar PV and other clean energy technologies are predicted to decrease further.

➔ **R&I challenge**: How can the cost of CSE be reduced to competitive levels with other clean energy technologies?

EU R&I SWOT assessment: Strength–Threat

Summary of SWOT assessment. The EU is a leader in R&I, and it already funds a number of Horizon Europe projects specifically targeting the criticality. However, non-EU countries lead with patents and private investment and also represent the bulk of the demand. Competition from non-EU countries is increasing in R&I. The risk of lower-cost commercialised solutions in non-EU countries is important to consider as a threat.

Proposed R&I intervention. The EU is supporting targeted R&I for this R&I challenge. An additional R&I intervention is not proposed at this stage, and a follow-up call to existing R&I programmes may be valuable if gaps are identified or further research is needed.

Table 8.3 SWOT – evidence overview for EU concentrated solar energy R&I

Strengths (internal – EU) The EU has provided significant funding for solar thermal power and high-temperature applications. For example, the NER 300 initiative provided approximately EUR 303 million towards five concentrated solar projects through two funding calls, in 2012 and 2014.[134] Under Horizon 2020, EUR 186 million was provided to CSP and concentrated solar heat (CSH) projects.[135] In 2021, worldwide installed capacity was approximately 6.5 gW, with 2.4 gW installed in the EU. There is also a large EU market for industrial process heat, which can be partly exploited by CSH systems.[136] Existing partnerships include the EU-SOLARIS consortium for research infrastructure for CSP and solar thermal energy and the EU S3 Energy Partnership for Solar Energy.[137] An upcoming Horizon call to addresses both the sustainability and the affordability criticalities looks for thermal storage solutions that are more cost effective and efficient, which will reduce the water consumption and capital investment requirements for CSP plants.[138] Horizon 2020 projects also looked at addressing these two criticalities: MinWaterCSP project (water saving), WASCOP (water saving), H2020- LC-SC3-RES-35-2020 (cost reduction).[139] Germany was the country with the third-highest number of innovative companies globally in 2017-2022, and the EU accounts for 31% of innovative companies.[140]	**Opportunities** (external) Among the Horizon Europe–associated countries, the UK has a CSP laboratory at Cranfield University that was launched in 2014.[141] Potential R&I solutions to the criticalities include improved cooling systems for water consumption reduction. This approach is being tested in Horizon Europe projects, such as WASCOP[142] and improving the thermal storage system for cost reduction (also being explored in Horizon Europe projects). Potential collaborators with a shared challenge include the US National Renewable Energy Laboratory, which is developing advanced materials that will improve the efficiency and durability of CSP components to reduce long-term costs of CSP projects and the U.S. Department of Energy's (DOE) National Solar Thermal Test Facility (operated by Sandia).[143]
Weaknesses (internal – EU) VC investment in the EU accounts for a small fraction of the global total, and the EU is experiencing a decline in investment.[144] The total number of high-value patents from all EU member countries has been decreasing since 2011, although the EU still remains the top compared to other countries/regions.[145] EU scientific publications have declined since 2019, and the EU has dropped from global leader to third position.[146]	**Threats** (external) According to IEA data,[147] global public investment in CSP research, development and demonstration is decreasing steadily. The United States and China are the leading countries in patent applications.[148] China was first for high-value inventions in 2020.[149] The top four countries for hosting innovative companies active in 2017-2022 include the United States, Japan and China.[150] Countries outside of Europe are expected to be the main driver for capacity addition until 2030, especially China, Chile, Morocco and countries in the Middle East and North Africa.[151] In China, the development of CSP

	is entering a high-speed phase, with more than 30 projects planned to be built by 2024.[152] The U.S. DOE's Solar Energy Technologies Office provides several funding programmes for research, development and demonstration projects of concentrating solar thermal power.[153] The United States has attracted the majority of VC investments.[154] Chinese organisations are emerging as international CSP project developers, a field where EU companies have traditionally been leaders. EU companies remain involved in international projects in the United Arab Emirates (UAE) and South Africa, and in several ongoing tenders. However, Chinese companies are taking a leading role based on expertise developed in the construction of over 1 gW of systems in their home market.[155] China has been working on building up an internationally competitive CSP industry and value chain since 2006 and has been building CSP projects domestically, and from 2020, China started to participate in international projects.[156]

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[135] European Commission (2023), *Clean Energy Technology Observatory, Concentrated solar power and solar heating and cooling in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.

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[145] European Commission (2023), *Clean Energy Technology Observatory, Concentrated solar power and solar heating and cooling in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.

[146] European Commission (2023), *Clean Energy Technology Observatory, Concentrated solar power and solar heating and cooling in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.

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[149] European Commission (2023), *Clean Energy Technology Observatory, Concentrated solar power and solar heating and cooling in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.

[150] European Commission (2023), *Clean Energy Technology Observatory, Concentrated solar power and solar heating and cooling in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.

[151] Renewable Technology (9 May 2019), China to Overtake Spain by 2024 as the Country with the World's Largest CSP Capacity; SolarPACES, CSP Projects Around the World (accessed 2023).

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[153] US Office of Energy Efficiency & Renewable Energy, Solar Energy Technologies Office, Solar Research and Development Funding Programs (accessed 2023).

[154] European Commission (2023), *Clean Energy Technology Observatory, Concentrated solar power and solar heating and cooling in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.

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8.4. Geothermal energy

8.4.1. Key criticality: availability and abundance of critical raw materials (aluminium, copper, nickel, titanium, chromium)

Description of criticality: Geothermal energy technologies rely on the use of the CRMs aluminium (in drilling platforms, pipelines, compressors, treatment systems); copper (turbines, alternators and accessories); nickel (turbines and alternators); titanium (gas treatment catalysts); and chromium (chromium steel 18/8 in gas treatment systems, turbines and alternators). The materials are available from one to four EU countries. However, global demand is expected to rise significantly, and the market is increasingly competitive, introducing a risk of scarcity and price increases that would affect the energy security of geothermal energy value chains.

➔ **R&I challenge**: How can the reliance and use of CRMs be reduced in geothermal energy?

EU R&I SWOT assessment: Weakness–Threat

Summary of SWOT assessment. The EU is not a leader in geothermal energy R&I (relatively, compared to rankings for other technologies). However, the EU is funding Horizon programmes, and there are opportunities for international collaboration, with trends of increasing public R&I investment in a number of countries, including Horizon Europe–associated countries (Norway and Canada). Alternatives to CRMs are not available currently, and such initiatives as recycling and reuse may not be sufficient to meet demand from geothermal energy, depending on both the scale of deployment of geothermal energy and the scale of global demand for CRMs.

Future considerations for increased deployment include research and engagement to support knowledge sharing and upskilling of regulators, including expertise and understanding for permitting.

Proposed R&I intervention. This criticality and R&I challenge are not currently addressed in EU R&I interventions. ETIP Geothermal have set out a strategic research and innovation agenda, including recommendations for R&I in materials and 'design-to-recycling' to increase circularity and reuse of materials in geothermal energy.[157] Another suggestion from the validation workshop was to introduce monitoring and reporting requirements for CRMs use in geothermal energy to promote a better understanding of the challenge and to promote interoperability and comparability. It is important to note that interventions around recycling and reuse will only partially address the criticality and that complementary action on general CRMs supply may be required.

- **R&I action**: with a broad challenge and no specific material alternative identified at this stage, an open Horizon Europe call setting out the desired outcome to reduce the need for CRMs in clean energy technologies through alternatives or circularity may be the most feasible and impactful. As solutions emerge, especially in the case of circularity, it may be beneficial to complement this intervention with regulation or standards driving adoption of circular design in geothermal energy.

- **R&I action – for batteries**: geothermal energy may contribute to supporting the security of supply of certain CRMs, such as lithium. With existing EU R&I programmes and demonstrations taking place, complementary targets or regulation encouraging geothermal energy operators to produce CRMs as a by-product would encourage uptake of these innovative solutions and practices.

Table 8.4 SWOT – evidence overview for EU geothermal energy R&I

Strengths (internal – EU)	**Opportunities** (external)
Combined budgets of EU framework programmes and Member State contributions for geothermal energy between 2010 and 2020 exceed those of any other country in the world.[158] Germany, Italy, France and the Netherlands are the EU countries with the largest R&I investment.[159] Horizon 2020 included EUR 208 million for geothermal energy projects, and Horizon Europe includes at least EUR 34 million.[160] The Innovation Fund also awarded grants to two geothermal energy projects.[161] In 2021, total installed geothermal district heating and cooling capacity reached 2.2 GWth in the EU, with more than 262 systems. The largest growth is happening in France, the Netherlands and Poland.[162] Existing partnerships contributed to the connectivity of the EU R&I ecosystem, including the Geothermal Energy Partnership[163] and ETIP Deep Geothermal.[164] The European Geothermal Energy Council also convenes research, industry and policymakers.[165] The Rijswijk Centre for Sustainable Geoenergy, at the Netherlands Organisation for Applied Scientific Research (known by the acronym TNO), in the Netherlands, is an innovation centre that tests drilling methods and materials and brings companies and universities together to progress geothermal energy developments.[166] The Horizon Europe 2023-2024 Work Programme includes at least 10 calls relevant to geothermal energy, totalling EUR 150.8 million. This includes the Horizon Europe project CRM-Geothermal developing CRM extraction from geothermal wells, building on prior EU-funded work, including a demonstrator site in France.[167]	Global interest is increasing R&I investment in the United States, Australia, China, Japan, Mexico, Korea, New Zealand and Canada, which are the countries with the largest research, development and demonstration (RD&D, equivalent to R&I) budgets and the largest number of potential collaborators.[168] The U.S. DOE announced up to USD 155 million (ca. EUR 144 million) funding in 2022 for research to address the technology and knowledge gaps in geothermal energy.[169] An existing international collaboration is the User4GeoEnergy project, led by Norway and Iceland.[170] Horizon Europe–associated countries: Norway, New Zealand and Canada are investing significantly in geothermal research.[171] Geothermal facilities can produce outputs additional to energy, including sustainable extraction of certain CRMs, such as lithium.[172] Opportunities to address reliance on CRMs include R&I for new technologies to improve 'design-to-recycling' approaches and waste separation and management; the development of sustainable geothermal components; and making use of recycled materials.[173] VC investment increased significantly in 2020 and 2022.[174]
Weaknesses (internal – EU)	**Threats** (external)
Private R&I investment has declined in the EU since 2010.[175] The EU ranks fourth globally for number of inventions and patents.[176] Whereas 33% of active VC companies are in the EU, only 4.1% of global VC investment went to the EU in 2017-2022.[177]	Estimated private R&I investment has declined globally since 2010.[178] The United States is the individual country with the largest investment.[179] The top three countries for high-value inventions in 2017-2019 were the United States, China and Canada. The top organisations for geothermal R&I investment in 2015-2019 are not EU-led.[180]

	The Inflation Reduction Act (IRA) in the United States provides substantial tax credits to accelerate commercialisation and deployment of geothermal systems.[181] The absence of technology-specific data for private R&I investment in geothermal energy make it difficult for private sector and VC firms to assess investment opportunities and may discourage investment in the sector.[182] There do not appear to be existing or developing solutions to the demand for CRMs for geothermal technology.

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[160] European Commission (2023), *Clean Energy Technology Observatory, Deep Geothermal Heat and Power in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.
[161] European Commission (2023), *Clean Energy Technology Observatory, Deep Geothermal Heat and Power in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.
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[166] TNO, Innovation Lab Geothermal Energy Open for Entrepreneurs (accessed 2023).
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[171] European Commission (2022), *Clean Energy Technology Observatory, Deep Geothermal Heat and Power in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg; New Zealand Government (May 2023), Government invests more than $24 million in regional projects''
[172] Szanyi, J., Rybach, L., Abdulhaq, H.A. (2023), Geothermal Energy and Its Potential for Critical Metal Extraction – A review, *Energies* 16(20), 7168, https://doi.org/10.3390/en16207168; CRM Geothermal (accessed 2023).
[173] ETIP-Geothermal (2023), Strategic Research and Innovation Agenda, ETIP Geothermal, (accessed 2023); pre-workshop exercise input.
[174] European Commission (2023), *Clean Energy Technology Observatory, Deep Geothermal Heat and Power in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.
[175] European Commission (2022), *Clean Energy Technology Observatory, Deep Geothermal Heat and Power in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.

[176] European Commission (2022), *Clean Energy Technology Observatory, Deep Geothermal Heat and Power in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.

[177] European Commission (2023), *Clean Energy Technology Observatory, Deep Geothermal Heat and Power in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.

[178] European Commission (2022), *Clean Energy Technology Observatory, Deep Geothermal Heat and Power in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.

[179] European Commission (2022), *Clean Energy Technology Observatory, Deep Geothermal Heat and Power in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.

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8.5. Hydropower

8.5.1. Key criticality 1: environmental impacts of hydropower

Description of criticality: Hydropower can have a very high ecological impact and has prompted negative responses from local communities. This may limit the possibility of further development of hydropower in the EU or initiatives to extend the life and use of existing infrastructure.

➔ **R&I challenge**: How can the biodiversity or ecology impacts of hydropower be reduced and mitigated?

EU R&I SWOT assessment: Strength–Opportunity

Summary of SWOT assessment. The EU is funding a number of programmes related to this criticality and it is a shared challenge globally, with opportunities for international collaboration. Environmental impacts have already been understood, and a number of potential solutions to develop have been identified, such as more sustainable strategies, with interconnecting reservoirs. Tools for objective assessment of biodiversity before and after project implementation are also available, although often not implemented.[183]

Proposed R&I intervention. The EU is supporting research in this space, and a number of solutions are available for implementation, such as monitoring. Expert inputs from the validation workshop noted that public opposition to hydropower projects in the EU was driven by a lack of understanding about types of hydropower plants and their impacts on the environment, and they were accompanied by the suggestion to carry out public engagement as part of an R&I intervention.

- **R&I action 1**: An impactful R&I intervention would be additional support for development and deployment of biodiversity impact monitoring technologies in new hydropower projects (supplemented by regulation or innovation adoption grants).

- **R&I action 2**: The EU should support research on public perceptions of hydropower and pursue public and key stakeholder engagement to understand concerns and address them where possible. Workshop participants highlighted that a complementary action to this could focus on development and deployment of multipurpose hydropower plants and assessment of appropriate locations for these multipurpose plants, whose benefits (including irrigation, flood control, water supply) are immediately obvious to the wider public and local communities.

8.5.2. Key criticality 2: physical vulnerabilities and impacts of climate change

Description of criticality: Climate impacts, including loss of glaciers, droughts and flooding, may significantly impact the ability of hydropower to operate in future through changing water levels in reservoirs.

➔ **R&I challenge**: How can the performance of hydropower be maintained or managed with changing weather patterns and extreme weather?

EU R&I SWOT assessment: Strength–Opportunity

Summary of SWOT assessment. The EU is funding a number of projects relevant to addressing this criticality, with actions on refurbishment of the ageing fleet, performance, flexibility, digitalisation and forecasting. The EU R&I ecosystem is also strong, with a significant proportion of global innovative companies based in the EU. The criticality is well understood; however, funding programmes are not targeted specifically at longer-term climate adaptation. The potential impact and risk from climate change depend on the type of hydropower and its use. For example, open-loop hydropower is more vulnerable than closed-loop, and pump-storage hydropower has low risk of impact from climate change.[184] The functionality of reservoirs is also affected by climate change.[185] International organisations have suggested potential solutions, such as floating photovoltaics combined with hydropower.

Proposed R&I intervention. The EU is supporting R&I to increase the flexibility of hydropower, digitalisation and hybridisation. With a range of potential solutions and the scale of risk being uncertain (uncertainty about the scale of climate change, the need for water storage), the view at the validation workshop was that it may be too soon to establish a call for long-term adaptation of hydropower, as there is not currently a sustainable strategy in place.[186]

- **R&I action:** A research programme could address the gap in current R&I programmes with the development of an evidence-based sustainable strategy for long-term climate adaptation planning, with consideration of the current solutions under development and other potential options (e.g. hybridisation with other technologies or use of interconnecting reservoirs). Water storage needs, flood control and other non-energy uses of hydropower relevant to climate adaptation should also be considered within a long-term climate adaptation strategy for hydropower.

8.5.3. Key criticality 3: abundance and availability of critical raw materials (aluminium, copper, permanent magnets)

Description of criticality: Hydropower technologies use CRMs in generators and permanent magnets for turbines, although in relatively low amounts. C hCThe materials are available from up to four EU countries; in the case of permanent magnets, production is concentrated in one non-EU country. Global demand is expected to rise, and the market is increasingly competitive, introducing a risk of scarcity and price increases that would affect the energy security of hydropower value chains.

➔ **R&I challenge**: How can the reliance and use of CRMs be reduced in hydropower?

EU R&I SWOT assessment: Weakness–Opportunity

Summary of SWOT assessment. EU hydropower R&I programmes do not appear to include critical material use in their scope. Alternatives to permanent magnets and the use of rare earths are being developed for wind energy and may be applicable to use in hydropower. In addition to alternatives, potential actions were identified with regards to use of recycled CRMs (i.e. aluminium) in hydropower.

Proposed R&I intervention. The EU should support knowledge exchange around alternatives to CRMs, in particular between the wind energy sector and hydropower sector, to reduce the need for permanent magnets.

Table 8.5 SWOT – evidence overview for EU hydropower R&I

Strengths (internal – EU)	**Opportunities** (external)
The EU is a leader in R&I, responsible for 33% of all high-value inventions globally (2017-2019) and hosting 28% of all innovative companies. In a globally expanding market, it also made up 50% of all global exports in hydropower, to a value of EUR 1 billion in 2019-2021.[187] Annual public R&I investment in the EU was between EUR 15 and EUR 26 million in 2012-2021.[188] Horizon Europe calls included in the 2023-2024 Work Programme provide up to EUR 24 million towards hydropower-related projects.[189] Sustainability and performance are considered in the current Horizon Europe work programme, e.g. hydropower infrastructure that is being refurbished,[190] or researching flexible energy management systems.[191] The XFLEX HYDRO EU-funded project is developing digital solutions to refurbish hydropower infrastructure and produce a resilient power system.[192] HydroFlex (Horizon 2020 project) looks at 'How will a more flexible Hydropower affect the environment and can an uneven flow rate from the turbines be dampened out?'[193] Climate change and adaptation**:** The EU company ENEL has developed short and long-term weather forecast models to predict climate changes to manage water resources. It is currently looking for 9-12 month forecasting models for Italy and Spain.[194] ETIP Hydro identifies research priority area 3.6, 'environmentally compatible solutions to reduce the negative impact of hydropower on **biodiversity**'. as very high priority and suggests several research topics, aiming to reach TRL 4-7 (there are currently no ongoing R&I activities).[195]	Potential collaboration: The United States, Switzerland, Canada, Norway, China and the UK are the top countries pursuing hydropower R&I and are major contributors of research publications.[196] Some of the research is focused on environmental considerations of hydropower. The current focus of innovation is on digitalisation of hydropower plants to increase flexibility.[197] There has been an increasing trend in global VC investments in hydropower in recent years, reaching EUR 110.5 million in 2021.[198] Horizon Europe–associated countries: Norway granted funding in 2016 to establish a new research centre for hydropower (HydroCen) as part of the Centres for Environment-Friendly Energy Research (FME scheme).[199] Its strategic research areas include environmental design for fish migration (biodiversity), digitalisation of and operation and climate effects on hydropower (performance). Through this, Norway and Canada formed a partnership on sustainable hydropower research in 2018-2022, with NOK 577 million (ca. EUR 50.2 million) funding spent in total (research focus: environment/fish migrations).[200] R&I could support environmentally friendly hydropower through ecolabelling (innovation opportunity), modelling and big data to create flexible management systems.[201] Learning opportunity: The feasible exploitation of hydropower in Brazil was lowered due to social and environmental impact concerns. The International Hydropower Association highlighted 'the necessity of a sustainable approach in balancing power generation with ecological conservation. This includes the use of less invasive run-of-river systems, comprehensive socio-environmental impact assessments, and ensuring enhanced community participation in decision-making processes'.[202] Climate impacts are well understood, and hydropower is highly vulnerable (particularly for run-of-river plants).[203] Impacts on water and floods may result in new potential hydropower sites or incentives for sustainable development.[204] Performance and climate change: International organisations (International

	Renewable Energy Agency (IRENA)) recognise the potential for hydropower infrastructure to be combined with, for example, floating PV to increase flexibility of the system. Co-developments of multiple technologies are an innovation opportunity for hydropower. Covering dams with PV could bring additional water storage benefits (maintained performance and reduced evaporation).[205] Potential solutions for CRMs: The Norwegian company Hydro (the third-largest hydro energy producer in Norway) is committed to EU circular economy initiatives for low-carbon aluminium production and recycling. It is also actively engaged in EU discussions on low-carbon product market development.[206] Experts noted that CRMs can be easily recycled from the refurbishment of plants.[207] For CRMs, lessons from other sectors, such as wind, may provide solutions or shared challenges to address, including around turbines and generators. For example, alternatives to permanent magnets are being developed for wind turbines.[208] Biodiversity impacts – a shared challenge: A United States–China partnership, funded through China's Ministry of Science, is researching biodiversity impacts of hydropower.[209] The EU is involved in the IEA TCP on hydropower, alongside China, Japan, Norway, the United States, Switzerland, Brazil, Australia and Finland. The work programme involves activities on biodiversity (fish and environment), climate change resilience (flood impact mitigation and reservoir sediment management) and improved performance (through repair work).[210]
Weaknesses (internal – EU) The EU received 28% of global early-stage investments. Despite the EU representing 75% of global investments, we have not found reports of EU companies funding research in the EU.[211] Horizon calls looking at upgrading or refurbishing dams sustainably do not highlight replacing or recycling CRMs.[212] Performance and climate change adaptation: Existing refurbishment projects could support solutions to climate change adaptation, although this criticality is not the	**Threats** (external) Global public investments in hydropower capacity have decreased by more than 10% in 2022 compared to the previous year.[216] Other countries, including China, India and the United States, have planned development projects to pursue capacity additions. Brazil leads in installed capacity in

primary aim of the calls, which have limited focus on climate adaptation. EU R&I calls do not place emphasis on biodiversity impacts (currently included indirectly, as 'environmental monitoring'). Opposition is relatively strong to new hydropower projects in the EU.[213] A workshop participant highlighted the lack of incentives for investment in large hydropower projects.[214] Additional services from hydropower, such as flood control and flexibility, are not viewed as adequately remunerated, with a lack of incentives for operators to exploit reservoirs for other uses.[215]	South America, with a hydropower potential of ca. 260 gW.[217] Global private investment in hydropower is very low. In 2020, only 3% of investments was from the private sector.[218] The United States and China dominate hydropower VC investment.[219] Climate change is identified as a key threat by ETIP Hydro, with impacts on both hydropower and copper mining (with copper required for hydropower).[220] The US IRA creates investment opportunities for hydropower.[221] The U.S. DOE funds small businesses to develop the supply chain in marine energy,[222] as well as flexible hydropower and marine energy research to serve the grid and reduce environmental impacts from changing flow rates.[223] The study team did not find evidence of a solution to reducing CRM use in hydropower magnets.

[183] Validation workshop.
[184] Validation workshop.
[185] Validation workshop.
[186] Validation workshop.
[187] European Commission (2022), *Clean Energy Technology Observatory, Hydropower and Pumped Hydropower Storage in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg., Publications Office of the European Union, Luxembourg.
[188] European Commission (2023), *Clean Energy Technology Observatory, Hydropower and Pumped Hydropower Storage in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg., Publications Office of the European Union, Luxembourg.
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[190] European Commission (2023), Horizon Europe Work Programme 2023-2024, Climate Energy and Mobility, call: HORIZON-CL5-2023-D3-02-09: Demonstration of sustainable hydropower refurbishment.
[191] European Commission (2021), Horizon Europe Work Programme 2021-2022, Climate Energy and Mobility, call: HORIZON-CL5-2022-D3-03-08 (Development of digital solutions for existing hydropower operation and maintenance).
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[195] Hydropower Europe (2021), Research and Innovation Agenda.
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[204] Pre-workshop exercise input.
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8.6. Ocean energy

8.6.1. Key criticality 1: sustainability and environmental impacts of ocean energy

Description of criticality: The environmental impacts are uncertain and could present a risk to the deployment of ocean energy in a context of increasing environmental protection regulation and public concern. For example, the risk of disturbance to marine animals is not well understood and salinity gradient inlet volumes could pose a risk of entrainment to fish and other organisms. Sustainability concerns may contribute to shaping public opinion, which will be important for successful deployment.

- ➔ **R&I challenge:** How can the biodiversity or ecology impacts of ocean energy be reduced and mitigated?

EU R&I SWOT assessment: Strength–Opportunity

Summary of SWOT assessment. Environmental impacts appear to be well understood in the EU and form part of existing and upcoming Horizon R&I funding. Globally, this is a shared challenge with potential for international collaboration and knowledge exchange about potential solutions. Mechanisms to accelerate the use of new evidence and transferable assessments from one project to the next would support the acceleration of deployment of ocean energy, for example with support for regulators and permitting agencies.[224]

Proposed R&I intervention. This criticality is well addressed in existing European R&I interventions. The study does not recommend further R&I interventions; however, it would be beneficial for the EU to ensure this shared international challenge is resolved with support for knowledge exchange and collaboration, whether through research partnerships or through exchange in international for a, such as the IEA.

8.6.2. Key criticality 2: broader sustainability – public opinion

Description of criticality: The environmental impacts are uncertain and could present a risk to the deployment of ocean energy in a context of increasing environmental protection regulation and public concern. For example, the risk of disturbance to marine animals is not well understood and salinity gradient inlet volumes could pose a risk of entrainment to fish and other organisms. Sustainability concerns may contribute to shaping public opinion, which will be important for successful deployment.

- ➔ **R&I challenge:** How supportive is the public about deployment of ocean energy?

EU R&I SWOT assessment: Weakness–Opportunity

Summary of SWOT assessment. Limited information was found about EU research on public attitudes to ocean energy, in particular attitudes in potential host coastal communities. Research in other countries has identified concerns and lack of understanding as a weakness for the EU, as negative public opinion could introduce barriers to deployment, noting that concerns were low from ocean energy stakeholders at the validation workshop.[225] However, this criticality can be resolved, at least to some extent, through R&I interventions.

Proposed R&I intervention. Based on the above analysis, the following intervention is proposed:

- **R&I action:** The EU should support research into public perceptions of ocean energy and influencing factors. Member States may consider delivering a public dialogue with potential host communities.

8.6.3. Key criticality 3: affordability

Description of criticality: The cost estimates (LCOE) for ocean energy are currently high, in part due to the level of innovation and resulting high capital costs.

➔ **R&I challenge**: How can the cost of ocean energy be reduced?

EU R&I SWOT assessment: Strength–Opportunity

Summary of SWOT assessment. Lowering LCOE is a key focus of ocean energy development at the international and national levels; the EU has a strong ocean energy R&I ecosystem and a number of upcoming R&I funding calls and targets that focus on cost reduction. Deployment of pilot projects, combined with finance mechanisms (e.g. revenue support in UK, commercial tenders in France), are expected to support the demonstration of cost-reducing technologies and enable wider deployment, following the example of offshore wind. France has launched commercial contracts, supporting demonstration and deployment with revenue. Potential solutions exist and are in development, including in Horizon Europe–associated countries with significant R&I strengths, and there is the potential for collaboration. A potential threat is the stagnation or reducing trend toward private investment in ocean energy.

Proposed R&I intervention. This criticality is well addressed in existing European R&I interventions. In the validation workshop, the programme of support for deployment was described as well funded and needing time to deliver.[226] Complementary finance support, such as revenue support and low-cost loans, would further enable deployment. Global competition should be monitored, and there is a need for an EU response if other regions provide favourable conditions for deployment, as industry will likely more towards opportunities.

- **R&I action**: Financial support would provide a complementary intervention to existing and upcoming R&I interventions. This may be best delivered by Member States.

8.6.4. Key criticality 4: abundance and availability of critical raw materials (copper, nickel, permanent magnets)

Description of criticality: Ocean energy technologies rely on the use of CRMs. The materials are available from up to four EU countries; in the case of permanent magnets, production is concentrated in one non-EU country. Global demand is expected to rise significantly, and the market is increasingly competitive, introducing a risk of scarcity and price increases that would affect the energy security of geothermal energy value chains.

- ➔ **R&I challenge**: How can the reliance and use of CRMs be reduced in ocean energy?

EU R&I SWOT assessment: Weakness–Opportunity

Summary of SWOT assessment. The EU Ocean energy R&I ecosystem is globally competitive and drawing on lessons from other offshore energy sectors. While the use of CRMs does not appear to be addressed in existing programmes or to be a priority research area, with the current TRL and lessons from the offshore wind and hydropower sectors, there may be an opportunity to reduce the requirement for CRMs. Demand for CRMs is expected to increase significantly with the global clean energy transition.

Proposed R&I intervention. Based on the above analysis, the intervention is proposed:

- **R&I action:** Limited information was found by this study on the scale of risk for ocean energy and potential technology-specific solutions. An initial scoping study would provide an evidence base to understand where technology solutions can be leveraged (e.g. alternative materials or design changes) and identify or develop circular economy initiatives suitable to ocean energy. Knowledge exchange with the offshore wind sector and opportunities for shared infrastructure – reducing demand for CRMs – would be beneficial.

