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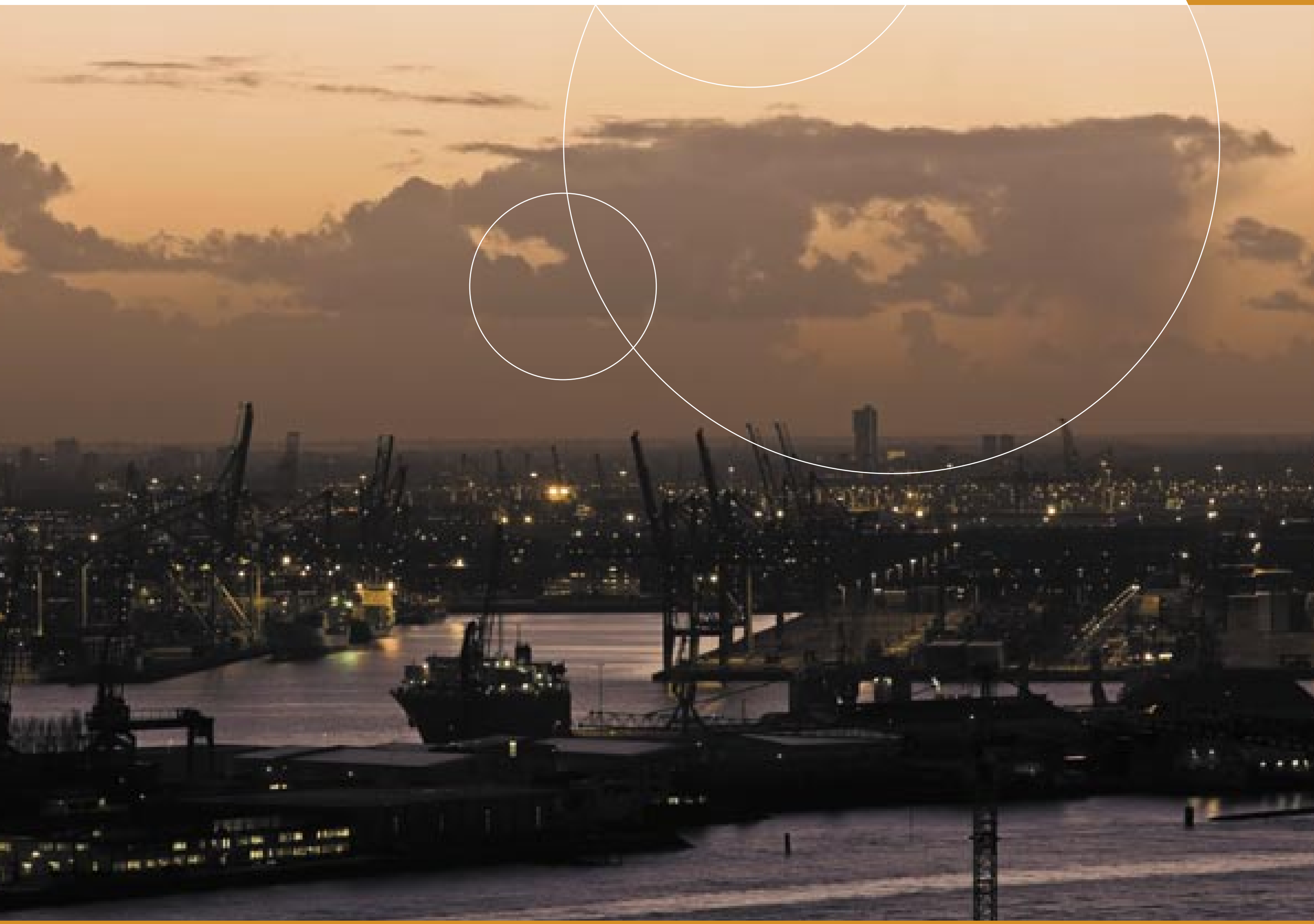


The LNG/oxyfuel route for new coal plants

Environmental benefits *plus* cost savings?

Commissioned by:

Ministry of Economic Affairs

As chance would have it, at both Rotterdam and Eemshaven it is not only coal-fired generating capacity that is planned, but also, within roughly the same time frame, construction of receiving terminals for liquefied natural gas, LNG.

