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THE LINDE GROUP

Linde

Baseload LNG Production in Stavanger

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Introduction.

As a leading engineering and industrial gases company, Linde are ideally positioned to capitalise on the dynamic natural gas market in several ways. As an engineering company, we design and build natural gas processing and liquefaction plants. And as a gases company, we can distribute and market the product and – if so desired by the customer – also operate the plant.

One of our most recent references for LNG base-load production with an annual capacity of 300,000 tons of LNG is a plant built at the Norwegian west coast near the city of Starvanger, started-up for commercial production in 2010. Thanks to Linde's proprietary, most energy-efficient liquefaction process, this new plant is

cutting emission levels significantly compared with similar plants of this scale.

The plant owner Skangass is a joint venture between the energy company LYSE Gass AS and the financial investor Celsius Invest. Through its marketing company Nordic LNG AS, it will mainly

target the Scandinavian and Baltic markets. Its customers will include the Linde subsidiary AGA Gas AB. Under the terms of the agreement between Linde's Gases Division and Skangass, AGA will buy a significant amount of LNG from the new plant yearly and market it itself.

With a LNG production capacity of 900 TPD or 0.3 MTPA the plant represents a new category of LNG plant types. This category of Small to Mid-Scale LNG plants shows the same reliability, robustness and safety features as world-scale LNG plants, while integration in existing sites is much less complex with moderate CAPEX and shorter project execution time.

The plant is operated in base load mode and employs intermediate storage of the LNG product in an insulated tank before it is loaded to road tankers or LNG carrier ships. The trucks carry the LNG over long distances to satellite stations in various cities of Norway. After revaporization of the LNG the natural gas is finally distributed to a variety of industrial and private consumers. Another part of the LNG is transported by LNG carrier ship to the Nynäshamn LNG receiv-

ing terminal in Sweden. There it is regasified in submerged combustion vaporizers and directly routed to a nearby refinery. A smaller quantity of the LNG received in this terminal is loaded into road trucks for transport to remote locations in Sweden.

As LNG is considered the most environmentally friendly hydrocarbon fuel, it is expected that this domestic natural gas initiative creates new gas

markets and provides a great improvement to the energy supply situation in Sweden. This paper describes the Stavanger LNG facilities from gas treatment, liquefaction with a single mixed refrigerant cycle in a coil-wound heat exchanger, through storage, to unloading and distribution of the LNG to various consumers in Norway and Sweden.

Small to mid-scale LNG plants to monetize natural gas.

Today, about 80 large LNG trains worldwide produce LNG for the world market. Plants currently under construction typically have train sizes in excess of 4.0 million tons of LNG per year (world-scale LNG). The latest world-scale LNG trains have LNG production capacities of 7.8 million tons LNG per year continuing the industry's trend towards ever bigger trains.

At the same time, the number of reservoirs supporting such large trains is limited. Additionally, such reservoirs may be difficult to access for var-

ious reasons such as remoteness, geological or political obstacles. Accessing those reservoirs requires more resources, capabilities and balance sheet strength than ever before.

The above mentioned circumstances have prompted some market players to evaluate mid-scale LNG technologies and opportunities, which means a train capacity between approx. 300.000 and 1.000.000 tons of LNG per year. The Stavanger LNG plant with an annual capacity of 300,000 tons of LNG utilizes a Linde patented single

mixed refrigerant processes, which is considered the most appropriate process technology for a base load LNG service of this size. Other processes available, such as single or double nitrogen expander processes, would require up to 80% more power and towards the upper end of the above-mentioned range have significant higher equipment count and have therefore not been considered for the Stavanger LNG plant project.

Small to mid-scale LNG plants versus world-scale LNG plants.

Safety and standards

Mid-size LNG technology does not compromise on safety, reliability, robustness and efficiency. Applied processes and equipment are well-proven in base load service, comply with API standards and generally accepted safety philosophies and are derived from world-scale LNG projects. However, based on standard industry risk acceptance criteria, necessary safety distances inside of mid-scale LNG plants are significantly lower than those of world-scale LNG plants. A comparison between an executed 0.3 and 4.3 million tpa LNG plant including respective calculations of risk contours result in safety distances from the centre of the process plant to the nearest possible location of the plant fence of about 250 m and 750 m for a world-scale LNG plant respectively. One main reason for the differences is the significantly increased amount of hydrocarbon inventory in world-scale LNG plants as a result of the increased mixed refrigerant cycle inventory and larger tank sizes.

Increased hydrocarbon inventory raises the potential fire and explosion loads which, in turn, tighten the requirements regarding the so called design accidental loads (DAL) for the plant equipment and bulk material. This either leads to increased investment cost for reinforcement of the equipment or to increased plot space requirements to bring down the degree of congestion.

Plot space, location and infrastructure

Plot space requirements of mid-scale LNG plants differ significantly from world-scale LNG plants. A mid-scale LNG plant including buildings, flare, LNG tank and utilities requires a plot space in the magnitude of 50.000 m², while world-scale LNG plants require in excess of ten times more plot space. Generally spoken world-scale LNG plants do not benefit from economies of scale regarding plot space, but may even require proportionally larger plot spaces than expected based on the sheer scale in capacity and equipment. There are several reasons for this tendency.

Firstly, a world-scale LNG plant in most cases requires a dedicated power generation system. Although the main refrigerant cycle compressors are often mechanically driven by gas turbines, the large amount of smaller size machinery which is driven by electrical motors constitutes such high demand on electrical power that it cannot be supported from existing electrical infrastructure. In contrast, mid-scale LNG plants are often connected to the electrical network and no dedicated power generation system is required, especially if the main refrigerant compressor is directly driven by a gas turbine.

Depending on the boundary conditions, mid-scale LNG plants up to a capacity of 500.000 to 700.000 tpa may use the electrical network to electrically drive the main refrigerant compressor. Furthermore, mid-scale LNG plants are often fed with pre-treated feed gas from existing pipelines systems. As a consequence, all or most plot space requirements for pre-treatment facilities, as well as condensate stabilization and fractionation units are eliminated. In such cases where small quantities of natural gas liquids are removed, for example to adjust the heating value or achieve a methane number of the produced LNG, removed hydrocarbons are preferably used as fuel for the turbine or hot oil system and no condensate or LPG tanks are required.

Construction of a mid-scale LNG plant also requires significantly less area for lay down and work camps. The sheer size of the work force in a world-scale LNG project (typically exceeding several thousand men in peak times) itself poses one of the major challenges, especially since most world-scale LNG plants are located in remote areas. Most of the world-scale LNG projects are greenfield projects for which a complete infrastructure incl. parking, access streets, administration buildings and also all utilities including the power plant must be established. In mid-scale LNG projects, the requirements for lay down areas

and work camps are moderate in comparison and in many cases a significant part of the work force recruits are from the region. In summary, plot area, work force and camp size as well as explosion loads and building heights are lower for mid-scale LNG plants. These factors, especially at the lower end of the capacity range, allow the LNG plant to be located in industrial zones and thereby also benefit from existing infrastructure. Some sites which are typically considered as a mid-scale LNG location such as refinery sites, iron ore, bauxite or container terminals may even offer wharf and jetty infrastructure. All the above can reduce overall mid-scale LNG project costs significantly.

