KEYWORDS: FLNG, operations, modularization, technology qualification, technology development

ABSTRACT

The Hammerfest LNG plant (Snohvit) has pioneered some of the recent trends of technology and environmental standards for the LNG industry, including full subsea production systems and multiphase transport, injection of CO₂ captured from the feed gas, electrical compressor drivers, use of high-efficiency aero derivative gas turbines, and a full MR process. Extensive prefabrication and modularization was used for the onshore plant, in order to meet the challenges of a remote location and relatively harsh climate. The plant was started in 2007, and after a run-in period with some modifications and adjustments, the plant is now operating well at its design nameplate capacity. Recent performance testing has confirmed the position as the world's most energy efficient LNG plant, with a liquefaction process efficiency of 243 kWh per ton LNG. The high efficiency contributes to a fuel use of less than 5% of the feed on a calorific basis. One of the important successes in operation has been the dramatic reduction in warm restart flaring, thanks to improved procedures and the combination of skills and experience from operation of cryogenic exchangers and feed pipeline. This innovative start-up method is now considered for floating LNG installations, where adaptation of the technology also may avoid shut-down of the process in case of delayed offloading. Experience gained from construction and operation of Hammerfest LNG has prepared Statoil for the demanding realities of new onshore and offshore LNG projects, where strict environmental requirements, remote locations and prefabricated and modularized construction generally set the scene. Further details will be provided in the paper.

INTRODUCTION AND BACKGROUND

The Snøhvit integrated field development and the Hammerfest LNG plant has pioneered some of the recent trends of technology and environmental standards for the gas industry, including full subsea production systems and long-distance multiphase feed transport, injection of CO₂ captured from the feed gas, electrical drivers for the refrigerant compressors, use of high-efficiency aero derivative gas turbines and a full Mixed Refrigerant process. The project represents an important reference for plant construction and operation in near-arctic conditions, where harsh weather conditions, winter darkness and remoteness give special requirements. Extensive prefabrication and modularization was used for the onshore plant, in order to meet the challenges of a remote location. The use of a pre-fabricated process barge concept represents a predecessor to Floating LNG which is a promising concept for offshore gas developments in several areas of the world.

Hammerfest LNG was started in 2007, and after a run-in period with some modifications and adjustments, the plant has demonstrated operation at the design nameplate capacity. Performance testing has confirmed its position as the world's most energy efficient LNG plant, with a liquefaction process efficiency of 243 kWh per ton LNG. The high efficiency contributes to a fuel use of less than 5% of the feed on a calorific basis. After the initial run-in period, modifications were done on the LNG process facilities to increase the
robustness, as reported to the LNG16 conference in 2010 [1]. Currently, work is in progress to debottleneck the gas treatment part of the plant where insufficient performance of key processing units has prevented operation at the expected regularity.

Experience gained from construction and operation of Hammerfest LNG and the full gas value chain operations have prepared Statoil for the demanding realities of new onshore and offshore gas and LNG projects, where strict environmental requirements, remote and/or harsh locations and pre-fabricated and modularized construction often set the scene. Statoil is pursuing several opportunities for LNG and gas developments worldwide, also focusing on frontier areas such as the arctic and the use of floating LNG (FLNG) to unlock offshore gas resources. The following sections provide insight into some of the technologies that may form the basis for complex onshore and offshore gas and LNG projects, with special emphasis on the Snøhvit development and current activities to support FLNG realization.

Key elements of the Hammerfest plant development, construction and operation are outlined, leading up to the present focus on new frontier LNG projects and the implementation of new technology and innovations in floating LNG installations. Important innovations, technology developments and qualification initiatives that address the challenges of offshore production of LNG are presented, and conclusions are drawn regarding the future possibilities of frontier LNG developments.

