NEWWAVE: A COMPETITIVE LARGE CAPACITY FLNG AVAILABLE IN THE SHORT TERM

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The authors as designers and builders of the first open-sea FLNG's have jointly developed NewWave™ FLNG. The result of several years of collaborative work, it brings substantial cost and schedule savings through:

- LNG output from a referenced hull is increased to above 7 Mtpa. The intensified cold section generates more revenue per unit of platform deck area while the reduction in MR inventory improves safety.
- Hull, mega-modular topsides and equipment subassemblies are built in locations selected to allow the best use of available skills. Finalised rotating equipment sub-assemblies can be string tested at the manufacturers premises without post-test disassembly, reducing schedule. Pre-commissioning of complete modules on the quayside greatly reduces costly on-deck hook-up and commissioning.
- Interfaces between hull and topsides are reduced, for example through new strategies for process cooling.
- All in all there is a reduction of project complexity and an improvement in project certainty.

This successful development has been achieved through careful definition of roles. Each was able to contribute its ideas and technology:

- Air Products developed an intensified version of its AP-DMR™ LNG Process using proven large coil wound heat exchangers with a reduced equipment count.
- BGHE contributed its new LM9000 gas turbine as well as developments in compressors.
- TechnipFMC added offshore project, process, structural and other engineering know-how. It developed the overall concept including non-cryogenic systems and LNG offloading.

The paper demonstrates that NewWave™ FLNG can be an attractive alternative to onshore liquefaction of offshore gas reserves showing much improved economics based on a preliminary technical-economic evaluation.
FLNG is in for a change and according to the authors is able to compete against a traditional onshore facility for the majority of cases where a large gas field is located offshore. This paper will describe the jointly developed NewWave™ FLNG that brings the Free of Board (FOB) price of LNG from FLNG to a point which is potentially competitive with the best onshore terminals while promising auto consumption levels that set new standards for the industry.

A new large capacity FLNG concept called NewWave is presented, integrating the considerable experience gained on the early FLNG projects. The current phase of development is focused on the cold section, essentially the liquefaction process and its reconfiguration for use offshore.

One of the conditions that enabled the first generation of FLNG development was that LNG prices were high, being linked to oil at $100 per barrel. This paid for the prudent technical choices that enabled these early pioneer projects to take FID. Designs were based on minimal modification to onshore LNG topside technologies and well proven FPSO construction practices.

Capacities of the early projects were modest - to keep process and project risks within manageable limits and also because studies at the time showed that large fields were best developed with a traditional onshore terminal even in very challenging locations.

Construction techniques followed oil FPSO practice in which relatively small modules are built in the same location as the hull, and where installation uses the floating cranes available in shipyards.

From 2016 onwards, oil linked LNG prices have been much lower to the point that they are aligned with US onshore LNG as determined from the Henry Hub price for natural gas supply and published tariffs for liquefaction. Hence any new concept must be substantially more productive per unit of CAPEX compared to the early projects.

The LNG industry has evolved by becoming efficient over time through economies of scale and the same can be expected to FLNG.

The authors have all contributed to the design and execution of the three-open sea FLNG projects that define this segment of the industry today – namely Petronas Satu, Shell Prelude and ENI Coral South.

TechnipFMC has developed the concept and acts as programme leader.

Like many suppliers to the oil and gas industry Air Products and BHGE used the quiet period of 2016/7 to invest in new equipment – respectively larger coil wound exchangers from a new facility in Florida and the purpose built LM9000, a large compact aero derivative gas turbine. The possibilities offered by this equipment is fully utilised by NewWave.
Mixed refrigerant processes are compact and efficient with a low equipment count. Air Products in collaboration with TechnipFMC and BHGE has developed an intensified version of its AP-DMR liquefaction process that offers a significant reduction in the number of drums and heat exchangers.

BGHE has contributed its LM9000 and its developments in compressor design that include liquid tolerant metallurgy, aerodynamics for high power density and reduced casings.

A number of principles have been followed in developing the concept:

- The solution must be industrially viable in the near term meaning that it is project ready. Designs are based, by default, on experience with referenced equipment and solutions. The capacity has been held at between 7-8 Mtpa which is within the possibilities of swivel stacks, single train gas pre-treatment and a single berth LNG loading station. When step outs are present it is considered possible to qualify the technology or equipment within the timeframe of a real project.
- As much as possible of the FLNG deck space must be dedicated to revenue generation for liquefaction
- Hook up and commissioning post-installation of the modules on the hull deck must be avoided or even eliminated.
- Collaboration between the parties planned upfront is part of the development as agreements put in place prior of working allowed uninhibited exchange. Each entity keeps its own IP and the rules developed have allowed a revolutionary concept to emerge.