Modularization

Module sizes and weights are considerably smaller for mid-scale LNG plants where even the tallest modules would not exceed a footprint of 20 m x 20 m and weights would not exceed 1,000 metric tons. Such sizes and weights can be easily lifted without being limited to only a few available special cranes, as would be the case for bigger modules being applied for world-scale LNG plants. Furthermore, sites are more accessible with smaller modules and it is likely that modules can be hauled in without dedicated new port investment in the case of mid-scale LNG plant modules. Last, but not least, a larger pool of potential module yards is available around the world for moderately sized modules. Some of the more complex and heavier modules of world-scale LNG plants can only be built by a handful of yards.

Project execution schedule

Prior to commencement of any significant plant engineering activities, items such as exploration on a world-scale LNG plant, appraisal and environmental approval activities as well as the development of field infrastructure may take many years. Plant engineering activities prior to a final investment decision (FID) in world-scale LNG, in most cases, involve a pre-FEED and a FEED study.

The latter already includes a significant level of detail engineering activities, including a 30% plant model as a basis for a reasonably precise cost estimate. This need for detailed engineering is to a large extent driven by the sheer size and complexity of world-scale LNG projects. It typically takes two years to complete pre-FEED and FEED activities prior to any final investment decision.

Mid-scale LNG projects, compared to world-scale LNG projects, are fast track projects. Securing off-take rights from existing natural gas pipeline systems prior to starting serious plant engineering activities takes comparatively little time. Mid-scale LNG projects in most cases can be tendered without upfront pre-FEED and FEED.

Based on a high-quality basis of design there are contractors available to quote a firm price for engineering, procurement and erection (EPC) of a mid-scale LNG plant. All in all it may take around fifteen months to properly prepare for final investment decision from commencement of plant engineering activities. Construction activities of mid-scale LNG projects will take in the order of one and a half years less than construction activities of world-scale LNG projects. Mid-scale LNG projects from commencement of first plant engineering activities can be expected to produce first LNG at least two years earlier than a world-scale LNG plant. Taking into account the entire project development phase mid-scale LNG projects, in many cases, will produce first LNG four to five years earlier than world-scale LNG projects.

Small to mid-scale LNG plants do not compromise on safety, reliability, robustness and efficiency in comparison to world-scale LNG facilities, while execution risks and time as well as capital requirements are significantly lower.

The Basics.

Basic data process design

The design of the plant is based on state-of-the-art natural gas liquefaction technology.

Design basis

The Stavanger LNG plant consists of natural gas treatment, gas liquefaction, LNG tank and loading facilities as well as utilities. The liquefaction process is based on a most efficient single mixed refrigerant cycle.

The LNG production capacity of the plant is 900 tpd with an expected on-stream time of 330 days per year. Design hourly liquefaction capacity is 37 t/h with a storage capacity of 30,000 m³ of LNG, which is the equivalent of approx. 12 days production. The capacity of the LNG send-out and distribution system meets the requirement of loading 25 - 100 m³/h by truck and 150 - 1,000 m³/h by ship (dependent on ship size).

Feed gas composition

Composition (mole %):

- Nitrogen	0.65
- Methane	88.22
- Ethane	8.43
- Propane	0.55
- Butanes	0.05
- Pentanes	0.00

In addition, CO₂ as well as traces of H₂S and sulfur are present in the feed gas. The feed gas operating pressure is 120 bar g.

LNG specification

Composition (mole %):

- Nitrogen	max 1.0
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Ambient site conditions

The average ambient temperature ranges from 30°C in the warmest to -15°C in the coldest month. The design temperature for air-cooling is 13.2°C.

Process features

The main process and utility units are illustrated in the block diagram in Fig 1. The mixed refrigerant cycle liquefaction process requires the components nitrogen, ethylene, propane, butane, and a portion of the compressed tank return gas (Linde patent). Refrigerant nitrogen and purge nitrogen are identical and both generated in a nitrogen package.

Utilities

Instrument air, nitrogen and demineralized water are produced within the LNG plant. Electric power, potable water and fire water are supplied from outside Battery Limit.

The tank return gas as well as vapour return from LNG loading is utilized as fuel gas. The fuel gas is used for flare pilots and fired heater of the hot oil unit. Not used fuel gas is sent as tail gas to the local gas grid at Battery Limit.

The hot oil system provides the process heat for the plant at two temperature levels. Two cycles are introduced, a medium temperature cycle for regeneration of the amine and a high temperature cycle for heating of regeneration gas for the driers.

The liquefaction process is based on a most efficient single mixed refrigerant cycle, which contains the components

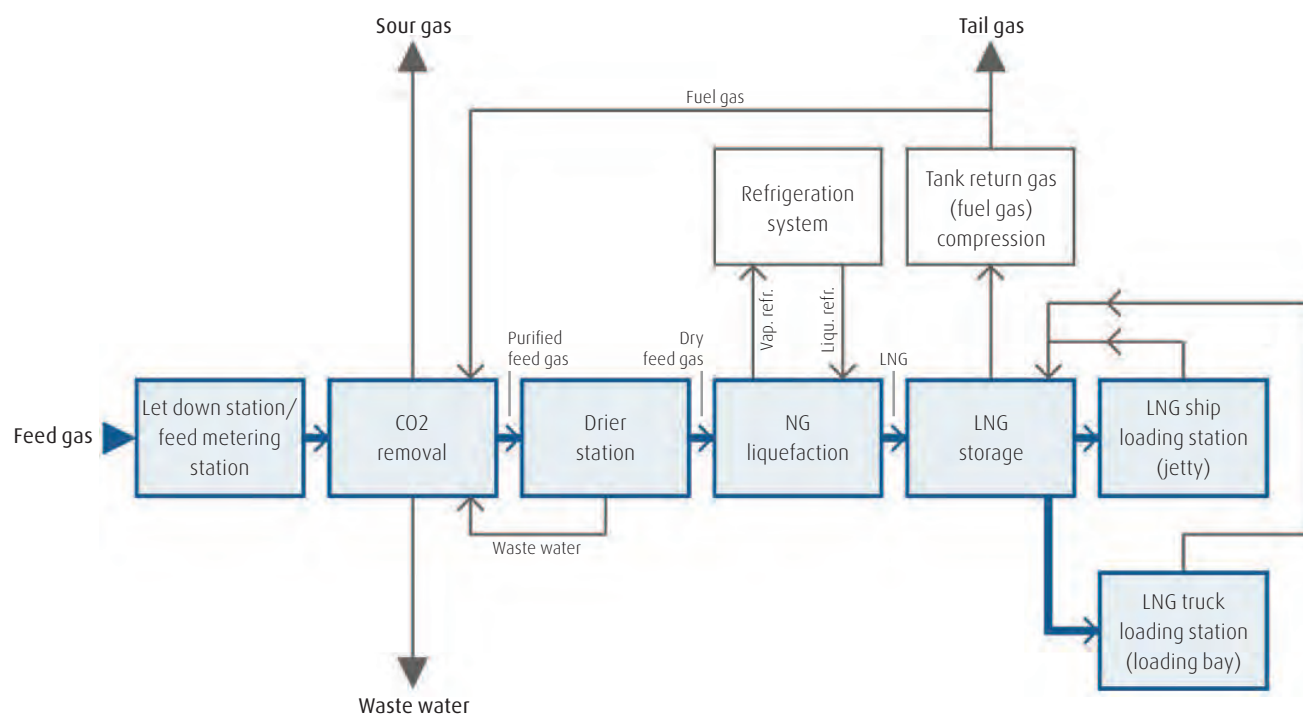


Fig1: Block diagram of the Stavanger LNG plant

nitrogen, ethylene, propane, butane and a portion of the compressed tank return gas (Linde patent). This process has a superb efficiency and is easy to operate.