SNØHVIT DEVELOPMENT AND CONSTRUCTION – REALIZING A FRONTIER LNG PROJECT

In view of the remote and arctic location (71 degrees north) with limited regional infrastructure and resources, a construction policy of maximum prefabrication was adopted for the Hammerfest LNG plant facilities. In particular it was decided that most of the process equipment and power and heat generation facilities would be assembled on a barge that would be installed in a specially prepared dry dock at Melkøya – the island close to Hammerfest where the onshore facilities are located.

All major modules were built at sites in Europe, including the process plant at a yard in Spain. Prefabricated units also included process and utility modules, the finger-type slug-catcher, MEG regeneration units, pipe racks and electricity substations. Most of the modules were shipped to Melkøya during 2005. Key deliveries were a shipment containing two MEG reclamation units and three electricity substations that arrived in February 2005, the cold-box assembly that arrived the following May, and the process barge, which arrived on a heavy-lift vessel after an 11-day journey in July 2005, Figure 1. The slug-catcher was prefabricated and transported to the island in two modules of more than 4,000 tonnes each.

Figure 1 - Barge with prefabricated LNG process facilities and power/heat generation system upon arrival at Melkøya. Left: Barge on heavy lift vessel near Melkøya. Right: Barge being floated in.
The total weight of the process barge, which measures 154 x 54 m and supports equipment structures up to 50 m tall, is 35,000 tonnes (topsides 25,000 tonnes, base 10,000 tonnes). On arrival at Melkøya, it was floated off the heavy-lift vessel and, after a couple of days' wait for suitable weather, winched into the dock. Water was drained from the dock and the barge concreted into place. The cold box assembly, which stands 60 m tall and weighs 2600 tonnes, is located alongside the barge.

The Hammerfest plant is based on a very compact layout and especially the process barge is built like a large offshore module. Thus, the Hammerfest plant and especially the process barge is a precursor to floating LNG, with many features of design, construction and operation that resembles the situation on the topside of a FLNG unit.

Costing roughly USD 8 billion, the full Snøhvit field development offshore and onshore ranks as the largest industrial project ever in northern Norway. It has contributed to substantial value creation and expertise development at local level. About 60% or the contracts for the Snøhvit project were placed with Norway’s supplier industry, a higher share than originally expected.

A possible capacity expansion by a second LNG train in Hammerfest was considered until fall 2012. Thorough studies and a good technical fundament for entering a FEED phase were prepared, but it was decided to stop the work when the license partners Statoil, Petoro, Total, GDF Suez and RWE DEA concluded that the current gas discoveries did not provide a sufficiently robust basis for further capacity expansion.

A NEW FRONTIER: FLOATING LNG

Over the last decades Statoil has accumulated experience as an operator of most types of floating production systems and has been a very active partner in several world-class deep-water floating production system developments. The company currently operates 14 floating installations. Five installations are ship based, three are Floating Production Storage and Offloading (FPSO) units and two are Floating Storage and Offloading (FSO) units. The remaining installations are tension leg platforms or semi-submersibles.

Since the mid-1980s Statoil has considered several FLNG designs with varying design parameters, including steel and concrete hulls, spread mooring and turret mooring, “at-shore” locations, and a range of production capacities and feed gas characteristics. Several LNG containment principles as well as tandem and side-by-side offloading solutions have been part of the concept studies. Figure 2 gives an overview of the FLNG concept development history, showing the range of concepts and capacities.
The remoteness of the Snøhvit gas field, which was discovered already in the eighties, triggered the idea of offshore LNG production on a floating unit. Early studies involved a 3 Mtpa FLNG unit based on a 350 m long floater with spherical (Moss type) storage tanks. In order to capture economy of scale effects, the liquefaction capacity was increased in later FLNG designs. Considerable work on a capacity range of around 6 Mtpa was done in relation to the MoU studies for NnwaDoro offshore Nigeria in 2002-2003, and later further optimized in a technology alliance with Aker and Linde. Such designs were considered technically feasible, but later developments indicated that larger designs (6-8 Mtpa) had higher execution risks. Smaller designs (1-2 Mtpa) did not yield attractive profitability.