The resultant key features are:

- Production rates of above 7 million tons per annum using a reference hull are available for any new project.
- The cold section of the process has undergone intensification through:
  - the use of a reduced number of large coil wound heat exchangers
  - the new LM9000 gas turbine,
- Development of intensified pre-treatment and utilities continues.
- Reduced space and weight of process cooling media compared to the seawater/recirculating freshwater of all first-generation designs.
- An intensified AP-DMR process designed to increase revenue and improve the return on investment, incidentally eliminates some unnecessary inventory of light hydrocarbon refrigerant.
- Construction of the hull will be performed in a shipyard while topside modules will be built in a yard with all facilities. Interfaces between the topsides and hull must be minimised
- Mega modules containing functional units that can be completed up to and including pre-commissioning prior to installation on the hull.
- Significant reduction of the Specific CAPEX.
- Project delivery schedule reduction.
Air Products

The liquefaction process developed for the NewWave initiative is an intensified AP-DMR process. It employs two mixed refrigerant cycles and two Coil Wound Heat Exchangers (CWHE). The feed is precooled in a two bundle Precooler Heat Exchanger (PHE) by the Warm Mixed Refrigerant (WMR). The WMR is compressed in a two-stages and liquid that is formed in the intercooler is further subcooled in the lower bundle of the PHE. It is then let down in pressure through a valve into the shell side of the PHE to cool the feed circuit, the cold Mixed Refrigerant (MR) circuit and auto-cool the two WMR circuits.

The vapor from the intercooler is further compressed, totally condensed by cooling water and subcooled in both bundles of the PHE. After this stream is let down in pressure through a valve into the shell side of the top bundle of the PHE, it further cools the feed and fully condenses the cold MR. Note that both precooling bundles are in the same stainless-steel pressure vessel.

Since the Cold Mixed Refrigerant (CMR) is completely condensed in the precooling exchanger there is no need for the high-pressure separator that is used in the AP-C3MR process and the standard AP-DMR process. For land-based plants the high-pressure separator improves efficiency However, for FLNG applications, eliminating the hydrocarbon inventory in the separator offers a reduction in the flare system and reduces the required deck space and topside weight. In the development of the NewWave offering, it was found that the efficiency penalty to fully condense the CMR in the PHE and eliminate the high-pressure separator was small. This is due to the use of equal WMR and CMR gas turbine drivers, resulting in a 50:50 WMR to CMR power ratio.

This process is powered by two LM9000 GE aero-derivative gas turbines, one driving WMR compression and one driving CMR compression. A single liquefaction train makes more than 3.8 MTPA LNG. The NewWave vessel will have two intensified AP-DMR liquefaction trains fed by a common pre-treatment train.

Figure 1: Intensified AP-DMR Liquefaction Process.
The PHE and Main Cryogenic Heat Exchanger (MCHE) are both coil wound heat exchangers (CWHE). Air Products’ CWHEs have been in LNG service for over 50 years and have been chosen for four floating LNG projects. They have a small footprint which is a benefit for floating LNG plants. More importantly, these exchangers are robust and able to withstand the large thermal gradients that can occur during start-up, shutdown and upset conditions of an LNG plant.

In order to keep up with projected market forecasts, in 2014 Air Products dedicated a new CWHE fabrication facility located adjacent to a deep water port in Manatee County, Florida, allowing the shipment of larger and heavier CWHEs than previously possible, such as the PHE CWHEs for NewWave. The CWHE bundles are wound on computer controlled winding centers (which are like very large lathes); Port Manatee’s winding centers have been designed to accommodate bundles with larger diameters, lengths, and weights. These new winding centers include advanced controls and reporting systems that allow the collection of data over Wi-Fi for in-process quality assurance, analysis, and future design and manufacturing improvement efforts. The new facility also has higher and heavier overhead crane capacity and larger capacity transporters which are used to move the completed tube bundles from the winding centers and to support them during telescoping (insertion) into the pressure vessel shell sections.