Design features with respect to safety, emission and noise requirements.

High material requirements

The feed gas pressure at battery limit is 180 bar (209 barg design pressure), which allows very efficient natural gas liquefaction, but on the other hand poses very high demands on equipment and material selection.

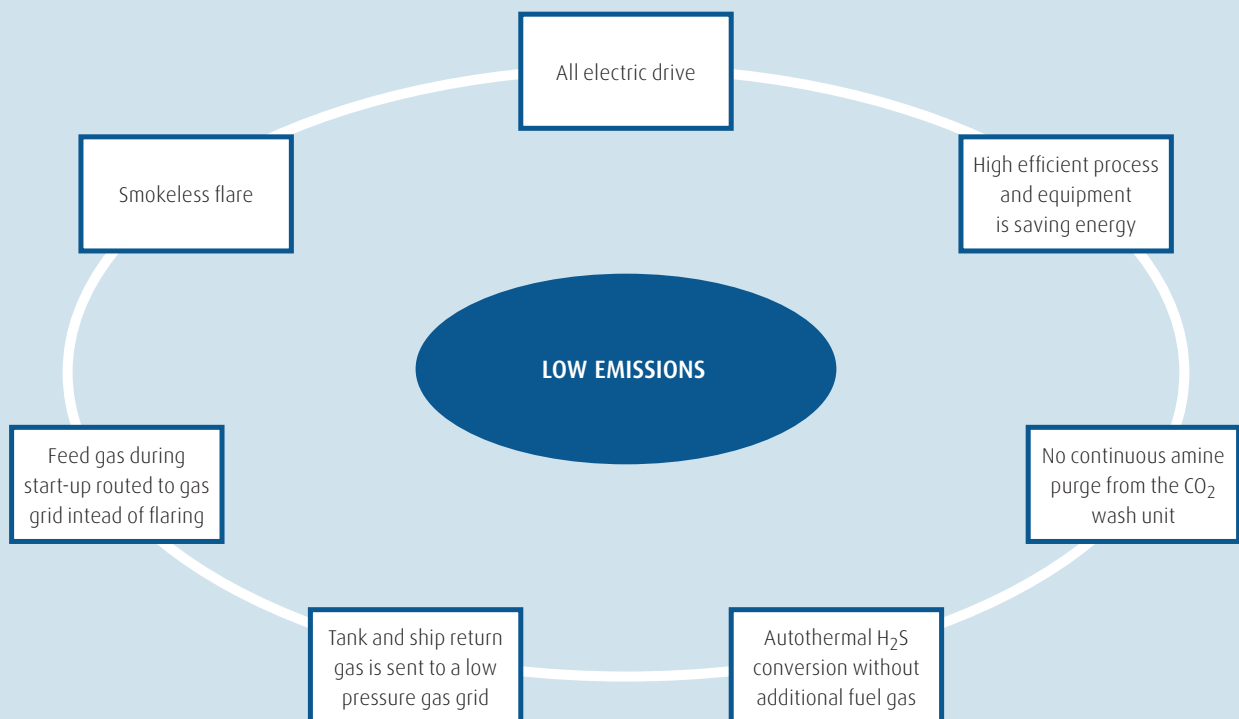
Special care has to be taken on tightness and safe operation. Usually small/mid-scale LNG plants use plate-fin heat exchangers for liquefaction. For the Stavanger coil-wound heat exchanger, Linde Engineering selected stainless steel as material, due to the following features:

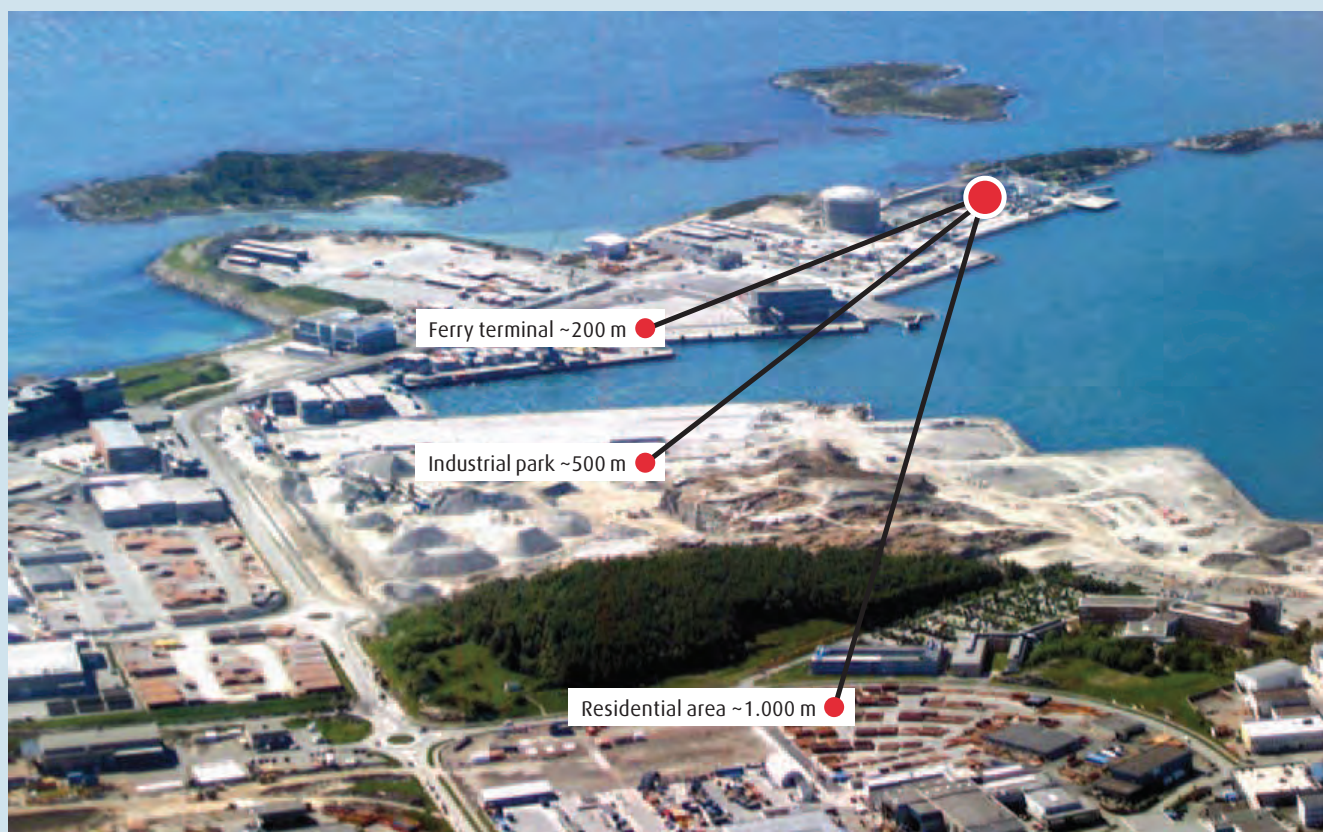
- Allowable stress is a factor 2 to aluminum
- Elongation at fracture is 5 times higher
- Extremely robust and flexible in operation

Low emission requirement

The diagram shows the challenging low emission requirements which had to be followed for the Stavanger LNG plant project due to the stringent permitting standard regime in Norway.