Consequently, we have recently developed and matured a FLNG design with 3-4 Mtpa production capacity to a pre-FEED level, Figure 3. This concept gives a good balance between profitability and execution risk. The concept is based on a DMR liquefaction process with four mechanical drivers, side by side LNG offloading (benign conditions), and external turret. Length of the hull is 425 m. The concept has been developed together with a major engineering contractor and an active supplier group.
Technical challenges of tilt and movement of vital process equipment, offshore adaptation of cryogenic systems and evaluation of offloading solutions for FLNG have been thoroughly addressed by technology qualification programs that are supported by modeling/simulation, laboratory experiments, and operational experience.

Many aspects of the experience from Hammerfest LNG plant design, construction and operation is of relevance for Statoil FLNG development. These factors include:

- Process facilities built on a barge, with compact “offshore” layout
- Use of aero-derivative gas turbines (LM6000) which also can be a good option for FLNG installations, either for electric drive, but also for direct mechanical drive.
- Sea water cooling of LNG process facilities
- A mixed refrigerant (MR) liquefaction process, with MR pre-cooling which would be the case also for FLNG facilities based on a DMR type of process
- Direct feed of feed gas to plant from subsea wells, with no offshore processing
- Use of plate-fin heat exchangers in cryogenic service for base load LNG and MR service

HSE is essential for selection and development of topside layout and modularization, as well as for the process design and the flare and blow down systems. Extensive Quantitative Risk Assessments have been completed for the shown concept, and Approval in Principle has been issued by ABS (American Bureau of Shipping).

Process efficiency is important related to economics as well as greenhouse gas emissions. The type of liquefaction process, the power and heat production system and the process cooling temperature are all important elements. In this respect Statoil is developing systems for deep, low temperature sea water intake for increased process capacity and efficiency, see the below text. To further minimize the environmental impact, systems for reinjection of CO₂ removed from the feed gas can also be implemented. Offshore reinjection of CO₂ removed from feed gas has been in use at the Statoil operated Snøhvit and Sleipner fields for many years, giving a good experience basis for design and operation of such systems.

Offshore offloading of oil and condensate has been a success story on the Norwegian continental shelf (NCS) over many years. Statoil has experience from several offloading methods such as tandem, side-by-side and submerged turret offloading. Offshore offloading of oil and condensate is currently used on eight fields on the NCS. To date, Statoil has successfully performed around 15 000 offloading operations. Over time, both technology and operations have been developed to ensure safe offloading in harsh conditions. Here the use of dynamic positioning (DP2) systems is essential. Building on this experience is important when moving into FLNG, where offloading safety and regularity are critical parameters.

Based on these long term developments and the broad experience in LNG and related marine and process technologies, Statoil is now ready to realize floating LNG.

**LNG/FLNG TECHNOLOGY DEVELOPMENT AND INNOVATION**

The following sections provide an overview of technology development and innovations that support and enable Statoil LNG and FLNG realization. Examples relate both to operational aspects and design aspects of LNG and FLNG installations.

**Snøhvit Optimizer** - A software tool for operational optimization of the Mixed Fluid Cascade (MFC) liquefaction system at Hammerfest LNG has been developed and is currently being implemented in the plant. The MFC process is based on three mixed refrigerant (MR) circuits where MR composition and several operational parameters can be optimized within given constraints, either to maximize LNG
production for given power input, or to minimize power use at given LNG production. The optimizer has been installed and is currently undergoing pilot testing in the plant. It is estimated that optimized process operation will gain 1-2% increased production capacity.

The basic version has a spreadsheet user interface which is linked to a detailed process model that is used for both reconciling of plant data and process optimization. An online version with a web-based interface using the existing Statoil Model Predictive Control (MPC) platform is also developed. The liquefaction process model and optimizer scheme has been developed in close cooperation with the research foundation SINTEF.