Modularization is an integral part of all FLNG designs. Air Products’ standard CWHE designs for either onshore or offshore LNG facilities already incorporate a high degree of modularization and pre-dressing capability. These CWHEs are typically multi-bundle designs, multiple exchangers in one package, with MR separation, liquid distribution and internal headering all contained within the pressure vessel envelope of the CWHE. Also, every Air Products’ CWHE is designed to be erected fully insulated with platform and pipe support extensions installed. Air Products CWHE is inherently designed for installation into a module. For each FLNG project, Air Products works closely with the topsides contractor to optimize the module and CWHE designs for the selected execution strategy. Air Products has done just that for the NewWave™ FLNG concept. For example, a CWHE can be designed to be self-supporting with piping, ladders and platforms supported by the pressure vessel shell of the CWHE, or a CWHE can be supported by the module structure itself. Alternatively, a sub-module containing the CWHEs, all required piping, insulation and platforms can be fabricated separately and mated with the rest of the mega-module at the fabrication yard.
Introduction

The main refrigeration cycle compressors are the largest single equipment item in terms of direct and indirect cost for an LNG facility. Proper solution greatly contributes to profitability and can lead opportunities for reducing cost associated to space, weight, utility requirements and maintenance. Aeroderivative gas turbine have been used exclusively in offshore application and there is extensive experience installing such machines in modules.

NewWave has addressed the challenge of CAPEX and OPEX and the total cost of ownership by selecting the right driver – in this case, the right turbine.

The LM9000 evolved from the proven power, endurance and uptime of the GE90 jet engine, operating on Boeing 777 aircraft since the GE90’s first flight in November 1995. Today’s GE90 engines maintain a reliability score of 99.98% over 50 million hr of flight, and the LM9000 follows in its performance. Designed specifically to fit the LNG application, the turbine will provide excellent performance under the most extreme conditions, able to withstand the harshest and most hazardous environments on and offshore. The LM9000 is the first gas turbine specifically designed to offer substantial benefits to LNG operators due to a combination of increased availability, power density and record efficiency.

On the compressor side, the technology has been driving a continuous development in the train arrangement. Optimization of casings size, side-stream mixing configuration, new impeller designs specifically developed to be coupled with the LM9000.

The LM9000 is powered by a DLE dual-fuel capability that yields low emissions at 15 ppm vol NOx. The power-to-size ratio of the LM9000 will deliver 67 MW ISO with 43% simple-cycle efficiency in a small package measuring 13.5 x 5 x 4.5 m. The design of the LM9000 utilises free-power turbine architecture with a unit that provides high efficiency, generating enough power to start the refrigerant compressors in a fully pressurised condition, saving time and cost. The free-power turbine enables the unit to operate over wide range of speed settings from 2400 rpm to 3870 rpm with virtually unaffacted power and efficiency, making it one of the most competitive gas turbines on the market. The free-power turbine also allows 50 Hz and 60 Hz power generation without needing a gearbox, which fits the requirements of NewWave.

The companion mini-skid will allow easy removal and swap of either the turbine’s super-core or the entire unit as needed for a quick repair turnaround in 24 hr, with a 50% increase of meantime between maintenance intervals versus current aeroderivative technology – the longest in the industry. The LM9000 consists of a twin spool gas generator, directly derived from the GE90-115B, coupled with a fully aeroderivative free-power turbine.

The combustor is an evolution of the well-proven DLE1.5 (dry low emissions) of the LM2500+G4 and LM6000PF+.
The LM9000 was designed for the purpose of meeting key LNG needs, with maintenance intervals only previously seen on heavy duty technology: 36 000 hr MTBO (meantime between outages) is considered best-in-class for an aeroderivative engine. This feature allows high availability for each 3.8 MTPA liquefaction train avoiding redundant parallel machine to minimise the equipment count and cost.

Standard centrifugal compressors (CC) are designed to process dry gas or gas mixed with a negligible amount of liquid.

Significant liquid content, namely liquid mass fraction (LMF) up to 30%, leads to rapid mechanical deterioration of the CC internals. Field experience has shown significant erosion and corrosion of compressor internals coupled with intense fouling.

Furthermore, even a small liquid ingestion is associated with non-negligible CC performance variations; as machine head and efficiency are both affected together with the machine rotor-dynamics.

However, the compression of gas containing significant amounts of liquid can yield to substantial advantages in size and efficiency as liquid removal stations can be reduced (and eventually eliminated).