Table 8.6 SWOT – evidence overview for EU ocean energy R&I

Strengths (internal – EU)	**Opportunities** (external)
The EU is leading global public R&I investments for ocean energy, representing 46% of global public investments, and EU companies have been the second-largest ocean energy investors in the past decade. VC investment was focused on late-stage investments in the EU.[227] The EU has an existing S3 interregional partnership on Marine Renewable Energy to pool regional resources in the fields of offshore wind and ocean energy.[228] The impacts of ocean energy on biodiversity and the environment are well understood in the EU.[229] With regards to biodiversity, Horizon Europe calls require projects to submit environmental monitoring data and mitigate environmental damage,[230] and they look to develop technology that contributes to 'the objectives of the Mission Healthy Oceans, Seas, Coastal and Inland Waters'.[231] In 2020, the Ocean Energy ETIP's strategic agenda called for good practices in enhancing benefits to biodiversity.[232] It only considered the importance of public acceptance in its 2016 strategic priorities.[233]	Horizon Europe–associated countries: The UK is one of the top countries in terms of ocean energy installation and with dedicated research organisations, such as the Offshore Renewable Energy (ORE) Catapult and the Supergen Offshore Renewable Energy Hub, devoted to research on sustainable wind and marine energy. [240] The ORE Catapult, for example, includes research activities to lower costs.[241] The Norwegian FME HydroCen investigated reducing the environmental impact and costs of hydropower, and specifically notes the collaboration with the EU in this effort.[242] Potential collaboration: South Korea is now the world-leading country in capacity.[243] Potential cost reduction solutions include development in materials and device survivability.[244] Existing collaborations include a collaboration between the UK Marine Energy Council, ORE Catapult and France, with a report produced on cost reduction pathways.[245] The IEA Ocean Energy Systems TCP has strategic objectives[246] around lowering LCOE and around sustainability and public acceptance.[247]

It is unclear to what extent this has led to targeted R&I work. With regards to cost, a number of Horizon Europe calls include aims to reduce the LCOE through materials development.[234] The European Commission's strategic energy technology (SET) plan has set wave and tidal stream LCOE targets[235] (also a priority research area for ETIP Ocean Energy, 2020).[236] Other sectors, in particular offshore wind, have shared challenges and may provide potential solutions. For example, the Danish company Ørsted became the first company to issue 'blue bonds' relating to offshore biodiversity.[237] France has introduced revenue support for ocean energy projects.[238] The latest environmental research data shows no significant impact to marine ecosystems.[239]	Shared challenges with potential for collaboration: The United States is driving ocean energy investment through the ocean climate action plan, with specific action on reducing climate change threats to ecosystems.[248] New Zealand's Sustainable Seas National Science Challenge also looks at this topic.[249] Ocean energy has the opportunity to learn from other sectors to reduce use of CRMs and increase recycling and circular economy initiatives.
Weaknesses (internal – EU) There are no calls in the current Horizon Europe work programme that consider public acceptance. ETIP Ocean only considered the importance of public acceptance in its 2016 strategic priorities.[250] UK research found ocean energy to be looked upon favourably by the general public,[251] but identified challenges around public acceptance for ocean energy in coastal populations, specifically with concerns around socio-economic and environmental impacts.[252] A US study had similar findings. [253] This study did not find targeted EU R&I aimed at reducing the use of CRMs in ocean energy.	**Threats** (external) Many countries outside of the EU, including the United States, China, Canada and the UK, have rolled out policies and funding, and they could compete with the EU by becoming global leaders, according to Ocean Energy Europe analysis.[254] VC investments in ocean energy stagnated at EUR 388 million in 2022, and early-stage investment appears to be decreasing. [255] The UK pledged to invest GBP 20 million (ca. EUR 23 million) per year from 2021 in the tidal energy sector, to develop technology and lower costs.[256] The United States and the UK dominate VC investment in ocean energy.[257] The U.S. DOE funds small businesses to develop the supply chain in marine energy[258] and flexible hydropower and it funds marine energy research to serve the grid and reduce environmental impacts from changing flow rates.[259] EU-based industry has previously moved to deploy outside the EU where revenue support and opportunities have arisen (e.g. U.S. DOE, Canada). International competition remains a key threat to EU leadership and to maintaining an EU-based value chain.

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8.7. Photovoltaics

8.7.1. Key criticality 1: availability and abundance of critical raw materials (silicon, copper, aluminium, nickel, boron, gallium, titanium, germanium, phosphorus)

Description of criticality: The production of solar PV requires a number of CRMs that are in limited supply within the EU or globally or that are concentrated in a limited number of non-EU countries.

➔ **R&I challenge**: How can the reliance on and need for CRMs in solar PV be reduced?

EU R&I SWOT assessment: Strength–Opportunity

Summary of SWOT assessment. Perovskite solar cells are a potential solution to this criticality, with the potential to become both more affordable than silicon-based PV, as well as accessible due to its ease of fabrication and potential for flexible and lightweight applications. The EU has leading expertise in perovskite solar cells, with existing research programmes and companies developing the technology. However, it is important to note that this SWOT assessment could rapidly change to threat without intervention, as most leading companies for perovskites are situated outside the EU and competition is likely to increase with other countries concerned with this criticality.

Proposed R&I intervention. Perovskites may provide a strategic opportunity for the EU to both reduce its reliance on CRMs for solar power and develop an EU-based supply chain for solar cells. R&I to increase efficiency, lifetime and circularity of photovoltaics also present potential solutions to reduce the use of CRMs, with industry already taking action. Actions focused on perovskites to specifically address CRMs in PV were highlighted by validation workshop participants as high impact and medium feasibility (due to early TRL).

- **R&I action**: The scale of the challenge should be carefully considered, with potential for a portfolio of R&I interventions to support the successful development and commercialisation of perovskite solar cells and development of EU skills and supply chain, for example complimentary Horizon Europe, European Innovation Council (EIC) and European Research Council (ERC) structural funds to provide a coherent and end-to-end package of support addressing lower TRL research challenges, late-stage development, university–industry exchange, and business growth, including start-ups.

8.7.2. Key criticality 2: supply chain location

Description of criticality: Over 90% of the PV module value chain is located outside the EU. The location of supply may change in future but not without significant political and economic efforts. One of the assumptions of the study is that supply chains outside the EU introduce a risk to energy security.

➔ **R&I challenge**: How can the solar PV supply chains be onshored to the EU?

EU R&I SWOT assessment: Weakness–Threat

Summary of SWOT assessment. The EU faces significant challenges with this criticality. The EU is not in a strong position to outcompete leading silicon PV suppliers with R&I and become cost competitive, as investment continues to increase globally. Part of the challenge for EU value chains is the energy intensity of some processes and the high cost of energy in Europe compared to competitor countries.[260] An alternative take on this challenge would be to focus on developing a new solar PV technology where the EU has existing strengths and comparative advantage over competitors, such as perovskite solar cells.

Proposed R&I intervention. R&I is not the primary solution to onshoring silicon PV value chains to the EU. This onshoring may more effectively achieved through acquisition or policy interventions, whilst acknowledging that this may come with significant costs. In the case of acquisition, complementary R&I programmes to support continued innovation and competitiveness may be key to achieving overall energy security objectives. Developing an EU-based perovskite value chain may provide an alternative solution. Proposed R&I interventions are suggested above.

- **R&I action**: A Horizon programme focused on increasing the energy efficiency of solar photovoltaic manufacturing processes would support the development of solutions enabling onshoring and cost competitiveness of an EU photovoltaics supply chain.

8.7.3. Key criticality 3: digital vulnerability

Description of criticality: Inverters needed for solar panels to operate flexibly within the smart grid carry a cyber security risk.

➔ **R&I challenge**: How can the digital security and reliability of solar PV inverters be ensured?

EU R&I SWOT assessment: Strength–Threat

Summary of SWOT assessment. The EU has policy and regulation in place with regards to cyber security. The sector is also focused on the cybersecurity challenge. However, cyber threats are continuously evolving, and the threats vary according to the size of PV installations.

Proposed R&I intervention. The solar power sector is working on this challenge. It may be beneficial to maintain these activities under review and ensure that ongoing cyber security research programmes are pursued with specific research on threats relevant to solar PV inverters and their effective mitigation.

8.7.4. Key criticality 4: skills

Description of criticality: For silicon-based solar cells, installation skills are required, and these are already scarce in some areas of the EU. The availability of a significant and distributed workforce can introduce a risk to the deployment and pace of deployment of solar panels across the EU. In the case of perovskites, research and development skills are needed for further development and EU advantage.

➔ **R&I challenge**: How can perovskite R&I and manufacturing skills be developed and maintained in the EU? Developing technical installation skills is not considered to be a research and innovation challenge.

EU R&I SWOT assessment: Weakness–Opportunity

Summary of SWOT assessment. The EU is currently supporting a number of R&I programmes for perovskite solar cells. This will inherently contribute towards training a skilled R&I workforce. A potential threat includes increasing competition for talent from non-EU countries.

Proposed R&I intervention. Existing and continued R&I programmes will contribute towards ensuring a skilled workforce pipeline in the EU. Part of the challenge identified in the validation workshop includes facilitating strong connections between industry and research, which could be encouraged through collaborative R&I activities and networking across industry and academia. Non-R&I interventions that may be relevant to consider include policy interventions to facilitate and incentivise the movement of skilled talent to the EU.

Table 8.7 SWOT – evidence overview for EU photovoltaic R&I

Strengths (internal – EU)	**Opportunities** (external)
The EU has been a major contributor to global public investments in PV R&I, representing 47% of global investments in 2010-2020.[261] Member States are also investing in PV. Within the EU, Germany had the highest level of private investment in PV.[262] Austria launched a PV programme in 2023, providing EUR 600 million funding to support the development of solar PV and storage systems.[263] Existing partnership include the S3 Energy Partnership on Solar Energy.[264] Upcoming Horizon Europe calls provide approximately EUR 86 million between 2023 and 2024 towards PV-related projects.[265] According to the 2021 annual report of European Climate Neutral Industry Competitiveness Scoreboard (CIndECS), the EU's competitiveness in the early-stage investments for PV is high.[266] The EU solar energy strategy includes the launch of an alliance and coordination of funds to promote investment in manufacturing in the EU.[267] The ETIP PV strategic R&I agenda challenges 1 (Performance Enhancement and Cost Reduction through Advanced PV Technologies and Manufacturing) and 2 (Lifetime, Reliability and Sustainability Enhancements through Advanced Photovoltaic Technologies, Manufacturing and Applications) detail objectives and	Solar PV is the most attractive renewable technology to private capital; 83% of investments in 2020 came from the private sector.[276] Horizon partners: Norway granted funding in 2016 to establish a new research centre for sustainable solar cell technology, as part of the Centres for Environment-Friendly Energy Research (SuSolTech, FME scheme).[277] Research includes work on sustainable silicon feedstock production, high-efficiency Si-based cells and modules.[278] Existing partnerships: Several member states of the African Union are developing PV power plants with investment through the EU–Africa partnership.[279] The Clean Energy Ministerial Clean Power workstream includes a global initiative on Transforming Solar Supply Chains, which Germany co-leads along with Australia, India and the United States.[280] The United States has funding programmes supporting perovskites R&I.[281] For cyber security related to PV converters, Australia and the UK both recognise the digital vulnerabilities and have conducted research to assess the threats.[282] Use of raw materials has been declining with technological progress and innovation, including efficiency gains, longer-lasting modules and alternative materials. The existence of a wide array of PV technologies means that the supply chain is not dependent on a single set of raw materials

pathways to deliver improved energy security on the raw materials front through R&I for PV.[268] CRM reduction is identified as a challenge by ETIP PV, and research is being conducted to contribute to the EU's CRMs strategy.[269] CRM alternatives: The EU is supporting Horizon Europe projects focusing on perovskites cells.[270] The PEPPERONI project funded by the EU has a consortium involving EU-based small to medium-sized enterprises (SMEs) to develop advanced solar cells, including perovskite cells.[271] The aims include increasing technology readiness to TRL 6-7.[272] Europe has notable expertise and a lead in the development perovskites technology (less reliant on CRM), with several EU companies, such as Evolar (Sweden), Saule Technologies (Poland) and Solaronix (France), currently setting up production lines.[273] Supply chain: R&I activities are notably focused on delivering more energy efficient and less wasteful production of both ingots and wafers to facilitate the diversification of the location of PV production.[274] For cybersecurity, the EU Cyber Resilience Act establishes high cybersecurity requirements, as well as common guidelines for inverter manufacturers.[275] The photovoltaics R&I community and industry are described as highly focused on cybersecurity, in particular resolving challenges of increased connectivity and reliability of protection against disruptions. Skills: The EU has many leading research institutes, laboratories and innovative companies in the area of perovskites (and other technologies).	with limited availability at a geological level.[283] Potential solutions in development that reduce the need for CRMs include perovskite cells, currently at TRL 3-4.[284] International cooperation is taking place on cyber security of PV inverters with IEA Photovoltaic Power Systems Programme (PVPS) TCP, Task 14.[285] Supply chain and skills: Opportunities to build closer partnerships between investors in new manufacturing capacity, on the one hand, and researchers and innovation providers, on the other hand, is a crucial factor to allow these new factories in the EU to remain competitive in a sector with very short technology cycles and rapidly evolving performances, cost-profiles and so on. This would support maintaining highly skilled workers in the EU by default.
Weaknesses (internal – EU) With regard to the global share of innovating companies and high-value patents for solar PV, the EU's competitiveness is low, as it hosts 25% of all innovating companies and EU countries hold 15% of all patents (2016-2018).[286] According to the 2021 annual report of CIndECS, the EU's competitiveness is medium for later-stage investments. [287] The ETIP has not yet included gaps in research skills.[288] No specific action to address research skills gaps in perovskites was found by this study.	**Threats** (external) China, the United States and India are making investments to increase capacity. The IRA in the United States provides investment and tax credits that will give a significant boost to PV capacity and supply chain expansion.[291] Both production data and new investment projects confirm the dominance of Asia, and in particular China, in the PV manufacturing landscape. Silicon solar cells, which represent over 95% of worldwide production, are mostly produced in China, while the EU retains a much smaller share.[292]

Targeted R&I programmes for cybersecurity of inverters were not identified by this study; however, workshop participants highlighted ongoing industry work and noted the new challenge of aggregators, who concentrate distributed PV capacity. ETIP PV recognised that there is a cybersecurity challenge due to an increased degree of connectivity of all sizes of installations, which need to also deliver a high reliability of protection against disruptions. Aggregators are also highly vulnerable to cyberattacks.[289] Photovoltaics manufacturing is very energy intensive, making the EU a difficult environment, given the recent energy price increases. Opportunities for economies of scale are also lacking for EU stakeholders.[290]	The PV value chain is largely concentrated in a single country – China – which represents up to 95% of the production for key segments of the value chain.[293] Only one of the top 10 perovskite manufacturers has headquarters in the EU; others are based in Korea, Japan, the United States, China and India. In particular, there is strong policy support for manufacturing capacity in India and the United States (e.g. there is auction schedule for PV and onshore wind in India).[294] Brazil has experienced increased investments in solar manufacturing facilities and utility-scale projects totalling over USD 20 billion (ca. EUR 18.5 billion), securing its supply chain.[295] For the cyber security criticality, although EU has regulations in place already, cyberattacks are evolving threats. The United States has developed a plan to collaborate with local companies to research the use of advanced inverters to improve grid reliability.[296] Increasing global R&I efforts in perovskite solar cells creates competition for mobile and highly skilled talent.[297] Lack of standards control and low quality of feedstock can be a challenge to maintaining quality of products in a competitive market.[298]

[260] Pre-workshop exercise input.

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[288] ETIP PV (accessed 2023).

[289] Pre-workshop exercise input.

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[291] IEA, Solar PV.

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8.8. Wind energy

8.8.1. Key criticality 1: availability and abundance of critical raw materials (copper, boron, nickel, rare earths, lithium, titanium, including those used in permanent magnets)

Description of criticality: Most wind energy technologies rely on the use of CRMs that are sourced outside the EU and in some cases from only one or few countries, with the potential for disruption and limited supply.

➔ **R&I challenge**: How can the use of CRMs be reduced in wind energy technologies?

EU R&I SWOT assessment: Strength–Opportunity

Summary of SWOT assessment. The EU has a number of Horizon Europe calls targeted at addressing CRMs supply for wind and should continue to support the development of alternative materials, design solutions, quality control for longer operation times, and circularity. A gap identified in the validation workshop included R&I for circularity in wind power technologies.[299]

Proposed R&I intervention. Based on the above analysis, the intervention is proposed:

- **R&I action**: A Horizon call should focus on the dual aim of reducing the use of CRMs and improving the circularity of wind energy.

8.8.2. Key criticality 2: physical vulnerability to climate change, including changing weather patterns and increasing extreme weather events

Description of criticality: The performance of wind energy is dependent on weather patterns and may be negatively affected by changing patterns caused by climate change. Extreme weather events may also cause physical damage to wind turbines, although in the validation workshop this was noted to be fairly low risk.

➔ **R&I challenge**: How can the performance of wind energy be maintained under conditions of changing weather patterns and extreme weather events?

EU R&I SWOT assessment: Strength–Opportunity[300]

Summary of SWOT assessment. The EU has a strong wind R&I ecosystem and is supporting relevant, if not specific, R&I for this criticality. Adaptation to climate change is a shared global challenge.

Proposed R&I intervention. Further R&I was not viewed as necessary at this stage by validation workshop participants. A proposed alternative was to set up a futures-focused call to ensure adaptation to extreme whether events was explores across all energy technologies. This may be beneficial to include in an energy system–wide R&I call.

Table 8.8 SWOT – evidence overview for EU wind energy R&I

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Strengths (internal – EU)

Private R&I funding for wind energy in the EU is highly concentrated in Germany and Denmark, where the leading European original equipment manufacturers (OEMs) concentrate their industry and value chains.[301] The EU's OEMs for offshore wind mostly source their components from European manufacturers.[302]

EU companies are among the leading investors in R&I in wind energy globally, closely followed by China.

The EU hosts about 38% of all innovators in wind energy, of which about 44% are VC companies and 56% are corporates. [303] The EU accounts for 83% of early-stage VC investments globally.[304]

EU companies lead in terms of high-value patents in wind energy technologies.[305]

The EU has an existing S3 interregional partnership on Marine Renewable Energy to pool regional resources in the fields of offshore wind and ocean energy.[306]

EU-based companies, such as ENERCON, use multipolar synchronous generators as an alternative to permanent magnet generators.[307]

Impacts from climate change are addressed in Horizon Europe programmes, focusing on damage-tolerant materials and 'considering different external conditions'. [308] ETIP Wind calls for 'solutions for operating in extreme conditions' as a medium R&I priority.[309]

ETIP Wind has recently recommended that Horizon Europe support opportunities and challenges of CRM supply.[310] The EU has some existing active research addressing the availability and abundance of CRMs in wind energy infrastructure.[311]

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Opportunities (external)

Horizon partners: The UK is one of the leading countries in offshore wind technology and is investing GBP 37 million on R&I.[312] The UK has some research hubs dedicated to offshore wind, e.g. ORE Catalpult[313] and the Supergen Offshore Renewable Energy Hub.[314] The latter targets technology developments and innovations to reduce the cost of wind energy and monitors environmental effects but does not explicitly consider the identified criticalities. Norway announced a NOK 120 million (ca. EUR 10.4 million) budget to build a new research centre for wind energy (FME NorthWind), focusing on reducing the environmental impact of onshore and offshore wind plants.[315]

Potential collaboration: The United States has announced more than USD 300 million (ca. EUR 278 million) on R&I projects focusing on high costs, environmental impacts, challenges of installation, and grid integration.[316]

Impacts of climate change on wind speeds and weather are well understood (icing, sea ice, extreme wind speeds, air density),[317] so developers can use this knowledge as a basis to develop technology. Research states that 'long-term trends for wind speed and wind power production are still rather contained compared to the trends related to temperature increase'.[318]

Existing collaboration: The IEA Wind Energy Systems TCP involves EU countries. Research tasks do not explicitly focus on CRMs or climate change adaptation.[319]

Materials use: Technologies exist that reduce material input up to 90% (e.g. airborne wind).[320]

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Weaknesses (internal – EU)

We found that R&I technology development is focused on energy management for different wind speeds and weather forecasting, rather than explicit solutions to climate change impacts on wind energy (e.g. HORIZON-CL5-2023-D3-02-14: Digital twin for forecasting of power production to wind energy demand[321]).

The EU received 16.5% of global late-stage investments.[322]

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Threats (external)

China is leading the world in relevant patenting activity, although only a small percentage of the patents are high value.[323]

Global investments in onshore wind in 2023 faced a17% year-on-year decline compared to 2022. Grid constraints, permitting challenges and faltering policy support in multiple markets are leading to a reduced global pipeline of ready-to-develop projects.[324]

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</table>

	Chinese OEMs have been increasing market share in recent years, as have other competitors, such as General Electrics (United States) and Hitachi, Mitsubishi and NTN (Japan).[325] The United States has an ambitious goal of producing 30 gW of offshore wind energy by 2030 and has invested more than USD 300 million (ca. EUR 278 million) in R&I projects.[326] There is strong policy support for manufacturing capacity in India and the United States (e.g. an auction schedule for PV and onshore wind in India).[327] In 2022, Engie and Vestas commissioned a wind project in Brazil, to be the largest wind farm in Latin America once complete.[328] The United States, China and the UK receive the most early-stage VC investment.[329] Early-stage VC investments in the onshore wind sector have declined in recent years, and offshore wind VC investments are modest. [330] UK–United States collaboration: GreenSpur Wind and Niron Magnetics have built a 15 megawatt (mW) offshore wind energy generator with rare-earth-free magnets.[331] Sandia National Laboratories in the United States has developed a similar generator.[332] Increasing global competition is highlighted as a potential threat to European OEMs, who do not currently have the production capacity to meet EU deployment targets and may need to compete in future with global value chains.[333]

[299] Validation workshop.
[300] Initially assigned as a Strength−threat from SWOT analysis but modified following validation workshop inputs.
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[302] European Commission (October 2023), Report from the Commission to the European Parliament and the Council, Progress on Competitiveness of Clean Energy Technologies, Publications Office of the European Union, Luxembourg.
[303] European Commission (2023), *Clean Energy Technology Observatory, Wind Energy in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.
[304] European Commission (2023), *Clean Energy Technology Observatory, Wind Energy in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.
[305] European Commission (2023), *Clean Energy Technology Observatory, Wind Energy in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.
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[307] ENERCON (accessed 2023).
[308] European Commission (2023), Horizon Europe Work Programme 2023-2024, Climate Energy and Mobility, call: HORIZON-CL5-2023-D3-02-15 (Critical technologies to improve the lifetime, efficient decommissioning and increase the circularity of offshore and onshore wind energy systems).
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[310] ETIP Wind (February 2023), ETIP Wind's Response to the EU Consultation on the Horizon Europe Strategic Plan 2025-2027.
[311] European Commission (2023), Horizon Europe Work Programme 2023-2024, Climate Energy and Mobility, call: HORIZON-CL5-2023-D3-01-05 (Critical technologies for the offshore wind farm of the Future), call: HORIZON-CL5-2023-D3-02-15 (Critical technologies to improve the lifetime, efficient decommissioning and increase the circularity of offshore and onshore wind energy systems); European Commission (2021), Horizon Europe Work Programme 2021-2022, Climate Energy and Mobility, call: HORIZON-CL5-2022-D3-01-02 (Demonstration of innovative materials, supply cycles, Recycling technologies to increase the overall circularity of wind energy technology and to reduce the primary use of critical raw materials).
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[313] ORE Catapult (accessed 2023)
[314] University of Plymouth, Supergen Offshore Renewable Energy Hub (accessed 2023).
[315] Research Council of Norway, Centre for Environment-friendly Energy Research on Wind Power (accessed 2023); U.S. Department of Energy (May 2021), EERE Cybersecurity Multiyear Program Plan, U.S. DOE, (accessed 2023).
[316] U.S. Department of Energy, Wind Energy Technologies Office, Offshore Wind Research and Development (accessed 2023).
[317] Energy Monitor (22 November 2021), Weekly Data: Changes in wind speed caused by climate change may affect future wind power output; Bonanno, R., Viterbo, F., Maurizio, R. G. (2023) Climate Change Impacts on Wind Power Generation for the Italian Peninsula, *Regional Environmental Change* 23, doi.org/10.1007/s10113-022-02007-w; Pryor, S.C., Barthelmie, R.J. (2010), Climate Change Impacts on Wind Energy: A review, *Renewable and Sustainable Energy Reviews* 14, 430-437, doi.org/10.1016/j.rser.2009.07.028
[318] Bonanno, R., Viterbo, F., Maurizio, R. G. (2023) Climate Change Impacts on Wind Power Generation for the Italian Peninsula, *Regional Environmental Change* 23, 23(15), doi.org/10.1007/s10113-022-02007-w.
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[321] European Commission (2023), Horizon Europe Work Programme 2023-2024, Climate Energy and Mobility.
[322] European Commission (2022), *Clean Energy Technology Observatory, Wind Energy in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.
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[326] U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, https://www.energy.gov/eere/wind/offshore-wind-research-and-development (accessed 2023).
[327] International Energy Agency (2023), Renewables 2023: Analysis and forecasts to 2028, IEA (accessed 2023).
[328] Mordor Intelligence (2023), Brazil Wind Energy Market Size and Share Analysis: Growth Trends & Forecasts (2024-2029), Mordor Intelligence (accessed 2023).
[329] European Commission (2022), *Clean Energy Technology Observatory, Wind Energy in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.
[330] European Commission (2022), *Clean Energy Technology Observatory, Wind Energy in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.
[331] Offshore WIND (July 2022), 15 MV Rare-Earth-Free Offshore Wind Turbine Seeks Path to Market.
[332] Green Car Congress (12 September 2022), Sandia Innovation Eliminates Reliance on Rare-Earth Metals for Large-Scale Wind Turbines.
[333] Pre-workshop exercise input.

8.9. Direct solar fuels

8.9.1. Key criticality 1: availability and abundance of critical raw materials (specifically bismuth, titanium metal)

Description of criticality: The production of direct solar fuels requires a number of CRMs, particularly those used as catalysts or in the electrodes (bismuth, titanium). The bismuth supply is dominated by one non-EU country, and natural abundance is limited.

➔ **R&I challenge**: How can the reliance on and need for CRMs in direct solar fuels be reduced?

EU R&I SWOT assessment: Weakness–Threat

Summary of SWOT assessment. This criticality does not appear to be addressed specifically in EU-funded R&I, and there do not appear to be technology-specific solutions in development.

Proposed R&I intervention. Processes for direct solar fuels are still in development, and it is not clear at this stage which efficient and viable fuel conversion technologies might dominate a value chain. Furthermore, without clearly defined processes, the scale of challenge with regards to use of CRMs is unclear, and no current solutions are in development.

- **R&I action**: A discovery research programme is recommended to explore and identify potential alternatives to CRMs for direct solar fuels to feed into wider technology development. Any discovery research programme carries significant uncertainty and risk, and must note that impact may not be achieved for many years.

8.9.2. Key criticality 2: supply chain complexity

Description of criticality: The components for direct solar fuels are highly specialised, and because the technology is still in development, the exact supply chain requirements are not finalised. The uncertainty and potential for future complexity in the supply chain introduce a potential risk, as complex supply chain may be more vulnerable to disruption or only as resilient as the weakest link.

➔ **R&I challenge**: How can the resilience of the future direct solar fuel supply chain be ensured?

EU R&I SWOT assessment: Strength–Opportunity

Summary of SWOT assessment. The EU is supporting R&I programmes focused on direct solar fuel value chains and their resilience, where supply chain complexity may be in scope or at least well understood. Mission Innovation provides an opportunity for international collaboration, including around digitalisation for more resilient supply chains.

Proposed R&I intervention. Existing EU R&I programmes should be complemented with aims and incentives to increase the resilience of the supply chain, and these aims should be included in subsequent R&I programmes.

8.9.3. Key criticality 3: skills

Description of criticality: As the technology for the production of direct solar fuels is still in development, highly skilled and specialised labour is needed. This is viewed as a major criticality for further development of the technology in the EU.

- ➔ **R&I challenge:** How can direct solar fuel R&I skills be developed and maintained in the EU?

EU R&I SWOT assessment: Strength–Threat

Summary of SWOT assessment. The EU is supporting R&I programmes that will contribute towards developing a specialised and expert workforce and aims to support the development of an EU industry with export potential. Other countries are also pursuing opportunities in direct solar fuels and may create competition for mobile talent if the EU does not continue to provide opportunities and incentives.

Proposed R&I intervention. With existing and upcoming R&I programmes contributing to developing a skilled workforce, specific R&I intervention is not recommended at this stage. However, such intervention should remain a point of attention to ensure that a continued pipeline of specialised talent is developed and incentivised to remain in the EU. Other policy actions may also support the retention of talent in the EU or attract international talent.

8.9.4. Key criticality 4: affordability

Description of criticality: With high costs of materials and equipment, as well as highly specialised pathways, direct solar fuel technologies face challenges to be competitive now and in the longer term. High costs are a threat to the energy security of the value chain.

- ➔ **R&I challenge:** How can the costs of direct solar fuels be reduced?

EU R&I SWOT assessment: Strength–Opportunity

Summary of SWOT assessment. The EU is supporting R&I for cost reductions, and there are potential opportunities for technological development to support cost reductions. Horizon Europe–associated countries, in particular the UK, are pursuing research for applications to sustainable aviation fuel and may provide a shared challenge for international collaboration.

Proposed R&I intervention. The EU is supporting R&I targeted at this challenge. A follow-up to existing R&I programmes may be valuable if gaps are identified or further research is needed. Sustained R&I funding would support the development of technologies with higher conversion efficiency and better catalysts.[334]

Table 8.9 SWOT – evidence overview for EU direct solar fuels R&I

Strengths (internal – EU)	**Opportunities (**external)
The EU is the second-most prolific region in scientific publications in 2021, following China, indicating a strong research culture	China, the United States, Korea, the UK and Japan are major countries for scientific publications and potential collaborators.[346]

and potential for innovation and private or VC investment opportunities. [335] The EU provided EUR 30 million in grants for solar fuels R&I in FP6and FP7, followed by EUR 63.6 million during Horizon 2020. The EIC Fuel from the Sun Artificial Photosynthesis Prize awarded EUR 5 million.[336] Existing partnerships include the S3 Energy Partnership on Solar Energy (from 2017) and the Solar Industry Regions Europe (SIRE) partnership.[337] The latter is supporting the EU strategy for solar energy. The SUNERGY community programme was launched in 2022 with EUR 4 million in funding. The community brings together more than 300 stakeholders and is developing a technology roadmap.[338] Horizon Europe includes relevant calls, with one call reinforcing international collaboration with countries in Mission Innovation to establish stronger renewable energy value chains[339] and another call for demonstration of the full value chain.[340] Cost reduction and maintaining European science and technology leadership through affordable and efficient solar fuel technologies are included as expected outcomes.[341] The call references supporting energy security. Calls from the previous work package (WP) do mention supporting training and skills development (technology agnostic).[342] CRMs are identified as a priority area for EU solar industry. SolarPower Europe has a supply chain sustainability workstream.[343] The EU Solar strategy also aims to build supply chain resilience (including for CRM).[344] This is executed in a general Horizon call on renewable energies and renewable fuel technologies.[345]	For example, the U.S. DOE Office of Basic Energy Sciences is one of the 'largest supporters of fundamental research into solar fuels' and funds the Fuels from Sunlight Energy Innovation Hub (now the Joint Center for Artificial Photosynthesis).[347] It is not clear whether it targets the identified criticalities. Mission Innovation launched a global initiative in 2016, IC5-Converting Sunlight into Solar Fuels and Chemicals, to discover affordable ways to develop direct solar fuels.[348] Horizon Europe–associated countries: The UK is investing in solar fuel research, including academic research, in particular in the context of developing solutions for sustainable aviation fuel.[349] Potential solutions are in development for cost reduction. Algae-based renewable fuels do not require CRMs, and algae-based catalysts can be engineered to produce solar fuels and complex chemicals.[350]
Weaknesses (internal – EU) Horizon Europe solar fuels calls considering sustainability and circularity aspects do not focus on reducing CRM use or supply chain resilience.[351] EU-based industry is there but not producing enough capacity, so the EU is not prepared for any negative impacts on CRM supply.[352]	**Threats** (external) The UK's Advanced Fuels Fund provides GBP 165 million (ca. EUR 193 million) to strengthen the sector and support UK projects to reach an 'investment-ready' state, including projects led by UK industry.[353] We did not find evidence of existing solutions to reduce CRM use in solar fuels technologies. Cost competitiveness is highlighted as an area of concern for solar fuels.[354]

[334] Validation workshop.

[335] European Commission (2022), *Clean Energy Technology Observatory, Direct Solar Fuels in the European Union – 2022 Status Report on Technology Development, Trends, Value Chains and Markets*, Publications Office of the European Union, Luxembourg.

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[337] European Commission, Solar Industry Regions Europe (SIRE) (accessed 2024); European Commission, Solar S3 Partnership (accessed 2023).

[338] European Commission (2023), *Clean Energy Technology Observatory, Solar Fuels in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets*, Publications Office of the European Union, Luxembourg.

[339] European Commission (2023), Horizon Europe Work Programme 2023-2024, Climate Energy and Mobility, call: HORIZON-CL5-2023-D3-03-07 (Digital solutions for defining synergies in international renewable energy value chains).