A snapshot of the user interface of the main spreadsheet is shown in Figure 4.

**Figure 4 – Snøhvit Optimizer (SNOP) user interface showing liquefaction system and menu for plant data import, reconciliation, and optimization of operational parameters**

The optimization is based on reconciled, operational data. The main optimization parameters are refrigerant compositions, refrigerant pressure levels and split temperatures between the natural gas process heat exchangers. The parameter ranges for the optimizer are restricted by given physical and operational limits and requirements.

**Use of vaporized/heated LNG for start-up with minimum flaring** - At the Hammerfest plant a new concept for cool-down of the cryogenic equipment prior to start-up has been implemented. The cryogenic heat exchangers and associated equipment in the liquefaction system are cooled down by circulation of refrigerant in the three refrigeration cycles. This is initially done using the three refrigerant compressors and only gas phase refrigerant. To be able to control the cooldown rate, and avoid too large temperature gradients, a small flow (5-10 t/h) of evaporated LNG is sent through the natural gas/LNG path of the system. Clean natural gas for this stream is produced by a stream of LNG from the storage tanks. The LNG is pumped to 80 – 90 bar(g) and then heated supercritically before it is used as heat sink in the cooldown process of the equipment. By this method, the natural gas system is close to normal operating temperature.
when feed gas is introduced into the plant. Also, liquid refrigerant and liquefied natural gas is accumulated on the tube side of the heat exchangers and in associated piping.

The initial reason for changing the start-up procedure was to reduce flaring during cooldown of the plant. Figure 5 shows the CO₂ emissions for six warm start-ups between January 2008 and June 2009. As can be seen, the plant can now be started up with CO₂ emissions of around 1 000 tons, compared to more than 10 000 tonnes using traditional cool down by feed gas expansion. Flaring time, from feed gas is opened from the pipeline to start of LNG production, is now limited to 1-2 hours compared to more than 20 hours with the original procedure.

In addition to the reduction in flaring, the concept of cooldown prior to start-up enables a shorter start-up time after a plant overhaul. The cooldown of the cryogenic equipment can be done in parallel to commissioning of the upstream systems, e.g. regeneration of the drier station.

![Figure 5 - CO₂-emissions from flaring for six warm start-ups of Hammerfest LNG plant.](image)

Flaring from introduction of feed gas from pipeline until LNG production is stabilized at 30%.

A further development of the concept of recirculating LNG from the LNG storage tanks has been evaluated to allow operation of the cryogenic part of a plant at minimum turn down capacity in full recycle mode. This would be attractive for FLNG installations in areas where harsh weather conditions are reducing offloading regularity. However, there will be some significant technical challenges that have to be studied in detail for each specific application, e.g. high heat demand for heating/vaporizing LNG and change of operating conditions for key equipment in the cryogenic system (scrub column and main cryogenic heat exchangers).

Technology qualification and safeguarding of FLNG acid gas removal - One of the critical technical uncertainties for the floating LNG process facilities is the influence of movement, acceleration and static tilt on the performance of the acid gas absorber. Even though amine-based acid gas removal is a well proven technology for onshore LNG, offshore conditions may give bypass of untreated or insufficiently treated feed gas due to movement or tilt of the absorber. The bypass risk is primarily related to the flow patterns of liquid and gas, and the movement of the solvent liquid in the absorber. Even a small bypass may have a major impact of liquefaction system operation due to risk of freeze out and blockage of heat exchangers at cryogenic temperature. In practice, a situation with off-spec feed gas (e.g. above 50-100 ppm CO₂) will require process shut down and resulting production losses which can become significant.
Statoil has conducted extensive studies on FLNG acid gas removal systems to understand the fundamental mechanisms and risk factors, and to build confidence in the performance and functionality of the systems at offshore conditions. The technology qualification work is carried out in close cooperation with major technology providers for acid gas removal systems and column internals.