Thus, the compression station footprint and cost can be reduced accordingly with relevant impact on the layout and cost. Moreover, the introduction of selected wet tolerant features can yield to increased reliability of machines where wet conditions (or mild wet conditions) are triggered during off-design operations.

Modularisation of compressor and drivers including pre-com and string test in Italy

Modern oil & gas operations must respond to evolving resource compositions and more remote and demanding environments, continually incorporating new technologies to increase efficiency and performance.

BHGE has been systematically evolving the modular approach to turbomachinery design. BHGE modules deliver impressive power and compression capabilities in remarkably compact configurations.

On the Avenza constructed yard are 240.000 sqm dedicated to O&G related modular construction & string testing activities. The site is equipped with a storage area with covered warehouses and load out capacity of 4000 tons.

It is located at 5 km from BHGE’s Massa plant and 0.5 km from the Port of Marina di Carrara. 14 platforms with a single module limit of 24 meters width, 60 meters length, no height limitation and 4000 tons of weight.

Avenza facility includes the technologies and capacity to test the completely assembled LM9000 string at full speed full load equipped with compressors drivers and process auxiliaries’ equipment including coolers. The Test rig maximum capability are fuel gas pressure up to 70 barg and power to 130MW. This is a unique facility worldwide and New Wave can take advantage to reduce development cost and schedule, while guaranteeing quality as the completed definitive compressor sub-assembly can be shipped from the place of manufacturing.
Figure 3: Kashagan gas compression system:
2 full process floating modules; 95x16x25 m and 4000 tons each barge.

Figure 4: Avenza yard
TechnipFMC

Process and facilities design, modularisation and layout

TechnipFMC assumes the role of NewWave project director, and designer of the overall concept. Particular contributions are in the process definition of the topsides, module layout for safety, constructability and installation, the interface with Turret and Mooring System (TMS) and subsea systems including evaluation of subsea processing. Lastly as market leader in LNG loading TechnipFMC brings its high availability LNG loading systems.

Some of the technical contributions are detailed below.

Mega-modularisation

TechnipFMC was the inventor and pioneer of the crane-free floatover installation method for offshore platform topsides\(^{(1)}\). Under the Unideck brand, integrated decks of 18,000 tonnes have been installed in the open sea and decks of 27,000 tonnes mated with hulls in sheltered water. More recently large process models have been successfully completed on a massive scale in high-value Asian module yards for the Koniambo Nickel smelter project and Yamal LNG. Jacking and skidding, including onto a floater are referenced techniques from projects such as Shell Malikai. The above can be combined in a skid-deck method to install the mega-modules on the hull deck.

Each module is designed to be independent of the others as far as possible. This minimises interfaces, and with technical buildings and safety related-systems in the module it eliminates cable pulling after installation on the hull.

These are functional modules: utilities; pre-treatment; and two modules for liquefaction, that allow full pre-commissioning and partial commissioning at grade on the quayside prior to installation. All commissioning activities that can be performed in the mega-module construction Yards, save an incredible time in project execution by reducing required preparation activities offshore, once the FLNG is placed at its final location.

Hook up and integration work post installation on the deck is reduced to a minimum.
Process cooling

One of the main contributors of the numerous interconnections between the hull and the topside modules on a conventional FLNG is the cooling system which is centralized in the hull where a closed freshwater cooling loop is cooled by exchange with once through sea water. The cooling water is then distributed to numerous process coolers which are located in most of the modules. For a liquefaction plant, the cooling duty is very large, and this results in large pipe diameters, crisscrossing the platform resulting in significant weight.

An alternative is to consider air cooling instead, however, a major drawback of traditional AFC’s is the significant loss of liquefaction process efficiency (representing perhaps 10% of LNG production for a given refrigeration compressor power) from the higher condensing temperatures for the WMR cycle in particular.

NewWave combines the advantages of both systems through hybrid cooling:
- Air cooling is used in the pre-treatment and utility modules and for de-superheating the discharge of the main refrigerant and natural gas booster compressors of the liquefaction unit.
- Direct seawater cooling is used for the WMR condenser and other services that directly affect liquefaction efficiency.

Air cooling uses AFC’s mounted directly on the module top deck above the compressor or process equipment. For their advantageous space and weight, Diesta exchangers are used throughout.

To avoid interfaces with the hull, seawater cooling pumps are dedicated to each mega-module and installed on a cantilever overhanging the edge of the platform on the opposite side to LNG loading arms.