High permitting standard regime in Norway





Stavanger LNG plant site location

Noise requirements

Due to the nearby settlement the Stavanger LNG plant must fulfill the challenging noise requirement of 53 db at battery limit. In order to fulfill this stringent requirement the following features were applied:

- Low noise fans and air-coolers
- Air-coolers partly housed-in
- Cycle compressor inside a noise hood
- Majority of piping and equipment is sound insulated
- Control Valves are low noise trims
- High demand to noise reduction at all equipment

High standard permitting regime in Norway

Beside the high standard permitting regime in Norway the Stavanger LNG project was facing further challenges through the following facts:

- Located on old refinery site within industrial zone
- Limited available plot space of 68 m x 47 m
- Challenging environment with nearby traffic, industrial and residential buildings
- Numerous residence reservations / objections managed and overcome by Linde and the client

Plant features.

Overall process

The plant consists of natural gas treatment and liquefaction, LNG storage tank, one LNG ship loading and one truck filling station. The natural gas is cooled, liquefied and subcooled in a coil-wound heat exchanger by a most efficient single mixed refrigerant cycle. This cycle provides cold temperatures by Joule-Thomson expansion and liquid vaporization of the mixed refrigerant within the shell of the CWHE. The refrigerant cycle is recompressed in an electric motor driven integrally geared turbo compressor.

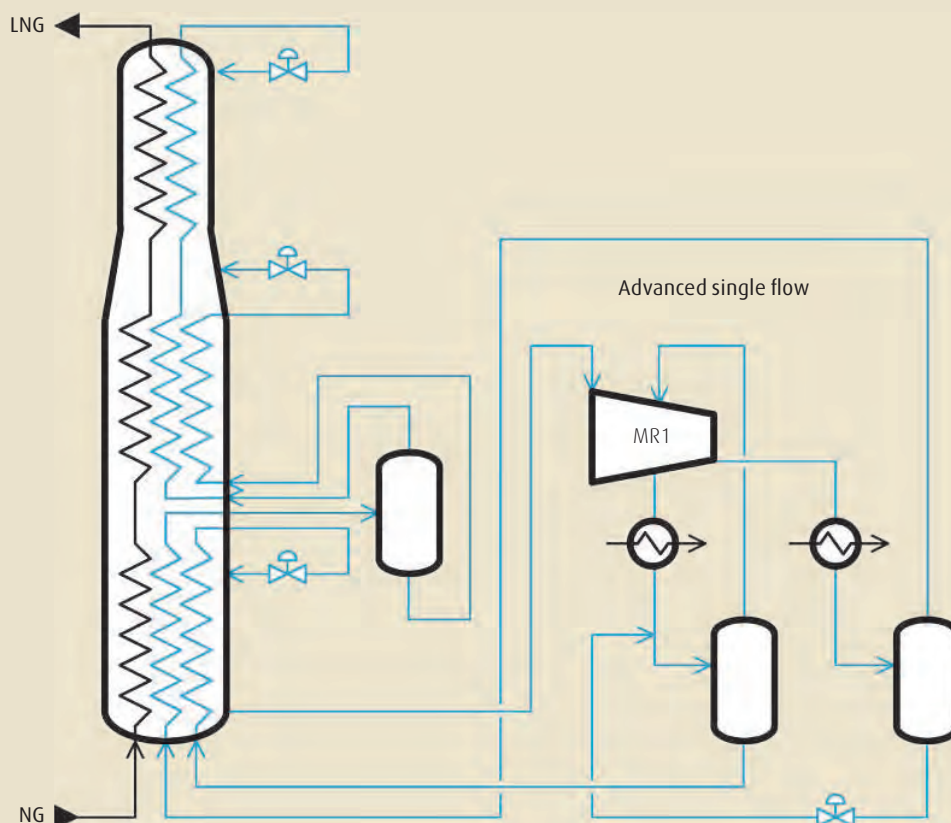
Natural gas treatment

Natural gas is received from Karstø natural gas processing plant with a pressure of 120 bara and a temperature of 10°C. The feed gas is routed to the amine wash unit (Linde design) for removal of CO₂. The sweet feed gas leaving the CO₂ wash column is routed to the drier station. The aMDEA CO₂ wash unit is a Linde designed unit customized to the high feed gas pressure of 110 bar.

Natural gas liquefaction

After CO₂ and H₂O removal, the natural gas is routed to the cold part of the process, which features three coil-wound heat exchanger bundles integrated in one shell ("rocket"), as well as several separation vessels. The natural gas is first cooled in the feed gas precooler. The purified gas is condensed in a feed gas liquefier and subcooled in a feed gas subcooler (fig. 2).

Fig 2: Linde patented natural gas liquefaction process LIMUM®





LNG truck loading station with 30,000 m³ LNG storage tank at Stavanger LNG plant

Refrigerant system

The refrigerant gas stream is withdrawn from the shell side of the precooling section of the cryogenic coil-wound heat exchanger. The refrigerant is slightly super-heated. It passes the cycle compressor suction drum and is compressed in the first stage of the refrigerant cycle compressor. It is cooled against air in the inter- and after-cooler resulting in partial condensation. The resulting liquid is separated in the cycle compressor intermediate discharge drums.

The liquid from the medium pressure discharge drum is routed to the cryogenic heat exchanger, where it is subcooled and used for the precooling of the natural gas after expansion in a Joule-Thomson valve.

The cycle gas from the high pressure drum is cooled to the same temperature, partly condensed and fed to the cold refrigerant separator.

The liquid from this separator is subcooled in the cryogenic heat exchanger to a low temperature so that it can be used efficiently as a refrigerant after expansion in a Joule-Thomson valve.

The vapor from the cold refrigerant separator is condensed and subcooled in the cryogenic heat exchanger to a sufficiently low temperature. This process step provides the final cold for the natural gas subcooling after throttling in a Joule-Thomson valve. After expansion to the lower pressure, the cycle gas streams are warmed up and vaporized in the common shell side of the cryogenic heat exchangers and returned jointly to the suction side of the first stage of the refrigerant cycle compressor.