[340] European Commission (2021), Horizon Europe Work Programme 2021-2022, Climate Energy and Mobility, call: HORIZON-CL5-2022-D3-02-08 (Demonstration of complete value chains for advanced biofuel and non-biological renewable fuel production).

[341] European Commission (2023), Horizon Europe Work Programme 2023-2024, Climate Energy and Mobility, call: HORIZON-CL5-2024-D3-01-04 (Improvement of light harvesting and Carbon fixation with synthetic biology and/or bio-inspired//biomimetic pathways for renewable direct solar fuels production), call: HORIZON-CL5-2023-D3-03-07 (Digital solutions for defining synergies in international renewable energy value chains), call: HORIZON-CL5-2024-D3-02-02 (Development of next generation synthetic renewable fuel technologies); European Commission (2021), Horizon Europe Work Programme 2021-2022, Climate Energy and Mobility, call: HORIZON-CL5-2022-D3-02-08 (Demonstration of complete value chains for advanced biofuel and non-biological renewable fuel production).

[342] European Commission (2021), Horizon Europe Work Programme 2021-2022, Climate Energy and Mobility, call: HORIZON-CL5-2021-D3-02-02 (Sustainability and educational aspects for renewable energy and renewable fuel technologies).

[343] SolarPower Europe, Supply Chain Sustainability (accessed 2023).

[344] European Commission (May 2022), EU Solar Energy Strategy.

[345] European Commission (2021), Horizon Europe Work Programme 2021-2022, Climate Energy and Mobility, call: HORIZON-CL5-2021-D3-02-02 (Sustainability and educational aspects for renewable energy and renewable fuel technologies); European Commission (2021), Horizon Europe Work Programme 2021-2022, Climate Energy and Mobility, call: HORIZON-CL5-2022-D3-02-04 (Technological interfaces between solar fuel technologies and other renewables).

[346] European Commission (2022), *Clean Energy Technology Observatory, Direct Solar Fuels in the European Union – 2022 Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.

[347] U.S. Department of Energy, DOE Explains … Solar Fuels (accessed 2023); Joint Center for Artificial Photosynthesis (accessed 2023).

[348] Mission Innovation, IC5: Converting Sunlight, https://mission-innovation.net/our-work/innovation-challenges/converting-sunlight/(*accessed* 2024).

[349] UKRI-Innovate UK, Sustainable Aviation Fuel Innovation Programme (accessed 2023).

[350] Pre-workshop exercise input.

[351] European Commission (2023), Horizon Europe Work Programme 2023-2024, Climate Energy and Mobility, call: HORIZON-CL5-2023-D3-01-07 (Demonstration of synthetic renewable fuel for aviation and/or shipping).

[352] PV Magazine (October 2023), Europe to add 58 gW of solar in 2023; SolarPower Europe, EU Solar Manufacturing Map (accessed 2023); validation workshop.

[353] UK Government, Department for Transport (9 January 2024), Advanced Fuels Fund (AFF) Competition Winners (accessed 2023).

[354] European Commission (2023), *Clean Energy Technology Observatory, Solar Fuels in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.

8.10. Carbon capture and storage

8.10.1. Key criticality 1: broader sustainability (environment impact)

Description of criticality: CCS is faced with a number of sustainability issues contributing towards an overall risk to the security of the value chain, in particular with regards to deployment. Concerns and environmental risks linked to CCS include fossil fuel lock-in, additional emissions from enhanced oil recovery for injection of carbon dioxide, leakage and seismic activity linked to carbon storage, potential negative impacts on local biodiversity of large infrastructure projects, and carbon leakages.

➔ **R&I challenge**: How can the environmental impacts of CCS be reduced or mitigated?

EU R&I SWOT assessment: Strength–Opportunity

Summary of SWOT assessment. The EU has a strong R&I ecosystem, is supporting R&I programmes that address this criticality and is putting together a strategy on carbon management. It is worth noting that significant R&I activities in this area are supported or taking place globally in the private sector, with knowledge potentially less likely to be shared.

Proposed R&I intervention. The EU is supporting R&I targeted at this challenge. A follow-up to existing R&I programmes may be valuable if gaps are identified or further research is needed.

8.10.2. Key criticality 2: broader sustainability (public opinion)

Description of criticality: The environmental impacts are uncertain and could present a risk to the deployment of CCS in a context of increasing environmental protection regulation and worsening public concern.

➔ **R&I challenge**: What factors influence public opinion on CCS and How can the public be better engaged with regards to deployment of CCS?

EU R&I SWOT assessment: Strength–Opportunity

Summary of SWOT assessment. The EU has a strong R&I ecosystem with regards to this criticality, with both EU programmes supporting R&I on this topic indirectly and other organisations in the EU pursuing specific research and public engagement. International research is also being carried out on the topic, providing opportunities for knowledge sharing.

Proposed R&I intervention. The EU is supporting R&I targeted at this challenge. A follow-up to existing R&I programmes may be valuable if gaps are identified or further research is needed.

8.10.3. Key criticality 3: affordability

Description of criticality: CCS has high capital and running costs and requires significant infrastructure; however, financial revenues are dependent on carbon markets and are currently limited. ➔ **R&I challenge**: How can CCS business and revenue models be commercially attractive? EU R&I SWOT assessment: Strength–Threat

Summary of SWOT assessment. The EU has a strong CCUS R&I ecosystem and is supporting R&I for cost reduction, including some work on societal readiness and business models. The policy framework is also evolving with the reform of the ETS and targets CO_2 storage. The commercial viability of CCUS is, however, tied to the carbon price, and it is uncertain how international carbon markets may evolve.

Proposed R&I intervention. R&I is not the prime mechanism to address this criticality. Policy to support viable business models may provide a more impactful solution and complement existing R&I, supporting cost reduction that is already taking place. Further development of DAC technology at higher TRL is needed, which will be critical for reducing the cost of CCUS.[355]

Table 8.10 SWOT – evidence overview for EU carbon capture and storage R&I

Strengths (internal – EU)	**Opportunities** (external)
Since 2020, the EU is ranked first globally for high-value inventions.[356] In 2021, EU public R&I investment reached the highest level since 2010. The Horizon 2023-2024 work plan includes EUR 78 million in funding for CCUS projects.[357] Private R&I funding for CCUS has been relatively stable in the EU, with Germany, France, the Netherlands, Italy and Spain being the top five countries in terms of private R&I investment in CCUS. In the EU, Sweden ranks the highest in VC investments (EUR 4.5 million).[358] In 2010, EU public investment in CCUS was at a 10-year high, with EUR 140 million in funding.[359] The NER300 initiative provided EUR 300 million in 2014. [360] The EUR 2 million Coordination and support action under Horizon Europe aims to fund CCUS hubs and clusters to accelerate progress along the CCUS value chain.[361] The Zero Emissions Platform is the relevant ETIP for CCS and CCU. The EU's NZIA sets a target for CO_2 storage capacity by 2030, creating a pull for CCS and CCU deployment. The EU's 2024 industrial	Potential for collaboration: The United States, Canada, Japan, Australia and Korea are the countries investing the most in RD&D.[371] Horizon partners: The UK pledged to invest GBP 115 million (ca. EUR 134 million) in R&I projects.[372] Norway established a new research centre for CO_2 capture, transport and storage as part of the Centres for Environment-Friendly Energy Research (FME scheme).[373] The Norwegian CCS Research Centre is a research consortium that includes several Norwegian universities, research institutes, and industry partners. The consortium is focused on developing new technologies and solutions for CCS, including methods for monitoring and mitigating the environmental impacts of CCS.[374] Global VC investment reached record high of USD 2.3 billion (ca. EUR 2.1 billion) in 2022.[375] The agenda for COP28 includes discussion and potential progress on global carbon trading.[376] Business confidence is increasing along with increased policy action and investment globally.[377]

carbon management strategy supports this, with a target of 250 million tonnes/year CO_2 injection capacity. The strategy aims to provide guidance on storage permitting and suitable sites ('investment atlas'), focusing on linking up CO_2 sources to storage and providing regulatory certainty.[362] The EU also recently reformed its Emissions Trading Scheme.[363] Horizon Europe calls for CCUS show considerations for environmental impacts. Examples include HORIZON-CL5-2023-D3-02-01 and HORIZON-CL5-2023-D3-01-17, which both include environmental impacts and risks in their project aims and requirements.[364] EU-based organisations are developing solutions and research on the environmental impacts of CCS, including TNO and Strategies for Environmental Monitoring of Marine Carbon Capture and Storage (STEMM-CCS).[365] Several Horizon Europe calls consider societal readiness and public opinion for CCUS, in some cases through deliberative activities with members of civil society.[366] EU-based institutions have researched public attitudes towards CCS, including the Danish Technical University (DTU) and private sector organisations, such as NearCO2.[367] Public opinion and societal considerations are addressed in such initiatives as the European Commission's public consultation on industrial carbon management (which includes aspects of CCS).[368] Several Horizon Europe programmes include aims to reduce the cost of CCUS directly or indirectly.[369] The C4U project includes work packages on societal readiness and business models.[370]	Existing partnership: Korea announced a Green Partnership with the EU intending to enhance cooperation on low-carbon technologies, including CCUS.[378] The Net-Zero Industries Mission led by Australia and Austria includes CCUS development and CO_2 transport and storage as key innovation priorities.[379] Germany and the Netherlands participate in the global Clean Energy Ministerial CCUS initiative, which brings together financing, industry collaboration and knowledge sharing.[380] The Carbon Dioxide Removal Mission (led by the United States, Saudi Arabia and Canada, with support from the European Commission) aims to reduce CO_2 emissions by 1000 million metric tonnes per year by 2030.[381] Public laboratories and universities in other countries are also researching public attitudes to CCS, including the US National Energy Technology Laboratory and Zurich Insurance's Institute for Environmental Decisions.[382] Alternative business models outside of the EU demonstrate the potential for EU models to adopt alternative, commercially viable business models for CCS. Examples include China's Yanchang integrated CCS demonstration project, which utilises a 'vertical integration model' involving a single company operating all elements of the CCS chain, from capture to transportation and storage.[383] The IEA states identified significant opportunity for cost reduction.[384]
Weaknesses (internal – EU) The EU is not the global leader for investment and publications. Germany is the only EU country in the top 7 countries globally for innovating companies.[385] There are a number of potential gaps identified in current EU R&I programmes, including on-board carbon capture and fuel production for waterborne transport and the use of CCU abatement technologies in the lifecycle of industrial products and processes.[386]	**Threats** (external) Other countries are making significant investments, including the private sector in the United States, Switzerland, the UK, Australia and Canada.[388] New entrants present a significant threat, with 40% of VC companies being new as of 2020.[389] The grant funding for international VC companies is twice that reported by EU companies.[390] VC investment is dominated by US companies, totalling around 80% of the cumulative total in the 2015-2022 period. In

EU VC investment is low relative to the top countries investing in VC. In recent years, in Germany, ventures between the years of 2010 to 2015 were high (EUR 16 million); however, between 2016 and 2021, VC investment plummeted.[387]	comparison, European companies represent 15% of the total investment.[391] The U.S. DOE has several programmes focused on CCS, which aim to develop new technologies and solutions for CCS that minimise its environmental impacts.[392] The Japan CCS Co., Ltd, is a joint venture among several Japanese companies that is focused on developing CCS projects in Japan.[393] The company has developed new methods for monitoring and mitigating the environmental impacts of CCS, including methods for detecting and preventing CO_2 leakage.[394] The UK announced GBP 20 billion (ca. EUR 23.3 billion) for the deployment of CCUS projects.[395] Uncertainty and lack of confidence in carbon markets, as well as the need for different business models across the CCUS value chain, may present risk to increasing investment and deployment.[396]

[355] Validation workshop.

[356] European Union (2023), *Clean Energy Technology Observatory, Carbon Capture, Utilisation and Storage in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets*, Publications Office of the European Union, Luxembourg. Definition: 'High-value inventions (or high-value patent families) refer to patent families that include patent applications filed in more than one patent office'.

[357] European Commission (2023), Horizon Europe Work Programme 2023-2024, Climate Energy and Mobility.

[358] European Union (2022), *Clean Energy Technology Observatory, Carbon Capture, Utilisation and Storage in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets*, Publications Office of the European Union, Luxembourg.

[359] European Union (2022), *Clean Energy Technology Observatory, Carbon Capture, Utilisation and Storage in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets*, Publications Office of the European Union, Luxembourg.

[360] European Commission, NER 300 Programme (accessed 2023).

[361] European Commission (2021), Horizon Europe Work Programme 2021-2022, Climate Energy and Mobility, call: HORIZON-CL5-2021-D3-02-12 (Integration of CCUS in hubs and clusters, including knowledge sharing activities).

[362] European Commission (February 2024), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Towards an ambitions Industrial Carbon Management for the EU; European Commission, Industrial Carbon Management – Carbon Capture, Utilisation and Storage Deployment (accessed 2023).

[363] European Council, Infographic – Fit for 55: Reform of the EU emissions trading system (accessed 2023).

[364] European Commission (2023), Horizon Europe Work Programme 2023-2024, Climate Energy and Mobility.

[365] TNO, Multi-partner ALIGN-CCUS Project (accessed 2023); STEM-CCS, www.stemm-ccs.eu (accessed 2023).

[366] European Commission (2023), Horizon Europe Work Programme 2023-2024, Climate Energy and Mobility, calls: HORIZON-CL5-2024-D3-02-11, HORIZON-CL5-2024-D3-02-12, HORIZON-CL5-2021-D3-02-12.

[367] Upham, P., Roberts, T. (2011), Public Perceptions of CCS in Context: Results of *NearCO₂* focus groups in the UK, Belgium, the Netherlands, Germany, Spain and Poland, *Energy Procedia* 4, 6338-6344, doi.org/10.1016/j.egypro.2011.02.650; Danish Technical University, Public Acceptance and Perception

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[368] European Commission, Industrial Carbon Management – Carbon Capture, Utilisation and Storage Deployment (accessed 2023).

[369] European Commission (2023), Horizon Europe Work Programme 2023-2024, Climate Energy and Mobility, call: HORIZON-CL5-2023-D3-02-01; European Commission (2021), Horizon Europe Work Programme 2021-2022, Climate Energy and Mobility, call: HORIZON-CL5-2021-D3-02-12, HORIZON-CL5-2021-D3-02-13.

[370] C4U (accessed 2023).

[371] European Union (2022), *Clean Energy Technology Observatory, Carbon Capture, Utilisation and Storage in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets*, Publications Office of the European Union, Luxembourg.

[372] UK Government, Department for Energy Security and Net Zero, CCUS Net Zero Investment Roadmap.

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8.11. Batteries

8.11.1. Key criticality 1: availability of critical raw materials (lithium, cobalt, nickel, aluminium, graphite, vanadium, manganese, copper, silicon metal, phosphorus, niobium)

Description of criticality: Batteries used today are heavily dependent on CRMs, and there is significant risk around future availability and risk to disruption of supply. Many of these materials are mined and processed outside the EU, and mining and processing is dominated by a small number of countries. Global demand is also expected to significantly increase, with risk of scarcity of resources if supply does not increase to meet demand. Furthermore, the environmental impact and related carbon emissions of mining these CRMs is significant, leading to global warming potential for lithium-ion batteries estimated at 30-200 kg CO_2 eq. per kWh. For redox-flow batteries, the production of vanadium pentoxide (V_2O_5) cathode has a global warming potential of 180 kg CO_2 eq. per kWh.

➔ **R&I challenge**: How can the reliance on and need for CRMs in batteries be reduced?

EU R&I SWOT assessment: Strength–Opportunity

Summary of SWOT assessment. Molten salt batteries or batteries without CRMs are a potential solution to this criticality. The EU has leading expertise in this area, with existing research programmes and companies developing the technology. However, it is important to note that this assessment could rapidly change to threat without intervention as competition is likely to increase with other countries concerned with this criticality.

Proposed R&I intervention. Based on the above analysis, the following interventions are proposed:

- **R&I action 1**: Batteries with reduced CRMs may provide a strategic opportunity for the EU to both reduce its reliance on CRMs and develop an EU-based supply chain for batteries. The scale of the challenge should be carefully considered, with potential for a portfolio of R&I interventions to support the successful development and commercialisation of batteries without CRMs. Examples are complimentary Horizon, EIC, ERC and structural funds to provide a coherent and end-to-end package of support addressing lower TRL research challenges, late-stage development, university–industry exchange and business growth including start-ups.

- **R&I action 2:** Further R&I to solve challenges regarding recycling of batteries is needed to improve overall access to CRMs and thereby reduce dependencies on imported CRMs and contribute to circular economy objectives. However, recycling and reuse have lower potential for impact on energy security than do batteries with reduced CRMs, as suggested above, and existing R&I programmes are ongoing, so this action is not proposed for the R&I action plan.

8.11.2. Key criticality 2: supply chain location

Description of criticality: Supply chains for raw materials are located in a small number of non-EU countries. The supply chain for lithium-ion batteries, including the supply chain for manufacturing equipment, is predominantly outside the EU, and it would require significant investment for an EU-based supply to become price-competitive.

➔ **R&I challenge**: How can the EU R&I ecosystem contribute to onshoring of battery technology?

EU R&I SWOT assessment: Weakness–Threat

Summary of SWOT assessment. The EU faces significant challenges with this criticality. The EU is not in a strong position to outcompete leading lithium-ion battery suppliers with R&I and to become cost competitive, because investment continues to increase globally. An alternative take on this challenge would be to focus on developing new battery technologies where the EU has existing strengths and comparative advantage over competitors, linking to the R&I action above.

Proposed R&I intervention. Significant investment in battery production within Europe has already been announced, and R&I may not be an effective solution to effecting onshoring of battery value chains to the EU. This may be more effectively achieved through acquisition or policy interventions. In the case of acquisition, complementary skills and R&I programmes to support continued innovation and competitiveness that may be key to achieving overall energy security objectives. Developing an EU-based CRM-free battery value chain may provide an alternative solution, with proposed R&I interventions suggested in key criticality 1.

- **R&I action**: The battery manufacturing supply chain is energy intensive, placing the EU at a disadvantage due to high energy costs in the EU. The EU should support Horizon programmes to improve the energy efficiency and circularity of battery manufacturing. The call should be open to allow for a range of stages of the supply chain and processes to be addressed, including manufacturing processes and alternative materials.

Table 8.11 SWOT – evidence overview for EU batteries R&I

Strengths (internal – EU)	**Opportunities** (external)
Two Important Projects of Common European Interest (IPCEI) on batteries R&I started in 2020 and 2021, with EUR 14 billion of private investment into battery value chain development in the EU, providing opportunities for private sector investment.[397] EU companies (particularly in Germany and Sweden) are set to gradually gain importance in the market by constructing new gigafactories.[398] Calls from the Horizon Europe 2021-2022 work programme aim to reduce the use of CRMs in batteries via circular economy and recycling initiatives.[399] Batteries Europe has a working group on CRMs looking at sustainable sourcing and	Horizon partners: The UK announced GBP 69.5 million (EUR 81 million) in funding for innovative, longer-duration energy storage projects.[408] Norway granted funding in 2016 to establish a new research centre on Zero Emission Energy Systems for Transport, as part of the Centres for Environment-Friendly Energy Research (FME scheme), with research areas 1 and 3 relating to batteries.[409] Northvolt is a Swedish battery manufacturer that is carrying out a joint venture (called Hydrovolt) with the Norwegian company Hydro, to recover valuable metals from batteries, aiming to recycle 12 000 tonnes of battery packs annually. [410]

processing, recycling EOL batteries and setting out a roadmap for CRMs and recycling.[400] The Swedish company Northvolt has developed a promising sodium-ion battery, with benefits including increased safety and sustainability and reduced use of CRMs.[401] Saft is a French battery manufacturer that is developing new battery chemistries that use fewer CRMs.[402] Germany has launched a research project called Battery Recycling 2.0, which aims to develop new recycling technologies for lithium-ion batteries. The project is funded by the German Federal Ministry of Education and Research and involves several universities and research institutions.[403] Finland has launched a project called BATCircle, which aims to develop a circular economy for the battery industry. The project involves several companies and research institutions and focuses on developing new recycling technologies and business models.[404] Research Production Battery Cells Germany (also known by the acronym FoFeBat) is a joint initiative between the German government and several companies, including the Fraunhofer Research Institution for Battery Cell Production. The project aims to support the development of a domestic battery cell industry by funding research and development, as well as the construction of battery cell factories.[405] Umicore, headquartered in Belgium, is a global materials technology company that specialises in recycling and refining metals, including CRMs used in batteries.[406] The EU has strengths in materials research and digitisation, which could accelerate R&I in materials and manufacturing.[407]	Global investment in battery energy storage exceeded USD 20 billion (ca. EUR 18.5 billion) in 2022, with notable investment in China, the United States, India, and the EU.[411] Private equity and VC investments in battery developers reached all-time highs in 2021, amounting to EUR 10.6 billion, indicating a strong interest in investing in battery technology. [412] Alternative technologies to lithium-ion batteries are being developed, with lower reliance on CRM, including, for example, sodium-ion batteries.
Weaknesses (internal – EU) Among the top 5 countries leading in battery innovation, Germany ranks fourth, and the other positions are occupied by countries outside of the EU.[413] Despite several EU initiatives, the supply gap for battery raw materials increased in 2021. Spent batteries are still mostly sent to Asia for recycling.[414] Recycling needs are expected to increase drastically in future, which the EU is as yet unprepared for.[415] CRM: There is a risk of scarcity of resources if supply does not increase with demand or	**Threats** (external) VC investment increased significantly in 2021 and 2021 and is dominated by the rest of the world, outside the EU.[420] Japan, Korea, China, the United States, Taiwan and Canada are the top countries for high-value inventions.[421] China, the United States and India are making significant investments in deployment projects. China in particular has capacity addition plans far exceeding those of other regions.[422]

demand does not move away from the increasingly scarce resources.[416] The EU has been slower at adopting lithium iron phosphate (shortened to LFP) technology, increasingly used in Asia due to its lower dependency on CRM cost effectiveness.[417] Battery supply chains are energy intensive, and the EU is not a cost-competitive environment for such processes.[418] Public perceptions of battery manufacturing and related processes was raised as an area of concern in the validation workshop.[419]	Japan has pledged JPY 120 billion (ca. EUR 738 million) between 2021-2030 to research battery materials and recycling technology, as part of its Green Innovation Fund.[423] The U.S. DOE is investing USD 192 million (ca. EUR 178 million) to advance battery recycling and remanufacturing technologies and for the Battery Recycling Prize, which has to date awarded USD 5.5 million (ca. EUR 5.1 million) for innovative solutions to collecting, sorting, storing and transporting spent and discarded lithium-ion batteries.[424] Examples of established battery recycling companies outside the EU are the Japan Portable Rechargeable Battery Recycling Center, which works with battery manufacturers, recyclers and government agencies to develop and implement recycling technologies and policies.[425] The IRA in the United States aims to support the development of a domestic battery industry by funding research and development, as well as the construction of battery manufacturing facilities.[426] China's Made in China 2025 plan includes targets for the production of eV and batteries and the new energy vehicle industry development plan, which includes subsidies for the development of battery manufacturing facilities.[427]

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8.12. Hydrogen

8.12.1. Key criticality 1: availability and abundance of critical raw materials (titanium, iridium, scandium)

Description of criticality: Hydrogen technology is dependent on CRMs for key components, with significant risk around future availability and risk to disruption of supply. Many of these materials are mined and processed outside the EU, and mining and processing are dominated by a small number of countries. Global demand is also expected to significantly increase, with risk of scarcity of resources if supply does not increase to meet demand.

➔ **R&I challenge:** How can the reliance on and need for CRMs in hydrogen technologies be reduced?

EU R&I SWOT assessment: Strength–Opportunity

Summary of SWOT assessment. This is a key challenge raised in the EU hydrogen strategy, with funding from the Clean Hydrogen JU and long-term research initiatives through the Clean Hydrogen Partnership.

Proposed R&I intervention. With existing programmes already addressing this issue, additional R&I intervention is not considered necessary at this stage.

8.12.2. Key criticality 2: broader sustainability (vulnerability to wider energy system dependence due to a significant requirement for renewable energy in hydrogen value chains)

Description of criticality: Large amounts of renewable energy are needed to produce hydrogen with electrolysers (including PEM and AEM), which can be subject to intermittencies. The electricity grid can also be subject to disruption, introducing a potential risk of the energy security of hydrogen value chains.

➔ **R&I challenge:** How can hydrogen production be more energy efficient and resilient to electricity supply disruption or flexibility?

EU R&I SWOT assessment: Strength–Opportunity

Summary of SWOT assessment. A number of Horizon Europe calls are addressing energy-efficiency challenges. This is a shared challenge, and there is targeted research in the United States and potential opportunity for collaboration.

Proposed R&I intervention. Existing EU programmes are addressing this challenge. The EU may wish to pursue further R&I programmes where gaps or further research are identified and pursue collaboration with other countries to accelerate solutions with international R&I and knowledge exchange. Inputs from the validation workshop to support this criticality were focused on development of the electricity grid.

8.12.3. Key criticality 3: broader sustainability and environment impact

Description of criticality: Large volumes of pure water are needed to produce hydrogen. PFAS are required for certain hydrogen value chains; however, the EU has a commitment to phase out use of PFAS.

➔ **R&I challenge:** How can hydrogen production be more environmentally sustainable?

EU R&I SWOT assessment: Strength–Threat

Summary of SWOT assessment. The EU is supporting relevant R&I with regards to potential environmental impacts of hydrogen, including water use. With regards to PFAS, regulation could create drivers for innovation, or further research on environmental impacts may identify PFAS materials with limited impact. Potential solutions are available, and the Clean Hydrogen Partnership has focused R&I support on alternatives to the fluoropolymer polytetrafluoroethylene (shortened to PTFE) membranes and on demonstrating the low environmental impact of fluoropolymers. However, in some cases, solutions are now commercialised by non-EU companies, which may create a threat introducing a competitive, EU-based solution.

Proposed R&I intervention. Based on the above analysis, the following intervention is proposed:

- **R&I action:** A dedicated research programme on the environmental impact of hydrogen and further evaluation of potential environmental impacts of PFAS used in hydrogen processes would support evidence-based policy.

8.12.4. Key criticality 4: affordability

Description of criticality: The costs of producing hydrogen, in particular with alkaline and PEM electrolysers, are currently high and they are uncertain for other technologies. Costs of electrolysers and the hydrogen are expected to decline in future; however, they are currently an important barrier in commercial implementation of the technology and in its energy security.

➔ **R&I challenge:** How can the cost of hydrogen production be reduced?

EU R&I SWOT assessment: Strength–Opportunity

Summary of SWOT assessment. This is a key challenge raised in the EU hydrogen strategy with funding from the Clean Hydrogen JU.

Proposed R&I intervention. Existing EU programmes are addressing this challenge. The EU may wish to pursue further R&I programmes where gaps or further research are identified.

8.12.5. Key criticality 5: supply chain complexity

Description of criticality: The supply chains for PEM are complex and are vulnerable to disruption. With regards to solid oxide and alkaline AEM, the supply chains are not yet established, and there is uncertainty over future complexity and vulnerability.

➔ **R&I challenge:** How can the resilience of hydrogen supply chains be increased?

EU R&I SWOT: Weakness–Threat

Summary of SWOT assessment. The EU is not currently supporting R&I focused on development of resilient hydrogen supply chains in the EU. With international competition and interventions, such as the IRA in the United States, increasing investment and incentives for supply chains outside the EU, there is a potential threat from inaction for developing supply chains.

Proposed R&I intervention. Based on the above analysis, the following intervention is proposed:

- **R&I action**: Given that there are a significant number of key criticalities, the EU should develop an open Horizon call for resilient hydrogen value chains, specifying the aims rather than the solutions to develop, to target energy security and resilience. Further to this, consideration of supply chain resilience should be incorporated into existing hydrogen R&I programmes to ensure that energy security is included as part of the development of future hydrogen supply chains in the EU.