Hybrid cooling provides many advantages:
- Minimum interconnection between mega-modules and between the topsides and the hull
- All compressors have their own air cooler to allow them to operate in a full recycle mode without the need for external seawater during testing and commissioning.
- The key process coolers of the liquefaction unit are cooled by seawater to maximize efficiency and consequently the LNG output.

Compact separators

Compact separators have become standard practice on recent FLNG projects. All separators are studied by a design group specialised in state-of-art separation equipment.

Non-cryogenic sections

- Gas reception
  - Novel MEG (Methanol Ethanol Glycol) reclamations technologies or electrically heated subsea production systems to reduce MEG quantities or eliminate MEG altogether
  - Swivel stack replacement with coiled flexible risers and electrical cables
- Pre-treatment
  - Gas processing has been widely used offshore such that compact and low weight solutions pre-existed FLNG. In the spirit of intensification to enable maximum LNG production capacity, a fundamental principle for NewWave FLNG, current offshore practice is being challenged and new processes are being evaluated. Promising technologies with low TRL have been screened and selected technologies are now part of a longer-term development plan. Let's call it FLNG 3.0.
    - Compact amine-based acid gas removal processes and Alternate non-amine CO2 removal processes vs commonly used
    - Compact dehydration
- Living Quarters (LQ) and Personnel On Board (POB) reduction
  - Extension of remote operations
  - Digitalisation of asset management
    - better predict time to trip,
    - single trip maintenance
Codes and standards: construction-oriented design

Designing for safety and safety systems
- Liquid inventory reduction to improve inherent safety
- Flare reduction
- Safety gaps/blast walls/fire protection/ cryogenic spill protection

LNG offloading

The increase of LNG production without a corresponding increase in hull dimensions means a reduction in the number of days of storage capacity and the need for high availability loading systems capable of high transfer rates.

When side-by-side loading is a bottleneck, a number of high availability offloading concepts are available to supplement or replace conventional side-by-side loading arms, including:
- ATOL (Articulated Tandem Offshore Loader),
- HiLoad® LNG PLS (a semi-submersible, dynamically positioned command vessel that facilitates safe connection of LNG transfer lines to unmodified LNG carriers with standard mid-ship manifolds), developed and commercialized by SEVAN SSP a SEMBCORP Marine subsidiary,
- A combination of the two above.

Economic comparison

Cost estimates indicate that the combination of process intensification, mega-modularisation, split construction between topsides, major packages and the hull, project execution timeframe and planning reduction bring savings in terms of specific CAPEX (USD/tpa) of between 30% and 40% compared to first-generation projects.

To this must be added the potential for future reductions through the progressive industrialisation of construction that FLNG offers. Digitalization that is in its infancy in the oil and gas industry can realise its full potential with such concepts.

Compared to an onshore facility it is not possible to generalise. The expectations of governments and populations in terms of opportunities for local construction companies and for employment must be weighed against a better controlled, staggered investment with improved schedule; an asset that will be offshore and out of view of cities and resorts; an industrial facility that will be very easy to decommission.
Conclusion

The uniqueness of NewWave is to have built on the experience from first generation FLNG by collaborative working between three leaders in their respective domains, each contributing know how and developmental technology. It anticipates the increase in the scale of output over time that has characterised the development of onshore liquefaction trains and associated export terminals.

The result is a solution for producing large offshore non-associated gas fields that should be competitive compared to an onshore liquefaction plant virtually anywhere in the world.

It sacrifices nothing in terms of emissions that in fact will be on a par with state-of-the-art plants onshore.

Construction of the vessels and topsides can be performed in a fully resourced industrial environment with the possibility of a stable workforce and construction management team.

- The workforce can be more diverse, including more women, and people who for many reasons are excluded form a remote construction site.
- It is possible to realize the full potential of digitalization, from HSE to material management and logistics to project planning and human resource planning. Prefabrication and construction can evolve towards automation and robotics.
- A greater level of standardization is possible with each project being able to benefit from lessons learnt.

At a time of concern that, faced with high demand, the worldwide shortage of skilled engineering teams and craft labour is delaying projects, large FLNG’s can provide LNG buyers with significant quantities of LNG with a predictable time line and budget by using an independent and less constrained execution model.

NewWave is available for projects now. The authors believe that several features make it an attractive proposition.

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