LNG cold: Opportunities for large-scale energy savings?

Assessment of opportunities for large-scale energy savings through the use of LNG cold in coal gasification and CO_2 storage

Report
Delft, November 2009

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More information about the study can be obtained from project leader Ab de Buck.

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Preface

Energy savings are in general the most effective way of reducing emissions of CO_2 and at the same time an option for reductions in costs.
One interesting option for large scale energy savings in the Groningen Eemshaven region and in the Rotterdam harbour is the utilisation of cold available from LNG terminals. As the LNG in LNG-terminals is evaporated at extreme low temperatures (-162 °C), this represents a vast amount of cold, up to 9 PJ or 240 MW.
This report describes options to utilize this cold in two major industrial processes planned in the two ports: coal gasification and CO_2 storage.

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Summary

In the Eemshaven and the port of Rotterdam three LNG terminals are planned or (already) in realisation. These terminals are potentially a large source of 'high quality' cold, for a 12 BCM LNG terminal this amounts to approx. 9 PJ (240 MW).
This study investigates options to utilise this cold by integrating the process of LNG evaporation with coal gasification and CCS.

Options for integration

Four potential options have been determined:
- Air separation.
- Cooling separation solvent in shift reactor.
- Turbine combustion air cooling.
- CO_2-compression and liquefaction.

For these options possible energy savings have been investigated as well as a first assessment of technical feasibility, economics and environmental effects. These are based on desk-study and interviews with industrial companies in the field of LNG and coal gasification.
Reference for these options is the situation in which LNG is evaporated using residual heat from a power plant.

Energy savings

The options could result in substantial savings of energy. These amount to approx. 1,5 PJ of primary energy consumption, or a gain of 2,7% in energy efficiency in the chain of electricity production and CCS. These figures are based on a 50% availability of LNG cold.

	PJ primary saving		Δ Energy yield Power plant (gasification part)	Comments
Availability LNG cold	**100%**	**50%**	**50%**	
Air separation	0.85	0.4	0.8%	
Cooling separation solvents in AGR[1]	0.15	0.08	0.1%	Figures for use of rectisol, lower savings for other solvents
Turbine combustion air cooling	1.0	0.35	0.7%	Potential lower savings if actual meteorology is taken into consideration
CO_2 liquefaction	1.3	0.7	1.1%	
Total	3.2	1.6	2.7%	

The amount of cold available from the LNG terminal is enough for (a combination of) all of the options mentioned.
The option with the largest potential is CO_2 liquefaction, followed by air separation and turbine combustion air cooling. The potential of the option

1 Acid Gas Removal Unit.

turbine air combustion cooling might decrease if more specific Dutch weather conditions are taken into consideration. For the option of cooling separation solvents in the acid gas removal unit (AGR) the potential will be substantial lower if other solvents are used than rectisol.

Intermittency of LNG terminal

An important aspect of the LNG terminal is intermittency. Terminals will probably not operate continuously, and depending on market conditions, will not send out gas. In these circumstances, no LNG cold will be available. Globally on average LNG terminals utilise approx. 50 - 70% of their capacity. In this study we assume that an average 50% LNG cold will be available.
The intermittence of the terminal requires full back-up provisions for cases that no LNG cold is available.

Investments

As indicated above, back-up provisions will be necessary due to the intermittency of the LNG terminal. We expect that these back-up provisions will be comparable in most cases to the reference situations when no LNG cold is available. In addition to this, integration of LNG cold requires additional investments for connection and transport of cold. These investments will depend on a range of location specific factors. A first estimate for an interstage cooling cycle for CO_2 compression/liquefaction is M € 30.

Operational costs and savings

The reductions in energy consumption result in potential large savings of costs. For the four options these amount to approx. M€ 14.=/yr. This figure includes also cost savings of M€ 3 due to a lower purchase of CO_2 emission rights. Operational costs have not been calculated. These will mainly include the operation of the additional provisions.

Feasibility and risks

The interviews with the companies in the field of LNG terminals and coal gasification indicate that intermittency of LNG terminals might be considered to be a major obstacle. As indicated this intermittency requires substantial back-up provisions for circumstances when no LNG cold is available.
A further complication appears that there is no definite answer whether the LNG terminal will eventually come into operation.

Technical feasibility

Most options seem more or less technically feasible, since these are in operation in Japan.
However, from the interviews it is noted that the integration of LNG cold air separation might result in complications in the operation of technical installations. A further point of attention is that turbine combustion air cooling might have serious effects on the gas turbine.

Environmental effects

The large savings of energy will also result in a reduction of CO_2 emissions with approx. 100 kton/yr, or approx. 10% of the rest-emissions of CO_2 of the considered integrated coal gasification unit and CCS.

Overview

Table 1 summarises the options investigated, possible energy savings, environmental effects and economic effects.

Table 1 **Overview of options for integration of LNG cold with coal gasification and CCS**

	Energy savings (primary, PJ/yr)	Emission reductions CO_2 (kton/yr)	Δ Energy yield power plant	Capex (+++ high, + low)	Oper. savings (M€/yr)	Remarks
Air separation	0.42	29	0.8%	+++	4.2	* Might complicate operation of gasification unit
Cooling separation solvents in AGR	0.08	5	0.1%	++	0.8	* Lower savings with other solvents than rectisol
Turbine air precooling	<0.32	<20	<0.7%	+	<3.1	* Lower savings due to Dutch climate conditions * Might influence gas turbine * 'Chiller' will result in extra ΔP
CO_2 liquefaction	0.65	45	1.1%	++	6.3	
Total	1,6	100	2,7%		14	

Overall it can be concluded that utilisation of LNG cold potentially can result in large energy savings, with air separation and CO_2 liquefaction as most promising options.

The figures in the table above are based on an indicative desk-study. The actual potential in the Eemshaven should be determined in a more specific investigation. taking the site specifics into account such as operational restrictions, availability issues and actual requirements for CO_2 storage. For the option of turbine air pre cooling more detailed meteorological data (how often can turbine air pre cooling really be effective) should be taken into consideration.

Given the large potential for energy- and cost savings, CE Delft advises the authorities and companies in the Eemshaven region to examine more closely technical the potential, investments and operational costs of the LNG integration in the Eemshaven region. Most interesting options appear CO_2 compression and air separation. Specific points for further examination include cost savings by emission-reduction of CO_2 in the EU-ETS, and the possibility of using LNG cold in post-combustion CO_2 capture (chilled ammonia).

1 Introduction

1.1 LNG terminals and coal-fired power plants Opportunities for energy integration

LNG terminals are being planned, and one is being built, at three sites in the Netherlands. At these LNG terminals a considerable amount of cold, around 300 MW or 9 PJ[2], will be released.
The parties are looking for options to make good use of this cold, one of which is in the nearby electricity power plants and CO_2 storage.
CE Delft had earlier investigated the possibility of using LNG cold in so-called oxyfuel coal-fired power plants and CO_2 storage. The result of the study was that cold can be used at different sites, namely in oxygen production, in boosting the turbine yield and in the compression and liquifaction of CO_2. The study revealed that this could lead to significant savings in terms of energy consumption and CO_2 emissions as well as costs.
In the Rotterdam and Eemshaven ports there are interesting initiatives for coal gasification, a technology that is increasingly attracting attention as a way to sustain the electricity supply. Coal gasification has come under the eye of the Energy Transition platform and the General Energy Council (AER) that in September 2008 advised the building of a demonstration power plant for CO_2 gasification and CO_2 storage. Equally in the autumn of 2008 the Energy Transition platform advised the State to make coal gasification a key component of future energy supply.

1.2 Opportunities for energy integration?

This study examines integration with coal gasification plants and CCS (CO_2 capture and storage). This is prompted by the two tangible initiatives in the Netherlands for coal gasification plants in the vicinity of LNG terminals. As for oxyfuel power plants oxygen is needed in the process. Therefore, similar options to use LNG cold are just as attendant as for oxyfuel power plants.

1.3 Policy context

At European, national and regional level government policy focuses on reducing CO_2 emissions. Energy saving and CO_2 storage are key options here. The objectives are listed Table 2.

[2] To illustrate the size: indicative calculations by CE Delft indicate that with 9 PJ of cold 1,500 skating rinks could be cooled!

Table 2 Policy objectives in relation to CO_2 reduction and energy saving

	EU	State	Rotterdam	North-Netherlands
Context	Package on Energy and Climate (April 2009)	Clean and economical (2007)	Rotterdam Climate Initiative (2007)	Energieakkoord (2007)
CO_2 reduction	-20% (2020 vs. 1990)	-30% (2020 vs. 1990)	-50% (2025 vs. 1990)	4,5 Mton < 2011, 15 - 20 Mton > 2011
Energy saving	-20% (2020 vs. Reference development)	2%/annually	2%/annually	Strategic theme: energy saving

1.4 Purpose of the study

This is the perspective from which SenterNovem commissioned CE Delft to analyse the options for using LNG cold in coal gasification plants. The purpose of this study is to do this as objectively as possible.
The study focuses on:
- Establish characteristic LNG terminal and coal gasification plant.
- Objectively identify potential options.
- Estimate potential of e-saving and CO_2 reduction.
- Identify potential benefits and risks/obstacles.
- Analyse the most promising options.

The underlying purpose of the study is to ensure that all parties are aware of the various options and can take account of these in their decisions, such as land issue, subsidy requests and investment decisions.
This report may be used as a 'placemat' in a workshop with industrial companies and respective government departments in Groningen.

1.5 Approach

This study has been carried out along the following lines:
- Desk study: 1st exploration of options and potential savings/reductions.
- Discussion of options with industrial companies.
- Elaboration of options.

The study has been performed by CE Delft, with support from KWA Adviseurs. In the context of the study discussions have been held with CGEN Power, Vopak LNG Project, Gasunie, RWE and NUON. Annex C contains a list of interviewees.