LNG storage and loading system

Main purpose of the LNG storage and loading unit is the intermediate storage of LNG prior to loading into LNG carriers at the jetty and/or to LNG trucks at the truck loading bay. The 30,000 m³ LNG storage is designed as full containment tank for LNG storage at atmospheric pressure. LNG vapor generated during zero ship loading, max. ship loading, zero truck loading and max. truck loading are routed via the LNG storage tank to the tank return gas compressors. Excess vapors, during loading of ships with increased tank temperatures at start of LNG loading are sent to the flare system.

Approx. 90% of the LNG production is exported by ship and 10% is exported by truck at the truck loading bay. The tank is filled continuously during operation of the liquefaction system at a filling rate of 83 m³/h respectively 37.500 kg/h.



LNG ship loading facility of the
Stavanger LNG plant

LNG ship loading

For LNG ship loading the LNG is pumped to the LNG carriers by means of one of 2 x 100 % ship loading pumps, which are installed inside the LNG tank. The LNG from the LNG ship loading pumps is routed via the LNG ship loading line and the loading hoses to the manifold of the LNG carrier at the jetty. The send out rates of the LNG ship loading pump can be up to 1.000 m³/h depending on the size of the LNG carrier. The flow rates are controlled by the variable speed of the electric motor.

During no ship loading operation, the LNG ship loading line is kept cold by continuously circulating LNG by means of one LNG truck loading pump via a recirculation line and LNG loading line back to the LNG storage tank. This is done to keep the loading system cold and gas free at all times, to allow immediate start up of ship loading after arrival of a LNG carrier.

LNG truck loading

During LNG truck loading the LNG is pumped to the LNG truck by means of the LNG truck loading pumps, which are installed in the LNG tank.

The LNG from the LNG truck loading pumps is routed via the LNG truck loading line and loading hose to the LNG truck at the LNG truck loading bay. During loading of LNG trucks the normal rate per pump is 65 m³/h. Both LNG truck loading pumps can be used simultaneously. The truck loading bay is designed to load 10 LNG trucks with a capacity of 50-58 m³ within 12 hours (daylight) around the year. This is equivalent to the export of 10 % of the LNG net production rate via the LNG trucks. Truck loads are metered by a weigh bridge.

Fuel system

The net flash/boil-off and displacement gas from the LNG storage tank is compressed in the tank return gas compressor to 12 bar a. Part of the tank return gas is routed to the fired hot oil heater as fuel gas. About 2000 m³/h are sent to the local grid as sales gas. For start-up, feed gas may also be used as fuel gas. It is expanded to fuel gas pressure and warmed up by the start-up fuel gas heater.

Hot oil unit

The hot oil system provides the process heat for the plant at two temperature levels. Two cycles are introduced, a medium temperature cycle for regeneration of the amine and a high temperature cycle for the heating of the regeneration gas for the driers. The heat for both cycles is provided by a hot oil heater, which is fired with fuel gas. The hot oil is heated to 260°C to supply heat for the regeneration gas heating. To allow for start-up during winter conditions, the system is heat traced.

Coil-wound heat exchanger.

A special feature of the cryogenic section of the plant is the coil-wound heat exchanger designed and built by Linde.

The coil-wound heat exchanger (CWHE) can be considered as the heart of the LNG plant. Its purpose is to liquefy the dried and cleaned natural gas (NG). This is realized by pre-cooling, liquefying and sub-cooling natural gas in a three stage heat exchanger. The Linde proprietary coil-wound heat exchanger technology perfectly fulfils the requirements for such equipment.

With its history going back as far as to the time when Carl von Linde for the first time successfully liquefied air on an industrial scale, Linde is now looking back on more than thousand coil-wound heat exchangers successfully manufactured and brought to operation. CWHE's are robust, compact and reliable and serve a wide field of applications with a large range of temperature, pressure and can be designed and fabricated in various materials. They are suitable for single as well as two phase streams and can

accommodate several process streams in one exchanger. Each CWHE is specifically tailor made for the thermal & hydraulic performance requirements. Heating surfaces up to 40,000 square metres can be installed in heat exchangers bundles with diameters up to 5.5 metres and a total weight of 250 tons in the Linde own fabrication facility. Larger units are feasible and are assembled in yards close to the coast.

In general a CWHE comprises multiple layers of tubes particularly selected for the anticipated service, which are wound helically around a centre pipe. For the reason of perfect tightness, the bundle tubes are welded to the tube sheet and for highest process efficiency the bundle is covered by an additional inner shell, the so called shroud. A highly developed distribution system above the bundle makes sure that for falling film evaporation, the installed heating surface is

used most efficiently. The proprietary suspension system allows the Linde CWHE to cope with large temperature differences and changes as well as sharp pressure drops during operation. In particular during start-ups, shut downs and operational upset conditions Linde CWHE are well known as a very robust equipment without any kind of bundle sagging. Temperature elements as well as laser-optic measurement devices installed during bundle winding provide the relevant data for optimum process control.

After assembly with the pre-fabricated pressure vessel shell, the complete CWHE is not only subject to pressure testing, but also extensive tightness testing with pure helium to ensure highest quality. Linde coil-wound heat exchangers are 100% self-draining which reduces possible corrosion defects, accumulation of process impurities and defrost time.

Stavanger coil-wound heat exchanger ready for delivery at Linde's own workshop in Schalchen, Germany



With the Stavanger project, for the first time a stainless steel MCHE for LNG liquefaction service was put into operation. Based on historical and market reasons, aluminium was the state of the art material for the application of a CWHE in natural gas business.

Even though aluminium is the state of the art material, stainless steel can provide some benefits. Among those benefits are factors such as higher design pressures and temperatures, higher material strength values and less or no tube leakage. Especially for off-shore and marine service stainless steel is by far better in fatigue resistance. As per Linde's experience it is not recommendable to use aluminium in any part of a heat exchanger for such applications.

Further, the transition joints from aluminium to steel piping becomes obsolete. External loads imposed from structural attachments such as platforms or pipe racks can be accommodated easily. Inspections on the heat exchanger and maintenance on the surrounding installation can be executed by local staff without special aluminium know-how.

The Stavanger CWHE is fully made of stainless steel, including all its internals. With a total weight of 120 metric tons and a heating area of about the size of a football field and tubes as long as the distance from Berlin to Copenhagen the MCHE ranges in the medium scale of world class MCHEs in LNG business. However, due to its unique material selection it can be considered as one of a kind.

Coil-wound heat exchanger for the Stavanger LNG plant at Linde's own workshop in Schalchen, Germany



The coil-wound heat exchanger at Stavanger LNG plant

Liquefaction of the feed gas is performed in one single core coil-wound heat exchanger arrangement. This feature provides high flexibility with respect to turn-down (turn-down ration of 50%) and is extremely robust concerning temperature stress. The coil-wound heat exchangers makes the most efficient process possible, since this multistream heat exchanger can be designed for the high liquefaction pressure in combination with a close temperature approach between the majority of the cold and warm process streams. Coil-wound heat exchangers are installed in all major LNG plants around the world and are therefore proven for LNG processes.