Table 8.12 SWOT – evidence overview for EU hydrogen R&I

Strengths (internal – EU)	**Opportunities** (external)
EU public R&I support has totalled EUR 150 million since 2008.[428] The EU produced 30% of global high-value inventions in 2018-2020. The EU adopted a strategy on hydrogen in 2020, which calls for long-term R&I investments for hydrogen as a fuel, as well as calling for research on securing CRM supply and reducing use and costs of hydrogen infrastructure.[429] The EU is developing the European Hydrogen Bank[430] to incentivise infrastructure deployment. The EU has ongoing and upcoming research on ‘hydrogen valleys’ through the Clean Hydrogen Partnership[431] and the S3 partnership[432] and at the R&I level.[433] Two IPCEIs are focused on hydrogen, with EUR 10.6 billion in public funding and up to EUR 15.8 billion in private funding providing support across the hydrogen supply chain.[434] The Clean Hydrogen Partnership supports R&I into alternatives to PTFE membranes (a Strategic Research Challenge) and	Existing partnership: New Zealand is collaborating with Germany to award funding for 2021-2026 to support the development of the German–NZ Green Hydrogen Centre.[451] The Net-Zero Industries Mission (led by Australia and Austria) includes developing hydrogen infrastructure roadmaps as a key innovation priority.[452] The Clean Hydrogen Mission (led by Australia, Chile, the UK, the United States and the EU) aims to ‘increase the cost-competitiveness of clean hydrogen’.[453] The Zero-Emission Shipping Mission (led by Denmark, Norway, South Africa and two industry partners) also aims to get at least ‘5% of the deep-sea fleet’ to run on hydrogen or advanced biofuels.[454] Horizon Europe–associated countries: Norway announced NOK 310 million (ca. EUR 27 million) in 2023 to establish two research centres for hydrogen.[455] The UK plans to provide GBP 240 million (ca. EUR 27.6 million) in funding in 2022-2025 for the development and deployment of low-carbon hydrogen production.[456]

demonstration of low-impact fluoropolymers.[435] Europe leads in number of manufacturing companies and in solid oxide electrolysis. [436] Several active Horizon Europe projects have consideration for reducing CRM use in hydrogen production, including the Clean Hydrogen Partnership.[437,438] Energy security and autonomy of supply are keys outcome of one Horizon call,[439] and energy efficiency is also addressed in other calls.[440] Water management and efficiency are targeted in some EU-based research.[441] Waste2bioHy (an FP7 project) looked at treating wastewater simultaneously with hydrogen production.[442] The Clean Hydrogen JU includes environmental and sustainability aspects (including water resources, supply chains, CRM supply) in its overall mission and investments (EUR 10 million).[443] A Trinomics study for the EU on supply chain resilience found that three of four suppliers of solid oxide electrolysers were based in the EU.[444] The importance of solid oxide supply chains is recognised by a global non-profit organisation (the Ammonia Energy Association).[445] Private companies within the EU focusing on cost reduction or increasing the efficiency include Siemens (Germany), which is focused on increasing efficiency and reducing the cost of hydrogen production,[446] and Bosch (Germany), which is focused on reducing the cost of hydrogen electrolysis. [447] The IEA Global Hydrogen Report 2021 states 'The largest shares of manufacturing capacity are in Europe (60%) and China (35%)'.[448] Polyfluoroalkyl substances (PFAS) for PEM: European Chemicals Agency (ECHA) regulation is recognised as a potential driver of new research into PFAS (as has happened in the United States).[449] CRMs and PFAs: EU research calls expected to achieve TRL 4 by the end of the project.[450]	The United States, Japan, Korea and Canada are investing significantly in R&I and may provide collaboration opportunities.[457] India also makes up one of the top 10 countries with regards to scientific publication outputs, and this may provide collaboration opportunities.[458] Private investments (including both VC and private equity) in hydrogen-related firms increased by more than 50% year-on-year in 2022.[459] Global VC investments in green hydrogen production companies have more than doubled over 2016-2021, reaching an all-time high since 2010, indicating a growing interest in investing in this technology.[460] Shared challenge: Energy efficiency and costs of electrolysers (including solid oxide) are priority research areas of the US government.[461] Shared challenge: The U.S. DOE has committed USD 693 million (ca. EUR 876 million) to help drive clean hydrogen costs down by 60% by 2026.[462] China is investing heavily in driving down the costs of more efficient hydrogen electrolysis through R&I.[463] Affordability: Alternative modes of hydrogen production exist, to open the market and introduce considerable amounts of hydrogen in the short term and result in reduced cost (e.g. bio-hydrogen, low-carbon hydrogen, residual wastes to hydrogen, gas reforming with CCS, gasification/pyrolysis of residual biomass).[464]
Weaknesses (internal – EU) Of the innovative companies worldwide, 28% are based in the EU.[465] Germany, France	**Threats** (external) It is estimated that Chinese companies have half of the world's alkaline electrolysis

and Denmark are the only EU Member States in the top 10 countries for innovative companies (there is room to invest in other EU countries to develop their business leadership). Water and PFAs (PEM): The overall circularity or sustainability is considered in some Horizon Europe projects (e.g. 'decreasing negative environmental and social impacts'), but water and PFAs are not addressed explicitly.[466] Many current EU R&I efforts are focused on hydrogen value chains but do not target individual criticalities for energy security identified in this study. Vulnerability: The main issue regarding electrolytic hydrogen production is the very high amount of additional renewable or low-carbon renewable electricity generation that is needed.[467]	manufacturing capacity and that American companies have most of the world's PEM electrolysis manufacturing.[468] The IRA and Bipartisan Infrastructure Law in the United States provides more than USD 9.5 billion (ca. EUR 8.8 billion) funding and tax credits for hydrogen production, significantly increasing the scale and profitability of the hydrogen industry in the United States.[469] The United States has the highest number of start-ups for hydrogen.[470] Japan launched its hydrogen strategy in 2023 and plans to generate JPY 15 trillion (ca. EUR 92 billion) of public and private investment in its hydrogen industry over 15 years. The budget will be shared between R&I and production subsidy.[471] The EU Clean Energy Technology Observatory (CETO) report noted that Japan had the second-highest number of innovative companies and the highest number of high-value inventions in 2018-2020.[472] **PFAs for PEM:** Hydrogen Europe recognises that there is no solution for PFAs, and incoming regulation from ECHA, restricting PFAs, could threaten the hydrogen sector.[473] Hydrogen Europe highlights that research is needed on this but does not envisage or expect breakthroughs. **PFAs for PEM**: The US company 3M and the Canadian company Ionomr (product: Pemion) have created PEM-containing alternatives to classic PFAs.[474] **Water:** The US company Plug is using methods to reduce water consumption (and therefore reduce pure water use).[475]

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[458] Commonwealth Scientific and Industrial Research Organisation (2022), Hydrogen RD&D Collaboration Opportunities: Global report, CSIRO, (accessed 2023).
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[460] European Commission (2022), Clean Energy Technology Observatory, Water Electrolysis and Hydrogen in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg.
[461] Department of Energy, Office of Energy Efficiency & Renewable Energy, Hydrogen Production: Electrolysis (accessed 2023).
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[463] S&P Global Commodity Insights (March 2022), China's First Hydrogen Plan Focused on Lowering Costs, Building Capabilities.
[464] Pre-workshop exercise input.
[465] European Commission (2023), Clean Energy Technology Observatory, Water Electrolysis and Hydrogen in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg.
[466] European Commission (2023), Horizon Europe Work Programme 2023-2024, Climate Energy and Mobility, calls: HORIZON-CL5-2023-D2-01-06 (Open Pilot Line/Test Bed for Hydrogen), HORIZON-CL5-2024-D3-02-02 (Development of next generation synthetic renewable fuel technologies).
[467] Validation workshop.
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8.13. Renewable fuels of non-biological origin

RFNBOs, direct solar fuels, hydrogen and CCU are interconnected, and it was challenging to find RFNBO-specific information; however, this technology was still analysed independently, for the sake of completeness.

8.13.1. Key criticality 1: supply chain complexity

Description of criticality: The supply chain for synthetic kerosene and its complexity are uncertain. In particular, complexity will be linked to the scale-up and availability of sustainable CO_2 from DAC, which is a supply chain that is still in development.

➔ **R&I challenge:** How can the resilience of RFNBO supply chains be increased?

EU R&I SWOT assessment: Strength–Opportunity

Summary of SWOT assessment. The EU has a strong CCUS and RFNBO R&I ecosystem and is supporting R&I for cost reduction. As RFNBOs are in early development stages, there is an opportunity to build consideration of this criticality into the development of the technology.

Proposed R&I intervention. Based on the above analysis, the following intervention is proposed:

- **R&I action:** This criticality would benefit form a targeted R&I programme, in line and adapted as the technology development progresses. For example, early-stage research may be valuable considering supply chain resilience. As technology development progresses, funding could focus on demonstrator programmes with objectives around supply chain resilience.

8.13.2. Key criticality 2: vulnerability to wider energy system dependence due to a significant requirement for renewable energy in renewable fuels of non-biological origin value chains

Description of criticality: Large amounts of renewable energy or hydrogen are needed to produce RFNBOs. The electricity grid can be subject to disruption,OC introducing a potential risk of the energy security of RFNBO value chains. The required development of electricity capacity may cause sustainability risks at the development locations (whether inside or outside the EU), which might obstruct other development and local energy availability.

➔ **R&I challenge:** How can the RFNBO value chain be more energy efficient and less vulnerable to grid-related disruptions?

EU R&I SWOT assessment: Strength–Opportunity

Summary of SWOT assessment. A number of Horizon Europe calls are addressing energy-efficiency challenges for hydrogen. This is a shared challenge, with targeted research in the US, resulting in a potential opportunity for collaboration.

Proposed R&I intervention. The criticality is also highlighted in the hydrogen section and under key criticality 3. An addition to the latter criticality may be valuable to consider any specificities for RFNBOs, where relevant, as part of existing or planned hydrogen efficiency R&I programmes.

8.13.3. Key criticality 3: affordability

Description of criticality: The costs of synthetic kerosene are linked to the cost of CO_2. In the case of synthetic kerosene produced through DAC of CO_2, costs are expected to be high, and considering that DAC is not the only source of carbon but has the potential to become the main source of carbon in future as other sectors decarbonise.

➔ **R&I challenge**: How can the cost of synthetic kerosene production be reduced?

EU R&I SWOT assessment: Strength–Threat

Summary of SWOT assessment. The EU has a strong CCUS and RFNBO R&I ecosystem and is supporting R&I for cost reduction. As RFNBOs are in early development stages, there is an opportunity to build consideration of this criticality into the development of the technology, including some work on societal readiness and business models.

Proposed R&I intervention. Technology-focused R&I for RFNBOs is not the prime mechanism to address this criticality directly. Additional policy research to support viable business models and R&I for hydrogen and carbon supply chains may provide a more impactful and effective solution. Complementary R&I may support cost reductions for the electrolyser.

- **R&I action**: A dedicated policy lab to identify viable business models needed to bring RFNBOs closer to market would help ensure that RFNBOs are affordable and resilient. Complementary studies on appropriate policy and regulatory interventions would support evidence-based policy to facilitate commercialisation. This solution was also highlighted for hydrogen in the validation workshop.

Table 8.13 SWOT – evidence overview for EU renewable fuels of non-biological origin R&I

Strengths (internal – EU)	**Opportunities** (external)
The EU is the top publisher of academic papers on RFNBO.[476] In 2017-2022, the EU attracted more than half of global late-stage investment.[477] EU R&I has supported the development of e-fuels technology with Horizon 2020 (EUR 114 million); however, Horizon Europe funding is more focused on feedstock, in particular hydrogen and carbon capture processes (that could then feed into an e-fuels value chain).[478] HORIZON-CL5-2024-D3-02-02 works towards the development of next-gen	Many projects outside of the EU focus on producing cost-effective green hydrogen, which is a critical component in the manufacture of synthetic kerosene.[490] EU researchers have collaborated the most for publications with researchers from the United Kingdom; Switzerland; and the rest of the world excluding the United States, China, Japan, South Korea and India.[491] Global investment in low emissions fuel increased by 66% from 2021 to 2022, reaching USD 13 billion (ca. EUR 12 billion); however, this includes biofuels.[492]

synthetic, cost-effective renewable fuel technologies.[479] RED III sets specific targets for RFNBOs, mandating that they account for at least 42% of hydrogen used in industry by 2030 and 60% by 2035. This is to encourage Member States to develop regulatory frameworks for achieving these targets.[480] ETIP's work on RFNBOs shows a commitment to research aimed at creating incentives for reducing the cost of RFNBOs, as well as an awareness of the key issues pertaining to the current costs.[481] Germany, France and the Netherlands have dedicated national research programmes to advance the development and cost reduction of RFNBOs.[482] Half of European companies working on these programmes are based in Germany.[483] The German Technical Inspection Association (known by the acronym TÜV SÜD) has launched a blockchain-based ecosystem that can track the renewable energy used for RFNBOs along the entire value chain, to deliver transparent and trustworthy certification.[484] There are various projects funded by the EU aimed at producing more viable, cost-effective green kerosene or kerosene precursors. Examples include: KEROGREEN [485] project, CARE-O-SENE [486] and KEROSyN100.[487] The EU Green Deal targets aviation emissions reductions of 89% by 2050. Synthetic kerosene is being developed as a sustainable aviation fuel (SAF), supported by the using the income generated by aviation emissions trading and future aviation fuel tax to foster R&I aimed at increasing energy efficiency and cost effectiveness.[488] Atmosfair – a non-profit organisation in Germany – aims to produce cost-effective, carbon-neutral synthetic kerosene by combining hydrogen generated by renewable electricity and CC with biomass.[489]	The U.S. DOE, the U.S. Department of Transportation, and the U.S. Department of Agriculture support research, development and analysis for SAF – which includes R&I relating to synthetic kerosene.[493]
Weaknesses (internal – EU) The criticalities are not specifically addressed for RFNBOs in EU R&I programmes.	**Threats** (external) The United States dominates VC investments.[494] The development of more efficient green hydrogen is an essential step towards reducing the cost of synthetic kerosene. China and Japan are key active players with regards to green hydrogen development.[495]

	The Joint Research Centre found no evidence of large private funding for e-fuels.[496]

[476] European Commission (2023), Clean Energy Technology Observatory, Renewable Fuels of Non-Biological Origin in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg.

[477] European Commission (2023), Clean Energy Technology Observatory, Renewable Fuels of Non-Biological Origin in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg.

[478] European Commission (2023), Clean Energy Technology Observatory, Renewable Fuels of Non-Biological Origin in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg.

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[482] DENA German Energy Agency (May 2023), Establishing a National Hydrogen Standard; Bouacida, I. (June 2023), France's Hydrogen Strategy: Focusing on domestic Hydrogen Production to decarbonise Industry and mobility, Research Institute for Sustainability Potsdam Discussion Paper; Platform Hernieuwbare Brandstoffen (2022), Results of Pilot Audits against Draft RED2 Requirements for RFNBO in Different Certification Schemes.

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[491] European Commission (2023), Clean Energy Technology Observatory, Renewable Fuels of Non-Biological Origin in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg.

[492] European Commission (2023), Clean Energy Technology Observatory, Renewable Fuels of Non-Biological Origin in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg.

[493] U.S. Department of Energy, Alternative Fuels Data Center: Sustainable aviation fuel (accessed 2023).

[494] European Commission (2023), Clean Energy Technology Observatory, Renewable Fuels of Non-Biological Origin in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg.

[495] Bruegel (August 2021), Hydrogen Development Strategies: A global perspective.

[496] European Commission (2023), Clean Energy Technology Observatory, Renewable Fuels of Non-Biological Origin in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg.

8.14. Heat pumps

8.14.1. Key criticality 1: availability and abundance of critical raw materials (copper, aluminium, nickel)

Description of criticality: Heat pumps require a significant amount of low-technology CRMs for semiconductor chips to operate. Disruption to global semiconductor value chains has resulted in delivery delays for heat pumps. The materials are available from up to four EU countries. However, global demand is expected to rise significantly, and the market is increasingly competitive, introducing a risk of scarcity and price increases that would affect the energy security of heat pump value chains.

➔ **R&I challenge:** How can the reliance on and need for CRMs in hydrogen technologies be reduced?

EU R&I SWOT assessment: Strength–Threat

Summary of SWOT assessment. The EU has a strong heat pump R&I ecosystem; however, there does not appear to be a technology solution for alternative materials. Recycling and circular economy initiatives may support the reuse of CRMs for heat pumps, and several EU initiatives exist already. The validation workshop noted that there was a need for more recycling infrastructure, likely focused on other materials and increasing demand. As demand for CRMs is expected to rise, further technology-agnostic intervention may be required.

Proposed R&I intervention. Recycling initiatives are in development, and further R&I was not deemed necessary at this stage.[497] With regards to the need for low-cost semiconductor chips, R&I mechanisms may not be the most effective to address security of supply. Policy may be better suited to this challenge, with a gap identified in the European Chips Act for low-technology electronics.[498] Semiconductor chip value chains, irrespective of the technology they are used for, were noted to be at risk in the validation workshop, and a separate criticality was identified for this.

8.14.2. Key criticality 2: physical vulnerability to wider energy system dependence due to a requirement for renewable energy to operate heat pumps

Description of criticality: Renewable energy is needed to operate heat pumps. Increased use of electricity for heating increases exposure to power outages and increased network connection capacity for companies. The electricity grid can be subject to disruption, introducing a potential risk of the energy security of heat pumps, with, for example, loss of heating during an electricity black-out. However, heat pumps have proven to be resilient to grid failures or anomalies, given their deployment in regions that have been affected by natural or human-made catastrophes, so the R&I challenge lies in their integration into a flexible electricity system.

➔ **R&I challenge:** How can thermal and electrical storage ensure that heat pumps are more resilient to electricity supply disruption, including by integration of these technologies into a flexible grid?

EU R&I SWOT assessment: Strength–Opportunity

Summary of SWOT assessment. The EU has a mature heat pump industry and an opportunity to set a market standard for resilient heat pumps. There are existing potential solutions to address the criticality.

Proposed R&I intervention. Based on the above analysis, the following intervention is proposed:

- **R&I action**: Existing solutions are available, and an effective approach to ensure that this criticality is addressed is regulation encouraging adoption of solutions and standards for resilient heat pumps.

Table 8.14 SWOT – evidence overview for EU heat pump R&I

Strengths (internal – EU) The EU is the global leader for public research investment and high-value inventions for heat pumps.[499] Most manufacturers' investment activities for production expansion are concentrated in Europe.[500] Relevant planned EU R&I includes Horizon-CL5-2023-D3-02-04 to increase performance and reduce environmental footprint of heat pumps (EUR 6 million), Horizon-CL5-2023-D3-02-06 for smart use of heat pumps (EUR 15 million), and Horizon-CL5-2023-D3-03-05 for a platform enabling integration of flexible heat pumps (EUR 5 million). Other planned EU R&I includes Horizon-CL5-2022-D3-01-10 (EUR 7 million), Horizon-CL5-2021-D4-01-04 (EUR 16 million), EIC Pathfinder Challenge (e.g. the topic clean and efficient cooling includes heat pumps in the scope).[501] Confidence in demand for industry: REPowerEU sets out the target for 20 million heat pumps to be installed by 2026 and close to 60 million by 2030.[502] This is supported with financing from the Social Climate Fund. An EU heat pump action plan is due for publication. Sales of heat pumps increased by 40% in Europe in 2022, with 3 million units sold.[503] The EU is home to 43% of innovating companies globally.	**Opportunities** (external) Significant players include Japan, Canada, Switzerland, Turkey and the UK.[504] Horizon partners: The UK plans to invest up to GBP 60 million (ca. EUR 70 million) through the Heat Pump Ready programme. It will support the development and demonstration of heat pump technologies and tools, as well as solutions for optimised deployment of heat pumps.[505] Turkey is receiving investments from the private sector to build R&I and production facilities. For example, Daikin Europe announced EUR 3.5 million investment in a Turkish R&I centre,[506] and Mitsubishi Electric announced GBP 89.6 million (ca. EUR 105 million) for a Turkish production plant.[507] Potential collaboration with the United States: It plans to invest USD 30 million (ca. EUR 27.7 million) in nine topic areas through the Buildings Energy Efficiency Frontiers and Innovation Technologies programme, with more than half of the projects related to heat pump R&I.[508] Potential existing solutions to grid failure are improvements in efficiency and flexibility,[509] including with integrated heat storage, [510] and building insulation to reduce heat loss.[511] International standards, including in the United States and the UK, include efficiency requirements. Recycling and substitution are viewed as potential strategies to mitigate the risk from CRMs, including reverting to simpler designs.[512]
Weaknesses (internal – EU) The Horizon Europe report *Strategic Plan 2025-2027 Analysis* highlights the need for demonstration of heat pumps in industrial environments, challenges with regards to	**Threats** (external) The United States leads in investments for companies, followed by Norway for early-stage investment.[516]

faster deployment and system integration, the need to cover wider temperature ranges and industry use cases, as well as heat upgrades. [513] The EU represented 10% of early-stage investment and 43% of later-stage investment in 2016-2021, totalling EUR 36.5 million.[514] Europe accounts for 9% of inventions, and we note that half are considered high value.[515]	The IRA in the United States provides rebates and a 30% tax credit for customers; the act is expected to incentivise the installation of heat pumps and increase its market share.[517] Heat pumps require copper, aluminium and nickel. These CRMs are all available in more than three EU countries. However, copper and nickel carry a medium abundance risk, and global demand is expected to significantly increase, with the potential that demand will outstrip supply. Of inventions globally, 58% were from China and 86% from the Asia-Pacific region. Only 1% of Chinese inventions are currently considered high value.[518] Japan, Turkey and the United States are part of the top five countries for high-value inventions.[519] China is a key collaborator with countries in the rest of the world (meaning non-EU).[520]

[497] Validation workshop.
[498] Validation workshop.
[499] European Commission (2023), *Clean Energy Technology Observatory, Heat Pumps in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.
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[501] European Innovation Council (2023), Work Programme.
[502] European Heat Pump Association (2022), REPowerEU: Heat pump strategy required to help sector deliver.
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[505] UK Government, Department for Business, Energy & Industrial Strategy (July 2022), Information about the Heat Pump Ready Programme.
[506] DAIKIN (November 2022), Daikin Europe Invests in New R&I Facilities in Turkey.
[507] RAC (May 2022), Mitsubishi Electric Invests £89.6m in European AC Production.
[508] U.S. Department of Energy (November 2023), BTO Announces BENEFIT 2024 Funding Opportunity up to $30 Million for Advances that Demonstrate, Optimize, and Facilitate Decarbonization of Building Systems; Cooling Post (August 2023), Heat Pump Projects in $46m DOE Funding Round.
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[512] European Commission, JRC (2023), The Heat Pump Wave: Opportunities and challenges, Publications Office of the European Union, Luxembourg.
[513] European Commission, DG RTD (2023), Horizon Europe Strategic Plan 2025-2027 analysis.

[514] European Commission (2023), *Clean Energy Technology Observatory, Heat Pumps in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.

[515] European Commission (2023), *Clean Energy Technology Observatory, Heat Pumps in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.

[516] European Commission (2023), *Clean Energy Technology Observatory, Heat Pumps in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.

[517] HVAC.com (July 2023), The Inflation Reduction Act "Pumps Up" Heat Pumps.

[518] European Commission (2023), *Clean Energy Technology Observatory, Heat Pumps in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.

[519] European Commission (2023), *Clean Energy Technology Observatory, Heat Pumps in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.

[520] European Commission (2023), *Clean Energy Technology Observatory, Heat Pumps in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.

8.15. Smart energy grid technologies

8.15.1. Key criticality 1: availability and abundance of critical raw materials and location of advanced electronics supply chains (palladium, cobalt, gallium, germanium, silicon, rare-earth materials)

Description of criticality: Smart grid technologies require a number of CRMs, in some cases only available from one or a small number of non-EU countries. Linked to this, the supply chains for advanced electronics are predominantly outside the EU, introducing potential risk to the security of these value chains. These criticalities are less relevant for eV smart charging.

➔ **R&I challenge:** How can the reliance on and need for CRMs in smart energy grid technologies be reduced?

EU R&I SWOT assessment: Weakness–Threat

Summary of SWOT assessment. The EU has set out policy ambitions to secure the supply of critical raw materials and semiconductors; however, securing supply is a significant challenge, and there is no technology-specific solution to reduce CRM use in smart energy grid technologies.

Proposed R&I intervention. There is currently no alternative to the use of CRMs in smart energy grid technology, and technology-agnostic initiatives will be needed to secure supply of CRMs and electronics.

- **R&I action 1**: R&I programmes should be undertaken to increase circular economy processes, recycling and reuse in smart technologies.
- **R&I action 2**: Actions should be taken as part of the EU Chips Act, and the Chips for Europe initiative should consider including clean energy technologies in their remit.

8.15.2. Key criticality 2: digital vulnerability

Description of criticality: Smart energy grid technologies are very digital dependent and inherently vulnerable to cyberattacks or disruption of digital networks, with potential negative impacts on the operation of the energy grid. AMI and HEMSs are vulnerable to data theft as well.

➔ **R&I challenge:** How can the digital vulnerability of smart energy grid technologies be reduced and mitigated?

EU R&I SWOT assessment: Weakness–Threat

Summary of SWOT assessment. The EU has initiatives specifically targeted at ensuring the cyber security of smart grid technologies. However, cyberattacks are a continuously evolving threat, and available, open-access information on this topic is sparse. Combined with the added risk of future digitalisation of energy systems and the importance of the grid to the development of numerous (intermittent) renewable energy–generation technologies requiring increased grid flexibilities, the EU lacks preparedness in this area. The development of smart grids to increase connectivity between EU countries will also be crucial.[521]

Proposed R&I intervention. Based on the above analysis, the following interventions are proposed:

- **R&I action 1**: Ongoing R&I programmes may support solutions to address cybersecurity risk, including research to ensure that cyber security can be maintained for legacy systems. Understanding of the evolution of threats would inform regulation and standards.

- **R&I action 2**: Cross-border programmes to increase coordination and cooperativity between Member States could include common actions on cybersecurity.

Table 8.15 SWOT – evidence overview for EU smart energy grid technology R&I

Strengths (internal – EU)	**Opportunities** (external)
Most key players in the smart eV charging market are based in the EU. The key players worldwide are ABB Group (Sweden/Switzerland), Bosch Automotive Service Solutions Inc. (Germany), Schneider Electric (France), GreenFlux and Alfen N.V. (Netherlands), Virta (Finland), Driivz and Tesla (the United States).[522] Demand for HEMS in the EU is expected to grow significantly in the coming years, with Germany being the largest market.[523] There are existing partnerships that the EU could (continue to) exploit, such as S3 Energy Partnership on Smart Grids.[524] The EU has set out policy targets and investments to reduce reliance on CRMs with the CRMs Act. Similarly, the EU Chips Act is intended to increase the resilience of EU semiconductor supply chains. EU-based supply chains may also support improved cybersecurity, with security by design and a reduced risk of back doors being introduced in non-EU value chains.[525] The Horizon 2020 project SPEAR looked at improving cybersecurity.[526] The revised Network and information security directive has been agreed and is due to be adapted. There are also proposals for a Cyber Resilience Act.[527] The European Standardisation Organisation, the European Committee for Standardization (known by the acronym CEN), the European Committee for Electrotechnical Standardization (known by the acronym CENELEC), and European Telecommunications Standards Institute (ETSI) have established the Smart Meters	Horizon partners: The UK has launched a Flexibility Innovation Programme to provide GBP 65 million (ca. EUR 76 million) funding for innovation of smart energy applications, including tariffs management, bi-directional electric vehicle charging, and smart metres.[531] Potential collaboration with the United States: The United States announced a Smart Grid Grants to invest USD 3 billion (ca. EUR 2.8 billion) between 2022 and 2026 on grid resilience technologies and solutions, including increasing transmission capacity, preventing system disturbances, integrating renewable energy, and integrating electrified vehicles, buildings, and other grid-edge devices.[532] Existing international partnerships: Denmark, Finland and Spain participate in the Clean Energy Ministerial Power Partnership (which includes work on smart grids),[533] while Italy co-leads the International Smart Grid Action Network, which includes other EU countries as well.[534] No existing alternatives exist to the use of CRMs. The United States and the EU were both first movers for the adoption and roll-out of advanced meters, with potential for shared challenges to be addressed with R&I collaboration.[535]

Coordination Group, with work on privacy and security and minimum-security requirements for smart metering.[528] The EU is expected to be the second-largest market for advanced meters, and a significant proportion of market leaders are based in the EU.[529] The EU has strengths in chips R&I, including world-leading research organisations and key companies in the global chips supply chain. Significant public funding is now being invested, including through an IPCEI with up to EUR 8.1 billion in in public funding.[530]	
Weaknesses (internal – EU) Limited information was available on publicly funder cyber security research. The EU is highly dependent on non-EU supply chains for electronics. Low investment in technological development of advanced meters was highlighted as a barrier.[536] The validation workshop noted that the EU will become digitally vulnerable in the event of further digitalisation and is currently unprepared to address this issue.[537] European utility companies scrambled to hire cybersecurity experts in the month following Russia's invasion of Ukraine, suggesting a lack of long-term cybersecurity strategy and a lack of preparation by European companies for cyberattacks.[538]	**Threats** (external) The IRA in the United States provides tax credits for the installation of smart meters. This is expected to largely increase the demand-side flexibility and optimise the electricity grid.[539] The IEA highlights several grid modernisation and digitalisation programmes in the EU, China, Japan, India, the United State and Canada.[540] Asia is expected to be the largest market for advanced meters.[541] Between 2020 and 2022, the average number of cyberattacks against utilities (including energy infrastructure) each week more than doubled worldwide.[542]

[521] Validation workshop.
[522] European Commission (2023), *Clean Energy Technology Observatory, Smart Grids in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.
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[527] European Commission (October 2022), Questions and Answers: EU action plan on digitalising the Energy system.
[528] CENELEC, Smart Grids and Meters (accessed 2023).
[529] European Commission (2023), *Clean Energy Technology Observatory, Smart Grids in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.
[530] European Commission (November 2023), European Chips Act – Questions and answers.

[531] UK Government, Department of Energy Security and Net Zero, Flexibility Innovation Programme (accessed 2023).
[532] U.S. Department of Energy, Grid Deployment Office, Smart Grid Grants (accessed 2023).
[533] Clean Energy Ministerial, 21st Century Power Partnership (accessed 2023).
[534] Clean Energy Ministerial, ISGAN – International Smart Grid Action Network (accessed 2023).
[535] European Commission (2023), *Clean Energy Technology Observatory, Smart Grids in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.
[536] European Commission (2023), *Clean Energy Technology Observatory, Smart Grids in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.
[537] Validation workshop.
[538] IEA (August 2023), Cybersecurity – Is the power system lagging behind?.
[539] Leap Energy (August 2022), How the Inflation Reduction Act Will Transform the Electric Grid.
[540] IEA (2023), Tracking Clean Energy Progress 2023: Smart grids.
[541] European Commission (2023), *Clean Energy Technology Observatory, Smart Grids in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets,* Publications Office of the European Union, Luxembourg.
[542] IEA (August 2023), Cybersecurity – Is the power system lagging behind?

8.16. Energy building and district heating technologies

8.16.1. Key criticality 1: availability and abundance of critical raw materials and location of advanced electronics supply chains (palladium, cobalt, gallium, germanium, silicon, rare-earth materials)

Description of criticality: Smart grid technologies require a number of CRMs, in some cases only available from one or a small number of non-EU countries. Linked to this, the supply chains for advanced electronics are predominantly outside the EU, introducing potential risk to the security of these value chains. These criticalities are less relevant for eV smart charging.

➔ **R&I challenge:** How can the reliance on and need for CRMs in smart energy grid technologies be reduced?

EU R&I SWOT assessment: Weakness–Threat

Summary of SWOT assessment. The EU has set out policy ambitions to secure the supply of critical raw materials and semiconductors; however, this is a significant challenge, and there is no technology-specific solution to reduce CRM use in smart energy grid technologies.

Proposed R&I intervention. There is currently no alternative to the use of CRMs in energy, and technology-agnostic initiatives will be needed to secure supply of CRMs and electronics.

- **R&I action 1**: R&I programmes are needed to increase circular economy processes, recycling and reuse in energy building and district heating technologies.
- **R&I action 2**: Actions taken as part of the EU Chips Act and the Chips for Europe initiative should consider clean energy technologies in their remit.

8.16.2. Key criticality 2: digital vulnerability

Description of criticality: Energy building and district heating technologies and very dependent on digital technologies and inherently vulnerable to cyberattacks or disruption of digital networks, with potential negative impacts on the operation of the technologies.

➔ **R&I challenge:** How can the digital vulnerability of energy building and district heating technologies be reduced and mitigated?

EU R&I SWOT assessment: Strength–Threat

The EU has initiatives specifically targeted at ensuring the cyber security of energy building and district heating technologies. However, cyberattacks are a continuously evolving threat, and available, open-access information on this topic is sparse.

Proposed R&I intervention. Based on the above analysis, the following intervention is proposed:

- **R&I action**: Ongoing R&I programmes may support solutions to address cybersecurity risk, including research to ensure cyber security can be maintained for legacy systems, as well as research understanding of the evolution of threats; this would inform regulation and standards.

Table 8.16 SWOT – evidence overview for EU energy building and district heating technologies R&I

Strengths (internal – EU) Existing EU S3 Energy Partnership on Sustainable Buildings.[543] The revised Network and information security directive has been adopted. There are also proposals for a Cyber Resilience Act.[544] A number of Horizon Europe projects are focused on the secure and resilience transition to a digital energy system, including eFORT[545] and SPEAR (the latter completed in 2021).[546] The CEN, CENELEC and ETSI have established the Smart Meters Coordination Group, with work on privacy and security and minimum-security requirements for smart metering.[547] The EU has strengths in chips R&I, including world-leading research organisations and key companies in the global chips supply chain. Significant public funding is now being invested, including through an IPCEI with up to EUR 8.1 billion in public funding.[548]	**Opportunities** (external) Potential collaboration with the United States: The U.S. DOE announced USD 10 million (ca. EUR 9.2 million) funding for innovations of district energy systems and energy management systems. The investment will be split between development and demonstration projects, on the one hand, and pilot projects for manufacturers to optimise energy efficiency through smart technologies, on the other hand, such as advanced sensors, controls, software platforms and data analytics.[549] AI and blockchain are two emerging technologies with potential to increase cybersecurity of energy technologies, such as smart meters and smart grids. Cybersecurity solutions are being launched by companies across the globe, including outside of the EU.[550]
Weaknesses (internal – EU) There is not currently an agreed cybersecurity standard for Europe, and retrofitting security can be challenging for meters that have already been installed.[551] Limited information is available on publicly (EU-) funded cyber security research. The EU is highly dependent on non-EU countries for electronics supply chains.	**Threats** (external) Cyber threats are constantly evolving and changing. Semiconductor and associated CRM value chains are critical for ACT. Electronics supply chains are vulnerable to shocks, and some of the required CRMs originate from one or a small number of countries. Recycling may contribute to the supply of these materials. However, demand is expected to continue to increase, with mining for new resources a requirement.