One way of reducing the risk is to install a safeguarding solution that prevents off-spec gas from entering the cryogenic heat exchangers. Here, several possibilities can be foreseen, but one promising solution is based on installation of an additional contactor between feed gas and lean amine downstream the absorber column, Figure 6. Typically, such a compact contactor can be based on a mixer that is insensitive to motion plus a compact separator. If needed, two stages of mixing can be installed.

The technology elements are well known, and there is experience from use of similar arrangements both for TEG drying of gas [2] and for H₂S removal [3]. This system can work in addition to the conventional absorber, or can be bypassed if not needed. In addition to reducing the risk, the concept can mitigate a costly over circulation of absorbent, which is usually the base design for FLNG. Typically, much less than 10% of the total amine circulation rate would be routed to the concurrent contactor. It is estimated that the solution can provide safeguarding up to concentrations of 600-700 ppm CO₂ in the outlet of the main absorber.

![Figure 6 - Safeguarding solution for FLNG acid gas removal by use of additional contactor](image)

This concept is now being experimentally verified in the Statoil labs as part of a technology qualification program. Important objectives will be to verify the approach to equilibrium for low CO₂-concentrations, clarify the effect of lean loading, and explore favorable combinations of temperature, gas to liquid ratio and activator concentration.

**Deep sea water intake and riser system for FLNG** - The floating LNG facility requires a large amount of cooling water, and a sea water intake system based on large diameter risers must be designed and installed. Cold seawater taken from a depth provides significant increase in process efficiency and capacity compared with taking the cooling water at a higher temperature near the sea surface. In many cases a temperature reduction of 15-20°C can be achieved by taking in deep sea water, and this typically corresponds to 15-20% higher production capacity based on improved liquefaction process efficiency. In addition, there are opportunities for air intake cooling to gas turbines that may further increase capacity.
Different sea water intake concepts are being considered:

- Free hanging riser bundle system located at the aft part of the vessel, Figure 7. The interface between the risers and the vessel may either be of the external caisson concept or be based on the simpler sea chest concept.
- Turret water intake system where the water intake is integrated into the turret design. This solution was extensively studied for the NnwaDoro FLNG concept.

Statoil is currently working with technology qualification activities covering a target water intake depth ranging from 400-1000 m.

Several aspects of the intake system are addressed in on-going R&D activities. The most important are:

- Global performance of the riser bundle in a sea current. Main focus is riser interference issues and loads at riser hang-off assembly.
- Hydraulic performance in terms of flow rate and pressure loss.
- Riser bundle concept. Design of a reliable pipe with sufficient ultimate load bearing capacity and lifetime durability.
- Design criteria for the riser bundle concept.
- Installation and maintenance philosophy.

**Figure 7 - Principles of a free hanging seawater riser bundle system located in the aft part of FLNG vessel**

**LNG offloading system developments** – Another key technical challenge for FLNG is LNG offloading in open sea conditions. Statoil has long experience from oil offloading operations in the North Sea and has proposed and patented a tandem system for LNG transfer [4]. This system was licensed to Framo Engineering in 2003 and has since then been further developed, now known as the OCT (Offshore Cryogenic Transfer) system, and qualified according to EN1474-3. A main advantage of the OCT system is that it is capable of maintaining a separation distance between the FLNG and the LNG carrier of up to 125 m.

The main component in the system is the flexible pipe. For the OCT system a vacuum insulated corrugated pipe-in-pipe from Nexans has been selected. Through a Joint Industry Project (2007-2011) the 16 inch CryoDyn500™ pipe has been qualified according to EN1474-2. The bending fatigue test was extended compared with the EN standard requirement to reflect five years of operation. A total of more than 1 million
cycles under cryogenic conditions were performed. An illustration of the OCT system and the Nexans CryoDyn500™ pipe is shown in Figure 8.