The robust design of the coil-wound heat exchanger is ideally suited for the pre-cooling, liquefaction and sub-cooling processes. During these processes, the refrigerant and product streams reach temperatures as low as -160°C.

Fig. 3 shows the coil-wound heat exchanger installed within a supporting steel structure at Stavanger site. The outer dimensions (length x diameter) of the three coil-wound heat exchanger sections are:

Precooler: 12 m x 2.2 m

Liquefier: 19 m x 2.0 m

Subcooler: 13 m x 1.3 m

After concentric stacking and welding in a steel structure, the combined coil-wound heat exchangers have an overall height of 44.5 m. Fig. 3 shows the cryogenic section with the coil-wound heat exchanger together with the separator in the permanent steel frame. In comparison to plate-fin heat exchangers, the coil-wound heat exchanger can withstand significantly higher thermal shocks. Thermal shocks may occur during start-up or shut-down or mal-operation.

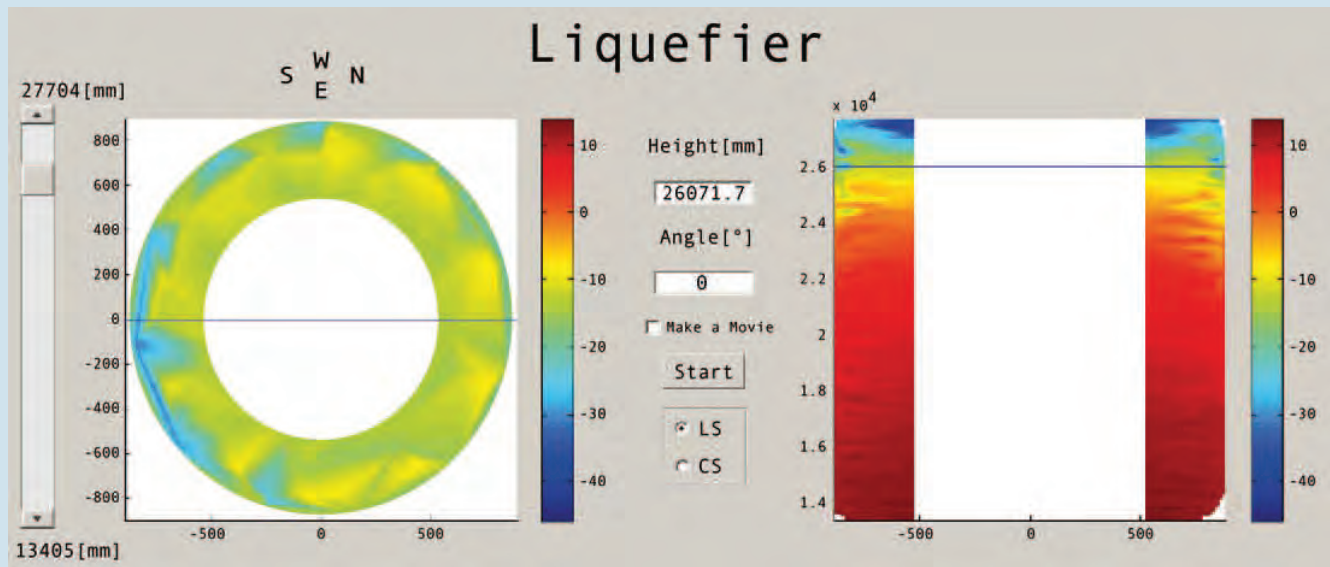


Fig. 3: Coil-wound heat exchanger (CWHE) at Stavanger LNG plant

Temperature measurement by optical fibers

The load dependent temperature profile in coil-wound heat exchangers is a desired quantity to further refine and improve the design. With knowledge of the temperature profile, pinch points can be analyzed and optimized and energy consumption can be reduced. A fiber based linear tem-

perature measurement system was built into the coil-wound heat exchanger to measure this data. The fiber measurement system allows remote operational assistance with measurement data backup from Linde head office in Pullach/Germany.



Temperature profile measured by optical fibers in liquefier section of coil-wound heat exchanger at Stavanger LNG plant

Temperature is probably the quantity that is measured most in LNG plants. Thermocouples or thermistors are mainly applied to piping, vessels and machinery. When looking at the main heat exchanger, special knowledge for installation of temperature measurements has been developed in the past. The aim was to gain insight into temperature distribution and thus liquid distribution inside the bundles of the coil wound heat exchanger (CWHE). However, more detailed information is coupled to number of measurement points and thus to installation effort.

The Stavanger CWHE has been equipped with a new approach to measure temperature, which is based on optical fibers. The fiber optic distributed temperature sensing (DTS) technique is an innovative way to obtain thousands of temperature measurements with comparatively low effort. A single optical fiber can replace many point sensors because temperature is measured along the fiber with a local resolution of down to half a meter. By co-installation of the fiber with the tubes during fabrication of the CWHE a huge amount of single measurement points is accessible from inside the bundle of the CWHE.

Briefly, the measurement principle is based on the Raman-effect as a result of laser-light transmitted through the fiber and scattering of spectral components in backward direction. This components travel to the starting point of the fiber where they are filtered and detected. The intensities of these spectral components are related to the temperature at the origin of this scattering process. Because the velocity of light propagation in the optical fiber is well known, the location can be determined from the time-of-flight of the returning backscattered light.

The DTS system enables more than 4000 single measurement points from the bundles of the Stavanger CWHE, which is a huge number compared to the few single point measurements used previously. During start-up of the LNG plant, the system has already proven its usefulness and successfully demonstrated its capabilities even at the low temperatures of natural gas liquefaction.

In the figure, the shell-side temperature distribution in the liquefier bundle during cool-down is shown in form of a longitudinal section. Since full 3D temperature data is available, also cross sections or iso-surfaces of temperature can be generated to visualize radial or axial distribution, pinch points or other effects.

This is truly a step change in process measurement. The wealth of information from this innovative measurement technique not only supports R&D and engineering for improvement of CWHEs but will also support our customers with valuable real-time data for optimizing energy efficiency or detecting critical states, e.g. in LNG-FPSO.

Fibre optic temperature measurement in LNG heat exchangers

In August 2009, the world's first coil-wound heat exchanger made completely of stainless steel for the liquefaction of natural gas (to be used in Stavanger, Norway) was delivered on time to the customer. This heat exchanger employs new temperature measuring technology using fibre optics (glass fibres).

These are capable of measuring temperatures throughout the entire CWHE, along both the length and diameter. The information is graphically displayed using special software. With this technology, it is possible to detect temperature changes and, indirectly, the distribution of liquid cooling agent at the edge of the CWHE. It is now possible, for the first time, to compare the theory with empirical data.

The principle of measuring temperatures using fibre optics has been known for some time and is based on the "Raman effect". The monochromatic

laser light that runs through the glass fibres is scattered on the SiO_2 lattice both elastically (i.e. with no change in colour) and also inelastically. The inelastic light scattering produces two signals which are respectively red and blue-shifted from the laser wavelength, referred to as Stokes and anti-Stokes lines.