[543] European Commission, Sustainable Buildings Smart Specialisation Platform (accessed 2023); Note the S3 platforms are now run through the S3 Community of Practice, and activities are now part of the S3 Thematic Platform and Thematic Smart Specialisation Partnerships.

[544] European Commission (October 2022), Questions and Answers: EU action plan on digitalising the Energy system.

[545] eFORT project, http://www.efort-project.eu/ (accessed 2023).

546 Secure and Private Smart Grid Project (SPEAR), http://www.spear2020.eu/ (accessed 2023).
547 CENELEC, https://www.cencenelec.eu/ (accessed 2023).
548 European Commission (November 2023), European Chips Act – Questions and answers.
549 U.S. Department of Energy (July 2022), DOE Announces $10 Million for Renewably Supplied District Energy Systems and Regional Smart Manufacturing Pilot Initiatives.
550 Smart Energy International (November 2022), Enlit Europe: Cyber solution launched for smart meter manufacturers.
551 ESMIG, Securing Smart Meters (accessed 2023).

8.17. Off-grid energy systems

For the purpose of this study, the scope of this technology group covers heating based on renewable gas (biogas tanks) and heating based on solid biomass (pellet stoves).

8.17.1. Key criticality 1: availability and abundance of critical raw materials (copper, nickel, aluminium)

Description of criticality: Off-grid energy systems rely on certain CRMs. In particular, copper presents a potential challenge, with limited resources and increasing demand.

➔ **R&I challenge:** How can the reliance on and need for CRMs in off-grid energy technologies be reduced?

EU R&I SWOT assessment: Weakness–Threat

Summary of SWOT assessment. The EU has set out policy ambitions to secure the supply of CRMs. However, there is no technology-specific solution to reduce CRM use in smart off-grid technologies.

Proposed R&I intervention. No technology-specific solution is currently in development, and more general CRMs initiatives are needed to secure supply.

- **R&I action**: A discovery research programme focused on developing off-grid technologies without or with fewer CRMs would support the identification of potential solutions. However, with discovery research, it may take a number of years before solutions reach commercial application.

8.17.2. Key criticality 2: broader sustainability and environmental impacts

Description of criticality: The feedstock used for production of biogas for off-grid heating based on renewable gas (biogas tanks) is sometimes illegally polluted by prohibited biowaste (for instance slaughterhouse waste) or fossil waste (for instance chemical waste). This could end up in the food chain, through the digestate produced in addition to biogas. For pellet stoves, local air pollution is a broader sustainability issue. With an increasing trend toward environmental protection and regulation, if these risks are not managed the security of the value chain may be at risk.

➔ **R&I challenge:** How can the environmental impacts of off-grid technologies be reduced and mitigated?

EU R&I SWOT assessment: Strength–Opportunity

Summary of SWOT assessment. The EU has supported R&I in this area, and there is an opportunity to collaborate with non-EU countries for whom this is a shared challenge.

Proposed R&I intervention. Based on the above analysis, the following intervention is proposed:

- **R&I action**: International partnerships with countries who have a similar challenge may be valuable to address this challenge, for example with Canada and countries of the African Union. This may include developing good practice or understanding of what might drive misuse of off-grid technologies in different communities to identify solutions, such as regulation or design features reducing environmental impacts.

Table 8.17 SWOT – evidence overview for EU off-grid technology R&I

Strengths (internal – EU)	**Opportunities** (external)
For the environmental impact criticality, there are already H2020 projects addressing the air pollution from pellet stoves by developing a new type of combustion system, with plans of commercialisation starting from 2022.[552] The Eco-design directive provides a mechanism to set design requirements for energy technologies. The European Commission has proposed to revise the Ambient air quality directive.[553]	Potential collaborations with the African Union: There are multiple innovation funds for off-grid technologies. The African Union is planning to offer USD 100 million (ca. EUR 92.6 million) through an Off-grid Energy Access Fund to subsidise innovative off-grid energy SMEs.[554] There is the potential for collaboration with India and African Union members who have experience in de-risking off-grid systems for private investments.[555] Collaborative development of standards, quality control and good practice may support the reduction of environmental impacts and misuse of off-grid technologies.[556] Horizon Europe–associated countries: The UK is pursuing work on air quality and taking policy action to improve air quality as a result of high pollution from wood-burning stoves.[557]
Weaknesses (internal – EU)	**Threats** (external)
The EU does not seem to have current programmes in place to address the criticalities identified.	Data and monitoring of environmental impacts of off-grid technologies may be challenging in some locations and facilitate misuse.

[552] European Commission (2019), The First Pellet Stove with Ultra-Precise Air Supply that Reduces to Near-Zero the Harmful Emissions Produced during Single Room Heating (accessed 2023).
[553] European Commission (2022), Proposal for a Directive of the European Parliament and of the Council on ambient air quality and cleaner air for Europe.
[554] The African Development Bank Group (2021), Off-Grid Energy Access Fund (OGEF).
[555] Waissbein, O., Bayraktar, H., Henrich, C. (2018), Derisking Renewable Energy Investment: Off-grid electrification, UN Development Programme and ETH Zurich, (accessed 2023).
[556] Doctors and Scientists Against Wood Smoke Pollution (accessed 2023).
[557] City of London, UK (February 2023), Mayor Announces Plans for New Buildings to Improve London Air Quality.

8.18. Energy transmission and distribution technologies

The scope of this technology group covers hydrogen storage and transportation, as well as HVDC transmission.

8.18.1. Key criticality 1: availability and abundance of critical raw materials (copper, aluminium)

Description of criticality: Energy transmission and distribution technologies rely on certain CRMs. In particular, copper presents a potential challenge, with limited resources and increasing demand. EU aluminium production has reduced in recent years due to increasing costs, with increasing EU dependence on imports from a small number of countries.

➔ **R&I challenge:** How can the reliance on and need for CRMs in energy transmission and distribution technology be reduced?

EU R&I SWOT assessment: Weakness–Threat

Summary of SWOT assessment. There is currently no alternative to the use of CRMs in energy transmission, and distribution technology, and technology-agnostic initiatives will be needed to secure supply of CRMs and electronics.

Proposed R&I intervention. Based on the above analysis, the following intervention is proposed:

- **R&I action 1:** An R&I programme would be valuable to increase recycling, to increase reuse in energy transmission and distribution, and to develop the sustainable production of aluminium and other alternatives.

8.18.2. Key criticality 2: digital vulnerability

Description of criticality: Cyberattacks on power grids in general and HVDC links in particular pose a significant and growing threat to the stability, reliability and security of the power system.

➔ **R&I challenge:** How can the digital vulnerability of energy transmission and distribution technologies be reduced and mitigated?

EU R&I SWOT assessment: Strength–Threat

Summary of SWOT assessment. The EU has initiatives that may include cyber security in scope but do not specifically target it. Cyber is a continuously evolving threat.

Proposed R&I intervention. Based on the above analysis, the following intervention is proposed:

- **R&I action**: R&I programmes may support solutions to address cybersecurity risk, including research to ensure that cyber security can be maintained for legacy systems, as well as research understanding of the evolution of threats; this would inform regulation and standards.

Table 8.18 SWOT – evidence overview for EU energy transmission and distribution technology R&I

Strengths (internal – EU) Horizon Europe includes EUR 1.3 billion in investment for HVDC R&I. Horizon 2020 provided EUR 849 million in public investment.[558] **Digital disruption**: There are EU calls in both Horizon Europe work programmes, which include outcomes to avoid cyberattacks and increase resiliency in transmission and distribution technologies (two projects so far: HVDC-WISE and NEWGEN).[559] Additional EU innovation action (higher TRL) includes an action on AC/DC protection strategies, in case of network disruption (this action is not specific to digital disruption).[560] Development of environmentally friendly cable and insulation materials was part of a recent Horizon Europe project.[561] Emerging direct current overhead lines (DC OHL) standards in Europe were referenced briefly in a Horizon call.[562] EU manufacturers are considered to be world leading.[563]	**Opportunities** (external) Horizon partners: The UK awarded GBP 6 million (ca. EUR 7 million) to support the exploration of using DC circuit breakers in HVDC hubs.[564] The Supergen Energy Networks Hub, based at Newcastle University, is devoted to research on energy networks towards the UK's 2035 Net-Zero emissions target.[565] Horizon partner: Norway developed a Centre for Intelligent Electricity Distribution (shortened to CINELDI) to 'empower the future smart grid' as part of its FME scheme.[566] Finland participates in the Clean Energy Ministerial Regional and Global Interconnection initiative, alongside China, Chile, South Africa, South Korea and the UAE.[567] The United States launched a HVDC Cost Reduction Initiative in 2023. It aims to reduce HVDC technology and long-distance transmission costs by 35% by 2035.[568]
Weakness (internal – EU) Programmes for increasing resilience of HVDC, MVDC and/or high-power transmission lines, projects contributing to the EU Alliance of the Internet of Things Innovation are considered in a Horizon Europe call, although advances toward digitalisation or reduction of digital vulnerability are not the primary driver of the call.[569] The EU is not a global leader in R&I for this technology.[570]	**Threats** (external) HVDC innovation is dominated by China, which holds the most patents.[571] High-power semiconductors supply is concentrated in Taiwan.[572]

[558] European Commission (2023), Clean Energy Technology Observatory, Smart Grids in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg.

[559] European Commission (2023), Horizon Europe Work Programme 2023-2024, Climate Energy and Mobility, call: HORIZON-CL5-2024-D3-01-17 (Development and integration of advanced software tools in SCADA systems for High, Medium and Low voltage AC/DC hybrid systems); European Commission (2021), Horizon Europe Work Programme 2021-2022, Climate Energy and Mobility, call: HORIZON-

CL5-2021-D3-02-08 (Electricity system reliability and resilience by design: High-voltage, direct current (HVDC)-based systems and solutions).

[560] European Commission (2023), Horizon Europe Work Programme 2023-2024, Climate Energy and Mobility, call: HORIZON-CL5-2023-D3-03-06 (Components and interfacing for AC & DC side protection system – AC & DC grid: components and systems for grid optimisation).

[561] European Commission (2023), Horizon Europe Work Programme 2023-2024, Climate Energy and Mobility, call: HORIZON-CL5-2024-D3-01-15 (HVAC, HVDC and high-power cable systems).

[562] European Commission (2023), Horizon Europe Work Programme 2023-2024, Climate Energy and Mobility, call: HORIZON-CL5-2024-D3-01-15 (HVAC, HVDC and high-power cable systems).

[563] European Commission (2023), Clean Energy Technology Observatory, Smart Grids in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg.

[564] Mott MacDonald (July 2023), Funding Secured for Development of New Electricity Network Technology to Enable Scale-Up of Offshore Wind in the UK.

[565] Supergen Energy Networks Hub (accessed 2023).

[566] CINELDI Centre for Intelligent Electricity Distribution.

[567] Clean Energy Ministerial, Regional and Global Energy Interconnection (RGEI) initiative.

[568] U.S. Department of Energy, Office of Electricity, HVDC COst REduction (CORE) Initiative (accessed 2023).

[569] Alliance for IofT and Edge Computing Innovation (accessed 2023); European Commission (2023), Horizon Europe Work Programme 2023-2024, Climate Energy and Mobility, call: HORIZON-CL5-2023-D3-01-12 (Development of MVDC, HVDC and high-power transmission systems and components for a resilient grid).

[570] European Commission (2023), Clean Energy Technology Observatory, Smart Grids in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg.

[571] European Commission (2023), Clean Energy Technology Observatory, Smart Grids in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg.

[572] European Commission (2023), Clean Energy Technology Observatory, Smart Grids in the European Union – Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg.

8.19. Smart cities

8.19.1. Key criticality 1: availability and abundance of critical raw materials and location of advanced electronics supply chains (palladium, cobalt, gallium, germanium, silicon, rare-earth materials)

Description of criticality: Smart cities require a number of CRMs, in some cases only available from one or a small number of non-EU countries. Linked to this, the supply chains for advanced electronics are predominantly outside the EU, introducing potential risk to the security of these value chains.

➔ **R&I challenge:** How can the reliance on and need for CRMs in smart energy grid technologies be reduced?

EU R&I SWOT assessment: Weakness–Threat

Summary of SWOT assessment. The EU has set out policy ambitions to secure the supply of CRMs and semiconductors. However, this is a significant challenge, and there is no technology-specific solution to reduce CRM use in smart energy grid technologies.

Proposed R&I intervention. There is currently no alternative to the use of CRMs in smart cities, and technology-agnostic initiatives will be needed to secure supply of CRMs and electronics.

- **R&I action 1**: R&I programmes are needed to increase circular economy processes, recycling and reuse in smart cities.
- **R&I action 2**: Actions taken as part of the EU Chips Act and the Chips for Europe initiative should consider clean energy technologies in their remit.

8.19.2. Key criticality 2: digital vulnerability

Description of criticality: Smart cities are very dependent on digital technologies and inherently vulnerable to cyberattacks or disruption of digital networks, with potential negative impacts on the operation of the energy grid.

➔ **R&I challenge:** How can the digital vulnerability of smart cities be reduced and mitigated?

EU R&I SWOT assessment: Strength–Threat

Summary of SWOT assessment. The EU has initiatives specifically targeted at ensuring the cyber security of smart technologies; however, cyber crime is a continuously evolving threat.

Proposed R&I intervention. Based on the above analysis, the following intervention is proposed:

- **R&I action**: Ongoing R&I programmes may support solutions to address cybersecurity risk, including research to ensure cyber security can be maintained for legacy systems, as well as research understanding of the evolution of threats; this would inform regulation and standards.

Table 8.19 SWOT – evidence overview for EU smart cities R&I

Strengths (internal – EU) The EU has a mission on climate-neutral and smart cities.[573] A number of projects are part of the Connected, Cooperative and Automated Mobility programme in Horizon Europe, including HORIZON-CL5-2024-D6-01-01, which has cybersecurity in scope. The EU has strengths in chips R&I, including world-leading research organisations and key companies in the global chips supply chain. Significant public funding is now being invested, including through an IPCEI with up to EUR 8.1 billion in public funding.[574] There are proposals for an EU Cyber Resilience Act.[575]	**Opportunities** (external) Horizon partner: Norway granted funding in 2016 to establish a new Research Centre on Zero Emission Neighbourhoods in Smart Cities. Nine pilot projects are running under the research centre.[576] The UK National Cyber Security Centre has published principles for secure design, management and build of smart cities.[577]
Weaknesses (internal – EU) The EU is not a global leader in smart city R&I. The EU is highly dependent on non-EU countries for electronics supply chains.	**Threats** (external) Cyber threats are continuously evolving.

[573] European Commission, EU Mission: Climate-neutral and smart cities (accessed 2023).
[574] European Commission (November 2023), European Chips Act – Questions and answers.
[575] European Commission (October 2022), Questions and Answers: EU action plan on digitalising the Energy system.
[576] Research Council of Norway, Centres for Environment-Friendly Energy Research (accessed 2023).
[577] UK Government, National Cyber Security Centre (May 2021), Connected Places: new NCSC security principles for 'Smart Cities', NCSC, (accessed 2024).

8.20. Other storage (compressed air energy storage and flywheels)

8.20.1. Key criticality 1: availability and abundance of critical raw materials (aluminium, copper)

Description of criticality: Many of these technologies rely on certain CRMs. In particular, copper presents a potential challenge, with limited resources and increasing demand. EU aluminium production has reduced in recent years due to increasing costs, with increasing EU dependence on imports from a small number of countries.

➔ **R&I challenge:** How can the reliance on and need for CRMs in energy storage value chains be reduced?

EU R&I SWOT assessment: Weakness–Threat

Summary of SWOT assessment. EU R&I initiatives do not appear to address this criticality, and it is unclear if a potential solution exists.

Proposed R&I intervention. Without a technology-specific solution, this criticality may be better addressed through technology-agnostic CRMs R&I.

- **R&I action**: A discovery research programme would be valuable to identify alternative materials or solutions to reduce the use of CRMs. Discovery research may take a number of years to achieve impact.

8.20.2. Key criticality 2: sustainability and environmental impacts

Description of criticality: The use of compressed air storage can lead to ground subsidence and seismic activity. While the risks associated with underground activities related to natural gas storage are well understood, the risks associated with compressed air storage are relatively unknown and require further research to resolve uncertainty.

➔ **R&I challenge**: What are the environmental impacts of compressed air storage? How can they be reduced and mitigated?

EU R&I SWOT assessment: Weakness–Threat

Summary of SWOT assessment. R&I with regards to this criticality does not appear to be a priority in the EU or in non-EU countries, with no evidence found of research into seismic activity risks of CAES.

Proposed R&I intervention

- **R&I action**: A targeted R&I research project would be valuable to develop a better understanding of the environmental impacts of CAES and potential mitigations.

8.20.3. Key criticality 3: supply chain complexity

Description of criticality: Compressed air storage is only suitable to certain areas. Extensive research and underground exploration are necessary and may involve considerable complexity for the construction and use of compressed air storage. Complexity introduces an increased risk of disruption and delay, affecting the security of the value chain.

➔ **R&I challenge:** How can the complexity of compressed air storage facilities and supply chains be minimised?

EU R&I SWOT assessment: Strength–Opportunity

Summary of SWOT assessment. The EU has carried out R&I and mapping activities to identify energy storage sites, although this was not specific to CAES. Research is ongoing globally, with potential for international collaboration.

Proposed R&I intervention. Pending the outputs of the relevant Horizon Europe projects, additional R&I may be beneficial if CAES was not covered in the scope.

Table 8.20 SWOT – evidence overview for EU other storage R&I

Strengths (internal – EU)	**Opportunities** (external)
Germany has one of two CAES plants in the world (the Huntorf plant), with a 321 mW storage capacity.[578] The other plant is in Alabama, United States. CRMs and the sustainability of long-term energy storage solutions (chemical, mechanical and thermic technologies) are addressed in some EU research programmes.[579] An EU R&I call on novel TES solutions for CSP considers the impact on health and sustainability.[580] Storage (hydrogen and CAES) is addressed in an EU call, by including an action to develop a European storage atlas.[581] The BRIDGE initiative is an EU cooperation group between EU-funded R&I projects that includes work on energy storage regulation (including CAES).[582] We anticipate that the development of regulation will have impacts on R&I advancements in CAES.	Academic researchers have developed a research methodology to identify storage locations in India and the UK, close to renewable energy–generation sites to avoid failure of CAES projects due to geographic or economic problems.[583] Suitability of location is a shared challenge/learning opportunity. Several CAES projects in the United States, Canada and Israel have been announced.[584]
Weaknesses (internal – EU)	**Threats** (external)
REPowerEU emphasises the need for energy storage, with plans to increase financial support to increase storage capacity in the EU. However, this is focused on liquid	There is no evidence of potential solutions for flywheels without silicon or copper, nor for CAES without copper or aluminium. We found no evidence of research into the seismic activity risks of CAES.

natural gas storage and does not reference other forms of energy storage.[585] Mentions of the sustainability of long-term energy storage solutions do not mention seismic activity.[586] The ETIPS SNET working group on storage R&I priorities does not reference CAES development or sustainability issues for long-term energy storage solution, including CAES. EASE also recognises the importance of CAES but does not identify future R&I in the listed criticalities.[587] The top 6 EU storage companies specialise in battery technologies, not other storage technologies.	

[578] Chen, L., Zheng, T., Mei, S., Zue, Z., Liu, B., Lu, Q. (2016), Review and prospect of compressed air energy storage system, *J. Mod. Power Syst. Clean Energy* 4, 529-541, doi.org/10.1007/s40565-016-0240-5; Energy Systems and Energy Storage Lab, Compressed Air Energy Storage (accessed 2023).

[579] European Commission (2023), Horizon Europe Work Programme 2023-2024, Climate Energy and Mobility, call: HORIZON-CL5-2023-D3-01-14 (Demonstration of innovative, large-scale, seasonal heat and/or cooling storage technologies for decarbonisation and security of supply); European Commission (2021), Horizon Europe Work Programme 2021-2022, Climate Energy and Mobility, call: HORIZON-CL5-2022--3-01-11 (Demonstration of innovative forms of storage and their successful operation and integration into innovative energy systems and grid architectures).

[580] European Commission (2023), Horizon Europe Work Programme 2023-2024, Climate Energy and Mobility, call: HORIZON-CL5-2023-D3-02-02 (Novel thermal energy storage for CSP).

[581] European Commission (2021), Horizon Europe Work Programme 2021-2022, Climate Energy and Mobility, call: HORIZON-CL5-2022-D3-01-11 (Demonstration of innovative forms of storage and their successful operation and integration into innovative energy systems and grid architectures).

[582] European Commission (2020), Study on Energy Storage – Contribution to the security of the electricity supply in Europe, Publications Office of the European Union, Luxembourg.

[583] King, M., Jain, A., Bhakar, R., Mathur, J., Wang, J. (2021) Overview of current compressed air Energy storage projects and analysis of the potential underground storage capacity in India and the UK, *Renewables and Sustainable Energy Reviews*, 139, 110705. https://doi.org/10.1016/j.rser.2021.110705

[584] PV Magazine (May 2021), The Best World Regions for Compressed Air Storage.

[585] European Commission (May 2022), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, REPower EU Plan.

[586] European Commission (2023), Horizon Europe Work Programme 2023-2024, Climate Energy and Mobility, call: HORIZON-CL5-2023-D3-01-14 (Demonstration of innovative, large-scale, seasonal heat and/or cooling storage technologies for decarbonisation and security of supply).

[587] European Association for Storage of Energy (accessed 2023).

8.21. Considerations for the wider energy system

The energy security assessment of clean energy value chains identified a number of criticalities where R&I challenges focusing on the wider energy system rather than technology-specific challenges may provide solutions. Interventions at the energy system level are not in scope of this study, so full SWOT assessments were not carried out for these. However, we include here a list of the system-wide challenges for EU energy security identified in this study and highlighted by validation workshop participants.

- **Key criticality 1**: added physical and digital vulnerability of the wider energy system that provides renewable energy for individual technologies to operate

A number of technologies examined by this study are dependent on the wider energy system for the supply of renewable energy as part of their operation. Energy security is a system characteristic, and a distributed smart energy system presents opportunities to mitigate and manage the risks to individual technologies. The energy system will also have vulnerabilities, and it will be important to ensure that these are well understood and planned for. For example, extreme weather events are currently most likely to have a local impact and only limited cascading or widespread consequences across the EU energy system. In future, as climate change affects weather patterns, the energy system may need to be resilient to multiple extreme weather events taking place at the same time or in rapid succession.

R&I challenge: How can the physical and digital resilience of the smart and flexible clean energy grid be strengthened?

- **Key criticality 2**: electronics and semiconductor value chains

With digitisation, technology value chains are increasingly reliant on the supply of semiconductor chips. In the case of clean energy technologies, a range of semiconductor chips are used, including low-tech chips and high-power chips. Validation workshop participants highlighted existing delays in their value chains – for example, heat pump orders have been affected by the global semiconductor chip shortages – and concerns that the European Chips Act is focused on high-performance semiconductor chips, whereas intervention is also needed for low-tech chips.

R&I challenge: How can resilient and secure semiconductor chips supply chains be established for EU value chains?

- **Key criticality 3**: availability and abundance of CRMs

CRMs are a key requirement for many clean energy technologies. This study examined solutions at the value chain level, for example potential alternatives to CRMs or recycling and reuse. Where an alternative does not currently exist, recycling and reuse is unlikely to be sufficient to meet increasing demand for CRMs, and further intervention may be required to secure CRMs supply chains. The EU has set out new policies, including the CRMs Act and Horizon Europe programmes. A high-level overview of these policies presented in the table below. A gap identified by this study is R&I on public perceptions in the EU for CRMs mining.

As CRMs are a key issue across clean energy technologies, a non-exhaustive review of existing initiatives was carried out. This identified a key R&I gap around public opinion and public dialogue about mining of CRMs (in the EU and beyond). Mining is typically perceived negatively, and public views may introduce barriers towards developing new mines in the EU and outside the EU.

R&I challenge: How can resilient and secure CRMs supply chains be established for EU value chains?

R&I challenge: What is the current public opinion of mining activities, and how can perception of mining be addressed (e.g. through outreach and awareness-raising activities on energy security and clean technology needs), particularly in potential host mining communities?

Proposed R&I action: Research and engagement activities with the public and key stakeholders would be valuable to understand concerns, share knowledge and evidence, and develop priorities for R&I where concerns are not being addressed (e.g. environmental impacts and benefits for host communities).

Table 8.21 SWOT – evidence overview for EU critical raw materials R&I

Strengths (internal – EU)	**Opportunities** (external)
The EU Critical Raw Materials Act sets targets for domestic extraction and sourcing of CRMs.[588] An industry alliance – European Raw Material Alliance – was formed in 2020. For VC investments, European start-ups have been successful at raising money for rare-earth elements, battery reuse and battery material supply.[589] The EU has several Horizon Europe Calls for CRMs in 2021-2022 WP[590] and 2023-2024 WP – specifically in Cluster 4 (Digital, Industry and Space).[591] Topics range from circularity to reducing environmental footprints to sourcing. The Horizon Europe work programme includes at least 10 calls relevant to geothermal energy, totalling EUR 150.8 million. This includes the Horizon Europe project CRM-Geothermal developing CRM extraction, building on prior EU-funded work, including a demonstrator site in France.[592,593] Europe has natural resources for a number of CRMs, with opportunities to develop mining to meet a portion of demand.	Horizon partner: The UK has the GBP 15 million (ca. EUR 17.5 million) Circular CRMs Supply Chains Programme. Focus areas include: mining, downstream, mid-stream, circular supply chains, and materials.[594] The US government issued a USD 10 million research funding (ca. EUR 9.3 million) in 2023 for a CRM accelerator. Research topics include: use of magnets with reduced CRM content, improved unit operations of processing and manufacturing of CRMs, CRM recovery from scrap and post-consumer products, and reduced CRM demand for clean energy technologies. This funding is available for both universities and business.[595] The U.S. DOE also issued a USD 150 million (ca. EUR 139 million) funding to advance cost-effective and environmentally responsible processes to produce and refine critical minerals and materials in the United States. This funding is eligible for both universities and companies.[596] Previous work to build on EU–Africa partnerships include the HORIZON-CL4-2021-RESILIENCE-01-05 project ('Building EU–Africa partnerships on sustainable raw materials value chains', CSA,[597] EUR 8 million). Geothermal facilities can produce outputs that are additional to energy, including sustainable extraction of certain CRMs, such as lithium.[598] Global investment in CRM development increased by 30%, following a 20% growth in

	2021. Lithium, copper and nickel received the most investment. Exploration activities also attracted increasing investments, with Canada leading the growth.[599]
Weaknesses (internal – EU) This study did not identify Horizon Europe projects addressing public perception specifically. Public perceptions towards mining are negative in the EU in part due to the perceived environmental harms of mining.[600] Public opinion is likely to play a role in permitting for new mines in Europe.	**Threats** (external) For VC investments, US companies raised most of the funds, at 45% of the total between 2018 and 2022. Canadian and Chinese start-ups are notably active in battery recycling and lithium refining.[601] There is a wave of policies to ensure supply of CRM. The IEA identified nearly 200 policies and regulations across the globe, with more than 100 of these enacted in the past few years. Some of these policies have included restrictions on import or export.[602] Demand is expected to increase significantly for CRMs globally, and recycling is not sufficient in itself to meet rising demand. Human Rights Watch has raised concerns about relying on audits and certification for good practice in raw materials mining.[603] Planned mines globally are not currently in line with expected increased demand.[604]

- **Key criticality 4**: digital vulnerability of the wider energy system and value chains

Cybersecurity is an increasing threat to energy security across possible futures. Digitisation of the energy system and value chains offers many opportunities for efficiency gains. However, a key concern highlighted during the validation workshop is the number of stakeholders involved and the lack of clear responsibility for cyber security, with missed consideration of how components and systems will interact with each other. Cyber threats continue to evolve, and it will be important for the EU to stay ahead.

R&I challenge: How can highly digitised value chains be secure?

R&I challenge: How can the smart energy grid be secure and resilient to cyber incidents?

- **Key criticality 5:** skills

Skills and the availability of talent formed a major theme of discussion at the validation workshop. Many clean energy technologies are already experiencing skills shortages, which are especially acute for those technologies requiring widespread installation. The skills shortage also impacts manufacturing and R&I, creating barriers to the development of EU-based supply chains. International competition for talent, especially from the United States with regards to R&I talent, is increasing. Clean energy technology value chains in some cases also compete with each other for talent.

Workshop participants highlighted existing initiatives and research to motivate and encourage people to train for work in clean energy technologies. The consensus view was that current initiatives are not sufficient and that an energy systems–wide review of skills requirement would be beneficial to set out next steps and manage competition among EU value chains.

R&I challenge: What are the short-, medium- and long-term skills needs of the clean energy transition and future energy system? How can these skills be developed and maintained?

Proposed energy system R&I action: A potential approach to addressing these challenges would be to launch an EU mission to deliver a secure and resilient clean energy system, creating opportunities to address system-wide energy security challenges, and calls for innovative and breakthrough alternatives to technologies that introduce vulnerabilities.

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[588] European Commission (March 2023), Proposal for a regulation of the European Parliament and of the Council establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) 168/2013 (EU) 2018/858, 2018/1724 and (EU) 2019/102.

[589] International Energy Agency (2023), *Critical Minerals Market Review 2023: Key market trends*, IEA, (accessed 2023).

[590] European Commission (2021), Horizon Europe Work Programme 2021-2022, Digital, Industry and Space. Calls: HORIZON-CL4-2021-TWIN-TRANSITION-01-20 (Reducing environmental footprint, improving circularity in extractive and processing value chains); HORIZON-CL4-2021-RESILIENCE-01-06 (Innovation for responsible EU sourcing of primary raw materials, the foundation of the Green Deal); HORIZON-CL4-2022-RESILIENCE-01-03 (Streamlining cross-sectoral policy framework throughout the extractive life-cycle in environmentally protected areas); HORIZON-CL4-2022-RESILIENCE-01-06 (Sustainable and innovative mine of the future); HORIZON-CL4-2022-RESILIENCE-01-08 (Earth observation technologies for the mining life cycle in support of EU autonomy and transition to a climate - neutral economy).

[591] European Commission (2023), Horizon Europe Work Programme 2023-2024, Digital, Industry and Space. Calls: HORIZON-CL4-2023-RESILIENCE-01-02 (Innovative technologies for sustainable and decarbonised extraction); HORIZON-CL4-2023-RESILIENCE-01-03 (Technologies for processing and refining of critical raw materials); HORIZON-CL4-2023-RESILIENCE-01-05 (Recycling technologies for critical raw materials from EoL products); HORIZON-CL4-2023-RESILIENCE-01-06 (Earth Observation platform, products and services for raw materials); HORIZON-CL4-2023-RESILIENCE-01-07 (Expert network on Critical raw materials); HORIZON-CL4-2023-RESILIENCE-01-09 (Recyclability and resource efficiency of Rare Earth based magnets); HORIZON-CL4-2024-RESILIENCE-01-01 (Exploration of critical raw materials in deep land deposits);
HORIZON-CL4-2024-RESILIENCE-01-11 (Technologies for extraction and processing of critical raw materials).