2 Coal gasification and LNG terminals

2.1 Introduction

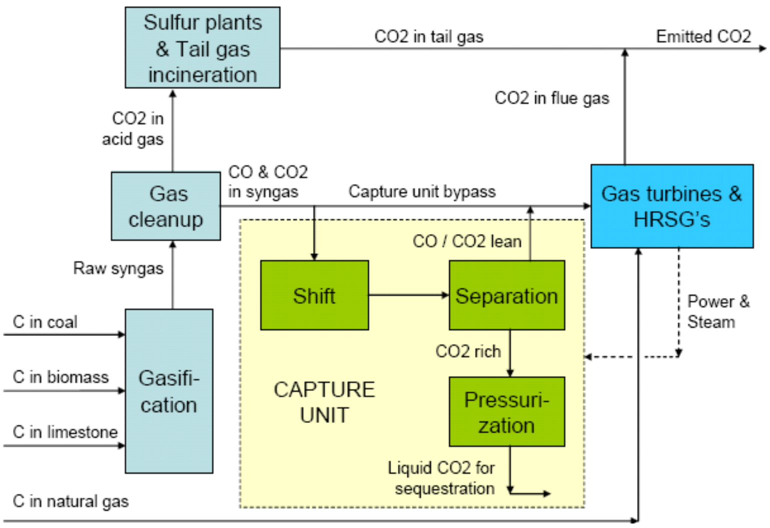
This study focuses on potential energy saving in a coal gasification plant with CO_2 capture through integration with an LNG terminal. Options for integration are compared with a coal gasification plant and LNG terminal without mutual integration.

2.2 Coal gasification

At this moment there are three tangible plans for coal gasification plants: the Magnum power plant of NUON in Eemshaven, and two initiatives of the Belgian C-GEN in Rotterdam and Vlissingen. The first is the most advanced[3] while the second and third are awaiting permits. There are also plans in the very early stage, at Shell and Essent in Moerdijk, among others. Of the three, two gasification plants have been planned in the direct vicinity of a future LNG terminal: the NUON/Magnum power plant in the Eemshaven and the C-GEN power plant at Europoort.

In coal gasification coal is converted with oxygen into CO and H_2. Then a further reaction occurs in a 'shift reactor' with steam producing CO_2 and H_2. The H_2 can then be used for the production of electricity and the CO_2 captured and stored.

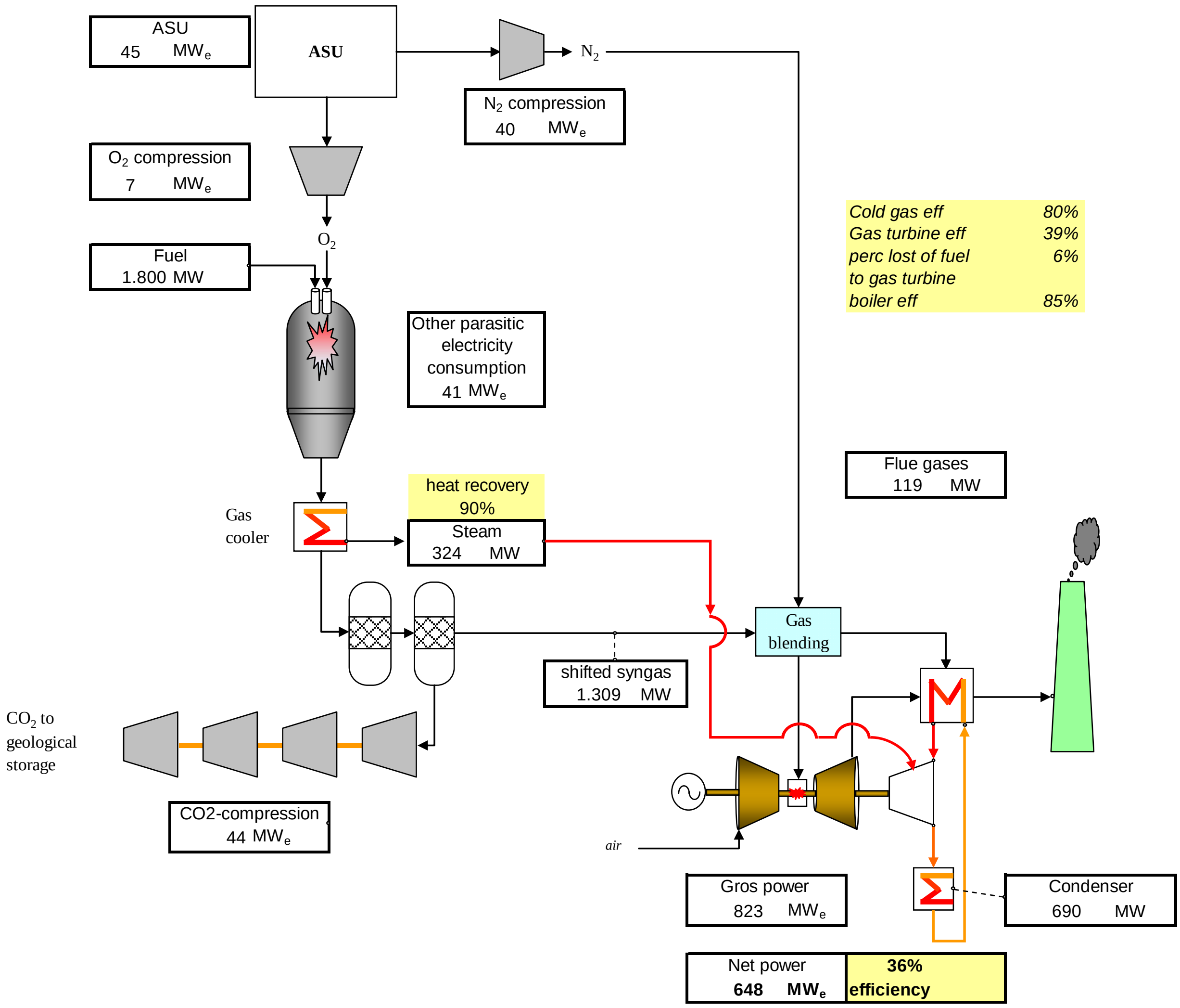
Figure 1 Process chart of a coal gasification + CCS unit (NUON Magnum)



[3] The investment decision has been postponed and the permit procedure has stagnated in relation to the appeal by conservation and environmental organisations.

The analysis relates to the intended Magnum power plant of NUON[4] with a capacity of 1,200 MW_e of which 800 MW_e is based on synthesis gas and the NG terminal of Essent in the Eemshaven with output capacity of 10–12 billion cubic metres of natural gas[5].
Figure 2 shows the energy balance for this power plant.

Figure 2 Energy balance coal gasification plant with CCS, without integration of LNG cold



Here we outline the measures and specifications under consideration. A more extensive discussion of the Magnum power plant and the measures under consideration are given in annex A.

[4] See http://www.nuon.com/company/Innovative-projects/magnum.jsp.

[5] See http://www.eemshaven-lng.nl/index.php?id=4.

2.3 LNG terminal

The starting point for the LNG terminal is a power plant with an output capacity of 12 Mton LNG. The produced gas is brought up to a Wobbe index of 49.1 (H_L gas quality) by adding nitrogen.

The industrial installation of a LNG Terminal comprises essentially:
- A loading pier.
- A container park with installation for the recondensation of evaporated LNG.
- A blending installation for blending N_2 and pumps for pressurising the LNG.
- A re-evaporation installation comprising several evaporators in which LNG is evaporated by externally supplemented heat.

In existing LNG terminals, as in Zeebrugge, seawater is supplemented to the LNG terminal. The evaporating LNG thereby extracts heat from the seawater. In the winter months the temperature of the seawater is too low and there is a risk of freezing. The seawater is then heated with natural gas, usually by means of a parallel submerged combustion vaporiser (SCV).

Heating the seawater requires a substantial use of energy. For the 12 BCM LNG terminal this is, based on the assumption of 0.10% fuel retention, approx. 1.7 PJ. The corresponding CO_2 emission is ca. 100 kton CO_2.

2.4 Reference: Heating LNG with residual heat from the e-power plant

At the LNG terminal of GATE being built in Rotterdam the LNG will not be heated with (possibly heated) seawater but with residual heat from the E-ON coal-fired power plant. This is also an option for the planned LNG terminal in Eemshaven.
Utilising residual heat leads to a considerable reduction of the required amount of energy in the LNG terminal (Table 3). This situation is taken as the reference in this study, which implies that in the options in chapter 3 no further energy saving is incorporated for the LNG terminal.

Table 3 Potential energy saving and CO_2 reduction by using residual heat of the coal-fired power plant

	Source of residual heat	
	Seawater (+ heating with auxiliary boilers)	Residual heat of e-power plant
Energy use (PJ)	170	< 0.1
Emissions of CO_2 (kton)	100	< 10

3 Options for utilising LNG cold

3.1 First exploration

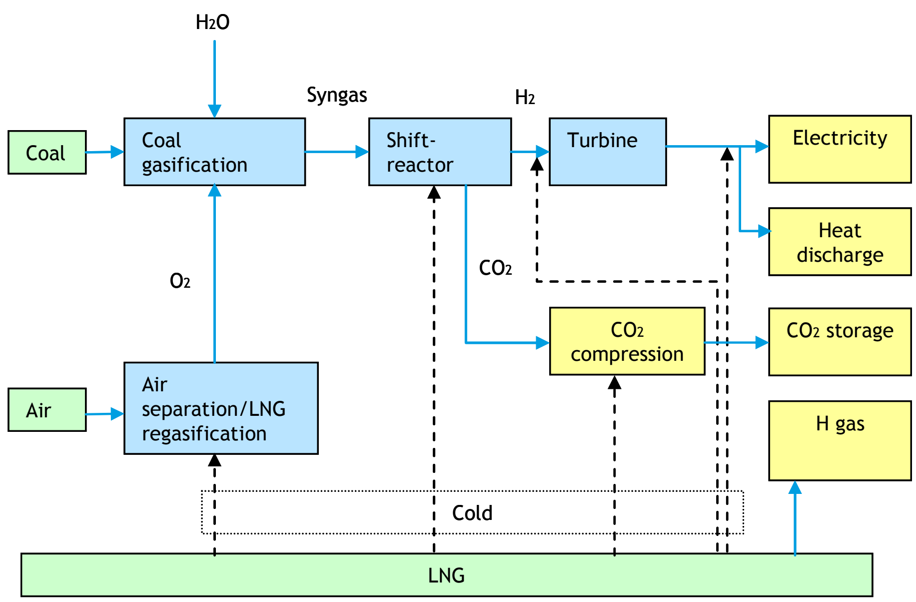
The desk study and discussions with the companies generated five possible applications of LNG cold.