However, the idea of using this principle in a coil-wound heat exchanger is new. The main advantages over the previous system are expected to be the improved control options. The new system will also provide important information regarding the efficiency and functionality of the cooling agent distributor.

The idea was implemented by installing glass fibres with an overall length of approximately 2,400 metres in the Stavanger heat exchanger. "The most difficult thing was to avoid bending the glass fibres ($d=0.2$ mm) during the manufac-

turing of the heat exchanger and to avoid damaging them during the welding work which was carried out in the following months. The outstanding cooperation of everyone involved, in particular the care and quality awareness demonstrated by the Linde manufacturing employees during production, was the key to success of this project", said Gerhard Dägling, the Project Leader responsible for installing the optical fibres.



Stavanger LNG plant

Project execution.

Linde Engineering successfully delivered to the client a fully operational base load LNG plant. The overall scope of work was to realize through all phases of project execution the implementation of a LNG production plant in Risavika near Stavanger in Norway, according to Norwegian/European Standard NS EN 1473. The LNG plant was built on a 300 m x 100 m plot, which was partly reclaimed from sea. The scope of work consisted of the complete LNG plant started-up for commercial production with all tests passed successfully.

The client provided the atmospheric LNG tank with a total capacity of 30,000 m³ and the LNG jetty as an open berth structure with concrete beams and slabs and a loading platform area of 40 m x 20 m. Linde's scope covered the whole process equipment for the LNG tank including the removable electric motor driven LNG Loading Pumps and the marine loading arm for the jetty with a capacity up to 10,000 m³/h (typical ship tank volume).

The plant achieved the status "commissioning completed and in all respect ready for LNG production" in August 2010, 1 month ahead of schedule.

This ahead of time completion was a result of the early definition of handover systems and pressure/electrical/instrumentation test packs during the engineering phase, which allowed a prioritised pre-manufacturing of piping, sequential piping installation and pressure testing, followed by a staggered mechanical completion of subsystems.

The construction phase was supported by the "integrated completion management system (ICM)", a newly developed and for the Stavanger project customized software package which allowed the detailed follow up and exact progress measuring of all relevant construction activities.

Linde along the LNG value chain.

Under the terms of the agreement between the Linde Gases Division and the owner of the Stavanger LNG plant Skangass, Linde Gases Division in Sweden (AGA) will buy a significant volume of LNG from the new plant each year.

A part of the Stavanger LNG product is transported by vessel to the Nynäshamn LNG receiving terminal in Sweden. It is partly regasified in submerged combustion vaporizers and routed to a nearby refinery. A smaller quantity of the LNG received in this terminal is loaded into LNG trucks for road transport to remote locations in Sweden.

LNG receiving terminal in Nynäshamn/ Sweden

Linde's subsidiary, Cryo AB from Gothenburg, has built this mid-scale LNG terminal in Sweden with a 20,000 m³ full containment LNG storage tank, which is the first terminal in the country. Linde's sister company AGA Sweden is the owner and operator of this terminal. AGA is engaged in the value chain of small-scale LNG, by shipping it from the LNG plant at Stavanger to the terminal, before distributing it by truck to the end clients.

CRYO AB has designed and manufactured more than 60 flat bottom tanks for cryogenic service, mostly for air gases, in Europe and South America. In addition, cryogenic equipment for natural gas has been delivered to a number of projects.

Construction site of the LNG receiving terminal
Nynäshamn, Sweden



LNG receiving terminal main operations

Fig. 4 shows a sketch of the LNG receiving terminal. Its purpose is to perform the following tasks:

- Receive, Liquefied Natural Gas from ships
- LNG storage
- Handle BOG (Boil Off Gas)
- Supply pressurized and gasified NG (GNG) to Nynäs refinery
- Discharge LNG to trailers

Ship unloading station (jetty)

The terminal receives LNG from LNG carriers on a regularly basis. The LNG is unloaded by means of LNG pumps on board of the carrier. LNG is pumped to a loading arm at the Jetty station and further to the LNG storage tank through an insulated pipe. The normal loading of the LNG ship loading pump is 1000 m³/h. Only one of two pumps is in operation, the other is in stand-by.

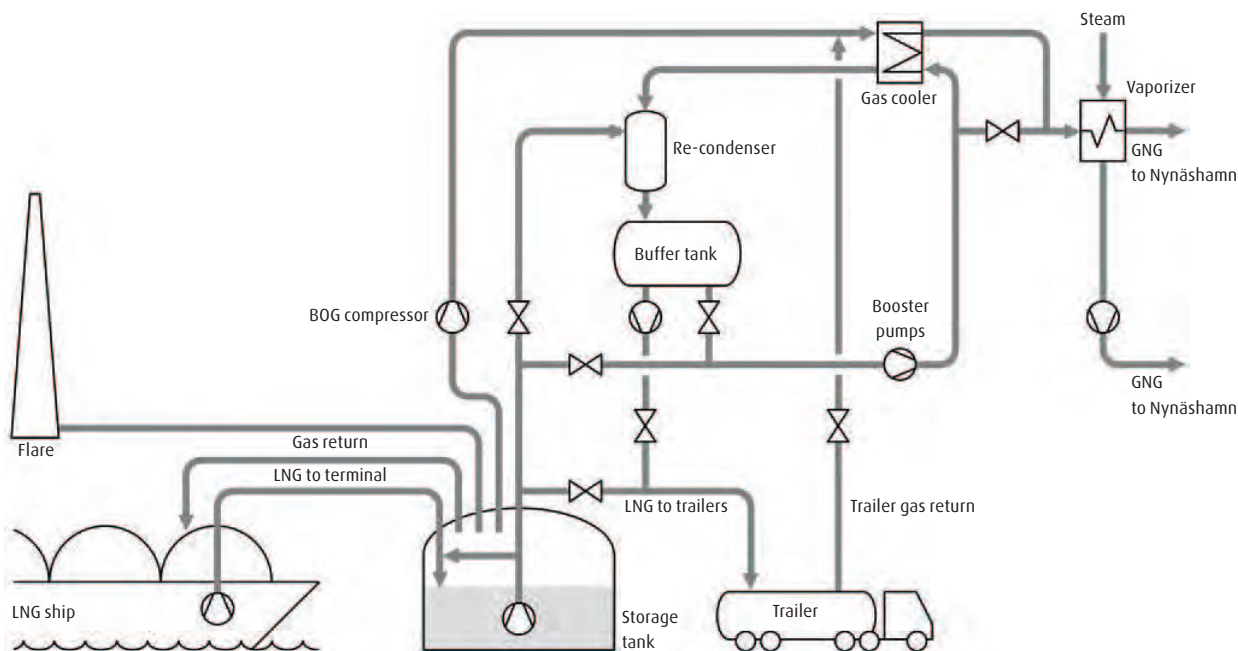
From the LNG storage tank vapor is routed back to the carrier via another insulated pipe and a separate loading (gas return) arm. The vapor return line relieves displacement gas in the storage tank caused by the "piston effect" from the raising liquid level. The vapor is transferred to the carrier where it counteracts the (vacuum) "piston" effect from the sinking liquid level.

