Driven by growing global natural gas reserves, favourable gas prices and stricter emission regulations LNG is beginning to substitute traditional oil-based fuels in marine or heavy vehicle engines, power generation and process industries.

This emerging “Merchant LNG” market calls for decentralized small-to-mid scale LNG plants and is now growing beyond a niche market, attracting new players.

The idea of StarLNG™ is to standardize and optimize a small-to-mid scale LNG plant based on a wide set of process variations. This “Process Toolbox” is designed to cover about 90% of real-life boundary conditions, with the following major benefits:

- Safety as for World Scale LNG
- Fast-track EPC time schedule
- Reduction of Capex
- Highly efficient process, easy to operate
- Modularized units for pre-treatment, process and main pipe racks
- Toolbox concept with many options

StarLNG™ delivers a generic LNG plant design for a 200 tpd (net liquefaction capacity) base case and many alternatives, with pre-engineered documents including a 3D CAD-model for a fully modularized plant – combining superb safety, reliability, ease of operations and efficiency with competitive prices and shortest execution schedule.

1 StarLNG™ – WHAT IS IT ALL ABOUT?

GAS IS OUR BUSINESS – since 1879: In the air separation industry, Linde standard ASUs (Air Separation Units) have been a success story for more than a century. Considering that LNG as a clean fuel is on the verge of breakthrough in the North American market, LINDE has now translated this standardization idea to Small-Scale LNG:

StarLNG™ is the leading standardized LNG plant concept maximising customer benefit in the capacity range of 60,000 to 1,000,000 gpd by:

Focussing on health, safety and the environment (HSE) to make LNG safe – anywhere, any time

- Pre-engineered process solutions and a modularised design approach to accomplish shortest delivery time with minimum on-site construction
- Applying toolbox approach to ease plant customization while maintaining the benefits of standardization
- Using simple, robust and easy to operate SMR process with highest efficiency, based on Linde’s proven technology
- Offering out of one hand the most competitive solution for all elements along the LNG supply chain for the benefit of our customers
2 LNG – WILL IT FUEL OUR NEAR FUTURE?

Pipelines are the usual way of delivering natural gas in the US, but in some situations this is not feasible or economical. Then, LNG is becoming more and more the preferred way to deliver natural gas, because LNG:

— can be delivered to remote customers by road without the need to construct pipelines
— can be stored conveniently
— may also be used as a fuel in vehicles like e.g. trucks

Driven by a stable trend to low gas prices, supported by the growing number of natural gas reserves brought on-stream in the near future, as well as by stricter emissions regulations, LNG is beginning to substitute traditional oil-based fuels in many areas: marine propulsion, heavy vehicle combustion engines, decentralised power generation, process industry and many more.

Since transportation of LNG over long distances faces economic headwind, due to heat leak-in causing regasification and potentially product losses, the emerging small-scale LNG market calls for smaller, decentralised LNG plants. According to Linde’s experience over the last decade, the plant size demanded by clients for this application ranges typically from approximately 100,000 to 600,000 gpd (0.05 to 0.35 MTPA), whereas today’s world scale LNG plants range around 5 MTPA. Still, the expectation for small scale LNG plants is to be economically competitive with the 100 times larger world scale LNG plants, a challenge that Linde has responded to by launching the StarLNG™ product: a standardized and optimised small-scale LNG plant offering superior capital and low operating cost while maintaining world-class safety standards, scale ability and flexibility for adjustment to specific project conditions.

StarLNG™ has been developed for the typical small-scale capacity range of 60,000 to 900,000 gpd (0.03 to 0.5 MTPA) and its liquefaction technology is based on Linde’s proprietary single mixed refrigerant technology LIMUM using plate-fin heat exchangers (PFHE). Many standard design solutions and features developed can also be applied for larger scale plants using the LIMUM process together with a coil-wound heat exchanger (CWHE), extending the capacity range to up to 2 mmgpd (1 MTPA), as shown in Figure 1.
3 SAFETY FIRST

LNG is not counted in the range of highly hazardous substances handled by the industry, but it is still a flammable hydrocarbon having, that is finally the purpose of gas liquefaction, a very high energy density. For example, the energy content of one 100,000 gal LNG tank equals about 7,500 MMBtu or 8 TJ. Furthermore, catastrophic accidents have happened at LNG facilities in the past, e.g. 1944 Cleveland, OH, USA or 2004, Skikda, Algeria, so safety should be at the top of the list in LNG business.