Table 4 **Possible applications of LNG cold in coal gasification and CO_2 storage**

Nr.	Option	Pretext	Explanation
1	Air separation, production of oxygen	Oxygen manufacture for coal-fired power plant	Use of LNG cold in air separation makes it possible, in principle, to compress the air at a lower temperature to the pressure required for air separation, which saves on compression work.
2	Cooling separation solvent in acid gas removal unit (AGR)	Coal gasification plant: acid gas removal unit (AGR)	The separation fluid in the acid gas removal unit (selexol, rectisol) works at low temperature (5°C and -40°C respectively). LNG could be used to produce this cold.
3A	Cooling the combustion air entering the gas turbine	Coal-fired power plant, gas turbine	Cooling combustion air for the gas turbine reduces the compression energy that the gas turbine has to supply and thus boost the yield.
3B	Possible cooling between the compression stages of the air to be compressed	Coal-fired power plant, gas turbine	Idem.
4	Cooling of the steam to be expanded in the steam cycle of the STEG	Coal-fired power plant, gas turbine	Cooling enables lower pressure to be realised in the steam cycle, leading to higher turbine yield.
5	Use of LNG cold to liquefy the captured CO_2	CO_2 compression	Use of LNG cold in CO_2 compression makes it possible, in principle, to compress CO_2 at a lower temperature to the pressure required for transport, thus saving on compression work.

The different options are shown in Figure 3.

Figure 3 Options for utilising LNG cold in coal gasification



3.2 Elaborating the options

3.2.1 Oxygen production

For this electricity consuming process we consider two options:

1. Deep cooling of air, using circulation of liquid N_2. And
2. Staged air compression with intermediate pre-treatment and cooling of air with liquid N_2.

Technical feasibility

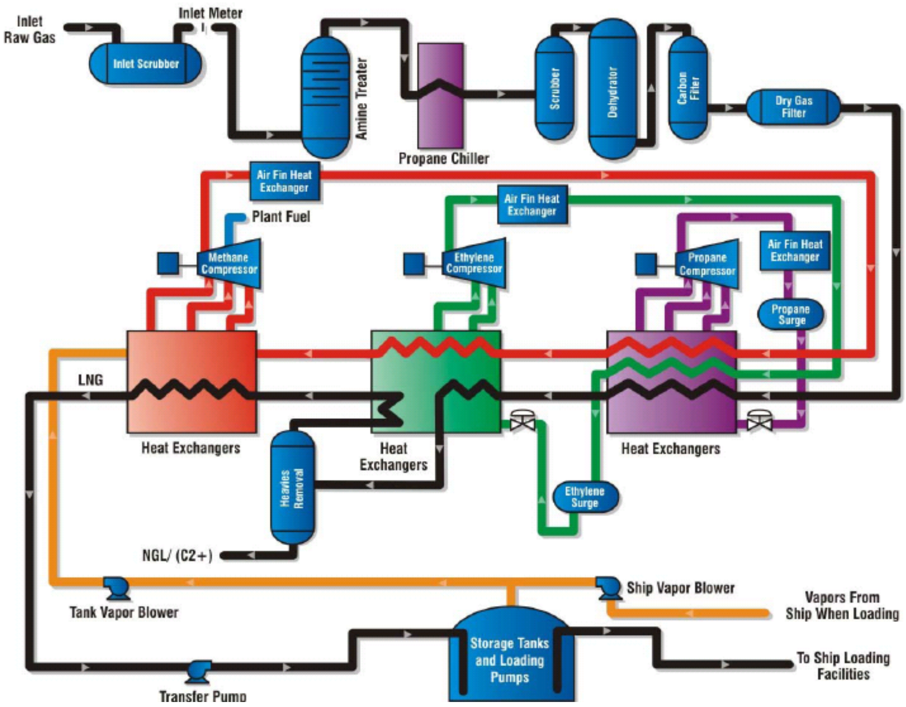
The first option can be considered mature technology, in operation at e.g. Foss s. Mer (France) and the LNG terminals (Osaka Gas and Nippon Gas) in Japan.

Figure 4 Air separation facility integrated with LNG terminal, copyright Osaka Gas, Japan

For the second application air for the ASU is first compressed to a pressure high enough (2.7 bar) to allow drying and removal of HC's and CO_2. The pretreated air is then cooled with circulating nitrogen which is in turn cooled with LNG cold to approximately -150°C. The cooled air is compressed to the pressure required for rectification (5 bars).
This application is not common in air separation. However, oxygen producing companies such as Air Products and Air Liquide did not deem this application not technically feasible.
Other arguments indicating the technical feasibility of this option are:

- Utilisation of external cooling cycles with low temperature compression are common in LNG liquefaction and in other processes with low temperature cooling or refrigeration cycles. So the compressor technology required for air compression at low temperature should be available.
- Utilisation of circulating nitrogen for heat or cold exchange is, as mentioned previously in this paragraph, standard technology in LNG based air separation in Japan.
- Low pressure dehydration and removal of CO_2 and other trace gases is feasible and well established. For example, the Axens multibed allows treatment of gases with pressures as low as 2.7 bar and has been applied in more than 60 installations.

Figure 5 Example of a LNG liquefaction plant with low temperature compression of cooling fluid



Integrated facilities for LNG evaporation and oxygen production have been operating without problems since the 1970s. Risks are controlled since liquid nitrogen is used as intermediate fluid, avoiding the risk of LNG coming into contact with oxygen.

Energy requirement and energy savings

The reduction in specific electricity consumption realisable by applying two-stage air compression with intermediate air cleaning and deep cooling with LNG has been estimated (CE, 2008) as 30%, from 235 kWhe/tonne O_2 to 165 kWhe/tonne O_2.

Given an oxygen consumption by the Magnum power plant of approx. 1.5 Mtonnes/year, total electricity consumption for conventional air separation amounts to 350 GWhe/year, a loss of approx. 4% points of energy efficiency. For integrated air separation using LNG cold this figure will decline to approx. 250 GWhe/year, a saving of approx. 100 GWhe/year, or 0.8 PJp, and a reduction of CO_2 emissions of 60 kton/yr. These figures are based on the ideal situation of 100% availability of LNG cold.

Intermittency and back-up provisions

Where no LNG is transported from the plant, oxygen will have to be used in the gasification process. This requires back-up provisions. Possible options might be:

- Extra compression capacity.
- Large back-up storage of liquefied O_2 and/or N_2.

On the other hand, if coal gasification is off-line, air separation can be expected to proceed since products (nitrogen, oxygen) can be stored. This would probably require larger storage facilities. However, this is unlikely given the high availability for the power plant and the fact that production stops will be planned a long time ahead.

Points of attention

From the interviews with industrial companies, the following points should be taken into consideration:

- Technological complication of process.
- Integration of LNG cold in oxygen production will make oxygen production dependent on the availability of the LNG terminal. Back-up provisions will be required in the case that no gas is transported from the terminal. The oxygen production should be able to switch smoothly from a situation where cold is available or not available. Costs of these back-up provisions.
- Safety requires that any contact between liquid oxygen and LNG should be avoided. Therefore a cooling cycle is required, as in operation in the Japanese terminals.
- Lack of clarity about whether a new LNG terminal will become operational, as long as it is not clear whether a new LNG terminal is being build, it is difficult to anticipate on the availability of LNG cold.
- When referring to the Japanese project it should be noticed that the Japanse gas market differs largely from the Ducth market: off take from Japanese LNG installation is base load while the Dutch LNG installation will be for peak load.

3.2.2 Cooling separation solvents in acid gas removal unit

In the acid gas removal unit (part of the shift-reactor in Figure 4) CO_2 and H_2 are separated, using specific solvents. Several types of solvents operate at lower temperatures, requiring substantial amounts of energy for cooling. LNG cold could possibly be used for cooling these solvents.
Three types of solvents are most commonly used: rectisol, selexol and sulfinol. These operate at different temperatures (Table 5).

Table 5 Separation solvents in shift reactor and temperatures of operation

Solvent	Temperature of operation (indicative)
Rectisol	-40 °C
Selexol	5 °C
Sulfinol	15 °C

Given the temperatures of operation, especially for applications of rectisol, cooling with LNG appears to be an interesting option. It is unclear whether for this application an interstage fluid is required.

Feasibility

Cooling separation fluids with LNG is not yet operational. However, cooling solvents like butane are used in Japan (annex B).

Energy requirement and energy savings

For rectisol applications possible energy savings amount to approx. 0.5–1% of final electricity production (CGEN, 2009). This is comparable with 0.2 to 0.4% efficiency increase of electricity production of the power plant. For a 840 MWe power plant operating 7,900 hours annually, and 100% integration with LNG cold, the net savings amount to approx. 20 GWhe/year or 0.15 PJp. This results in the avoidance of 11 ktonnes of CO_2 emission annually relative to the average Dutch electricity production park. For other solvents energy savings will be substantially less. These have not been calculated.

Intermittency and back-up provisions

Back-up provisions will be necessary in the event no LNG is transported and will include cooling with an alternative medium.