[592] CRM Geothermal (accessed 2023).

[593] ETIP Geothermal (2019), *Report on Competitiveness of the Geothermal Industry*, ETIP Geothermal, (accessed 2023).

[594] UKRI-Innovate UK, Circular Critical Raw Materials Supply Chains Programme (accessed 2023).

[595] U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy (November 2023), DOE Announces Funding Opportunity for Critical Materials Accelerator Projects to Advance Critical Materials Supply Chains Solutions.

[596] U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, Funding Notice: Critical materials innovation, efficiency, and alternatives (accessed 2023).

[597] CSA: Coordination and support action.

[598] Szanyi, J., Rybach, L., Abdulhaq, H.A. (2023), Geothermal Energy and its potential for critical metal extraction – A review, *Energies* 16(20), 7168, doi.org/10.3390/en16207168.

[599] IEA (2023), Critical Minerals Market Review 2023: Key market trends.

[600] The Hague Centre for Strategic Studies (September 2022), Cobalt Mining in the EU: Securing supplies and ensuring Energy justice.

[601] IEA (2023), Critical Minerals Market Review 2023: Key market trends.

[602] IEA (2023), Critical Minerals Market Review 2023: Key market trends.

[603] Human Rights Watch (May 2023), EU's Flawed Reliance on Audits, Certifications for Raw Materials Rules.

[604] Climate Foresight (April 2023), Moving Mining Back to Europe.

R&I ACTION PLAN

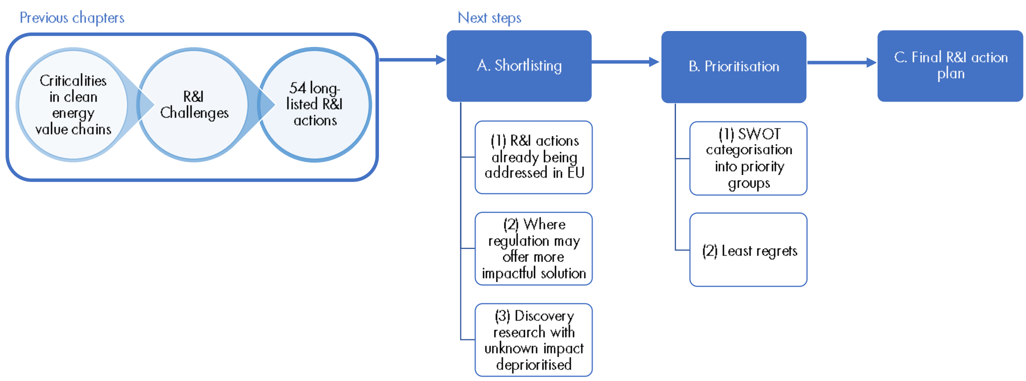
This section presents the R&I action plan developed by this study, bringing together the work across all tasks (Tasks 1-4). The action plan outlines 30 promising R&I opportunities for clean energy value chains in scope of this study. The results of the prioritisation and rationalisation of R&I interventions are described in Section 9, and the action plan itself is presented in Section 10.

9. Shortlisting and prioritisation of R&I interventions for inclusion in the R&I action plan

The analysis presented in the previous section sets out R&I challenges and corresponding R&I interventions that are proposed for the key energy security criticalities of each clean energy security value chain.

A process of prioritisation and rationalisation, described in the methodology section (Annex A, Section 7.2.4), was followed to develop the R&I action plan. Figure 9.1 outlines the steps used to shortlist the R&I actions.

Figure 9.1 Outline of how R&I actions were shortlisted



9.1. Shortlisting of R&I challenges for the action plan

Fifty-four R&I interventions were identified across the clean energy technology value chains. Where the R&I challenge and proposed intervention are the same, we have presented them as one intervention, and in some cases more than one R&I intervention is proposed per challenge.

The first step in prioritisation was to discount the R&I challenges where existing targeted R&I programmes are already in place and no further action is currently required, as the EU is already working to tackle these R&I challenges. In these cases, it will be valuable to review the need for further or continued R&I upon completion of the R&I programmes or if the external context changes. The criticalities and associated technologies relevant to this are:

- Environmental impact – CCUS, ocean energy, wind energy;
- Cost of technologies – CSE, direct solar fuels, hydrogen;
- CRM availability and abundance – hydrogen, heat pumps;
- Digital vulnerability – PV;
- Public opinion – CCUS;
- Energy efficiency – hydrogen, RFNBOs;
- Supply chain resilience – other energy storage (CAES); and
- Skills – direct solar fuels.

The second step was to consider whether R&I presents an effective solution to the challenge or if other interventions would be more impactful. Six R&I challenges were discounted in this stage: feedstocks (bioenergy and advanced biofuels); supply chains (PV, energy grids and networks[605]); cost (CCUS); and skills (PV). In some cases, complementary R&I interventions addressing the challenge are included in the action plan. In the case of RFNBOs and hydrogen (criticalities: affordability, and vulnerability to the wider energy system), workshop participants suggested a policy lab or regulatory sandbox to bring the technologies to market.

Four R&I challenges had no currently known solution to the question 'How can the use of CRMs be reduced?[606] In these cases, a discovery research programme is proposed; however, discovery research carries high risk, and it is likely to take a number of years before a solution is developed to application. These challenges were not prioritised for inclusion in the action plan, due to uncertainty about their potential impact and the time needed for them to contribute to energy security.

R&I interventions with potential to be addressed through other R&I interventions – as described in the least-regrets review (Section 9.3) – were also removed from the list of actions.

The shortlisting process and full list of actions not shortlisted, along with detail on why they were not included, is presented in Annex F.

9.2. Prioritisation of R&I interventions for inclusion in the action plan based on SWOT analysis

The remaining 30 R&I challenges were prioritised for inclusion in the R&I action plan based on their SWOT characteristics. The method for prioritisation is described in Annex A, Section 7.2.4. The priorities can be summarised as follows:

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[605] Smart energy grid technologies, smart cities, energy building and district heating technologies, energy transmission and distribution.

[606] Relevant technology groups: Other storage (flywheels and CAES); Off-grid energy tech; Direct solar fuels; Smart energy grid technologies, Smart cities, energy building and district heating technologies, Energy transmission and distribution.

- **First priority for action (Weakness–Threat):** There is little to no R&I activity within the EU, and there are external threats to the system.

- **Second priority for action (Strength–Threat):** The S–T category was prioritised over S–O because external threats include non-EU competition or challenges with no known solution, which need to be mitigated.

- **Third priority for action (Strength–Opportunity):** This is prioritised over the W–O category because there is room for immediate impact or activity in the R&I space due to strong EU R&I ecosystem and the chance to collaborate with other countries.

- **Fourth priority for action (Weakness–Opportunity):** This is the last category prioritised for action. Although these are also of high importance, the lack of existing industry or expertise in the EU means these interventions will take longer to develop and may not have short- or medium-term impact.

Some additional R&I challenges (and corresponding actions), based on missing criticalities and identified by experts during the validation workshop, were also included and are denoted with an asterisk in Table 9.1.

Table 9.1 Remaining R&I actions following initial shortlisting[607]

First priority for action: Weakness–Threat	Second priority for action: Strength–Threat
Geothermal energy – How can the use of CRMs be reduced? **Photovoltaics** – How can an EU-based supply chain be supported to be globally competitive? **Batteries** – How can an EU-based supply chain be supported to be globally competitive? **Hydrogen** – How can supply chain resilience be improved? **Smart energy grid technologies, smart cities, energy building and district heating technologies, energy transmission and distribution** – How can the supply of CRMs be secured? **Storage (CAES)** – How can the environmental impact be reduced or mitigated? **CRMs (technology agnostic)** – What affects public perceptions of CRM mining?	**Bioenergy** – How can the security and availability of feedstocks be improved? (2 proposed interventions) **Hydrogen** – How can the environmental impact of hydrogen be reduced or mitigated? **Smart energy grid technologies, smart cities, energy building and district heating technologies, energy transmission and distribution** – How can the digital vulnerability be reduced or mitigated? **Hydrogen and RFNBOs** – How can the cost of production be reduced to competitive levels and products brought to market?

[607] Some additional R&I challenges (and corresponding actions), based on missing criticalities and identified by experts during the validation workshop, were also included and are here denoted with an asterisk.

Third priority for action: Strength–Opportunity	Fourth priority for action: Weakness–Opportunity
Advanced biofuels – How can the security and availability of feedstocks be improved? (2 proposed interventions) **Hydropower** – How can the environmental impact be reduced or mitigated? **Hydropower** – What factors influence public opinion?* **Hydropower** – How can performance be maintained or managed with a changing climate? **Photovoltaics** – How can the use of CRMs be reduced? **Wind energy** – How can the use of CRMs be reduced? **Wind energy** – How can the digital vulnerability of wind energy be reduced and mitigated?* **Direct solar fuels** – How can supply chain resilience be increased? **Batteries** – How can the use of CRMs be reduced? **RFNBOs** – How can supply chain resilience be increased? **Off-grid energy technology** – How can the environmental impact be reduced or mitigated? **Ocean energy** – How can the cost be reduced to competitive levels? **Heat pumps** – How can vulnerability of energy system disruptions be reduced?	**Ocean energy** – What factors influence public opinion?

The R&I interventions are included in the action plan and described in further detail in Section 9.4.

9.3. Least-regrets and futureproofing of R&I interventions

A final review, taking a least-regrets and futures lens, was used to identify where an R&I intervention has the potential to address more than one criticality or may have potential benefit across the future scenarios. A number of opportunities were identified, and these are described below.

- **Advanced biofuels and bioenergy – How can the security and availability of feedstocks be improved?** With a shared energy security criticality and R&I challenge, intervention for either advanced biofuels or bioenergy should consider synergies and opportunities to resolve the challenge for both value chains where appropriate. The proposed R&I interventions could be combined into one call.

- **Hydropower, ocean energy, wind energy – How can the use of CRMs be reduced?** Given the similarities among the technologies and their shared challenge around the use of CRMs, intervention for each of these technologies should consider synergies and opportunities to resolve the challenge for each value chain where appropriate. The proposed combined R&I intervention is a knowledge-exchange programme among the wind energy, ocean energy and hydropower sectors to complement the intervention for wind energy.

- **Photovoltaics – How can R&I skills be developed and maintained in the EU?** Skills are an output of R&I programmes, supporting people and talent to deliver. As such, particular consideration of this challenge is included in other interventions for photovoltaics.

- **Smart energy grid technologies, smart cities, energy building and district heating technologies, energy transmission and distribution.** These four technology categories have the same two R&I challenges: How can electronics supply chains be secured, and how can cybersecurity be improved? These are merged where appropriate.

- **Skills.** Across value chains and future scenarios, availability of skills was highlighted as a key potential challenge for energy security. An output of some R&I interventions is skills and training, and where possible, skills development should be considered across the action plan.

- **Cybersecurity.** Across value chains, digitisation is increasing, both in the value chains themselves (for example in manufacturing processes) and in the energy system itself. At the value chain level, where relevant, R&I interventions should consider cybersecurity as part of the aims or scope of the intervention.

- **Circularity, repairability and maintenance.** Future strains on value chains may be offset to some extent through the increased lifetime of clean energy technologies. Interventions to enable repairability by design and quality control would add further security to clean energy technologies by ensuring they can operate for longer. Such interventions would also reduce the need for further imports or replacement of technology.

10. Final R&I action plan

A total of 30 R&I actions are prioritised as opportunities to strengthen or maintain EU energy security of clean energy value chains. An additional, 31st action is proposed to address the energy security of the energy system as a whole.

Four technology categories have the same two R&I challenges: smart energy grid technologies, smart cities, energy building and district heating technologies, energy transmission and distribution. These are presented as individual actions to ensure that each value chain criticality is addressed; however, it may be appropriate to merge some of the interventions in a targeted call in upcoming Horizon work programmes.

The final list of 30 shortlisted R&I actions, ordered by priority grouping (described above and in detail in Annex A, Section 7.2.4.), is summarised below. Further details and nuances are found in the following section, where the actions are presented by technology, with actions numbered accordingly. The description of each R&I action includes the key energy security criticality being addressed, the corresponding R&I challenge, and a description of the R&I intervention, with consideration of feasibility and impact. Where relevant, potential collaborations, links to other R&I challenges, and considerations for successful impact have been noted.

To account for changes from the original action plan, based on feedback from the validation workshop, some R&I challenges have been reworded to bring more nuance to the criticality or corresponding R&I challenge.

10.1. Prioritised list of R&I actions

Table 10.1 Finalised R&I actions

Priority group[608]	Technology and criticality	Proposed R&I action (suggested call title – full details in Section 10.2)
1 (W–T)	Batteries – supply chain location	Improving the energy efficiency of battery manufacturing and recycling.
	Critical raw materials – security of CRM supply	Public engagement research on mining of CRMs.
	Energy transmission and distribution technologies (and smart energy technologies, including grids, cities) – availability and abundance of CRM	Increasing circular economy processes, recycling and reuse of electronics for smart energy technologies.
	Geothermal energy – availability and abundance of CRM	Increasing circular economy processes, recycling and reuse of electronics for smart energy technologies
	Hydrogen – supply chain resilience	A call for solutions to increase the resilience of hydrogen value chains.
	Other storage (CAES) – sustainability and environmental impacts	Developing a better understanding of the potential locations for underground CAES
	PV – supply chain location	Collaborative industry programme to increase the efficiency of PV manufacturing in the EU

[608] Priority group 1 (Weakness–Threat): there is little to no R&I activity within the EU and there are external threats to the system; priority group 2 (Strength–Threat): prioritised over Strength–Opportunity because external threats include non-EU competition or no known solution, both of which need to be mitigated; priority group 3 (Strength–Opportunity): prioritised over Weakness–Opportunity (priority group 4) because there is room for immediate impact or activity in the R&I space due to strong EU R&I ecosystem and the chance to collaborate with other countries.

Priority group[608]	Technology and criticality	Proposed R&I action (suggested call title – full details in Section 10.2)
	Smart energy grids, smart cities, and energy buildings and district heating technologies – availability and abundance of CRMs and location of advanced electronics supply chains	Increasing circular economy processes, recycling and reuse of electronics for smart energy technologies
	Smart energy grid technologies and energy building and district technologies – digital vulnerability	Addressing cybersecurity risks to smart energy grid, building and district heating technologies
2 (S–T)	Bioenergy – abundance of feedstock	R&I action 1: Public engagement research to explore acceptability of biomass production and the bioeconomy
2 (S–T)	Bioenergy – abundance of feedstock	R&I action 2: R&I to improve the availability of feedstocks for bioenergy in the EU
2 (S–T)	Energy transmission and distribution technologies – digital vulnerability	Addressing cybersecurity risks to transmission and distribution technologies
2 (S–T)	Hydrogen – broader sustainability and environment impact	Research into the environmental impact of hydrogen
2 (S–T)	RFNBOs and CCU – affordability	Policy lab on business models for RFNBOs
2 (S–T)	Smart cities – digital vulnerability	Assessing digital vulnerabilities as part of the smart cities mission
3 (S–O)	Advanced biofuels – abundance of feedstock	R&I action 1: Collaborative industry R&I to improve availability of feedstocks for advanced biofuels
3 (S–O)	Advanced biofuels – abundance of feedstock	R&I action 2: Innovation action to understand and develop alternative biomass sources
3 (S–O)	Batteries – availability of CRMs	Reducing the need for CRMs in batteries
3 (S–O)	Heat pumps – vulnerability to wider energy system dependence	Developing policies, regulations and standards for resilient heat pumps
3 (S–O)	Hydropower – environmental impacts	Development and deployment of monitoring tools for biodiversity impacts of hydropower

Priority group[608]	Technology and criticality	Proposed R&I action (suggested call title – full details in Section 10.2)
	Hydropower – physical vulnerabilities and impacts of climate change	R&I programme to develop a long-term climate adaptation strategy for hydropower technologies, with consideration of hybridisation and other potential solutions
	Hydropower – environmental impacts (public opinion)	Research and engagement on public perceptions of hydropower to understand and address concerns where possible
	Ocean energy – affordability	Financial support mechanism to support demonstration and deployment of ocean energy technologies
	Off-grid energy systems – environmental impacts	International collaboration on the environmental impacts of off-grid heating
	PV – availability and abundance of CRM	Supporting the development and commercialisation of perovskite solar cells in the EU
	Direct solar fuels – supply chain complexity	Increasing the resilience of the photo- and thermochemical solar fuel supply chains
	RFNBOs and CCU – supply chain complexity	Scale-up and demonstration of DAC for the production of renewable fuels of non-biological origin
	Wind energy – availability and abundance of CRM	Increasing the circularity of wind energy and reducing the use of CRMs
	Wind energy – digital vulnerability	Addressing the digital vulnerabilities of wind energy
4 (W–O)	Ocean energy – public opinion	Addressing the digital vulnerabilities of wind energy

10.2. R&I actions by technology

10.2.1. Advanced biofuels

Action 1

Proposed R&I intervention: Collaborative industry R&I to improve availability of feedstocks for advanced biofuels

Expected outcome: Collaborative industry R&I topic leading to two main outcomes:

1. Development of novel and cost-effective biofuel processes

2. Development of an EU circular value chain for feedstocks and advanced biofuels

Scope: This is particularly relevant when considering replacing waste-based advanced biofuels (the biomass fraction of mixed municipal solid waste and industrial waste, biowaste from private households and forestry), where there is a limit to the amount of biomass waste available and suitable for use, possibly giving rise to competition with other applications of the feedstock (e.g. in chemistry). With a high feedstock demand, there is a risk of greenwashing by adding illegal (fossil/biomass) feedstocks, although a new EU database for biofuels that is being established will mitigate possible fraud risks. Supply chain complexity also increases when feedstocks need to be imported from outside the EU.

The EU has significant strengths in R&I, performing well with regards to global rankings for high-value patents and existing R&I programmes, including through the Circular Bio-based Europe JU. With a number of potential technology solutions available, a key weakness is lack of private investment in the EU compared with other countries. A collaborative industry R&I programme would create incentives for private investment and enable EU-based industry to develop and deploy novel technologies, contributing towards their global competitiveness and delivering the aims of a secure, EU-based biofuels value chain. The intervention should focus on practical development and deployment of promising novel and existing feedstocks to enable use of EU-sourced biofuels and mobilisation of so far unused biogenic resources, which prevents the proliferation of waste just because it can earn money by making biofuels.

This intervention was considered to have potential for high impact and high feasibility by validation workshop participants.

- **Key energy security criticality addressed**: abundance of feedstock, with links to the complexity of the supply chain and broader environmental sustainability considerations

- **Relevant value chain:** waste-based advanced biofuels (replacement of)

Proposed type of action[609]**:** Research and innovation action (RIA), ERC or EIC Pathfinder

Expected TRL at end of project: 1-4

- **Potential for collaboration**[610]**:** A number of existing collaborations could be leveraged, including the Integrated Biorefineries Mission, the Zero-Emission Shipping Mission, and the EU-Japan collaboration on advanced biofuels. The Horizon Europe–associated countries Norway and the UK also present potential for collaboration with existing programmes.

[609] Possible types of action: research and innovation action (RIA); innovation action (IA); coordination and support action (CSA); ERC grant (starting/ consolidator/ advanced/ synergy, proof of concept); training and mobility action (MSCA, slightly modified and renamed); EIC funding instruments (Pathfinder, Transition, and Accelerator); pre-commercial procurement (PCP); public procurement of innovative solutions (PPI); prizes (inducement/recognition). Source: EU Learning (accessed 2023); Catalyze, Horizon Europe 2023 - Handbook, (accessed 2024).

[610] Collaboration opportunities that are highlighted are based on our research in Chapter 8, which identified key players in this topic area. However, list this should not be considered exhaustive.

- **Links to other key criticalities and R&I challenges:** This intervention is linked to the other Advanced Biofuels interventions, with potential for synergies and added value to be considered.

- **Consideration for successful implementation:** Policy intervention is crucial to resolve uncertainty about advanced biofuels feedstocks. R&I is complementary in this case and will not form the primary solution to the criticality.

  With consideration of the future, cybersecurity may be an important factor to include in such a programme if solutions in development are highly digitised.

  For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with sustainable agriculture and food security, water security, affordability, biodiversity and sustainable land management.

Action 2

Proposed R&I intervention: Innovation action to understand and develop alternative biomass sources

Expected outcome: Finding alternative biomass sources to replace primary crop–based biofuels, whose abundance is dependent on cultivation and availability of land. This should avoid creating (indirect) land use change. Areas to be addressed under this intervention include:

- understanding crop growth conditions
- efficiency improvements
- potential biodiversity and carbon sequestration co-benefits
- sustainable exploitation of unused areas and biomass volumes

Scope: In particular, this should focus on finding alternative biomass sources to replace primary crop–based biofuels, whose abundance is dependent on cultivation and availability of land, without creating (indirect) land use change.

Efforts could focus on bacteria- or algae-based biofuels (still at research phase/low TRL, covered in our value chain assessments, Annex C, 9.1.1). Other specific suggestions include growing biomass crops outside current fertile cropland, with R&I on crops and their growth conditions for potential application to marginal or abandoned land areas; potential co-benefits, such as improved biodiversity and carbon sequestration; feedstock flexibility and development of sustainable value chains; planning for circular waste management and future biofuel, biochemical and biomaterial production; use of complex feedstock, such as from food factories; development of technology for biomass pre-treatment for purification and drying supporting biofuels, biomaterials and biochemical supply chains.

This intervention was considered to have potential for high impact and high feasibility by validation workshop participants.

- **Key energy security criticality addressed:** abundance of feedstock

- **Relevant value chain:** primary crop–based advanced biofuels (alternatives to) and algae-based advanced biofuels

Proposed type of action: Innovation action (IA)

Expected TRL at end of project: 7-9

- **Potential for collaboration:** A number of existing collaborations could be leveraged, including the Integrated Biorefineries Mission, the Zero-Emission Shipping Mission, and the EU-Japan collaboration on advanced biofuels, the United States and Canada. The Horizon Europe–associated countries Norway and the UK also present potential for collaboration with existing programmes.

- **Links to other key criticalities and R&I challenges:** This intervention is linked to the other Advanced Biofuels interventions, and the potential for synergies with RFNBOs and CCUS and added value should be considered – for example, solutions that simultaneously provide biomass and increase soil carbon sequestration.

- **Consideration for successful implementation:** Policy intervention is crucial to resolve uncertainty about advanced biofuels feedstocks. R&I is complementary in this case and will not form the primary solution to the criticality.

  With consideration of the future, cybersecurity may be an important factor to include in such a programme if solutions in development are highly digitised.

  For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with sustainable agriculture and food security, water security, affordability, biodiversity and sustainable land management.

10.2.2. Bioenergy

Action 3

Proposed R&I intervention: Public engagement research to explore acceptability of biomass production and the bioeconomy

Expected outcome: Research and public engagement to support knowledge sharing and public acceptance on opportunities and co-benefits for biomass production and the bioeconomy, to make better use of biomass cascading and of existing or unused resources, forests, land and crops.

Scope: This is particularly relevant for primary crop–based and forest-based bioenergy, where woody biomass is restricted under the sustainability criteria under RED II. Future, further restrictions may increasingly limit access to this material type, posing a risk to the security of bioenergy supply, particularly in light of the expected increase of forest residues (including their potential use in bioenergy with carbon capture and storage (BECCS)). Although this TRL is at 9, ensuring the public are well informed on policies and activities to ensure sustainability is key to preventing risks to feedstock supply.

The EU has significant strengths in R&I, performing well with regards to global rankings for high-value patents and existing R&I programme, including through the Circular Bio-based Europe JU. With a number of potential technology solutions available, a key area to address is the understanding of policymakers, NGOs and other stakeholders of forest management, trade-offs, and pathways for the valorisation of low-value by-products and wastes that cannot be used otherwise and for sustainable forest management.

This intervention was developed based on gaps identified by validation workshop participants, and it thought to have potential for high feasibility and high impact.

- **Key energy security criticality addressed**: abundance of feedstock, with links to broader environmental sustainability considerations

- **Relevant value chain:** primary crop–based and forest-based bioenergy

Proposed type of action: CSA

Expected TRL at end of project: n/a

- **Potential for collaboration:** A number of existing collaborations could be leveraged, including with Horizon Europe–associated countries, such as the UK and Canada, and with countries with notable activity (e.g. the United States).

- **Links to other key criticalities and R&I challenges:** This intervention is linked to the other Advanced Biofuels and Bioenergy interventions, with potential for synergies between these technologies.

- **Consideration for successful implementation:** Policy intervention is crucial to resolve uncertainty about advanced biofuels feedstocks. R&I is complementary in this case and will not form the primary solution to the criticality.

  With consideration of the future, cybersecurity may be an important factor to include in such a programme if solutions in development are highly digitised.

  For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with sustainable agriculture and food security, water security, affordability, biodiversity and sustainable land management.

Action 4

Proposed R&I intervention: Research and innovation to improve the availability of feedstocks for bioenergy in the EU

Expected outcome: Horizon Europe call focused on understanding crop growth conditions, potential biodiversity and carbon sequestration co-benefits, credible sustainable governance systems, and sustainable exploitation of unused areas and biomass volumes.

Scope: Specific suggestions include R&I on crops and their growth conditions for potential application to marginal or abandoned land areas; potential co-benefits, such as improved biodiversity and carbon sequestration; feedstock flexibility; and the development of sustainable value chains.

This intervention was considered to have potential for high impact and high feasibility by validation workshop participants.

- **Key energy security criticality addressed:** abundance of feedstock
- **Relevant value chain:** primary crop–based and forest-based bioenergy

Proposed type of action: RIA

Expected TRL at end of project: 4-6

- **Potential for collaboration:** A number of existing collaborations could be leveraged, including with Horizon Europe–associated countries, such as the UK and Canada, and with countries with notable activity (e.g. the United States).
- **Links to other key criticalities and R&I challenges:** This intervention is linked to the other Advanced Biofuels and Bioenergy interventions. There are additional potential synergies and added value with respect to biodiversity and climate change adaptation, for example solutions that simultaneously provide biomass for bioenergy and increase soil carbon sequestration.
- **Consideration for successful implementation:** Policy intervention is crucial to resolve uncertainty about advanced biofuels feedstocks. R&I is complementary in this case and will not form the primary solution to the criticality.

  With consideration of the future, cybersecurity may be an important factor to include in such a programme if solutions in development are highly digitised.

  For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with sustainable agriculture and food security, water security, affordability, biodiversity and sustainable land management.

10.2.3. Batteries

Action 5

Proposed R&I intervention: Improving the energy efficiency of battery manufacturing and recycling

Expected outcome: Horizon Europe topic focused on improving the energy efficiency of battery manufacturing and recycling. Battery manufacturing is energy intensive, contributing to higher costs for manufacturing in the EU compared with other countries due to comparatively higher costs of energy. R&I focused on improving the energy efficiency of manufacturing and recycling processes (linked to action 6) would provide a mechanism to increase competitiveness for an EU-based supply chain, address currently missing capabilities, such as raw materials processing, and develop skills and know-how for an EU battery supply chain.

Scope: This should focus on the construction phase of mature battery technologies, such as lithium-based batteries, which require advanced machinery, skilled labour and, in general, high energy use. Increased efforts in recycling of Li-ion and other types of batteries would make Europe less dependent on external countries that are major producers of most of the CRMs needed for the production of Li-ion batteries. Reducing the price of Li-ion batteries would improve European competitiveness with the four key players in lithium production.

This intervention was suggested by workshop participants, and is thought to have potential for high impact but low feasibility.

- **Key energy security criticality addressed**: supply chain location outside the EU (lithium-based batteries)
- **Relevant value chain:** lithium-based batteries

Proposed type of action: RIA or EIC transition

Expected TRL at end of project: 5-6

- **Potential for collaboration:** International collaborations should be considered, in particular with Horizon Europe–associated countries, such as the UK and Norway, which are pursuing work in this area and may provide opportunities for collaboration, and with countries with strong R&I outputs in this field (e.g. India). The EU already has a new strategic partnership with Norway on raw materials and battery value chains.[611]

- **Links to other key criticalities and R&I challenges:** This intervention is linked to the other batteries intervention. Beyond this action plan, policy intervention may also be necessary to address the criticality. For example, acquisition may be more effective for onshore battery supply chains, while R&I can provide a complementary intervention to ensure global competitiveness is maintained.

- **Consideration for successful implementation:** Objectives for circularity should be embedded as part of the call to ensure optimal management of critical material resources and compliance with EU ambitions for circularity.

  With consideration of the future, cybersecurity may be an important factor to include in such a programme if processes in development are highly digitised. Skills are also a key factor to consider for a viable commercial supply in the EU, and the package of interventions should consider how to best nurture and maintain a pipeline of talent, including with movement of talent between research and industry.

  For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with affordability and environmental impacts.

[611] European Commission (March 2024), EU and Norway Sign Strategic Partnership on Sustainable Land-based Raw Materials and Battery Value Chains.

Proposed R&I intervention: Reducing the need for CRMs in batteries

Expected outcome: Portfolio of R&I interventions to support the successful development and commercialisation of batteries without critical raw materials, including sodium batteries.[612] This would include a package of Horizon, EIC, ERC and structural funds to provide end-to-end support addressing lower TRL research challenges, later-stage development, university–industry exchange and business growth for promising innovative companies and start-ups.

Scope: Batteries with reduced or no CRMs provide a strategic opportunity for the EU to build on its research strengths to reduce reliance on CRMs while developing an EU-based supply chain for batteries. The research is also an opportunity to leverage key strengths in digitisation to accelerate materials research and manufacturing. Validation workshop participants noted that the package should look at the entire battery value chain, including shortening the lead time for commercialisation and recycling. This is particularly relevant given evidence from redox-flow batteries, where the main component (vanadium pentoxide) is not mined in Europe and therefore Europe is dependent on imports. Inclusion of recycling considerations in the package would avoid potential geopolitical availability issues (e.g. most of zinc production is in China) and contribute to circularity and energy-efficiency goals (e.g. production from recycled aluminium is about 90% less energy intensive than production from raw ores).

This intervention was considered by validation workshop participants as having potential for high impact with challenges for feasibility. Costs of this intervention and global competition contribute to low feasibility. However, the cost and impact on energy security of significant trade disruption to battery value chains is high and should be considered as part of the rationale for pursuing this intervention.

- **Key energy security criticality addressed**: availability and abundance of CRMs (lithium, cobalt, nickel, aluminium, graphite, vanadium, manganese, copper, silicon metal, phosphorus and niobium)

- **Relevant value chain:** metal-ion batteries (based on sodium, zinc and aluminium)

Proposed type of action: Pillar II Mission, portfolio approach (package of Horizon, EIC, and ERC funds)

Expected TRL at end of project: 1-9

- **Potential for collaboration:** International collaborations should be considered, in particular with Horizon Europe–associated countries, such as the UK and Norway, which are pursuing work in this area and may provide opportunities for collaboration, and with

[612] Li, Y., Vasileiadis, A., Zhou, Q., Lu, Y., Meng, Q., Li, Y., Ombrini, P., Zhao, J., Chen, Z., Niu, Y., Qi, X., Xie, F., van der Jagt, R., Ganapathy, S., Titirici, M. M., Li, H., Chen, L., Wagemaker, M. and Hu, Y. S. (2024), Origin of Fast Charging in Hard Carbon Anodes, *Nature Energy* 9, 134–142. https://doi.org/10.1038/s41560-023-01414-5

countries with strong R&I outputs in this field (e.g. India). The EU already has a new strategic partnership with Norway on raw materials and battery value chains.[613]

- **Links to other key criticalities and R&I challenges:** This intervention is linked to the other batteries intervention. Beyond this action plan, relevant challenges and R&I interventions examined by this study include geothermal energy for lithium extraction and wider CRMs interventions.