The LNG/oxyfuel route: a good example of energy integration

To keep CO_2 emissions from newly planned power plants at the Dutch ports of Rotterdam and Eemshaven within acceptable limits, underground carbon sequestration will be essential. At these locations there are advanced plans for building a number of gas- and coal-fired power plants where the CO_2 will need to be separated from the flue gas before it can be sequestered. Flue gas separation is energy-intensive, however. There will also be considerable residual emissions of both NO_x and CO_2.

If coal is burned in pure oxygen rather than air, the flue gas consists to a very large extent of CO_2, allowing it to be sequestered directly. Residual emissions of NO_x and CO_2 will be significantly lower, moreover. As chance would have it, at both Rotterdam and Eemshaven it is not only coal-fired generating capacity that is planned, but also, within roughly the same time frame, construction of receiving terminals for liquefied natural gas, LNG. If the power plants are integrated with these terminals, this will create scope for an alternative route whereby the vast amount of cold available at the LNG terminals is utilised to produce oxygen, used in turn for firing the power stations.

According to a study carried out by CE Delft at the request of SenterNovem*, this integrated 'LNG/oxyfuel route' leads to a major improvement in overall energy efficiency. The efficiency is approximately 43 percent: 5 to 6 percentage points more than without integration with LNG cold. These gains are not just relative to firing a coal plant with air, but also when the LNG/oxyfuel route is compared with firing the plant with oxygen not sourced from LNG terminals.

Preliminary results indicate that besides these gains in energy efficiency, total energy generating costs are also lower with this integrated route.

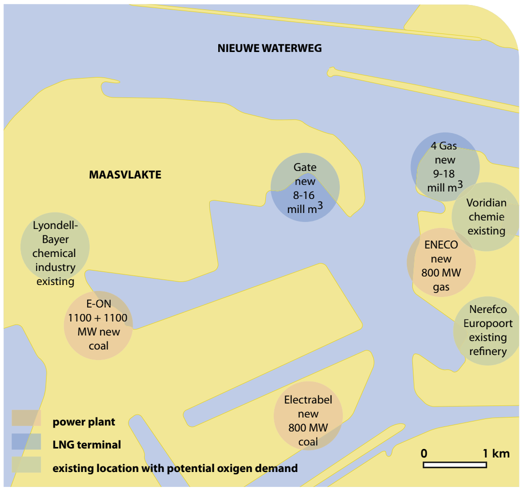
* The relevant report is available from SenterNovem, as detailed at the end of this brochure.

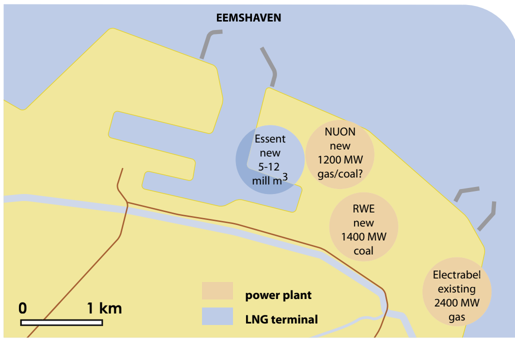
New generating capacity and government CO_2 reduction targets

At the ports of Rotterdam and Eemshaven there are plans to build new electrical generating capacity. All in all, construction of about 5,300 MWe capacity is envisaged, 4,500 MW of which will be coal-fired. This will generate vast quantities of CO_2; for a typical power plant, about 5 Megatonnes a year.

There are ambitious government CO_2 reduction targets in place in the Netherlands. Rotterdam has announced that it is to cut its CO_2 emissions by 50 percent in 2025 compared with 1990, while the national government seeks to achieve a 20 to 30 percent reduction by 2030. If these targets are to be achieved, CO_2 capture and storage at new coal-fired power plants is unavoidable.

More or less parallel to construction of these power plants, three LNG receiving terminals are also planned, with a combined annual send-out capacity of approximately 40 billion m^3 of natural gas, roughly equivalent to total Dutch consumption. Because of the very low temperature at which the liquefied gas is stored (minus 163°C), this LNG stream embodies a vast quantity of cold energy, with a 12 billion m^3 terminal representing around 10 PJ of cold.