Points of attention

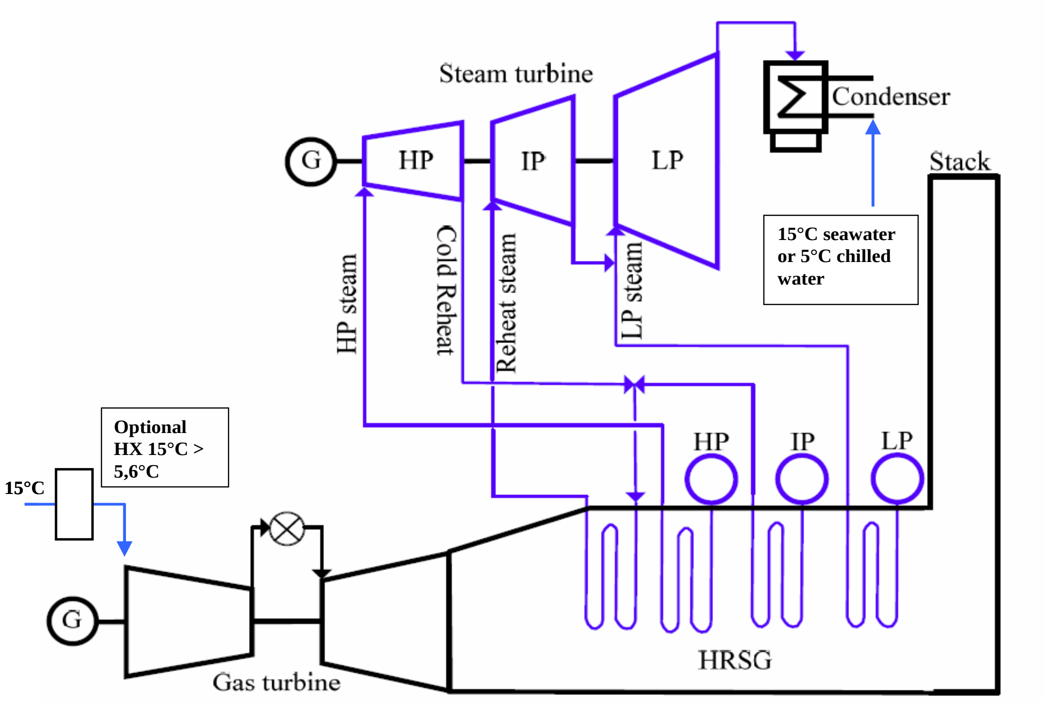
This option has only been put forward by one company and is not broadly considered. The main points of attention are:

- Costs of back-up provisions.
- Effectiveness for solvents operating at higher temperature. When solvents that operate at higher temperatures are used, possible gains for energy efficiency will be substantially lower.

3.2.3 Cooling air entering the gas turbine

Cooling the intake air of the gas turbine will reduce the compression energy required for the gas turbine. This will result in an increase of energy efficiency. This option will be effective in situations with high temperatures and low relative humidity. In these cases this can result in a substantial increase in efficiency of the gas turbine.

Figure 6 Steam and Gas turbine. Options for cooling in-going burning air and cooling condenser water



Two technological options can be distinguished: Cooling the intake air of the gas turbine, and cooling the air in between compression steps.
In our calculations, incoming air is cooled down in a chiller from 15°C to 5.6°C. This cooling will require an interstage fluid. A side-effect of the 'chiller' is that it will require some extra pressure (1st estimate: approx. 10 mbar). This extra ΔP will also be required in the event that no cooling is needed or is available, and this will then result in additional energy being used.

Feasibility
Cooling the intake air will probably have an impact on the operation of the gas turbine. Company interviews indicate that this option would require close communication with the gas turbine supplier in order to check whether it complies with the specifications of the gas turbine. However, this appears feasible as in Japan (annex B) cooling the intake air of the gas turbine is already in operation.

Energy requirement and energy savings
Actual efficiency will depend largely on actual temperatures and humidity. Cooling will have a substantial effect when temperatures are high and humidity is low, so most potential can be expected during summer months. Our calculations indicate that, presuming an average ambient temperature of 15°C and cooling air to 5.6°C, as well as 100% integration with LNG cold, this option can save approx. 1.0 PJp/year of natural gas or 50 ktonnes/year of CO_2 emissions. However companies indicate that calculating with more specific patterns of temperature and relative humidity, energy savings will be substantially lower (CGEN, 2009; Vopak LNG Projects, 2009). Companies interviewed have the opinion that energy savings will be rather small. Efficiency will furthermore be dependent on the availability of the LNG terminal. The option is especially effective during the summer, and it might be possible that LNG terminals will mostly transport gas during the winter months (when demand is highest).

Back-up provisions
LNG terminal. If no LNG cold is available, the gas turbine of the power plant can function without the additional cold. Therefore, back-up provisions appear not to be necessary. As indicated before, a side-effect of the chiller might be that in situations without LNG cold some energy is needed for the additional pressure required.

Points of attention
The companies interviewed indicate that they doubt whether this option will be feasible. On one hand they indicate that actual energy-savings will be relative small in the Dutch climate. On the other hand the technical feasibility might be complicated (impact on gas turbine) and investments relatively high.

3.2.4 Cooling condenser water turbine
A lower temperature of condenser water can be realised by circulating cooling water (possibly with glycol) cooled against evaporating LNG. This kind of circulating cooling water is already in use at the LNG terminal in Barcelona (Ripoll, 2006). A lower temperature in the condenser will mean that steam from the steam turbine can be expanded further, and produce more power.

Feasibility
In principle, circulating cooling water appears to be technically feasible as it is already in use at the LNG terminal in Barcelona (Ripoll, 2006).

Energy savings
According to our calculations, cooling condenser water from an average of 15°C to 5°C results in a saving of 0.27 PJ. However, this cooling will require a large amount of LNG cold, 20.9 PJ. Therefore, it appears to be a very ineffective way of using LNG cold. The background of the large amount of LNG cold needed is the small ΔT between over the condenser. Given the large amount of LNG cold required this option has not been studied any further.

3.2.5 CO_2 compression

LNG cold can be used for compression and for liquefaction of CO_2, prior to transport and storage. A compression to 120 bar at 20°C has been studied and it was found that in this condition CO_2 is supercritical, and can be transported over large distances and stored in underground storage locations. According to the specifications of the gasification unit the study focuses on an emission of 4 Mton CO_2.

Reference

The reference situation is a 4-step compression with intercooling, as shown in Figure 7.
Figure 8 shows the corresponding pressure enthalpy diagram.

Figure 7 **CO_2 compression: Reference situation with compression in 4 steps**

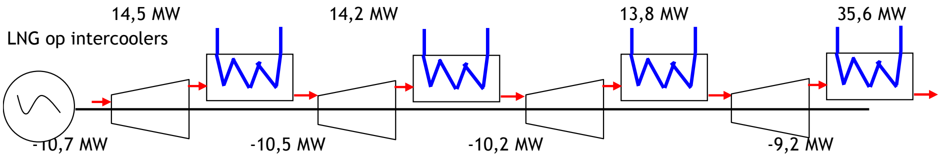
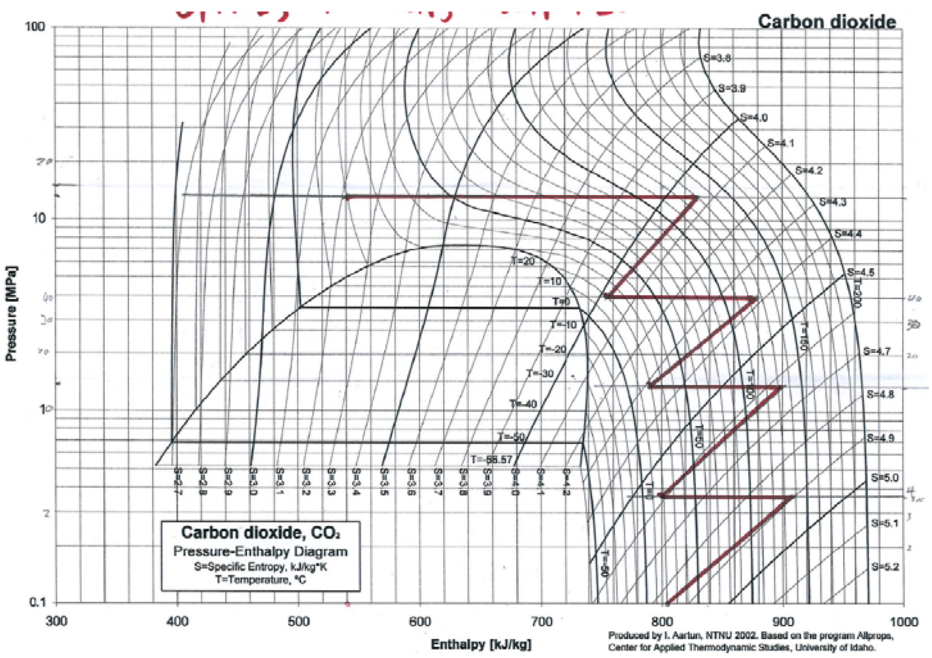


Figure 8 **Pressure Enthalpy diagram for CO_2 compression**



Total energy use of the compression amounts to 1.35 PJe, or 2.3 PJ.

CO_2 compression using LNG cold

In the alternative option LNG cold is being used to liquefy CO_2. As a result only the two first compression steps are required, followed by liquefaction of CO_2. This is shown in Figure 9. Figure 10 shows the corresponding pressure-enthalpy diagram. As two compression-steps are avoided, total energy required is reduced to 1.3 PJ.

Because CO_2 will turn into ice when cooling at low pressures, the CO_2 will have to be dried prior to liquefaction[6]. Drying probably involves application of a standard technology, e.g. a molecular sieve. For this option an interstage cooling liquid will be required.
For this option an intermediary cooling cycle is required.