LNG storage tank

The LNG Storage Tank at the Terminal has a working capacity of 20,000 m³ and is a "full containment tank" with operating pressures slightly above atmospheric pressure. Two LNG pumps are submerged in the liquid. LNG is pumped either to the re-condenser, to LNG trailers and/or to the booster pumps for refinery gas supply. Internal pump recirculation and continuous cooling of external piping are also important tasks for the LNG pumps.

On top of the LNG storage capacity, the storage tank, by its vapor space, also accommodates a great gas buffering capacity. This gas buffering capacity is used to collect and even out pressure swings in the entire "uncompressed" gas volume of the terminal. This includes discharge gas from safety, and thermal relief valves. All such gas sources are connected to the storage tank vapor space via a main blow-off line.

Fig. 4: Process overview of the LNG receiving terminal in Nynäshamn/Sweden





Truck unloading at LNG satellite station

Trailer loading station

During loading of LNG trucks the normal loading rate per pump is $65 \text{ m}^3/\text{h}$. Both LNG truck loading pumps can be used simultaneously. The expected total time for filling a trailer is close to one hour, including time for connection and disconnection. The actual filling time is 45 min. At simultaneous filling of two trailers, the total LNG flow rate is $150 \text{ m}^3/\text{h}$. Thus, with the two filling stations operating in parallel, theoretically some fifty trailers could be filled every 24 hours.

Boil-off gas system

Two boil-off compressors, each with 100 % capacity, are installed at the terminal. The main task is to evacuate excessive boil-off and displacement gases in order to keep the pressure in the storage tank within acceptable limits. The compressed gases are diverted to the re-condenser.

Re-condenser and LNG buffer tank

In order to enhance the flexibility of the terminal output, a recondenser with buffer tank is installed. The recondenser converts the compressed boil-off gas to LNG. The LNG is delivered to the refinery gas system or to trailers. The buffer tank increases the amount of converted BOG since LNG can be stored at occasions with low consumption, e.g. between trailer filling when the refinery is down.

Refinery gas system

The refinery gas system pressurizes and vaporizes LNG. The gas is delivered to the adjacent Nynäs refinery at the required pressure and temperature, also leaving a control margin to the refinery process. In order to maximize the BOG condensation, the LNG is taken from the buffer tank whenever LNG is available. If not, LNG is taken directly from the storage tank.

Pressurization is done by means of booster pumps located under the buffer tank. Vaporization and heating to acceptable temperature is carried out by means of steam heated “water bath” vaporizers. From the vaporizers, the gasified natural gas (GNG) is routed further to the refinery.

Production process

In order to avoid operational interruptions, systems and components are redundant as far as reasonable. Basically all critical equipment has $2 \times 100\%$ capacity. In some cases the 100% load does however not include special, seldom occurring combinations of operation. There are also two trailer fill stations, however not primarily as a backup measure. Critical instruments have a “2/3” arrangement, meaning that the instrument has three sensors and one of these may fail without causing an instrument failure.

LNG ship loading arm installed on the jetty of the Stavanger LNG plant



Plant overall operational philosophy

The terminal is designed for unmanned operation. Control and supervision may well be performed from a remote control room. Alarms will be transferred to operators on duty, directly via SMS or from the remote control room. All safety functions will be controlled by the PLC at the terminal. The functions in the remote control room will also be available at the local control room in the service building.

The trailer filling process will be operated by the truck driver. The trailer filling procedure has automatic functions for fast and reliable service. At ship unloading, the jetty has to be attended by at least two operators. The operator will be in contact with the ship and the remote control room during the whole unloading process. Before unloading from the ship, the operator will have to inspect the equipment involved in the operation lines, valves and instruments.

Environmental aspects have been considered when designing the terminal including design of process control. Emissions of NG to the environment are almost totally eliminated and emissions of combustion gases (flaring) will only take place at rare occasions and only as a measure to avoid release of unburned combustible gas.

Terminal layout and safety considerations

The terminal will be divided into four separate areas; jetty area, tank area, process area and tank filling area. This layout, based on the condition of the surroundings, provides increased security since a potentially hazardous event in one of the areas is not likely to affect the other areas.

All steel structures, piping systems and other metal parts and equipment are connected to a common equipotential bounding system. A zone classification will prevent the existence of ignition sources at the terminal.

Additional precautions during ship unloading

If any problems occur during ship unloading, pumping will cease immediately and valves to isolate the transfer pipeline will close in a predetermined sequence. This sequence follows recommendations by SIGTTO, Society of International Gas Tanker and Terminal Operation. It is controlled by equipment on the tanker and on shore. The emergency shut down, ESD, procedure can be initiated either from the ship or from the shore.

LNG truck loading station of the Stavanger LNG plant



Closing remarks.

Small and mid-scale LNG technology will enable industrial users, such as refineries and power plants, in stranded markets to switch to cost efficient and environmental friendly gas. The demand for natural gas in Norway and Sweden is projected to increase in the near future. The Stavanger LNG plant in connection with the Nynäshamn LNG receiving terminal will open a new era in meeting the increasing demand in this area.

With the introduction of such LNG plants, combined with the respective transport and regasification infrastructure, natural gas markets can be dynamically developed. It is evident that natural gas, as a cleaner fuel, will play an increasingly important role in the primary energy mix.

With the LNG from Stavanger plant, a high degree of flexibility in the energy supply will be made available to the benefit of all natural gas consumers with fluctuating or peak demand profiles.

The Stavanger LNG plant provides a means to commercialize indigenous natural gas resources. This, in return, supports the local economy and provides additional labor.

Furthermore the Stavanger LNG plant provides a "rubber tire pipeline" to small natural gas consumers in Norway and Sweden. The transport of LNG via tanker trucks makes the distribution of natural gas to intermediate-sized consumers also possible.

Some of the target regions are not connected to major gas pipelines, since the initial gas consumption rate would not justify such a large investment. Therefore, the LNG supply will initiate the penetration of these regional markets with environmentally friendly fuel.

Mid-scale LNG plants are an economically interesting alternative to world-scale LNG plants. While export schemes appear to require plant capacities above 500.000 tpa, merchant LNG schemes appear economically attractive already at smaller capacities. Mid-scale LNG plants, by virtue of their moderate size and complexity, have the potential to be located in industrialized areas which allows investment in infrastructure to be kept at reasonable levels. Capital requirements and execution risks are significantly lower than in world-scale LNG projects. Moderate size and complexity allows companies lacking the resources of an international oil & gas major to develop and even fully control an LNG project while enjoying an equal amount of off-take, level of safety, quality, reliability and a comparable efficiency as in a minority shareholding of a world-scale LNG project. Moreover, mid-scale LNG offers a unique opportunity to monetize local or regional gas surpluses of moderate size in a fast track fashion.

With the introduction of such small to mid-scale LNG plant types combined with the respective transport infrastructure, natural gas markets can be dynamically introduced and developed.

Designing processes – constructing plants.

Linde's Engineering Division continuously develops extensive process engineering know-how in the planning, project management and construction of turnkey industrial plants.

The range of products comprises:

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