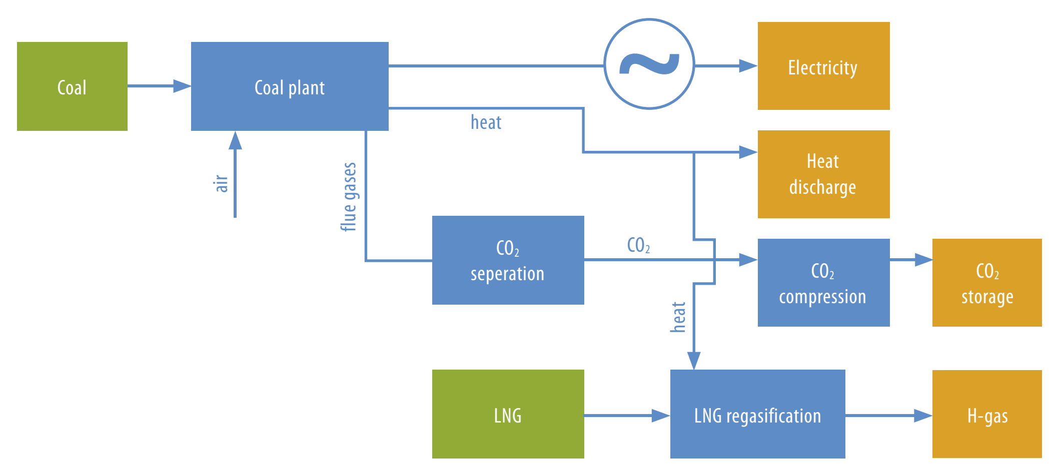
Planned power plants and LNG terminals at Rotterdam and Eemshaven.

CO_2 separation in 'stand-alone' power plants: major loss of energy efficiency

In the standard coal-fired power stations that are currently planned, CO_2 will have to be separated from the flue gases before it can be sequestered. In this type of 'post-combustion' CO_2 capture, the chemical absorbent MEA or chilled ammonia is used. A disadvantage of this process is that it consumes a large amount of energy. Calculations indicate that this will reduce the overall energy efficiency of the power plant by about nine percent, from 47 to 38 percent. This means that about 25 percent more fuel will be required to achieve the same electrical output, with an equivalent increase in emissions.

As the figure shows, downstream of the coal plant process there is heat integration with the LNG terminals. The coal plant off-gases are cooled using the cold from the LNG plant. This set-up, currently planned at the two Rotterdam LNG terminals, saves about 2.5 PJ compared with the situation in which the LNG is reheated using seawater.

STAND-ALONE COAL PLANT INCL. POST COMBUSTION



The oxyfuel option

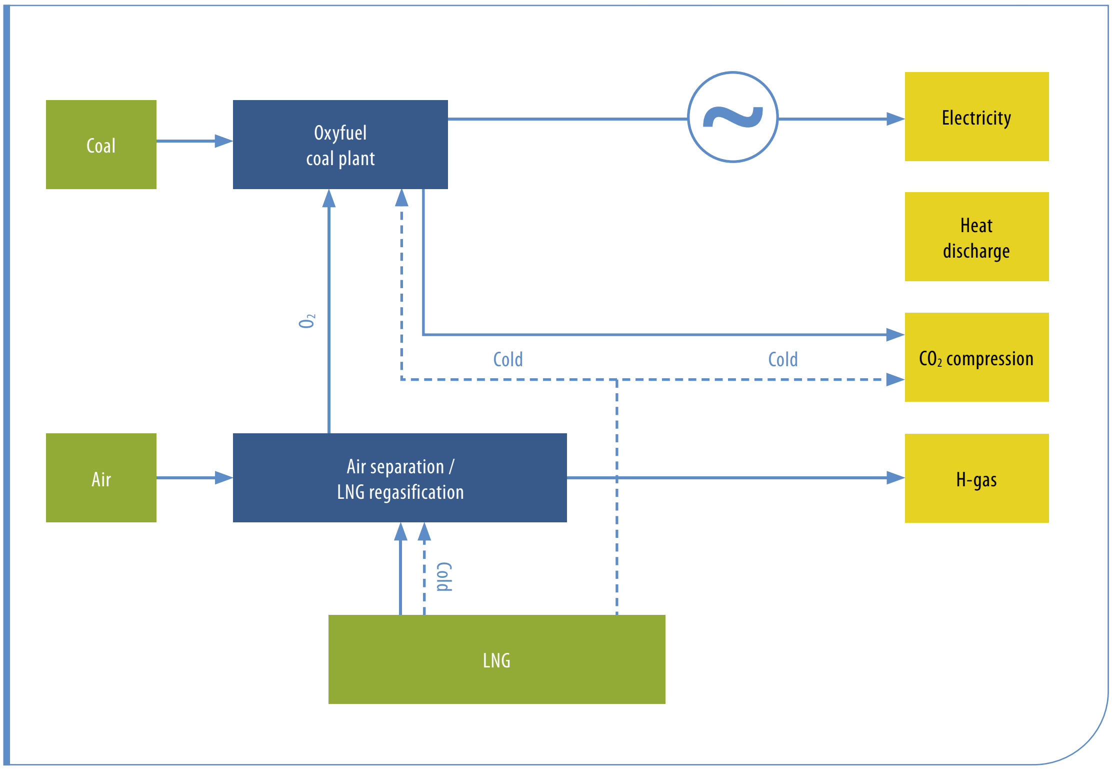
There is an alternative to post-combustion capture for capturing combustion CO_2: the 'oxyfuel route'. In this route oxygen is first produced in an air separation plant and the coal subsequently burned in an atmosphere of pure oxygen (as 'oxyfuel'). The flue gas now consists primarily of CO_2, removing the need for a downstream CO_2 separation plant. The drawback of this route, however, is that oxygen production is energy-intensive. On balance, this route leads to similar losses of energy efficiency as post-combustion capture, thus giving a similar figure for overall efficiency: around 37 percent. The two situations are summarised in the following table.