Figure 9 **Use of LNG cold in compression and liquefaction of CO_2: Option #1 Liquefaction of LNG (simplified scheme, without molesieves and regeneration of fluids)**

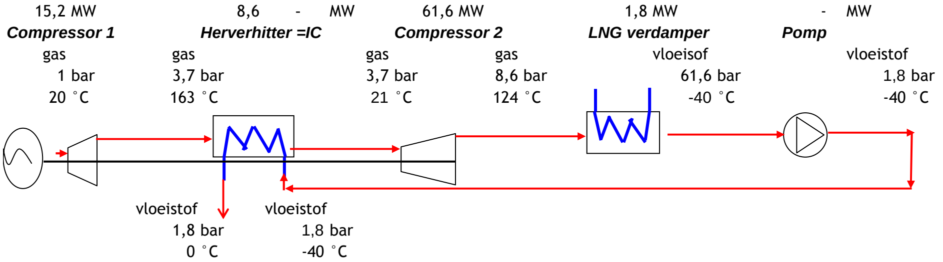
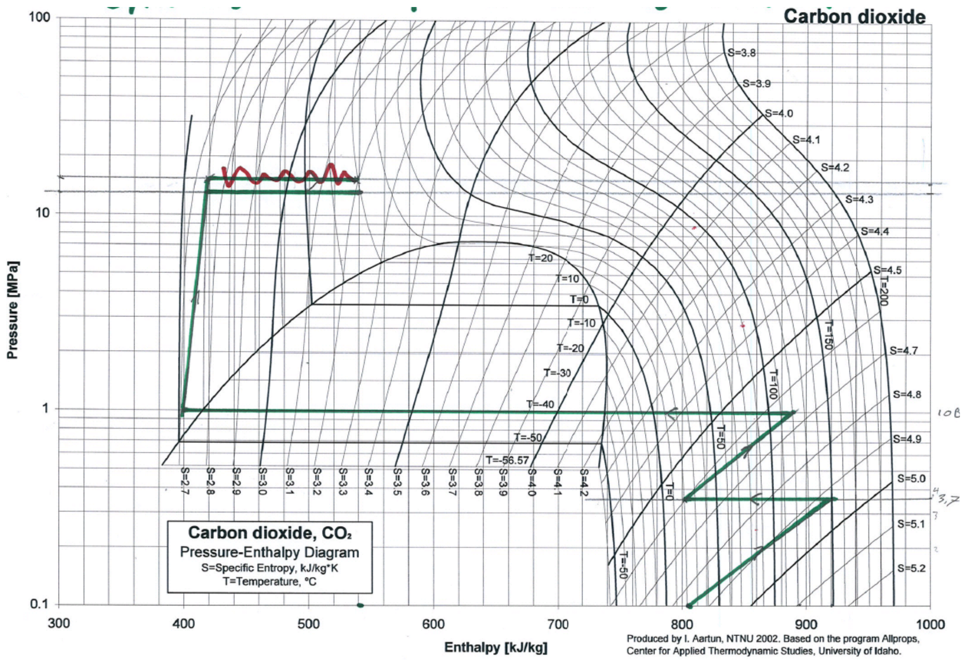


Figure 10 **Pressure enthalpy diagram for compression and liquefaction of CO_2**



Technical feasibility

Our assumption is that the isolated CO_2 from the gasifier can be liquefied just as the CO_2-rich off-gases produced in hydrogen production and ammonia production. This also is consistent with the fact that deep dehydration by refrigeration is also a standard technology in natural gas treatment, applied for example at the Den Helder gas treatment facility of NAM and to be applied at the Vattenfall Oxyfuel demonstration power plant in Schwarze Pumpe. Given the utilisation of LNG cold already applied for CO_2 liquefaction and the technical status of refrigeration as a gas treatment process, we assume this integration to be a technically proven, industrial-scale process.

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[6] This also applies to the hydrogen plant off gases.

Energy requirement and energy savings

The specific electricity consumption required for both configurations was calculated as 50 kWhe/tonne CO_2 for the integrated configuration and 95 kWhe/tonne CO_2 for the conventional 4-stage compression configuration. Assuming separation and liquefaction of 4 Mtonnes CO_2 per year, combined compression + liquefaction will require approx. 0.70 PJe/year, whereas conventional 4-stage compression would require 1.35 PJe/year. Therefore, this option results in an energy saving of 0.65 PJe. Savings in primary energy consumption are approx. 1.3 PJp.
Without using LNG cold CO_2 compression will reduce the total energy efficiency of the power plant by approx. 4.4%. Using LNG cold, this would be approx. 2.3%, or a net gain of energy efficiency of 2%.

Intermittency of LNG terminal – back-up provisions

The processes of CO_2 transport and CO_2 storage should proceed continuously, which requires back-up provisions for situations when no LNG cold is available. This will probably imply the need for the two CO_2 compressors from the reference situation to be available.

Points of attention

- Most companies interviewed did consider this option and concluded it to be technically feasible.
- Costs for an intermediary cooling cycle. An initial estimate is approx. € 10 m.
- One company indicated considering supply and transportation of captured CO_2 at 30 bar to the storage location. This situation is comparable with the intended OCAP/Barendrecht project for storage of CO_2 captured at Shell Pernis Hycon gasifier.
  However, for storage a much higher pressure will be required. Most abandoned gas fields still contain residual amounts of natural gas, having a residual pressure of some tens of bar and this pressure will have to be compensated if CO_2 is to be injected into this field. Next to this the intrinsic geological pressure of the reservoir at 2 – 4 kilometres depth will have to be compensated. Thirdly, in order to inject large quantities of CO_2 the CO_2 will have to be compressed increasingly with increasing amount of CO_2 already present in the storage. Simply because more CO_2 in the reservoir means higher pressures.
  The generally accepted picture is that for optimum utilization of the considered geological storage facility the CO_2 has to be converted into a supercritical 'fluid'.
  Therefore our conclusion is that though a company may have the opportunity of supplying captured CO_2 at a relatively low pressure of 30 bar injection additional compression is required. In case of supply and transportation of captured at 30 bar this will probably be located at the well head.
- The CO_2 liquefaction facility should not necessarily have to be owned and operated by the power plant operator or LNG terminal operator. It could instead be operated as a third and independent facility buying cold from the LNG terminal and selling compression and liquefaction services to the power producer. Such a construction would remove objections that the power plant is more complex and that there would be extra contractual obligations related to this option if implemented at the power plant itself.

3.3 Intermittency of LNG terminal operation

The possibilities for utilization of LNG cold during the year are determined by the send out profile of regasified LNG during the year. The LNG terminal may regasify LNG in partial load during the warmer months of the year, thereby having a lower capacity of providing LNG.

The demand of cold by the gasifier will remain more or less constant year round except for periods of down time.

Since there is no operational LNG terminal in the Netherlands we have no practical reference for the Dutch situation to draw practical operational experiences from.
However the various experts that were interviewed in the cause of this project unanimously indicated that there is no certainty about the send out volumes and utilization level of LNG terminals with contract structures such as Gate or Eemshaven LNG Terminal. The only indication that can be given is that globally LNG terminals on average are utilized at 50 - 70% of their name plate capacity. Experiences from the Fluxys terminal at Zeebrugge indicate that there is a distinct difference in send out volumes between summer and winter - in general a very high send out in winter and a very low send out – sometimes being zero for months at a time – in summer. According to the interviewed experts one may also expect for the Dutch terminals under construction that in the long run these will show a send out profile comparable to that of the Fluxys Zeebrugge terminal.

The indications by the experts mean that there is no guarantee with respect to LNG cold availability. This in turn implicates that any integration between LNG terminal and gasifier considered will have to be combined with a full back up installation for the process in which the LNG cold is considered to be applied.

For this study we estimate an average availability of LNG-cold of 50%. For the option turbine combustion gas cooling we estimate a lower overall availability of LNG-cold (30%) as especially in summer months less LNG will be sent out.

4 Assessment of the options

4.1 Technical feasibility

It is apparent that four applications for LNG cold in coal gasification and CO_2 storage would be feasible. The summary below does not incorporate the cooling condenser water measure since this demands an excessive amount of LNG cold in relation to the potential saving.

Table 6 Options for cold integration, state of the engineering

Nr.	Type of integration	Maturity (is technology in operation ?)	Remarks from companies interviewed
1	*Air separation:* * Deep cooling of air * Staged air compression, 2nd stage (after separation of H_2O and CO_2) using LNG-cold	* In operation in Japan * Theoretical, but seems feasible	* Might complicate operation of gasification unit
2	*Cooling separation solvent in acid gas removal unit*	* Theoretical, but seems feasible	* Depends on type of separation solvent used
3	*Turbine combustion air cooling* Cooling of combustion air with LNG cold	Mature, compare: • Utilization of LNG cold for gas turbine at Osaka Gas	* Might have serious impact on operation of gas turbine
4	*CO_2 compression:* CO_2 liquefaction with LNG cold	Mature, compare: • CO_2 liquefaction at Osaka Gas • Gas treatment by refrigeration, e.g. at Den Helder NG treatment facility	

4.2 Energy: potentially feasible savings

Table 7 gives a summary of the identified measures and therewith the maximum savings possible for energy use. The calculated savings are based on the fully continuous operation of the LNG terminal and coal gasification plant/CO_2 capture, as well as a 50% availability of LNG cold.
Figure 11 gives the corresponding energy balance, Figure 12 a simplified process scheme.