- **Consideration for successful implementation:** With consideration of the future, cybersecurity may be an important factor to include in such a programme if processes in development are highly digitised. Skills are also a key factor to consider for a viable commercial supply in the EU, and the package of interventions should consider how to best nurture and maintain a pipeline of talent, including with movement of talent between research and industry.

  For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with affordability and environmental impacts.

10.2.4. Geothermal energy

Action 7

Proposed R&I intervention: Implementing a 'design-to-recycling' scheme for geothermal energy

Expected outcome: Open Horizon Europe call with the aim of implementing a 'design-to-recycling' scheme, including reducing and reusing CRMs in geothermal energy.

Scope: Equipment used to extract heat from Earth's interior relies on CRMs, in particular aluminium, copper, nickel and titanium. Aluminium is used in buildings, pipelines, platforms and equipment, such as compressors. Copper and nickel are used in turbines and alternators that generate electricity. Copper is also used in cooling towers and other accessories. Titanium is a catalyst in the gas treatment system for removal of odorous H_2S. Copper and nickel have a medium abundance risk, with rising demands for these raw materials. These two metals are therefore on the CRMs list for the EU.

CRM use in geothermal is limited relative to that in alternative renewable energy technologies. Additional workshop feedback highlighted the need to extend this action to materials in geothermal energy along the life cycle of the plant, including PFA use and waste separation and management.

With no specific material alternatives identified at this stage, a call would provide an opportunity to better understand the scale of challenge, for example with monitoring and reporting of CRM use, as well as potential solutions, such as design for recycling and novel materials. Knowledge exchange, regulation or standards may provide complementary support for implementation of solutions.

[613] European Commission (March 2024), EU and Norway Sign Strategic Partnership on Sustainable Land-based Raw Materials and Battery Value Chains.

- **Key energy security criticality addressed**: availability and abundance of CRMs (specifically aluminium, copper, nickel).

- **Relevant value chain:** construction phase of geothermal plants (CRM use), EOL phase (all material, including for casing and cementing)

Proposed type of action: RIA

Expected TRL at end of project: 4-6

- **Potential for collaboration:** The existing collaboration User4GeoEnergy may provide opportunities for further collaborations in future. The Horizon Europe–associated countries Canada and Norway are also pursuing research in this area, as are other countries with high potential for geothermal energy. The EU also has strategic partnerships with Horizon Europe–associated countries and EU overseas territories (Norway, Greenland, Ukraine, Canada), African Union countries (Namibia, Zambia, the Democratic Republic of Congo) and others (Kazakhstan, Argentina, Chile), which have been formed to diversify supply chains and that could be leveraged.[614]

- **Links to other key criticalities and R&I challenges:** Beyond this action plan, wider CRMs interventions are relevant.

- **Consideration for successful implementation:** For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with affordability and environmental impacts.

10.2.5. Hydrogen

Action 8

Proposed R&I intervention: A call for solutions to increase the resilience of hydrogen value chains

Expected outcome: A call to support the development of solutions to increase the resilience of a future commercial value chain, as hydrogen technologies are still in development. This may include digital solutions, process efficiency improvements, reduced reliance on CRMs and water, design considerations for reduced complexity, and standard performance benchmarks. For example, solid oxide electrolysis electrodes operate at very high temperatures (700 to 850 °C), which allows the use of relatively cheap nickel electrodes and a low electricity demand; the possibility to use waste heat should be explored.

Scope: The supply chains for PEM are complex and are vulnerable to disruption. With regards to solid oxide and AEM, the supply chains are not yet established, and there is uncertainty over future complexity and vulnerability.

[614] European Commission (March 2024), EU and Norway Sign Strategic Partnership on Sustainable Land-based Raw Materials and Battery Value Chains; European Commission (November 2023), EU and Greenland Sign Strategic Partnership on Sustainable Raw Materials Value Chains.

- **Key energy security criticality addressed:** supply chain resilience[615]
- **Relevant value chain:** Solid oxide electrolysers (work at high temperature), electrodes and catalysts (CRM), and AEM (membrane component, water use)

Proposed type of action: RIA, IA (for above TRL 5)

Expected TRL at end of project: 4-6

- **Potential for collaboration:** Existing partnerships to build on include a Germany-New Zealand centre, the Net-Zero Industries Mission, the Clean Hydrogen Mission and the Net-Zero Shipping Mission. The United States, Japan, Korea and Canada (the latter two of which are Horizon Europe–associated) are investing significantly in R&I and may provide collaboration opportunities.
- **Links to other key criticalities and R&I challenges:** Consideration of supply chain resilience should be incorporated into existing and upcoming hydrogen R&I programmes to ensure energy security is included as part of the development of future hydrogen supply chains in the EU.
- **Consideration for successful implementation:** With consideration of the future, cybersecurity may be an important factor to include in such a programme if processes in development are highly digitised. Skills are also a key factor to consider for a viable commercial supply in the EU, and the intervention should consider how to best nurture and maintain a pipeline of talent, including with movement of talent between research and industry.

  For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with sustainable water use, affordability and environmental impacts.

Action 9

Proposed R&I intervention: Research into the environmental impact of hydrogen

Expected outcome: A research topic to provide additional information on the environmental impact of hydrogen. In particular, research should focus on further evaluation of potential environmental impacts of PFAS used in hydrogen processes in PEM fuel cells. Increasing the understanding of potential impacts of PFAS use in hydrogen processes would support evidence-based policy for regulation of the use of PFAS in hydrogen or identify alternative solutions.

Scope: To produce hydrogen using electrolysing technologies, large amounts of pure water are needed. In addition, specifically for PEM, PFAS are needed. Currently no viable alternatives are available; therefore a blanket ban on PFAS would strongly impact the possibilities for hydrogen production through electrolysis.

[615] This encompasses a number of hydrogen criticalities (supply chain complexity, CRM), as our study showed these were connected in this instance.

The EU is supporting relevant R&I with regards to potential environmental impacts of hydrogen, including water use. With regards to PFAS, regulation could create drivers for innovation, or further research on environmental impacts may identify PFAS materials with limited impact. Potential solutions are available; however, in some cases they are now commercialised by non-EU companies, which may create a threat to EU competitiveness to be countered by introducing a competitive EU-based solution. Increasing the understanding of potential impacts of PFAS use in hydrogen processes would support evidence-based policy for regulation of the use of PFAS in hydrogen or identify alternative solutions.

This intervention was suggested by validation workshop participants as having potential for high impact, but they noted potential challenges around feasibility.

- **Key energy security criticality addressed: b**roader sustainability
- **Relevant value chain:** PEM fuel cells (PFAS in membranes)

Proposed type of action: RIA

Expected TRL at end of project: 1-4

- **Potential for collaboration:** Many countries are pursuing R&I on hydrogen with potential for collaboration, whereas others are concerned with the environmental impacts of hydrogen production processes.
- **Links to other key criticalities and R&I challenges:** n/a
- **Consideration for successful implementation:** For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with sustainable water use, affordability and environmental impacts.

10.2.6. Renewable fuels of non-biological origin and carbon capture and utilisation

Action 10

Proposed R&I intervention: Scale-up and demonstration of DAC for the production of RFNBOs

Expected outcome: Targeted R&I topic to intensify research on DAC applications specifically for RFNBO production, to address considerations for supply chain resilience as technology development progresses. In particular, this should focus on advancing the TRL of this technology, including demonstration at the commercial level and supply chain development.

Scope: For the production of e-kerosene, green hydrogen and CO_2 are needed. Use of fossil fuel sources of CO_2 will be prohibited as per 2041, following the Delegated Act on Recycled Carbon Fuels. At the same time, DAC is still low TRL and very energy intensive due to the relatively low concentration of CO_2 in the air and the high temperatures needed. The scale-up and related availability of sustainable CO_2 from DAC is uncertain. In addition, DAC has not been demonstrated at commercial level and this supply chain still needs to be set up.

The EU has strong CCUS and RFNBO R&I ecosystems. As both DAC and RFNBOs are in earlier technology development stages, there is an opportunity to bring together the communities, where relevant, to address supply chain questions and ensure that the future commercial value chain is resilient. This programme could also act as a mechanism to identify policy challenges or uncertainty and to identify other concerns to resolve.

- **Key energy security criticality addressed:** supply chain complexity
- **Relevant value chain:** direct air capture of CO_2 and proximity of DAC and electrolysers would be an advantage, because it would involve lower transport costs/infrastructure needed for transport

Proposed type of action: EIC Transition, EIC Accelerator, ERC grants or IA

Expected TRL at end of project: 6-9

- **Potential for collaboration:** EU researchers collaborate most with the UK, Switzerland, and rest of the world excluding the United States, China, Japan, South Korea and India, and there are existing networks to build on for an international collaboration.
- **Links to other key criticalities and R&I challenges:** This criticality and R&I challenge are linked to CCUS and affordability. Capturing and using or storing the CO_2 for biofuel processes and bioenergy production is very promising to maximise the climate impact of the biomass we have available; this links to the RFNBO and CCUS topics.
- **Consideration for successful implementation:** With consideration of the future, cybersecurity may be an important factor to include in such a programme if processes in development are highly digitised. Skills are also a key factor to consider for a viable commercial supply in the EU, and the intervention should consider how to best nurture and maintain a pipeline of talent, including with movement of talent between research and industry.

  For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with affordability and environmental impacts.

Action 11

Proposed R&I intervention: Policy lab on business models for RFNBOs

Expected outcome: A dedicated policy lab to identify viable business models needed to bring RFNBOs closer to market would help ensure that RFNBOs are affordable and resilient. Complementary studies on appropriate policy and regulatory interventions would support evidence-based policy to facilitate commercialisation. This solution was also highlighted for hydrogen in the validation workshop.

Scope: Synthetic kerosene production costs depend to a large extent on the price of electricity, which is related to the location and meteorological conditions. The EU has a strong CCUS and RFNBO R&I ecosystem and is supporting R&I for cost reduction. As

RFNBOs are in early development stages, there is an opportunity to build consideration of this criticality into the development of the technology, including some work on societal readiness and business models. Technology-focused R&I for RFNBOs is not the prime mechanism to address this criticality directly, but additional policy research to support viable business models and R&I for hydrogen and carbon supply chains may provide a more impactful and effective solution. Complementary R&I may support cost reductions for the electrolyser.

- **Key energy security criticality addressed:** affordability
- **Relevant value chain:** synthetic kerosene production (use phase in synthetic kerosene life cycle)

Proposed type of action: CSA

Expected TRL at end of project: n/a

- **Potential for collaboration:** n/a
- **Links to other key criticalities and R&I challenges:** This criticality and R&I challenge is linked to hydrogen and RFNBOs key criticality 2: vulnerability to wider energy system dependence.
- **Consideration for successful implementation:** With consideration of the future, cybersecurity may be an important factor to include in such a programme if processes in development are highly digitised. Skills are also a key factor to consider for a viable commercial supply in the EU, and the intervention should consider how to best nurture and maintain a pipeline of talent, including with movement of talent between research and industry.

  For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with affordability and environmental impacts.

10.2.7. Wind energy

Action 12

Proposed R&I intervention: Increasing the circularity of wind energy and reducing the use of CRMs

Expected outcome: A Horizon Europe call that focuses on the dual aim of reducing the use of critical raw materials and improving the circularity of wind energy. This intervention should be complemented with a knowledge-exchange programme to share lessons and solutions among the wind energy, ocean energy and hydropower sectors.

Scope: The use of CRMs in all of the wind energy technologies poses risks in terms of energy security, especially as wind energy is expected to play a major role in the European and global transition towards clean energy technologies. The CRMs used in on- and offshore wind turbines with highest risk according to the EU are copper, boron/borate, nickel and light and heavy rare-earth materials. Airborne wind energy systems also use lithium and titanium.

The EU has a number of programmes targeted at addressing CRM supply for wind, and it should continue to support the development of alternative materials, design solutions, quality control for longer operation times and circularity due to the anticipated importance of wind energy in future EU energy supply. Gaps identified in the validation workshop included R&I for circularity in wind power technologies.

Validation workshop participants suggested this intervention would have high impact and high feasibility.

- **Key energy security criticality**: availability and abundance of CRMs (copper, boron, nickel, rare earths, lithium, titanium)

- **Relevant value chain:** production of turbines, generators (including permanent magnets), cables and controller units and electronics in onshore and offshore wind turbines

Proposed type of action: RIA or MSCA

Expected TRL at end of project: 5-6

- **Potential for collaboration:** Existing collaborations for wind energy include the IEA Wind Energy Systems TCP, although work does not specifically focus on this challenge. The Horizon Europe–associated countries UK and Norway also pursue work on wind energy with potential for collaboration. The EU also has strategic partnerships with Horizon Europe–associated countries and EU overseas territories (Norway, Greenland, Ukraine, Canada), African Union countries (Namibia, Zambia, the Democratic Republic of Congo) and others (Kazakhstan, Argentina, Chile), which have been formed to diversify supply chains and that could be leveraged.[616]

- **Links to other key criticalities and R&I challenges:** This intervention has links and potential for added benefit to the equivalent criticality for ocean energy and hydropower. Wider interventions relevant to securing the supply of CRMs may also be relevant.

- **Consideration for successful implementation:** For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with affordability and environmental impacts.

[616] European Commission (March 2024), EU and Norway Sign Strategic Partnership on Sustainable Land-based Raw Materials and Battery Value Chains; European Commission (November 2023), EU and Greenland Sign Strategic Partnership on Sustainable Raw Materials Value Chains.

Proposed R&I intervention: Addressing the digital vulnerabilities of wind energy

Expected outcome: Increased resilience of wind energy technologies through research assessing digital vulnerabilities and developing solutions. This topic should be embedded in a call for wind energy.

Scope: The majority of wind turbines use remote communication systems in order to monitor and control the wind turbine. A 'zero-dynamics attack' is a cyber-attack that cannot be detected by the monitoring output and that exploits the internal dynamics of a system in order to cause damage. In the case of a wind turbine, this may involve an attack that causes an uncontrolled/unstable rotational speed.

Digital attacks may cause significant damage to wind turbines, and cybersecurity is an evolving threat. Wind farms are increasingly digital dependent and vulnerable to cyberattacks or disruption of digital networks, with potential negative impacts on the operation of the energy grid. R&I programmes could incorporate a consideration of how to best manage risks from legacy technology and public information.

- **Key energy security criticality addressed:** digital vulnerability[617]
- **Relevant value chain:** electronics (construction phase of wind energy life cycle) and use phase of life cycle; these relate to all types of wind energy covered in this study

Proposed type of action: RIA, ERC or EIC

Expected TRL at end of project: 4-6

- **Potential for collaboration:** Existing collaborations for wind energy include the IEA Wind Energy Systems TCP, although work does not specifically focus on this challenge. The Horizon Europe–associated countries UK and Norway also pursue work on wind energy, with potential for collaboration.

- **Links to other key criticalities and R&I challenges:** This intervention has links to wider challenges around cybersecurity of the energy system.

- **Consideration for successful implementation:** Key considerations about cybersecurity are the interfaces between technologies and systems and the range of stakeholders involved. It may be valuable to ensure networks of relevant stakeholders are involved to ensure a clear understanding of responsibility and of potential cascading effects or risks.

  For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with affordability and environmental impacts.

[617] Digital vulnerability was identified as a missing key criticality during the validation workshop.

10.2.8. Ocean energy

Action 14

Proposed R&I intervention: Financial support mechanism to support demonstration and deployment of ocean energy technologies

Expected outcome: The EU has a strong ocean energy R&I ecosystem, and a number of upcoming R&I funding calls include a focus on cost reduction. Cost reductions are expected to follow the example of offshore wind, with demonstration and deployment projects now crucial to enable cost reduction. France has launched commercial contracts, supporting demonstration and deployment with revenue. Low-cost loans and revenue support would further encourage demonstration and deployment (mid- to high TRL), leveraging private investment in R&I (de-risking) and ensuring that the EU remains an attractive location for industry in a competitive environment. Financial support would provide a complementary intervention to existing and upcoming R&I interventions to reduce the cost of ocean energy technologies.

Scope: Since procedures, materials and manufacturing of ocean energy devices are not streamlined, both CAPEX and operating expense (OPEX) are currently high, but they are due to become lower with the commercialisation of more projects and with the increase in installed capacity. The LCOE estimates for ocean energy technologies are >0.1 EUR/kWh, which is linked to technological complexity and economy of scale of the technologies and therefore high CAPEX cost. In addition to CAPEX, maintenance costs could also be reduced with increased material durability.

The largest costs are attributed to structural components and power conversion system of device, followed by moorings to keep the device in its place (wave and tidal technologies). In ocean thermal technologies, the heat exchanger is 30-50% of the total cost, while in salinity gradient technologies, costs are driven by the cost of membranes (50-80% of total cost). Additional financial support to reduce the costs of these specific components would complement existing programmes working on LCOE reductions in ocean energy,

This intervention was viewed as high impact, high feasibility by validation workshop participants.

- **Key energy security criticality addressed:** affordability
- **Relevant value chain:** structural components and moorings (wave and tidal technologies), heat exchanger (ocean thermal), membranes (salinity gradient)

Proposed type of action: IA, EIC Transition or EIC Accelerator

Expected TRL at end of project: 7-9

- **Potential for collaboration:** Existing collaborations to build on include a France–UK collaboration and the IEA Ocean Energy Systems TCP. South Korea and Norway also present opportunities for collaboration.
- **Links to other key criticalities and R&I challenges:** Affordability can influence public opinion, which links to the other ocean energy R&I action.

- **Consideration for successful implementation:** With consideration of the future, cybersecurity may be an important factor to include in such a programme if processes in development are highly digitised. Skills is also a key factor to consider for a viable commercial supply in the EU, and we note that ocean energy is currently benefiting from maritime industry skills pipelines. The intervention should consider how to best nurture and maintain a pipeline of talent, including with movement of talent between research and industry.

  For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with affordability and environmental impacts.

Action 15

Proposed R&I intervention: Public engagement research on ocean energy

Expected outcome: Research and public engagement with regards to public perceptions of ocean energy and considerations for public support for deployment. Member States with potential host communities may consider delivering public dialogues.

Scope: Limited information was found by this study about research on EU public attitudes to ocean energy, and there are mixed opinions on the impact of ocean energy on the environment (e.g. some note that ocean energy is not yet applied at large scale, so impacts of large-scale installations are not known yet), which could lead to negative public perceptions. Research carried out in non-EU countries has identified concerns that may introduce barriers to deployment. This intervention would address this gap in EU research and enable further action if required.

- **Key energy security criticality addressed**: broader sustainability and environmental impacts of ocean energy (public opinion)
- **Relevant value chain:** tidal, wave and ocean thermal energy technologies (regarding research on ecological effects)

Proposed type of action: CSA or MSCA

Expected TRL at end of project: n/a

- **Potential for collaboration:** UK and US researchers have carried out studies with coastal populations in their respective countries and may be able to share their experience and provide expertise.
- **Links to other key criticalities and R&I challenges:** Environmental impacts and affordability are factors that can influence public opinion, with links to this challenge and potential consideration of priority areas for future R&I depending on findings. There are opportunities to explore the overlap between ocean and wind energy regarding this criticality, e.g. co-location of wind and wave projects could reduce negative public perceptions through the added benefits that hybridisation can bring.
- **Consideration for successful implementation:** For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with affordability and environmental impacts.

10.2.9. Hydropower

Action 16

Proposed R&I intervention: Public engagement research on hydropower

Expected outcome: Research and engagement on public perceptions of hydropower to understand and address concerns where possible

Scope: Hydropower has a potentially very high ecological impact due to dam and reservoir installation, including modification of hydrological regimes and aquatic habitats, water quality, barriers to fish migration, introduction of pest species and impact on sedimentation, impoundment and methane emissions. Further, there is a possible negative social impact of large-scale dams because the building of dams may involve resettlement of local communities, impact the few remaining pristine waterways in Europe, increase the risk of waterborne diseases and influence cultural heritage sites. Lastly, there is also a public safety risk as dams become older.

Validation workshop participants stressed that public opposition to hydropower is the biggest risk to further development of the technology. The public is not well aware of the benefits and impacts of hydropower, nor of the solutions that exist for some of the environmental impacts (e.g. modernisation of existing hydropower, multipurpose hydropower. developing hidden hydro in existing infrastructures, new pumped hydro using existing reservoirs, and abandoned mine closed-loop hydropower).

The EU has supported research on the environmental impacts of hydropower, with an increased understanding now available, as well as potential solutions and strategies, such as interconnecting reservoirs to mitigate negative impacts. Engagement with the public would support a better understanding of both the public's concerns and views around solutions and the available evidence on environmental impacts of hydropower.

This intervention was suggested by workshop participants and is thought to have potential for high impact and feasibility.

- **Key energy security criticality addressed**: broader sustainability and environmental impacts of hydropower (public opinion)
- **Relevant value chain:** all value chains across the life cycle of a dam

Proposed type of action: CSA or MSCA

Expected TRL at end of project: n/a

- **Potential for collaboration:** The United States, Switzerland, Canada, Norway, China, and the UK are the top countries pursuing hydropower R&I and may have shared challenges with regards to public perceptions. Opportunities for learning and knowledge exchange with countries with strong hydropower infrastructure and experience with socio-environmental impacts (e.g. Brazil) are available.
- **Links to other key criticalities and R&I challenges:** This challenge is linked to the other hydropower R&I action included in this plan.

- **Consideration for successful implementation:** For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with sustainable water use, affordability and environmental impacts.

Action 17

Proposed R&I intervention: Development and deployment of monitoring tools for biodiversity impacts of hydropower

Expected outcome: Incentives and support to implement monitoring of biodiversity impacts of hydropower, for example regulation or innovation adoption grants. This would produce tools for objective assessment of biodiversity to inform both technology development and future regulation.

Scope: The EU is supporting research in this space, and a number of solutions are available for implementation. Tools for objective assessment of biodiversity before and after project implementation are also available (e.g. modernisation of existing hydropower; developing hidden hydro in existing infrastructures, including new pumped hydro using existing reservoirs and abandoned mine closed-loop hydropower; regulatory frameworks, such as faster licensing with monitoring, and subsequent adaptive management programmes, such as the existing voluntary green label), although often not implemented. An impactful R&I intervention would provide incentives or support to implement monitoring of biodiversity impacts specifically, such as regulation or innovation adoption grants. With monitoring data available, a more robust evidence base could be developed to understand impacts, both positive and negative, and to better inform policymakers and the public.

This intervention was suggested by workshop participants, and is thought to have potential for high impact and feasibility.

- **Key energy security criticality addressed:** environmental impacts of hydropower

- **Relevant value chain:** monitoring of environmental impacts from hydropower infrastructure (dam, reservoir, control gate, penstock, turbine, power lines, powerhouse, transformer, generator)

Proposed type of action: RIA (for TRL below 5), IA, PPI, or EIC Accelerator

Expected TRL at end of project: 5-9

- **Potential for collaboration:** Horizon Europe–associated countries, such as the UK, Norway and Canada, are top countries pursuing hydropower R&I. Opportunities for learning and knowledge exchange with countries with strong hydropower infrastructure and experience with socio-environmental impacts (e.g. Brazil) are available. Opportunities to collaborate beyond Horizon Europe–associated countries lie with countries with strong R&I outputs in this field (e.g. the United States, China, Switzerland).

- **Links to other key criticalities and R&I challenges:** This challenge is linked to the other hydropower R&I action included in this plan.

- **Consideration for successful implementation:** For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with sustainable water use, affordability and environmental impacts.

Action 18

Proposed R&I intervention: Developing a long-term climate adaptation strategy for hydropower technologies

Expected outcome: The impacts of climate change on different hydropower technologies are understood to varying extents, and there are a range of potential solutions. A gap in current R&I programmes is long-term climate adaptation planning and development of an evidence-based sustainable strategy, for example hybridisation with other technologies (e.g. with floating PV) or use of interconnecting or multipurpose reservoirs. Water storage needs, flood control and other non-energy uses of hydropower relevant to climate adaptation should also be considered within a long-term climate adaptation strategy for hydropower. The main aim of this programme would be to identify suitable actions or design considerations for existing and new hydropower that are needed in the near term to ensure long-term, resilient operation of hydropower. For example, the resilience of hybridised technologies (hydropower and floating PV) could be limited due to water level variation or ice in the water, while multipurpose reservoirs may encounter issues from the larger water volumes and civil structures needed. These issues must be studied and considered.

Scope: Climate change will affect the timing of inflow to the reservoirs because it will lead to increasing snow melt in spring and decreasing glacier melt in summer. Glacier retreat could result in an opportunity for new, multipurpose reservoirs at new glacier lakes. Several projects in the Alps have been identified which could yield new, multipurpose reservoirs for energy supply and water management. Similarly, multipurpose hydropower reservoirs could be used to mitigate the effects of floods and droughts in increasingly arid zones in Europe. This intervention should include consideration of hybridisation and non-energy uses of hydropower relevant to climate adaptation.

- **Key energy security criticality addressed**: physical vulnerability to climate change
- **Relevant value chain:** primarily dams and reservoirs

Proposed type of action: Pre-commercial procurement (PCP), followed by specific R&I activities in activities suggested by the adaptation strategy output from this action

Expected TRL at end of project: n/a

- **Potential for collaboration:** Horizon Europe–associated countries, such as the UK, Norway and Canada, are top countries pursuing hydropower R&I. Opportunities to collaborate beyond Horizon Europe–associated countries lie with countries with strong R&I outputs in this field (e.g. the United States, China, Switzerland).
- **Links to other key criticalities and R&I challenges:** This challenge is linked to the other hydropower R&I actions included in this plan, as well as cross-cutting issues with other technologies (e.g. biodiversity)

- **Consideration for successful implementation:** For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with sustainable water use, affordability and environmental impacts.

10.2.10. Heat pumps

Action 19

Proposed R&I intervention: Developing policies, regulations and standards for resilient heat pumps

Expected outcome: A dedicated policy lab or regulatory sandbox to identify viable policy, regulation and standards for resilient heat pumps, to promote the development and deployment of heat pumps throughout the EU

Scope: Increased use of electricity for heating also increases exposure to power outages and needs increased network connection capacity from companies. Existing solutions are available, and an effective approach to ensure this criticality is addressed is regulation, encouraging adoption of solutions and standards for resilient heat pump value chains. Regulation can also lead to further innovation; an example of this includes research needed for industrial heat pumps, to ensure safe EOL disposal of refrigerants and development of new technologies for safe refrigerants that comply with F-gas regulation.

The intervention has high feasibility and high potential for impact.

- **Key energy security criticality addressed**: vulnerability to wider energy system disruption (e.g. vulnerability to physical disruptions of the electricity grid, supply chain of semiconductor chips and emerging digital vulnerability)
- **Relevant value chain:** semiconductor chips, refrigerants, electronics (when connecting pumps to the wider energy system)

Proposed type of action: IA

Expected TRL at end of project: 7-9

- **Potential for collaboration:** Collaboration within the EU will also be key to increase preparedness, in particular initiatives that target having positive effects on lowering the costs.
- **Links to other key criticalities and R&I challenges:** Improving standards more broadly could decrease the installation time of heat pumps and hence decrease the pressure on labour needs, thereby impacting skills criticality. This cross-cutting action could lead to future research (to comply with regulation) on methods to ensure affordability, broader sustainability, and supply chain vulnerability (further research on semiconductor chips).
- **Consideration for successful implementation:** For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with affordability.

10.2.11. Off-grid energy technology

Action 20

Proposed R&I intervention: International collaboration on environmental impacts of off-grid heating

Expected outcome: International collaboration to address the challenge of environmental impacts of off-grid heating, for example by understanding drivers for misuse and identifying good practice, design solutions or regulation to reduce environmental impacts.

Scope: The operation of a biogas tank needs a continuous supply of biomass. The use of biogas for heating will require a relatively continuous supply of biogas that can be stored in the tank. A sustainability risk relates to the material that might be used as feedstock, as the feedstock used for production of biogas for biogas tanks is sometimes illegally polluted by prohibited biowaste (for instance slaughterhouse waste) or fossil waste (for instance chemical waste). This could end up in the food chain, through the digestate produced in addition to biogas.

International partnerships with countries that have a similar challenge may be valuable to address this challenge, for example with Canada and the African Union. This may include developing good practice or understanding of impact drivers.

- **Key energy security criticality addressed:** environmental impacts
- **Relevant value chain:** biogas tank and feedstock (regarding misuse), pellet stoves (regarding air pollution)

Proposed type of action: PCP, IA or EIC grants

Expected TRL at end of project: 6-9

- **Potential for collaboration:** The EU has existing collaborations with the African Union with regards to off-grid technologies. Other countries, such as the UK, have also identified air pollution from off-grid energy technology as a challenge.
- **Links to other key criticalities and R&I challenges:** n/a
- **Consideration for successful implementation:** For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with affordability, environmental impact and health.

10.2.12. Direct solar fuels

Action 21

Proposed R&I intervention: Increasing the resilience of the photo- and thermochemical solar fuel supply chains

Expected outcome: Existing EU R&I programmes or subsequent or parallel R&I programmes should be complemented with aims and incentives to increase the resilience of the photo- and thermochemical solar fuel supply chains.

Scope: The components required for direct solar fuels are highly specialised. The technology is also still in development phase (maximum TRL for direct solar fuels from thermochemical routes: 5), meaning components and materials are still being researched. The specialised character and ongoing research are the main supply chain complexities for this technology.

A 2021 Commission-funded study[618] found that the direct solar pathway for producing hydrogen, methanol, ethanol and methane struggled to be competitive compared with fossil-based methods, even in the long term (2050-2100), mainly due to high costs for energy and other inputs.

- **Key energy security criticality addressed:** supply chain complexity
- **Relevant value chain:** light absorbers, sensitisers, heat exchangers

Proposed type of action: RIA, ERC grants or EIC Pathfinder

Expected TRL at end of project: 4-6

- **Potential for collaboration:** Mission Innovation provides an opportunity for international collaboration, including around digitalisation for more resilient supply chains.
- **Links to other key criticalities and R&I challenges:** This intervention provides an opportunity to also address the skills (providing further opportunity for skills development), CRMs and affordability criticalities.
- **Consideration for successful implementation:** With consideration of the future, cybersecurity may be an important factor to include in such a programme if processes in development are highly digitised. Skills is also a key factor to consider for a viable commercial supply in the EU. The intervention should consider how to best nurture and maintain a pipeline of talent, including with movement of talent between research and industry.

  For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with affordability and environmental impact.