ROUTE	COMBUSTION GAS	MAIN SOURCE OF ENERGY EFFICIENCY LOSS	OVERALL EFFICIENCY
Post-combustion capture	Air	CO_2 separation	38% [± 3%]
Oxyfuel	Oxygen	Oxygen production	37% [± 3%]

Construction of LNG terminals coal plants creates scope for integration: the LNG/oxyfuel route

With new power plants and LNG terminals scheduled for more or less simultaneous construction in the Netherlands, we have a unique opportunity for process integration, investigated by CE Delft in a recently completed study.
At the heart of this so-called 'LNG/oxyfuel route' is thoroughgoing integration of LNG terminal operations, air separation and coal-fired power generation, using the cold embodied in the LNG to produce oxygen. That oxygen is then used to fire the coal plant, creating flue gases that are 'pure' CO_2 that can be stored without further processing, thus obviating the need for a downstream CO_2 separation unit, with all the energy consumption implied. In the process as currently conceived, the cold from the LNG is also used for CO_2 compression and for cooling the coal plant steam cycle.

OXYFUEL FIRED COAL PLANT INTEGRATED WITH LNG RECEIVING

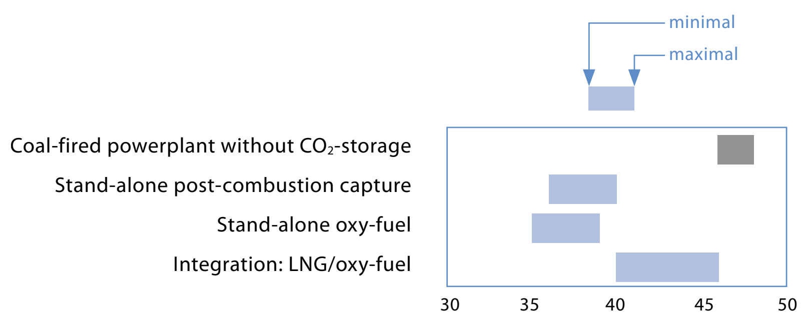


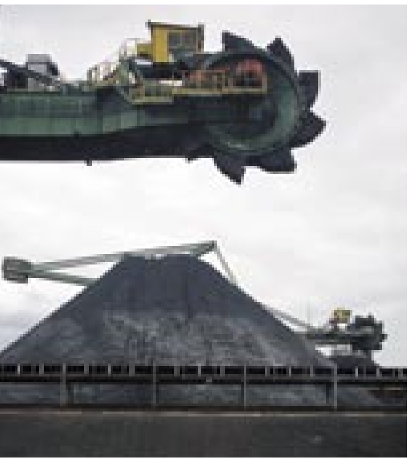
The energy efficiency of the process variants

In the CE Delft study the overall energy consumption, emissions and costs of the LNG/oxyfuel route and the stand-alone option with post-combustion capture were calculated, in both cases using flow chart concepts encompassing the process chain through to CO_2 capture and compression. Calculations were based on a 1000 MWe coal-fired power plant, roughly the same as currently planned, and an LNG terminal with 12 billion m^3 send-out capacity, representing about 10 PJ cryogenic energy. In the concept used, some of this energy is used for oxygen production and some for CO_2 compression and cooling of the coal plant steam cycle.