Table 7 **Summary of energy aspects and impact of measures on CO_2 emissions (indicative)**

	PJ primary saving	PJ primary saving	Kton CO_2 economised	Δ Energy yield Power plant (gasification part)	Comments
Availability LNG cold	**100%**	**50%**	**50%**	**50%**	
Air separation	0.85	0.4	30	0.8%	
Cooling separation solvent AGR	0.15	0.08	5	0.1%	Figures for use of rectisol, lower savings for other solvent
Turbine air precooling	1.0	0.35[7]	20	0.7%	
CO_2 liquefaction	1.3	0.7	45	1.1%	
Total	3.2	1.6	100	2.7%	

In total around 35-40% of the available LNG cold could be used with the measures indicated.

7 Assumption: netto LNG-cold 30% of time available.

Figure 11 Energy balance with complete integration of LNG cold

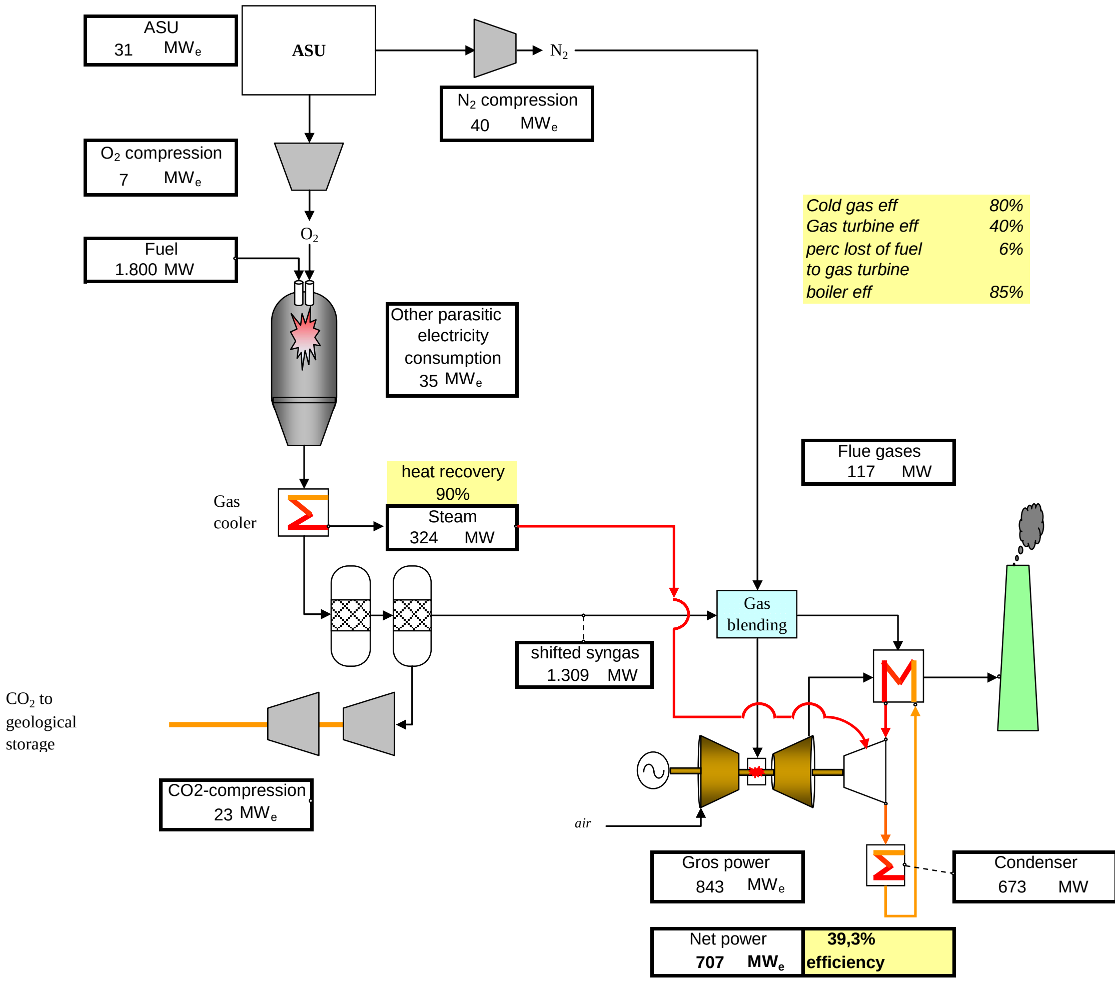
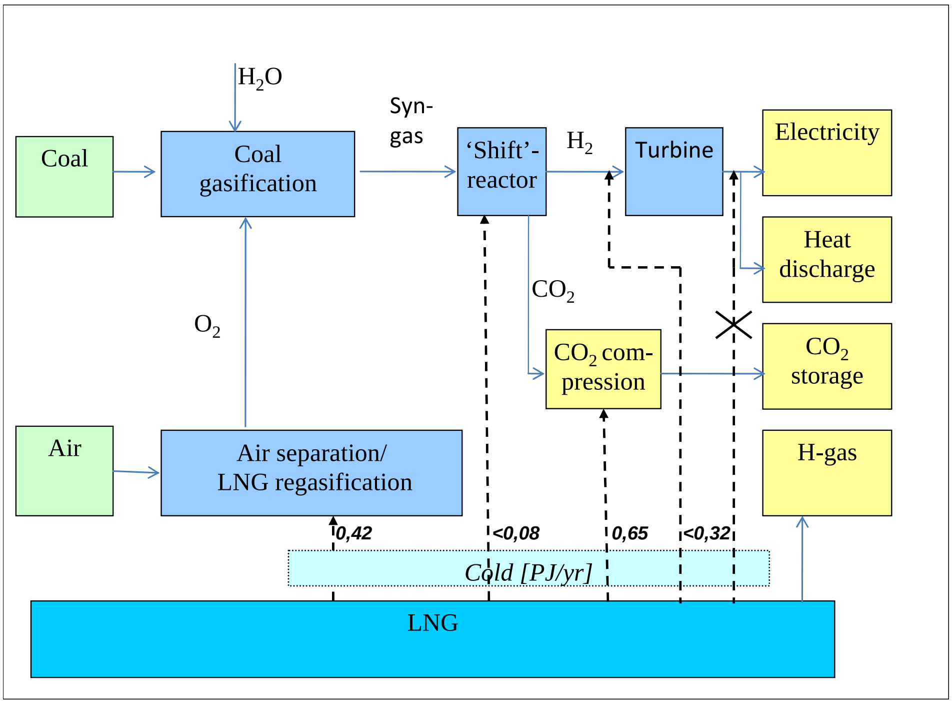


Figure 12 Simplified process scheme with options for utilisation LNG cold



4.3 Environmental effects

The energy use saving reduces the emissions of the coal gasification plant and the CO_2-capture and storage facilities. Table 8 shows the potential reductions in emissions of CO_2 and the heat discharge via cooling water. Data are based on a gasification plant equipped with CCS, resulting in approx. 905 kton emission of CO_2. An average 50% availability of LNG-cold is assumed.

Table 8 Potential reductions in emissions of CO_2 and NO_x when using LNG cold in coal gasification and CO_2 storage

	Emissions CO_2 coal gasification (kton/yr)	Heat discharge cooling water (PJ/yr)
Reference	905	19.3
Potential savings utilising LNG cold	800	19.1

4.4 Economy

The costs and benefits of the various integration options are mainly determined by the extra capital investments required and the gains by energy savings. Gains also include reduced CO_2 emissions and corresponding emission rights. An qualitative estimate has been made of the required capital investments.

4.4.1 Capital investments

Table 9 shows a first indication of key investments for each option. These tend to correspond with the realisation of the reference installation without LNG integration. In other words: in LNG integration the 'normal installation' is necessary, with specific additions for integration with LNG.

Costs for additional provisioins will depend on a variety of factors, including the amount of cold available, distances of transport, obstacles in the transport route, need of interstage liquid, etc. A first estimate of costs for an interstage cooling cycle (based on ethane) is M€ 30.=.
In general costs will substantially lower in case installations are located close to each other.

Table 9 **Initial indication of required investments and back-up provisions**

Option	Equipment	Back-up provisions	Indication of costs (+++ relatively high, + relatively low)
Air separation	Storage-facilities of liquid N_2/O_2	Compressors in ASU (cf. reference)	+++
Cooling separation solvent AGR	Interstage cooling cycle	Alternative cooling medium	++
Turbine combustion air cooling	Chiller		+
CO_2 compression	Interstage cooling cycle	Compressors (cf. reference) Alternative cooling medium	++

4.4.2 Operational costs and savings

The use of LNG-cold will result in cost savings due to lower costs for the use of energy as well as lower costs for the purchase of CO_2-emission rights. Energy costs are calculated using a future energy price of € 70/MWh, taking into account future development of electricity prices (www.endex.nl). Costs for CO_2 emission rights have been calculated wit a price of € 30/ton CO_2.
Total cost savings are presented in Table 10. In these figures an average availability of LNG-cold of 50% is taken into account. It appears that the use of LNG cold results in substantial savings in energy costs, amounting to approx. M€ 14/yr.
Additional costs for the operation of additional equipment have not been calculated. These will depend strongly on the specific situation.