Figure 8 - Framo OCT system (Patented by Statoil) and Nexans CryoDyn500™ flexible pipe (Illustration courtesy of Framo Engineering and Nexans)

In 2012 several additional tests, not required by the EN 1474-2 standard, were performed. The main test was to investigate possible flow induced vibrations during high velocity vapor return flow. A full scale test was performed at NMI Euroloop in Rotterdam under the management of the TNO research organization in the Netherlands. In the test, natural gas at velocities of above 30 m/s was tested. The measured vibration levels were acceptable. To investigate the effect of loss of vacuum, a full diameter complete pipe was filled with liquid nitrogen and cooled to -196°C before the vacuum was broken and the temperature development in the armoring layers was measured with acceptable results.

The CryoDyn500™ pipe has through the extensive testing proven to be a very robust and safe pipe with very good insulation properties and double containment function by the pipe-in-pipe solution. This pipe also has the advantage that it is produced in complete lengths without axial joints.

For side-by-side offloading Statoil has together with an offshore equipment supplier proposed a system based on 16” flexible multi composite hoses. In September 2012 a co-operation agreement was signed to further develop and qualify this solution. The intention of the system is to increase the operational envelope of side-by-side offloading, and to lower the weight and space requirements of the side-by-side offloading system. The system is currently in a patenting process.

Tilt and movement of spiral wound heat exchanger (SWHE) - A floating LNG plant will be exposed to tilt and motions that may affect the thermal and hydraulic performance of the cryogenic heat exchangers. The motions will also give additional mechanical forces on the exchangers and their foundations. These aspects were thoroughly investigated in a qualification project in co-operation with Linde in the period of 2003-2007 [5]. The project covered the following main activities;

- Fluid flow test
- Heat transfer test
- Numerical modeling
- Mechanical testing
Two test facilities were erected, one small scale test plant to study adiabatic fluid flow behavior and one semi industrial sized plant to study thermal, hydraulic and mechanical performance.

The main testing was performed by a 5 m tall heat exchanger placed on a movable platform, simulating tilt and oscillations representing North Sea conditions. The shell-side test fluids were evaporating hydrocarbon mixtures.

In Figure 9 the main test facility and an example of measured shell-side temperatures are shown.

Through the test program knowledge and competence to adapt and modify SWHE design to FLNG requirements has been established. Design rules for SWHE in moving and tilted environment have been gained from the experiments and theoretical studies. Ownership of technology developed in the Technology Alliance between Linde and Statoil was transferred to Linde when the Alliance expired in 2007, but Statoil has retained a right to use the generic knowledge on cryogenic heat exchanger behavior under offshore conditions.

SUMMARY AND CONCLUSION

The development and implementation of technology for gas production, processing, liquefaction and transport, plus extensive operational experience from offshore and onshore production facilities, has prepared Statoil for today’s demanding challenges of complex gas field developments. Here, the Snøhvit field development and the Hammerfest LNG plant are key references, including full subsea production systems, long-distance multiphase transport, onshore LNG facilities with compact and prefabricated design, and operations in a harsh environment.

Experience from Snøhvit is of great importance for new projects, especially for frontier developments such as arctic projects or floating LNG production. A large share of the world’s remaining petroleum reserves is located in cold Arctic regions where people, the environment, transport vessels and installations are all more vulnerable. Statoil is one of the petroleum industry’s pioneers when it comes to offshore production in these areas.

In many areas of the world Floating LNG is a commercially attractive solution for development of offshore gas reserves, and Statoil is building on experience from the current offshore and LNG operations to realize FLNG. The FLNG technology is ready, although not fully proven since no units are in operation yet.
The paper has outlined some of the key elements of the Hammerfest plant development, construction and operation, leading up to the present focus on new frontier LNG projects and the implementation of new technology and innovations in future FLNG installations for Statoil. Important innovations, technology developments and qualification initiatives that address the challenges of offshore production of LNG have been presented.

REFERENCES