Overall, the LNG/oxyfuel route leads to an energy consumption of 62 PJ, compared with 72.5 PJ for the stand-alone option with post-combustion capture. This represents an energy efficiency of 43 percent for the coal-fired power plant: about 5 percentage points better than the stand-alone variant. The improvement over 'oxyfuel without LNG integration' is similar.

ENERGETICAL EFFICIENCY FOR 4 ALTERNATIVE OPTIONS





Environmental benefits, too, with the LNG/ oxyfuel route

The NO_x and CO_2 emissions of the LNG/oxyfuel concept were also evaluated, and it was found that this route leads to substantially lower emissions of both than in the stand-alone variant (with post-combustion capture).

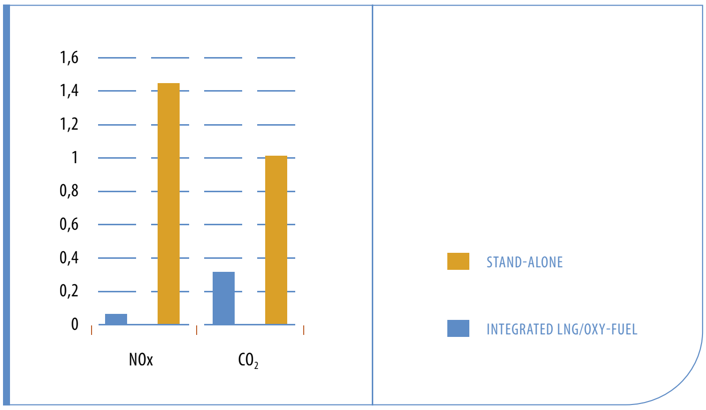
NOx

NOx emissions have a major impact on local air quality and acidification. The stand-alone coal plant with post-combustion CO_2 capture produces around 1.4 Mt NO_x emissions. This is substantial when compared with the 55 Mt that Dutch industry as a whole is permitted to emit in 2010. The LNG/ oxyfuel route has virtually zero NO_x emissions. This is due in the first place to less NO_x being formed because of the virtual absence of nitrogen in the combustion gas, and secondly to the fact that residual NO_x can be captured in the CO_2 compression step.

CO_2

The stand-alone coal-fired power plant emits around one Mt of CO_2 annually. This is because the CO_2 separation unit does not capture all the CO_2; efficiency is around 90 percent.

EMISSIONS NO_X (KT/YR) AND CO_2 (MT/YR)



The financial side of the LNG/oxyfuel route

As the pilot study has shown, the LNG/oxyfuel route evidently offers a number of advantages in terms of energy efficiency and environmental impact. When it comes to the financial and economic side, matters are less clear. Nowhere in the world is there a complete plant in operation that uses the LNG/oxyfuel route, and the same holds for the route with post-combustion capture.

In calculating the investment and operating costs of the LNG/oxyfuel route, two variants were considered: one with high costs, based on the configuration of a standard coal-fired power plant, the other with low costs, in which several potential cost savings in the new plant were factored in. The first of these derives from the fact that it appears feasible to dimension an oxyfuel power plant considerably smaller than existing designs. Process designer Foster-Wheelder estimates that a 55 percent reduction in size can be achieved. In addition, it may be possible to dispense with separate de-SO_2 and de-NO_x provisions, as these off-gases are to be removed in the CO_2 compression step.