Table 10 **Possible cost savings using LNG-cold (based on 50% availability of LNG cold)**

	Energy savings		Emissions CO_2		Total Savings
	Gwhe/yr	M€/yr	Kton/yr	M€/yr	M€/yr
Air separation	48	3.3	29	0.9	4.2
Cooling separation solvent AGR	9	0.5	5	0.15	0.8
Turbine combustion air cooling	35	2.5	20	0.6	3.1
CO_2 compression	75	5.0	45	1.3	6.3
Total	170	11	100	3.0	14

4.5 Summary

Table 11 Overview of options for saving using LNG cold for coal gasification and CO_2 storage (based on 50% availability of LNG cold)

Option	Possible energy savings	Possible reduction CO_2 emissions (kton/yr)	Technical feasibility	Investments (1st indication)	Operational savings (M€/yr)	Remarks from interviews
Air separation: * Deep cooling of air * Staged air compression, 2nd stage (after separation of H_2O and CO_2) using LNG-cold	0.42	29	* In operation in Japan * Theoretical, but seems feasible	+++	4.2	* Might complicate operation of gasification unit
Cooling separation solvent in AGR	0.08	5	* Theoretical, but seems feasible	++	0.8	* Depends on type of separation solvent used, less savings with other solvents than rectisol
Turbine combustion air cooling Cooling of combustion air with LNG cold	<0.32	20	Mature, compare: Utilisation of LNG cold for gas turbine at Osaka Gas	+	3.1	* Effect probably lower due to Dutch climate conditions * Might have serious impact on operation of gas turbine * 'Chiller' will result in extra ΔP
CO_2 compression: CO_2 liquefaction with LNG cold	0.65	45	Mature, compare: • CO_2 liquefaction at Osaka Gas • Gas treatment by refrigeration, e.g. at Den Helder NG treatment facility	++	6.3	
Total:	1.6	100			14	

5 Conclusions

1. LNG terminals have a large potential of high quality cold. For a 12 BCM terminal (with 100% operation) this represents approx. 9 PJ or 300 MW. Policies on the European, national and regional levels focus on realisation of energy-savings and reductions of CO_2 emissions.

2. Current developments in the ports of Rotterdam and in the Eemshaven move into the direction of (the) use of waste-heat from power plants for heating LNG. This will result in substantial energy savings, compared to the use of (pre heated) sea water, in the order of 2.5 PJ. However, options exist in which the intrinsic energetic value of LNG cold is used on a more higher level.

3. The current study focuses on integration options between a LNG terminal and coal gasification and CO_2 storage. This is based on the casus of a 12 BCM LNG terminal, a 800 MW coal gasification power plant, and 4 Mtons of CO_2 transport and storage. Four options appear technically feasible:

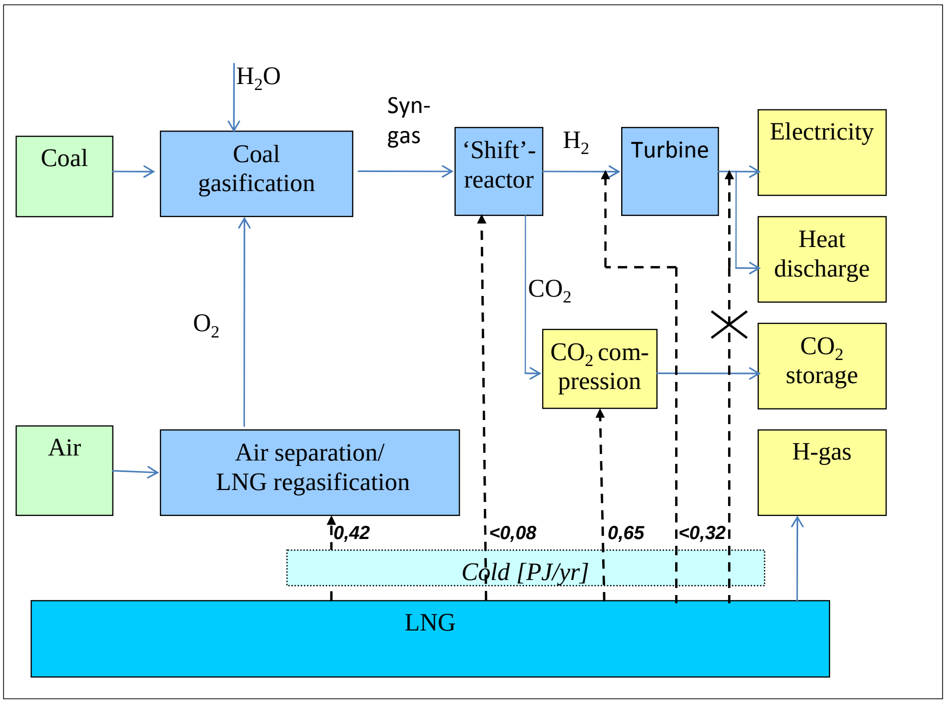
Air separation: * Deep cooling of air * Staged air compression, 2nd stage (after separation of H_2O and CO_2) using LNG cold
Cooling separation solvent in AGR (Acid Gas Removal Unit)
Turbin e-combustion air pre cooling Cooling of combustion air with LNG cold
CO_2 compression: CO_2 liquefaction with LNG cold

4. In the situation where all options are applied, with a 100% availability of LNG cold, total primary energy savings amount to 3.2 PJprim. The amount of cold available in the considered LNG terminal is enough to make full use of all of these options.

5. Possible energy-savings depend strongly on the availability of LNG cold. In case the LNG terminal is not in operation (no gas is sent out), no cold will be available, and potential energy savings will not be possible.
Globally, on average, LNG terminals are utilized at approx. 50 - 70% of time. In our calculations we have estimated an average availability of 50%. Probably LNG terminals will be utilised more in the winter than in the summer. For the option turbine air pre cooling (which is only effective during days with high temperatures), a net availability of 30% is assumed.

6. The resulting potential savings of primary energy consumption are shown in Figure 13.

Figure 13 Potential energy savings utilising LNG cold (LNG cold 50% available)



7. From the interviews conducted, it appears that companies have studied options for LNG integration, some in more detail than others. In general companies indicate that the intermittency of the LNG terminal is a major obstacle for investments in integration options. A further complication is the insecurity whether the LNG terminal will be realized after all.

8. Regarding the option of air separation an objection might be the technical complication of the installations, esp. since vital units in the Air Separation Unit will be connected to the LNG cold. This might have a negative impact on the security of operation. However, it should also be noticed that integration of LNG cold with air separation is in operation in Japan since several decades.

9. Regarding the option of turbine air pre cooling, probably the actual potential will be lower when actual meteorological circumstances are taken into account. An obstacle for this option is that this might have serious consequences for the operation of the gas turbine.

10. Regarding the potential of the option of cooling separating solvents in the AGR (Acid Gas Removal Unit) it should be noticed that this option is only relevant when a solvent is used that operates at a low temperature, like rectisol at -40°C; for other solvents the potential is far lower.

11. Due to intermittency of LNG evaporation, for most options background provisions will be necessary. These tend to correspond with the realisation of the reference installation without LNG integration. In other words: in LNG integration, the 'reference installation' is necessary, with specific additions for integration with LNG.

12. Capital investments for LNG integration have not been studied in detail. These depend on local specific factors like the amount of cold to be transported, distances of transport, physical obstacles in the transport route and need for an interstage cooling liquid. In general investments will be higher when an interstage cooling liquid is required. A 1st estimate of costs for an interstage cooling cycle is approx. M€ 10. Probably, the highest investments will be needed for the option of air separation, followed by the options of CO_2-compression and cooling separation solvents in the shift reactor. Investments for turbine air pre cooling will probably be lower.

13. The energy savings of integrating LNG cold, are substantial. For the four options the corresponding cost savings amount to approx. M€ 14/yr. Operational costs for the integration options have not been calculated. These will depend strongly on the capital investments and the specific situation. It can be expected that they will be substantial lower than the possible savings.

14. The main conclusions have been summarised in the table below. All data are based on a 50% availability of LNG cold.

	Energy savings (primary, PJ/yr)	Emission reductions CO_2 (kton/yr)	Δ Energy yield power plant	Capex (+++ high, + low)	Oper. savings (M€/yr)	Remarks
Air separation	0.42	29	0.8%	+++	4.2	* Might complicate operation of gasification unit
Cooling separation solvent AGR	0.08	5	0.1%	++	0.8	* Lower savings with other solvents than rectisol
Turbine air precooling	0.32	20	0.7%	+	3.1	* Lower due to Dutch climate conditions * Might influence gas turbine * 'Chiller' will result in extra ΔP
CO_2 liquefaction	0.65	45	1.1%	++	6.3	
Total	1.6	100	2.7%		14	

15. The figures in the table above are based on an indicative desk-study. The actual potential in the Eemshaven should be determined in a more specific investigation, taking the site specifics into account. For the option of turbine air pre cooling more detailed meteorological data (how often can turbine air pre cooling really be effective) should be taken into consideration.

16. Given the large potential for energy- and cost-savings, CE Delft advises the authorities and companies in the Eemshaven region to conduct a specific study for the Eemshaven region. In which technical potential, investments and operational costs of the LNG integration are investigated, especially focusing on the options of CO_2 compression and air separation. Other points for further examination include cost savings by emission-reduction of CO_2 in the EU-ETS, and the possibility of using LNG cold in post-combustion CO_2 capture (chilled ammonia).

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Annex A Example of coal gasification unit: the NUON-Magnum power plant

Figure 14 gives a picture of the planned Magnum power plant, which serves as reference for the calculations conducted in this study. This installation initially comprises three gasifiers and 3-5 STEG's. A fourth gasifier may be added after 2040. Figure 15 gives the corresponding process scheme.