[618] Buffi, M., Prussi, M., Scarlat, N. (2022), Energy and Environmental Assessment of Hydrogen from Biomass Sources: Challenges and perspectives. *Biomass and Bioenergy,* 165. https://doi.org/10.1016/j.biombioe.2022.106556

10.2.13. Other storage (compressed air energy storage)

Action 22

Proposed R&I intervention: Developing a better understanding of the potential locations for underground CAES

Expected outcome: A research programme with the aim to develop a better understanding of the potential locations for underground CAES. The extensive exploration for underground storage space adds considerable complexity to the construction and use of CAES, since CAES can only be deployed in areas where suitable underground cavities are available. Besides this, the (environmental) risks of compressed air storage in depleted gas fields are relatively unknown and necessitate additional research. The findings of this research may also potentially increase local acceptance.

Scope: In the CAES process, electricity drives a compressor to compress air, which is then injected at high pressure into substantial underground areas, such as depleted gas fields, salt caverns or, potentially, aquifers, as well as above-ground vessels. When electrical power is needed, the stored compressed air is heated and subsequently expanded through a turbine to drive a generator. Salt caverns used for underground activities can potentially cause subsidence and seismic activity. Although soil subsidence is a natural part of cavern construction, it can be managed and mitigated if necessary. The risk of seismic activities measured at storage caverns are not as well understood as those measured at gas fields. Furthermore, the extraction of salt and underground activities frequently encounters limited backing from the local community, primarily due to concerns regarding subsidence and seismic events.

While the risks associated with underground activities related to natural gas storage are well understood, the risks of compressed air storage are relatively unknown and R&I on the challenge is a current gap in the EU and in countries elsewhere. Furthermore, there is also a knowledge gap on the preferred use of underground space for energy storage in general. Underground storage areas can serve the purpose of storing hydrogen as well as compressed air. As it is uncertain whether there will be enough suitable storage space for hydrogen, it is most likely that storage space for CAES is in competition with underground storage of hydrogen. Hence, the primary focus of the research programme should be determining which type of storage (compressed air or hydrogen) exhibits a predominant preference for utilising underground storage sites.

- **Key energy security criticality addressed:** environmental impacts
- **Relevant value chain:** compressor and expansion system, above-ground storage tanks prior to injection, location of storage sites

Proposed type of action: RIA, IA

Expected TRL at end of project: 5-7

- **Potential for collaboration:** The UK, the United States, Canada, India and Israel are pursuing work in this area and considering locations for deployment, and a potential shared challenge for collaboration exists.
- **Links to other key criticalities and R&I challenges:** n/a

- **Consideration for successful implementation:** For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with affordability and environmental impact. To ascertain whether CAES or hydrogen demonstrates a predominant preference for utilising underground storage sites, it is necessary to examine the energy system holistically, considering the utilisation and storage of hydrogen in its entirety.

10.2.14. Photovoltaics

Action 23

Proposed R&I intervention: Collaborative industry programme to increase the efficiency of PV manufacturing in the EU

Expected outcome: A Horizon Europe collaborative industry programme to support initial new supply chains focused on increasing the efficiency of solar PV manufacturing processes in the EU. This would support the development of solutions enabling onshoring and cost competitiveness of EU-based PV supply chains.

Scope: There is not sufficient manufacturing capacity of solar cells in the EU, and current mining and manufacturing is largely based outside the EU and mainly in one country (China), which appears to be the weakest link of the solar PV value chain in the EU. Entering the market with EU cells and modules is difficult because production costs are lower in Asia. In addition, valuable high-purity silicon is currently not yet being recovered for high-grade reuse in solar cells. Since producing silicon requires a lot of energy, there is room for improvement from a sustainability point of view; it is a technical and economic challenge to recover high-quality silicon from the waste stream.

Onshoring silicon PV value chains to the EU may be effectively achieved through acquisition or policy interventions, although we acknowledge that there are significant costs associated with onshoring. In the case of acquisition, complementary R&I programmes to support continued innovation and competitiveness may be key to achieving overall energy security objectives. With this in mind, R&I to improve the energy efficiency of solar cell manufacturing processes would enable an EU-based supply chain to be more competitive.

To complement this, activities regarding energy-efficient recycling of silicon from waste streams would feed into energy-efficiency and circularity objectives. Validation workshop participants noted that low-technology semiconductor chips are also essential for Si-PV value chains, in particular for the inverters. Efficient recycling projects could contribute to this action.

This intervention was suggested by validation workshop participants for its potential high impact.

- **Key energy security criticality addressed:** supply chain location outside the EU

- **Relevant value chain:** construction of silicon-based PV modules and CRMs within modules

Proposed type of action: EIC Transition, EIC Accelerator or PCP

Expected TRL at end of project: 5-7

- **Potential for collaboration:** Potential for collaboration with African Union countries to establish a more resilient supply chain, as Africa is the main supplier of raw materials after China. Existing partnerships include the EU–Africa partnership and the Clean Energy Ministerial Clean Power workstream, which includes a global initiative on Transforming Solar Supply Chains (co-led by Germany, Australia, India and the United States).

- **Links to other key criticalities and R&I challenges:** Developing an EU-based perovskite value chain may provide an alternative solution, and proposed R&I intervention is included in this R&I action plan.

- **Consideration for successful implementation:** Circularity and repairability should be embedded in this intervention to ensure resource efficiency is maximised and in line with wider EU ambitions. This is particularly relevant for CRMs and implementation may benefit from support or regulatory intervention to incentivise recycling.

  With consideration of the future, cybersecurity may be an important factor to include in such a programme if processes in development are highly digitised. Skills is also a key factor to consider for a viable commercial supply in the EU. The intervention should consider how to best nurture and maintain a pipeline of talent, including with movement of talent between research and industry.

  For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with affordability and environmental impact.

Action 24

Proposed R&I intervention: Supporting the development and commercialisation of perovskite solar cells in the EU

Expected outcome: A portfolio of R&I interventions to support the successful development and commercialisation of perovskite solar cells. Alongside this, the investment will support the development of EU skills and supply chain. Therefore, this investment should consist of complimentary Horizon, EIC and ERC structural funds.

Scope: Perovskites may provide a strategic opportunity for the EU to both reduce its reliance on CRMs for solar power and develop an EU-based supply chain for solar cells. Perovskite solar cells are not commercially available yet; therefore the scale of the challenge should be carefully considered to design a portfolio of interventions to provide a coherent and end-to-end package of support, addressing lower TRL research challenges, late-stage development, university–industry exchange, and business growth, including start-ups.

In terms of cell components and mitigating supply chain vulnerability, raw materials need to be sourced and processed. Various layers are stacked and processed to create the solar cell structure. Subsequently the thin-film module needs to be assembled. Ancillary components, such as inverters and wiring, are also part of the supply chain. Once installed, regular maintenance and monitoring are needed to ensure optimal performance. A recycling method for perovskite solar cells is not operational right now, and infrastructure for recycling on a large scale is not established, which may eventually lead to modules being disposed of rather than recycled. Therefore, the portfolio of interventions must look at the entire value chain.

Workshop participants viewed this intervention as having potential for high impact and high feasibility.

- **Key energy security criticality addressed**: availability and abundance of CRMs (silicon, copper, aluminium, nickel, boron, gallium, titanium, germanium, phosphorus – perovskites do not need these materials)

- **Relevant value chain:** entire value chain of perovskite solar cells (construction phase and recycling of components, to move away from CRM-heavy PV technologies)

Proposed type of action: Pillar II Mission (portfolio of Horizon, EIC and ERC, structural funds)

Expected TRL at end of project: 1-9

- **Potential for collaboration:** Existing partnerships include the EU–Africa partnership and the Clean Energy Ministerial Clean Power workstream includes a global initiative on Transforming Solar Supply Chains, which Germany co-leads along with Australia, India and the United States. The United States also has a funding programme supporting the development of perovskite solar cells. The EU also has strategic partnerships with Horizon Europe–associated countries and EU overseas territories (Norway, Greenland, Ukraine, Canada), African Union countries (Namibia, Zambia, the Democratic Republic of Congo) and others (Kazakhstan, Argentina, Chile), which have been formed to diversify supply chains and that could be leveraged.[619]

- **Links to other key criticalities and R&I challenges:** The challenge is linked to the other photovoltaics action and the skills criticality identified in the assessment.

- **Consideration for successful implementation:** Circularity and repairability should be embedded in this intervention to ensure resource efficiency is maximised and in line with wider EU ambitions.

  With consideration of the future, cybersecurity may be an important factor to include in such a programme if processes in development are highly digitised. Skills are also a key factor to consider for a viable commercial supply in the EU. The intervention should

[619] European Commission (March 2024), EU and Norway Sign Strategic Partnership on Sustainable Land-based Raw Materials and Battery Value Chains; European Commission (November 2023), EU and Greenland Sign Strategic Partnership on Sustainable Raw Materials Value Chains.

consider how to best nurture and maintain a pipeline of talent, including with movement of talent between research and industry.

For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with affordability and environmental impact.

10.2.15. Smart cities

Action 25

Proposed R&I intervention: Assessing digital vulnerabilities as part of the smart cities mission

Expected outcome: R&I activities to assess digital vulnerabilities and develop solutions, embedded in the mission for smart cities. These complementary R&I programmes, incorporated in the existing mission, would consider how to best manage risks from legacy technology and the management of personal data, de-risking the development of technologies and their implementation.

Scope: Cybersecurity is an evolving threat. Smart cities are very dependent on digital technologies and are inherently vulnerable to cyberattacks or disruption of digital networks (e.g. hacks on autonomous driving technologies, availability, replay, integrity, confidentiality and authenticity attacks on smart meters) with potential negative impacts on the operation of the energy grid. With an existing mission for smart cities, complementary R&I programmes could be incorporated, including for consideration of how to best manage risks from legacy technology and the management of personal data.

- **Key energy security criticality addressed:** digital vulnerability
- **Relevant value chain:** sensors, digital hardware and software (use phase)

Proposed type of action: RIA or PCP

Expected TRL at end of project: 4-6

- **Potential for collaboration:** This is a shared challenge across countries, with potential opportunities for collaboration with key partners or in cases where challenges are not considered to be sensitive.
- **Links to other key criticalities and R&I challenges:** The challenge is linked to wider cybersecurity and digital vulnerability of energy systems and technologies.
- **Consideration for successful implementation:** Key considerations with regards to cybersecurity are the interfaces between technologies and systems and the range of stakeholders involved. It may be valuable to ensure networks of relevant stakeholders are involved, to ensure a clear understanding of responsibility and of potential cascading effects or risks.

10.2.16. Smart energy grid technologies, smart cities, energy building and district heating technologies

Action 26

Proposed R&I intervention: Increasing circular economy processes, recycling and reuse of electronics for smart energy technologies

Expected outcome: Recycling and reuse of electronics is currently low, and as early generation technologies reach end of life, there is an opportunity to support EU supply through recycling and reuse of these resources. This intervention would develop circular economy processes to increase the recycling and reuse of electronics for smart energy technologies. In particular, this intervention should focus on the opportunities to reuse CRMs and on providing mechanisms to increase self-sufficiency within the EU.

Scope: Smart energy grids, smart cities and energy building and district heating technologies are based on advanced electronics and control technologies containing CRMs (e.g. palladium, cobalt, gallium, germanium, silicon and rare-earth materials). In addition, the semiconductors and chips needed for these electronics are mainly manufactured in a limited number of countries outside the EU. Criticalities also relate to circularity. Especially the recycling rate of CRMs should improve, for the EU to be able to be more self-sufficient in the supply of these materials.

Recycling and reuse of electronics are currently low, and as early generation technologies reach end of life, there is an opportunity to support EU supply through recycling and reuse of these resources.

- **Key energy security criticality addressed**: availability and abundance of CRMs and location of advanced electronics supply chains (palladium, cobalt, gallium, germanium, silicon, rare-earth materials)
- **Relevant value chain:** construction and EOL phases in the life cycles of these technologies (less relevant for electric vehicle smart charging), including e-waste and cable waste, AMI (which often incorporate semiconductors)

Proposed type of action: RIA, PPI or EIC Transition

Expected TRL at end of project: 4-6

- **Potential for collaboration:** The United States was another first mover with the adoption and roll-out of smart energy technologies and may face shared challenges, with potential for collaboration. The EU also has strategic partnerships with Horizon Europe–associated countries and EU overseas territories (Norway, Greenland, Ukraine, Canada), African Union countries (Namibia, Zambia, the Democratic Republic of Congo) and others (Kazakhstan, Argentina, Chile), which have been formed to diversify supply chains and that could be leveraged.[620]

[620] European Commission (March 2024), EU and Norway Sign Strategic Partnership on Sustainable Land-based Raw Materials and Battery Value Chains; European Commission (November 2023), EU and Greenland Sign Strategic Partnership on Sustainable Raw Materials Value Chains.

- **Links to other key criticalities and R&I challenges:** The challenge is linked to wider challenges regarding the supply of CRMs and electronics.

- **Consideration for successful implementation:** The EU has set out policy ambitions to secure the supply of CRMs and semiconductors. Actions taken as part of the EU Chips Act and the Chips for Europe initiative should consider clean energy technologies in their remit.

  With consideration of the future, cybersecurity may be an important factor to include in such a programme if processes in development are highly digitised. Skills is also a key factor to consider for a viable commercial supply in the EU. The intervention should consider how to best nurture and maintain a pipeline of talent, including with movement of talent between research and industry.

  For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with affordability and environmental impact.

10.2.17. Smart energy grid technologies, energy building and district heating technologies

Action 27

Proposed R&I intervention: Addressing cybersecurity risks to smart energy grid, building and district heating technologies

Expected outcome: This intervention would develop solutions to address cybersecurity risk, including research to ensure cybersecurity can be maintained for legacy systems and that understanding of the evolution of threats informs regulation and standards.

Scope: Both smart energy grid and some building and district heating technologies (HEMSs and smart meter infrastructure) are digital dependent, which inherently makes them vulnerable to cyberattacks or disruptions of the digital network. This vulnerability could negatively impact the functioning of the energy grid. AMI and HEMSs are vulnerable to data theft as well.

Cybersecurity is an evolving threat. The Smart Meters Coordination Group working on privacy and minimum-security requirements should be supported with complementary R&I to ensure monitoring of threats and development of solutions. This should include consideration of the risks of data theft.

- **Key energy security criticality addressed:** digital vulnerability

- **Relevant value chain**: AMI, ACT and HEMSs

Proposed type of action: RIA and/or PPC

Expected TRL at end of project: 5-6

- **Potential for collaboration:** The United States was another first mover with the adoption and roll-out of smart energy technologies and may face shared challenges, with potential for collaboration.

- **Links to other key criticalities and R&I challenges:** The challenge is linked to wider cybersecurity and digital vulnerability of energy systems and technologies.

- **Consideration for successful implementation:** Key considerations with regards to cybersecurity are the interfaces between technologies and systems and the range of stakeholders involved. It may be valuable to ensure networks of relevant stakeholders are involved to ensure a clear understanding of responsibility and of potential cascading effects or risks.

10.2.18. Energy transmission and distribution technologies

Action 28

Proposed R&I intervention: **I**ncreasing circular economy processes, recycling and reuse of electronics for smart energy technologies

Expected outcome: R&I programme to increase recycling and reuse in energy transmission and distribution and develop the sustainable production of aluminium and other alternatives. The call would take a two-pronged approach, looking for opportunities to replace copper with aluminium more energy efficiently and to incorporate sustainable aluminium.

Scope: Both copper and aluminium are indispensable for HVDC cables as the metal conductors are made of either of these materials. Copper has better electro-physical performance, though aluminium is often preferred over copper for very long distances due to its lighter weight.

There are currently no alternatives to CRMs in this technology; however, aluminium may present a potential solution to limited copper resources. EU aluminium production, however, has been reduced in recent years due to increasing energy prices (aluminium smelting is energy intensive) and may benefit from support to meet EU supply needs. The call would take a two-pronged approach, looking at opportunities to replace copper with aluminium more energy efficiently and to incorporate sustainable aluminium.

- **Key energy security criticality addressed**: availability and abundance of CRMs (copper, aluminium)

- **Relevant value chain:** HVDC cabling (particularly mass-impregnated cables)

Proposed type of action: RIA, PPI or EIC Transition

Expected TRL at end of project: 4-6

- The EU also has strategic partnerships with Horizon Europe–associated countries and EU overseas territories (Norway, Greenland, Ukraine, Canada), African Union countries (Namibia, Zambia, the Democratic Republic of Congo) and others (Kazakhstan, Argentina, Chile), which have been formed to diversify supply chains and that could be leveraged.[621]

- **Links to other key criticalities and R&I challenges:** This challenge is linked to wider challenges around availability of CRMs.

- **Consideration for successful implementation:** Circularity and repairability should be embedded in this intervention to ensure resource efficiency is maximised and in line with wider EU ambitions.

- With consideration of the future, cybersecurity may be an important factor to include in such a programme if processes in development are highly digitised. Skills is also a key factor to consider for a viable commercial supply in the EU. The intervention should consider how to best nurture and maintain a pipeline of talent, including with movement of talent between research and industry.

- For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with affordability and environmental impact.

Action 29

Proposed R&I intervention: Addressing cybersecurity risks to transmission and distribution technologies

Expected outcome: Ongoing R&I programmes that support solutions to address cybersecurity risks to transmission and distribution technologies (in particular risks to the AC–HVDC systems), including research to ensure that cyber security can be maintained for legacy systems and that understanding of the evolution of threats informs regulation and standards.

Scope: Cyberattacks on power grids in general and HVDC links in particular pose a significant and growing threat to the stability, reliability and security of the power system. The European power grid is an interconnected system. A successful cyber-attack on an HVDC link can have severe consequences, which can propagate through the entire European system. In principle, the system should be able to overcome the outage of any single piece of infrastructure, e.g. an HVDC link. However, the loss of a key power transmission component, such as an HVDC link, makes the system considerably more vulnerable. An attack on two or more HVDC links or a situation where an attack on an HVDC link coincides with another outage could have severe effects throughout the system. The potential results include power outages and thus loss of power supply to vital infrastructure (hospitals, water treatment plants, etc.) and loss of productivity through business disruption.

Cybersecurity is an evolving threat. The energy grid and HVDC links may be particularly vulnerable. Ongoing R&I could ensure monitoring of threats and development of mitigation.

[621] European Commission (March 2024), EU and Norway Sign Strategic Partnership on Sustainable Land-based Raw Materials and Battery Value Chains; European Commission (November 2023), EU and Greenland Sign Strategic Partnership on Sustainable Raw Materials Value Chains.

- **Key energy security criticality addressed:** digital vulnerability
- **Relevant value chain:** AC–HVDC cabling and links

Proposed type of action: IA

Expected TRL at end of project: 7-9

- **Potential for collaboration:** The UK has a shared challenge, including with regards to interconnectors between the UK and the EU.
- **Links to other key criticalities and R&I challenges:** This challenge is linked to wider challenges around cybersecurity of the energy system.
- **Consideration for successful implementation:** Networks of key stakeholders should be developed to ensure clarity of responsibility and understanding of potential weak links or vulnerabilities at the interface between energy transmission and distribution technologies and the rest of the energy system. This could include knowledge sharing of near misses where appropriate.

  Skills is also a key factor to consider for a viable commercial supply in the EU. The intervention should consider how to best nurture and maintain a pipeline of talent, including with movement of talent between research and industry.
- For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with affordability and environmental impact.

10.2.19. Critical raw materials

Action 30

Proposed R&I intervention: Public engagement research on mining of CRMs

Expected outcome: Research and public engagement on mining of CRMs to provide a better understanding of public concerns and mechanisms to address them (e.g. sustainable mining practices with minimal environmental impact, improved working conditions and operations). This will be important to enable domestic production to be increased, thereby de-risking a range of clean energy technologies, and would inform both technical approaches and policy and regulation in this area, as well as to enable international production to ensure consistent supply and imports from countries outside of the EU. This is a shared, international challenge requiring cooperation.

Scope: CRM mining will increase to meet demand for the clean energy transition, both in the EU and outside of it. Public perceptions of mining are often negative, and a full understanding public concerns and mechanisms to address them to build support for mining in the EU is a gap in existing R&I programmes.

- **Key energy security criticality addressed:** availability and abundance of CRMs

- **Relevant value chain:** mining of all CRM, in particular cadmium telluride and perovskite PV (supply of cadmium, telluride, copper, lead); batteries (cobalt, lithium); and semiconductors and microchips in smart technologies, where public opposition is a risk within and out of the EU due to mining practices and environmental impact

Proposed type of action: RIA or CSA

Expected TRL at end of project: n/a

- **Potential for collaboration:** Existing partnerships with African countries may provide further opportunity for collaboration. In particular, the EU has existing strategic partnerships with Namibia, Zambia and the Democratic Republic of Congo that have been formed to diversify supply chains.
- **Links to other key criticalities and R&I challenges:** The challenge is linked to the wider CRM challenges across technologies and the discovery research programmes suggested in Annex F (not shortlisted due to risks from unknown impacts of early-stage research).
- **Consideration for successful implementation:** Public engagement can help identify trade-offs and key priorities for R&I where concerns cannot be addressed.
- For implementation in line with the Sustainable Development Goals, consideration should be given to ensure alignment with affordability and environmental impact.

10.2.20. Additional action: energy system

Additional action (action 31)

An additional action is proposed to begin to address the common criticalities and the interconnectedness of the energy system and the co-dependencies of different technologies.[622]

Proposed R&I intervention: Horizon Europe Mission for the future resilient and secure EU clean energy system

Expected outcome: Address skills questions, CRM needs for energy technologies, cybersecurity and other challenges, such as permitting or management of the smart distributed energy system. Addressing the question holistically with a Horizon Europe Mission would provide system-level focus and priority at the EU level for the development of a future resilient and secure EU clean energy system.

Scope: Energy security is a system characteristic, and this study identified a number of system R&I challenges that a mission could address. Without a systems view, key issues

[622] Note the difference between system-level actions and actions that can apply to multiple technologies (e.g. action 30, on public perceptions on mining); the latter are not system level, i.e. they do not investigate interconnectedness and how technologies interact through grid connections, digitisation and technology hybridisation, among others. The system-level action presented is specifically on how CRM needs create competition between technologies.

may be missed, in particular at the boundaries where technologies interact or compete with each other for resources. This mission could address skills questions, CRM needs for energy technologies, cybersecurity and other challenges, such as permitting or management of the smart distributed energy system.

- **Key energy security criticality addressed**: availability and abundance of CRMs (silicon, copper, aluminium, nickel, boron, gallium, titanium, germanium, phosphorus)

- **Corresponding R&I challenges addressed**: How can the use of CRMs be reduced? How can the physical and digital resilience of the smart and flexible clean energy grid be strengthened? How can highly digitised value chains be secure? What are the short-, medium- and long-term skills needs of the clean energy transition and future energy system? How can these skills be developed and maintained?

Proposed type of action: Horizon Europe Mission

Expected TRL at end of project: 1-9

- **Potential for collaboration:** Existing partnerships include the EU–Africa partnership and the Clean Energy Ministerial Clean Power workstream, which includes a global initiative on Transforming Solar Supply Chains, which Germany co-leads along with Australia, India and the United States. The United States also has a funding programme supporting the development of perovskite solar cells.

- **Links to other key criticalities and R&I challenges:** The challenge is linked to the wider energy system R&I challenges.

CONCLUSIONS AND REFLECTIONS

Through a detailed analysis of clean energy value chains, the R&I landscape, and potential futures for energy security, we have developed a comprehensive R&I action plan for the EU which sets out 30 actions that can be taken to mitigate risks and capitalise on strengths to help ensure EU energy security to 2050 as we transition to clean energy technologies. We found that each clean energy value chain operates differently and faces its own unique challenges. However, we also see some common risks and challenges emerging across many of these value chains, such as the need for specific skills and access to CRMs, some of which are not currently readily available within Europe. These are critical challenges to address in the context of the Critical Raw Materials Act [623] and the NZIA[624], which demand a shift towards domestic production in the EU and are particularly pertinent given the scale of ambition for a rapid transition as specified in the recent 2040 climate target.[625] We also note that not all technologies are represented in the final R&I action plan. This is not because the excluded technologies are less important, but because the EU is already taking action to address many of the challenges we have identified, through its existing Horizon Europe investments, actions or strategies, showing that some of this work is already in place to secure Europe's energy future. However, there are still areas where action can be taken to improve the focus of R&I activity or address some topics that are overlooked or under-resourced. Within the 30 R&I actions proposed, we identify nine top priority actions, prioritised based on our SWOT analysis, that should be pursued immediately to address key threats and weaknesses in the energy value chains explored. These are summarised below.

Technology and criticality	Proposed R&I action
Batteries – Supply chain location	Horizon Europe programme focused on improving the energy efficiency of battery manufacturing and recycling
CRMs – Security of supply	Research and public engagement on mining of CRMs
Energy transmission and distribution technologies – Availability and abundance of CRMs	R&I programme to increase recycling and reuse in energy transmission and distribution and develop the sustainable production of aluminium and other alternatives
Geothermal energy – Availability and abundance of CRMs	Open Horizon Europe call with the aim of implementing a 'design-to-recycling' scheme, including reducing and reusing critical raw materials in geothermal energy
Hydrogen – Supply chain resilience	Horizon programme with a call for solutions to increase the resilience of hydrogen value chains
Other storage (CAES) – Sustainability and environmental impacts	Research programme with the aim to develop a better understanding of the potential locations for underground CAES

[623] European Commission (2023), Critical Raw Materials: Ensuring secure and sustainable supply chains for EU's green and digital future.

[624] European Commission (2023), *Net-Zero Industry Act: Making the EU the home of clean technologies manufacturing and green jobs*, (accessed 2023).

[625] European Commission (February 2024), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Securing our future: Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society. COM/2024/63 final

Technology and criticality	Proposed R&I action
PV – Supply chain location	A Horizon Europe collaborative industry programme to support initial new supply chains, focused on increasing the efficiency of solar PV manufacturing processes in the EU
Smart cities, buildings and district heating technologies and grids – Availability and abundance of CRMs and location of advanced electronics supply chains	R&I programmes to increase circular economy processes, recycling and reuse of electronics for smart energy technologies
Smart energy grid technologies – Digital vulnerability	Ongoing R&I programmes to support solutions to address cybersecurity risk, including research to ensure cybersecurity can be maintained for legacy systems and that understanding of the evolution of threats informs regulation and standards

Although this study has been effective in providing an overview of a wide range of technologies and in considering how these clean energy value chains should be stress tested against a range of potential future scenarios, we can also identify some gaps and areas where future work should be carried out to further strengthen our understanding and to ensure future EU energy security, as detailed below.

First, although this study has highlighted the key energy security criticalities for clean energy technology value chains, the wide scope of the study – covering a mix of technologies and areas of application – means that many technology categorisations are not comprehensive, which was highlighted in the validation workshop. PV, for example, can be broken down further into integrated PV, including building-integrated photovoltaics (BIPV), vehicle - integrated PV (VIPV), AgriPV and floating PV (FPV). Similarly, workshop participants noted that the hydropower criticalities were technology specific and that solutions would vary between hydropower systems. They also noted that while the study accounts for biogas boiler, pellet stove and thermal collector off-grid systems, electricity-based off-grid systems (PV, heat pumps and batteries) are also important to study and should be accounted for in future studies. Despite these differences, several criticalities emerged consistently across the different value chains, including CRM availability and abundance, digital vulnerability, and skills, so additional analyses may confirm that the suggested R&I actions remain important to ensure energy security of clean energy technologies. Should there be a need for further granularity, individual, technology-specific studies are proposed to complement this study's findings.

Second, although the EU has several ongoing projects and R&I programmes relevant to the identified criticalities, scale must be considered, particularly the potential market share of the technology and the scale of the criticality. For example, CRM use may create a much more vulnerable critical point in the value chain in some technologies, such as batteries, than in other technologies, such as geothermal energy, where CRM use is minimal.[626] Although market shares were considered for the criticalities, the scale of each technology and the resulting potential scale of the criticality should be considered when investing in R&I activities.

[626] The reason that this was still shortlisted as a key criticality is that we decided to shortlist CRMs for all technologies where the criticality was longlisted in the first place. We did so because many of the materials in question (such as Cu, Al, Ni) are needed for almost all technologies, so it would be arbitrary to assign the associated supply risks to certain technologies and not to others, even if the necessary volumes of these materials differ across the technologies.

Indeed, although it was not the primary aim of this study, an interesting by-product of our energy security assessment is that it also showed which technologies have *limited* energy security risks associated with them – for example the risks associated with geothermal energy and with energy building and district heating technologies and off-grid energy systems are low.

Third, not all identified criticalities have R&I solutions, and the EU is already running programmes to address many of the criticalities identified by the study. Further development of clean energy technologies may need support through additional regulatory sandboxes and policy research, to allow these technologies to reach their full potential. We have suggested non-R&I activities and noted where policy or regulatory action is more appropriate and where R&I can play a complementary – if not primary – role in bringing these technologies to market to ensure energy security. Close collaboration between the research and policymaking sides of clean technology deployment is also vital, and policy should be monitored consistently to ensure appropriate R&I developments are in place. This is relevant when considering emerging policy and regulation: R&I actions to address PFAs in hydrogen technologies can only be planned once PFA regulation is in place, for example, while digital vulnerability is a common criticality across technologies that should be monitored closely due to the rapidly changing regulations and advances in digitalisation and cyberthreats.

Finally, across the study and the validation workshop discussion, the question of how clean energy technologies will interact and interconnect with each other in the future clean energy technology system is crucial. In particular, validation workshop participants discussed hybridisation (e.g. hydropower/PV, co-location of wind and wave projects, RFNBO and CCUS crossovers, heat pump/batteries), multiple benefits, and social dimension as key methods to futureproof the energy system and safeguard against common criticalities (including biodiversity). Similarly, findings from the study highlighted how grid developments can mitigate or challenge renewable energy–generation technologies, and the co-dependencies of each technology should be accounted for in future studies. Further work exploring these interconnections and dependencies would be complementary to the findings of this study.

Through the scenarios, we were able to test the robustness of clean energy value chains across a wide range of potential futures. By stress testing across a wide range of futures, we are able to ensure that we develop an action plan that remains valid and relevant regardless of what changes in the wider landscape take place to 2050.

A systems-level study would therefore complement the findings of this study, in particular by identifying where energy security criticalities of one technology can be mitigated through the system and which criticalities introduce potential cascading or compounding risks into the energy system. For example, disruption to one energy technology supplying electricity may be straightforward to mitigate by increasing demand from another energy technology. However, if multiple extreme weather events affect a number of energy sources at once, wider energy security may be affected. Considering value chains in isolation is also a related challenge that can be addressed in this way. Such a systems-level study should account for conflicts arising from competing technologies with similar aims and should include a reflection on acceptable trade-offs to ensure security of the wider energy system (e.g. food versus feedstock in bioenergy, storage needs for CAES versus hydrogen, conflicts in water uses, coupling of technologies could increase digital vulnerabilities).

Energy security is evolving with the clean energy transition. Whereas currently energy security crises are often sudden shocks caused by global events and price rises, in future energy security crises may be more predictable, as we begin to understand the pinch points in each value chain as these become more frequent and caused by delays in supply chains or weather events. Sudden and unexpected shocks will be mostly caused by malicious actions, such as cyberattacks.

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In the coming decades, energy security will depend less on uninterrupted access to fossil energy sources and will be increasingly determined by access to clean energy technologies, materials and components. This study, delivered by RAND Europe, CE Delft and E3-Modelling for the European Commission, assessed the energy security challenges of 17 clean energy value chains now and looking to 2050, and identified 30 R&I actions to address them. The bespoke methodology brought together futures methods and macroeconomic modelling, value chains analysis and strategic decision-making tools to set out priorities for action.

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