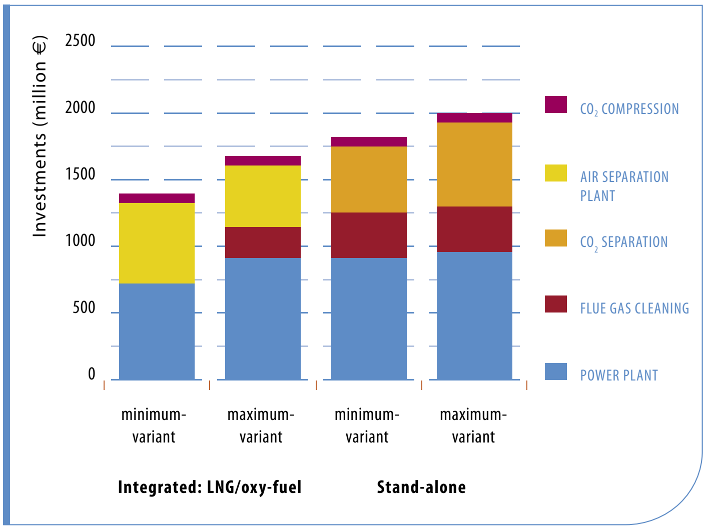
Investments

Investments for the envisaged LNG-integrated oxyfuel plant are similar to or perhaps lower than those for a coal plant with post-combustion carbon capture. A post-combustion capture facility will require roughly the same level of investment as an air separation (oxygen production) plant.

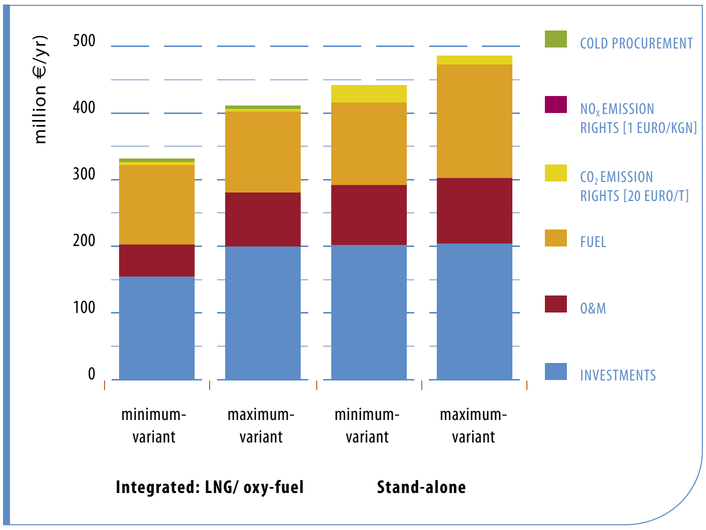
Operating costs

In terms of operating costs, too, the LNG/oxyfuel route probably scores better. To start with, fuel costs sill be lower because of the greater energy efficiency of the process. Secondly, there will be cost savings on CO2 emission rights because of the lower CO2 emissions. Capital expenses and maintenance costs will also be proportionally lower.

INVESTMENTS



OPERATING COSTS



Technical feasibility of the LNG/oxyfuel route

Although the integrated process comprising LNG terminal, oxygen plant and coal-fired power plant is nowhere yet operational, most of the individual elements are either commercially proven or in an advanced stage of development. In broad brushstrokes, two basic steps can be distinguished:

1. Integration of LNG regasification and oxygen production.
2. The oxygen-fired coal plant.

The first step is already operational and the second is at the demonstration project stage.

1. EXPERIENCE WITH INTEGRATION OF LNG REGASIFICATION WITH OXYGEN PRODUCTION: THE OSAKA GAS LNG TERMINAL

At the Osaka Gas LNG terminal in Senboku, Japan, integration of LNG vaporisation with oxygen production has been a commercial operation for many years now. This terminal, which came on stream in 1972, has an annual capacity of 8.0 billion m^3 gas. A substantial portion of the cryogenic energy available at the terminal is used for processes in adjacent industrial facilities, as chronicled below.

1977, 1982, 1993:	oxygen production
1979, 1982:	electricity production (cryogenic power generation)
1980:	CO_2 compression
1987, 2004:	cryogenic integration with adjacent chemical industry and refineries

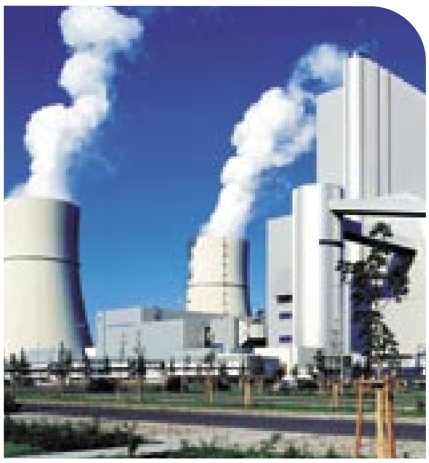
LNG terminal integrated with oxygen plant. Photo: Osaka Gas, Japan

2. EXPERIENCE WITH COAL-FIRED OXYFUEL POWER PLANT: VATTENFALL'S SCHWARZE PUMPE PILOT PLANT

Although oxyfuel combustion of coal is not yet commercially operational, it is at an advanced stage of development. In the German industrial district Schwarze Pumpe the Swedish energy company Vattenfall is building a 30 MWe pilot plant, scheduled for start-up in 2008. After experience has been gained with this pilot, a programme of upscaling is scheduled, through to a 1000 MWe commercial facility in 2020.