Figure 14 The structure of the Magnum multifuel power plant

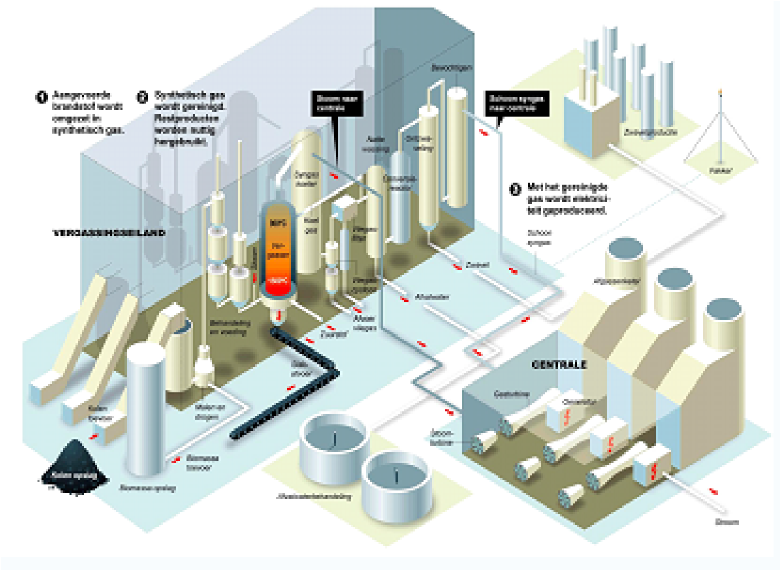
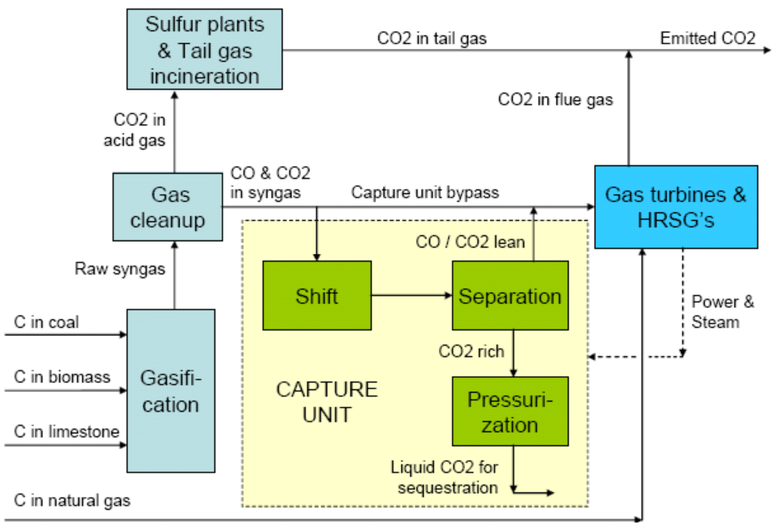


Figure 15 Diagram of the gasification and CO_2 capture



The power plant produces synthesis gas based basic load power. To be able to supply extra peak power natural gas in the STEG supplements synthesis gas to respond to peak electricity demand.

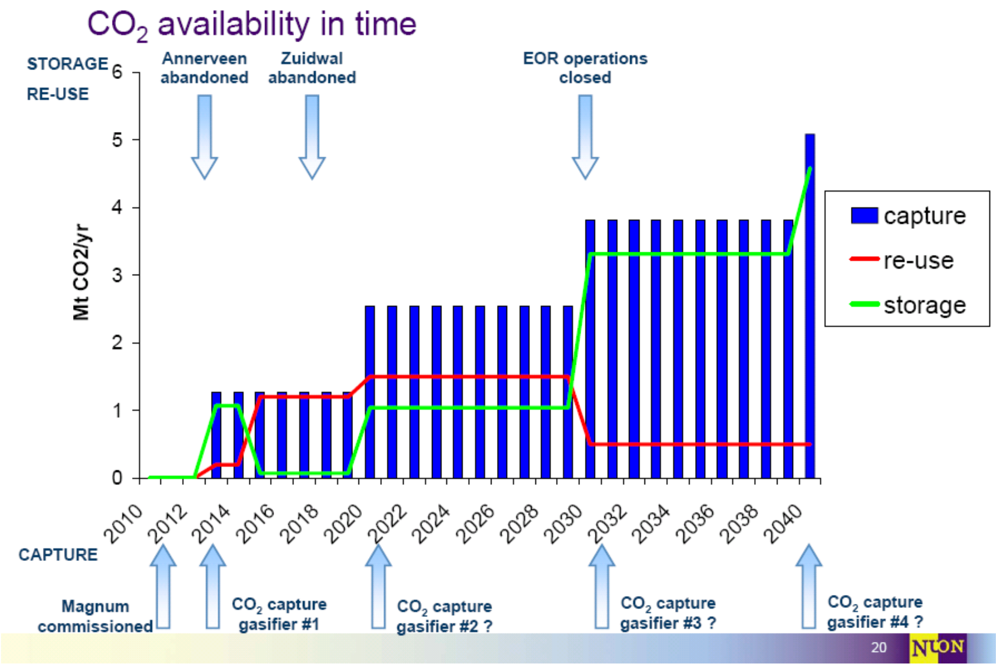
The power plant has a maximum production of about 1,200 MW_e and a maximum fuel consumption of 2,600 MW.
The three gasifiers are comparable with the gasifier of the Willem-Alexander power plant in Buggenum and have a maximum fuel consumption of around 1,800 MW capacity. The cold gas efficiency[8] is around 80%. As for energy content a maximum of 30% of biomass or petrocokes can be gasified as well.

Natural gas is used directly as fuel in the STEG's and for partial load production and can probably be used to a greater extent if one of the gasifiers is out of operation, intended or otherwise. The net electric yield for natural gas is around 54% and for synthesis gas around 58%.

Based on the fuel specifications provided and indicated fuel the most likely scenario used is a CO_2 annual emission of 4.0 Mton CO_2.

According to Environmental Impact Assessmentits CO_2 capture will be implemented in several phases. Every 8-9 years one of the gasifiers will be equipped with a capture installation in the period 2013 until 2031. In the design and building of the Magnum power plant account is taken of the addition of the three capture installations.

Figure 16 **Intended implementation of CO_2 capture technology**



The phased implementation may have to deal with the phased availability of potential storage capacity of adequate scope in the vicinity of the power plant and/or with developments in the field of gasifier technology.

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8 The energy content of the synthesis gas, compared with the energy content of the gasified fuel.

For capture a standard industrial washing process with a physical absorption agent (like Selexol or Rectisol) will be used. There are tens of washing installations around the world with one of these two absorption agents in use in gasifiers for coal or the residual flows of refineries (including petrocokes), whereby the purified synthesis gas is used as fuel and/or raw material for chemicals like hydrogen, ammonia, synthetic natural gas or methanol.

The washing process and the corresponding reactor to convert CO into CO_2 will be put in place after synthesis gas cleaning[9].

CO_2 capture produces a synthesis gas with a high hydrogen (H_2) content. Combusting such a gas in a gas turbine is still not a standard technology and thus technology development is required for both material usage and the design of gas turbine burners.

Various presentations by NUON about CO_2 capture at the Magnum power plant suggest that around 80% of the carbon from the fuel of the synthesis gas will be washed. The net electric yield of the gasifier and STEG combination will fall according to the statement in the MER by 8% points from 44 to 36%.

9 This contains dedusting, sulphur removal and halogene removal.

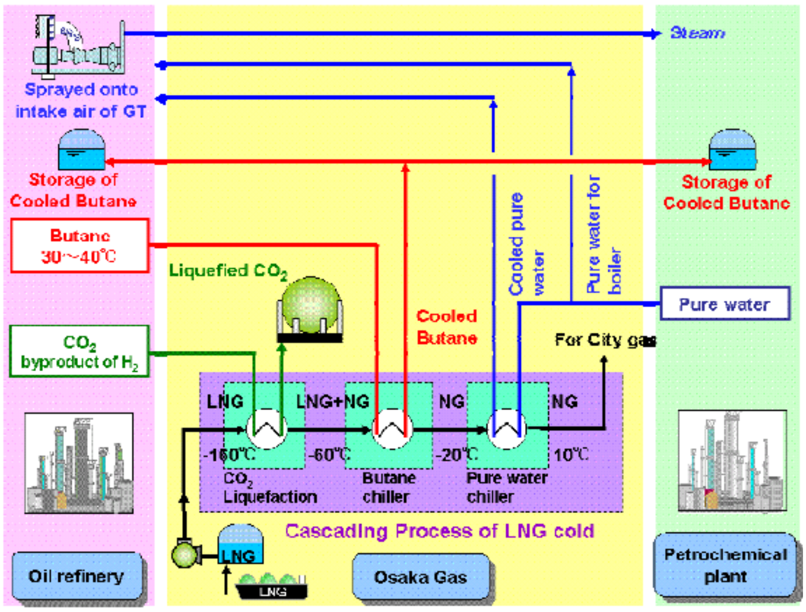
Annex B LNG-integration at Osaka Gas, Osaka, Japan

Application of LNG cold has been under development in Japan for the past 35-30 years. Japan, having little natural gas and other fossil fuels resources of its own, has been a major importer of LNG ever since LNG production technology became mature. Major importing companies are Tokyo Gas and Osaka gas, both applying comparable utilizations for LNG cold.

In Japan the cold of LNG is utilized for:
- Cryogenic power production.
- Air separation.
- Liquefaction of concentrated CO_2 gas flows (e.g. residual gases from hydrogen production).
- Production of CO_2 ice or carbonic acid ice.
- Production of cold water for humidification of gasifier intake air.
- Air intake cooling, applying an intermediate cooling water cycle.
- Deep freezing of food products.
- Cold source for chemical industry.

These applications are meanwhile being implemented in Europe as well. An example is air intake cooling at Barcelona[10].
All options are being applied on an industrial scale and can therefore be regarded as proven technology.

Figure 17 Example of LNG cryogenic energy cascade process at Senboku terminal (Osaka Gas), Japan



10 See: http://www.fwc.com/publications/tech_papers/files/Gastech%202005%20FW%20Iberia%20LNG%20CCGT%20integration.doc

Annex C Interviews

During the study interviews were held with the following companies:

Tabel 12 Interviews held

Company	Company activity	Who
CGEN Power	Development of coal gasification installations	Mr G. Janssen
Vopak LNG Projects	* Co-owner of Gate terminal	Mr C. van der Ben
Gasunie	* Co-owner of Gate terminal and the future Eemshaven LNG terminal * Exploration, transport and sale of gas	Mr K. Hoving (by phone)
RWE	* Development of a coal-fired incineration plant in Eemshaven * Co-owner of Gate terminal and the future Eemshaven LNG terminal	Mr E. ter Horst (by phone)
NUON	* Development of a coal-fired gasification installation in Eemshaven (Magnum power plant)	Mr M. Kanaar; Mr H. Raas