Several features of the demonstration plant:

- *Oxygen production:*
  As there is no large source of cold like a LNG terminal at the site, the oxygen is produced in a dedicated air separation plant. This requires substantial energy inputs, reducing the efficiency of the process to around 37 percent.
- *Temperature control:*
  Oxyfuel combustion generally creates higher temperatures. This is prevented by recirculating the flue gases.
- *Smaller power plant:*
  Several components (boiler, turbine, dust filters) have been dimensioned smaller than in a standard power plant, because around 80% less combustion air is required. This means lower investment costs.
- *No de-NO_x or de-SO_x:*
  The Vattenfall pilot plant has no de-NO_x en de-SO_x provisions, as these gases are to be removed in the CO_2 compression step. Again, this means savings on investments.



Photos: Vattenfall Europe AG

Conclusions

Four main conclusions can be drawn with respect to the LNG/oxyfuel route:

1 *Realistic and promising concept*

The concept of integrating LNG cold, oxygen production and a coal-fired oxyfuel power plant appears to be both realistic and promising. Although not yet operational anywhere in the world, all the individual elements are either already commercially applied or soon to be tested in a demonstration project. The study indicates that this route offers clear advantages in every respect to concepts in which the coal plant operates as a 'stand-alone' unit, with air rather than oxygen being used as a combustion gas, and CO_2 having to be separated from the flue gases post-combustion.

2 *Substantial energy savings*

At the scale of LNG terminal investigated (12 Mt/year), the amount of cold available from such a terminal is more than sufficient for producing the oxygen required for a 1,000 MWe oxyfuel-fired power plant. In addition, the LNG cold can be used for cryogenic power generation and CO_2 compression. Altogether, this leads to energy savings of around 9 PJ. The energy efficiency of the integrated facility is about 43 percent, five to six percentage points better than the stand-alone variant.

3 *Better for the environment*

In environmental terms, too, the oxyfuel variant scores far better. Emissions of NO_x are negligible, compared with around 1.4 kt for the stand-alone variant, while CO_2 emissions are lower by about a factor three.

4 *Probably more cost-effective*

With respect to costs there are considerable uncertainties, for both the oxyfuel and the stand-alone variant. Nonetheless, initial calculations indicate that the integrated oxyfuel variant could well be the more cost-effective of the two. The main savings would come from the superior energy efficiency: in short, less fuel, a smaller plant and lower CO_2 emissions.

Recommendations

a Make full use of the scope for integration by siting LNG terminals and coal-fired generating capacity close together.

b Anticipate integration in the design stage of new LNG terminals and power plants.

c Where anticipation is still unfeasible, leave scope in the design for retrofits.

d Undertake further technical and economic studies to evaluate the LNG/oxyfuel route, geared specifically to the situation at Rotterdam and Eemshaven ports.

January 2008

This brochure was produced in the framework of the industrial energy-saving programme *'Energiebesparing Bedrijfsleven - Ketenefficiency Verbreed'* being implemented for the Dutch Ministry of Economic Affairs by SenterNovem. It was written in collaboration with CE Delft on the basis of 'The 'oxyfuel' route - Integration of LNG regasification, oxygen production and power generation: An exploratory study of environmental and economic impacts' (title translated), a study conducted by CE Delft for SenterNovem.

The full (Dutch-language) report can be ordered from SenterNovem's front office: phone (030) 239 35 33, e-mail info.mja@senternovem.nl. It can also be downloaded as a pdf file via www.senternovem.nl/mja/publicaties.

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Catharijnesingel 59
Postbus 8242
3503 RE Utrecht
Phone (030) 239 34 93
Fax (030) 231 64 91

Swentiboldstraat 21
Postbus 17
6130 AA Sittard
Phone (046) 420 22 02
Fax (046) 452 82 60

www.senternovem.nl
info@senternovem.nl

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