Lind prioritizes safety, irrespective of their size, our client or the region they are sold to. Our corporate HSE essentials request safety to be our behavior 100% of the time. So “safety first” has also been the mind-set for development of Linde’s standard LNG plant. As a consequence, significant effort has gone into safety design and safety reviews of the process and the plant layout, all of which is now documented in standard documents like:

- Detailed HAZOP Report
- Detailed HAZAN Report
- Hazardous Area Plan
- Fire Fighting Plot Plan
- Fire & Gas Detection Plot Plan
- Quantitative Risk Assessment Report

Within the QRA, sensitivity calculations have been performed to demonstrate the risk to external population caused by different LNG storage tank alternatives, like e.g.:

- Flat bottom tank, single containment
- Flat bottom tank, full containment
- Sphere with secondary impoundment
- Bullets with and without secondary impoundment

This analysis provides an excellent basis to consult our clients about which type of storage they should select for a given Site in view of risk exposure to external population.

4 DOES STANDARDIZATION CONTRADICT FLEXIBILITY?

Standardization is a typical approach in the industry to accommodate clients requesting lower cost, higher quality and shorter delivery time of a previously custom-designed product. So for small-scale LNG plants, it is not a question whether standardization is a requirement, the question is how this can best be done.

When attempting to copy the successful methods for standardization of Linde ASUs, there are two things making ASU standardization a lot easier than LNG:

- ASU “feedgas” (air) is always about the same, much unlike natural gas compositions and pressures being quite dependant on geography and gas source.
- ASU market is very mature, with high order quantities and established design standards, unlike small scale LNG plants which used to be a niche product until recently

So for LNG, there is a very wide range of possible design conditions, no clearly established “sweet spot” requirements and historically limited number of orders.

It was therefore concluded that development of a fixed standard plant was not the right approach, because it would either be designed to deal with all worst case requirements and hence be totally overpriced, or be designed for some arbitrarily selected conditions and hence be unsuitable for all other.

Instead, Linde’s approach was to perform standardization with a toolbox approach, or more explicitly developing a range of standardized solution modules responding to all process requirements typically found for small-scale LNG plants. For a specific application, it is then possible to assemble a plant from these standardized modules such that all project process requirements will exactly be met. The toolbox approach allows to easily customize plants to a wide range of conditions while maintaining standardization benefits.

The following example in combination with Figure 2 illustrates the toolbox idea:

- Ideally, the composition of the feedgas reflects the desired composition of the LNG product such that a straight-through liquefaction can be applied. This is the most simple process and therefore chosen as base case (Liquefaction Unit).
- If a feedgas contains heavier hydrocarbons (HHCs) like Hexane or heavier, freezing will occur during liquefaction unless their concentration has been lowered sufficiently. Preferred solution to remove those HHCs is to add a knock-out drum to the base case, operated at a controlled temperature below the dew point of HHCs (HHC Separator).
- Some lighter hydrocarbons like ethane or propane would be uncritical with regard to freezing, but may still be undesirable to accumulate at higher concentrations in the LNG product e.g. if this is to be used as vehicle fuel. Preferred solution to remove those components is to add a Strip Column to the base case liquefaction process.
- High nitrogen content of a feedgas may require removal for its adverse effect on energy consumption, LNG product heating value or safety concerns at the LNG storage tank (stratification and roll-over). In such case, implementation of a nitrogen rejection column to the base case liquefaction process will be the method of choice (N2-removal Unit).
All these process alternatives can be contained in the liquefaction coldbox and by appropriate selection of the above process modules from the toolbox, a StarLNG™ plant can be designed for most pipeline gas compositions worldwide.

Note: the pipeline gas has been selected as feedstock of choice, because it has already undergone some basic pre-treatment (like e.g. water -removal or hydrocarbon dew-point control) whereas provision of these systems individually for a small scale LNG plant to run on well-gas will normally be economically prohibitive.

5 IS LOWEST INVESTMENT INCONSISTENT WITH LOWEST OPERATIONAL COST?

The StarLNG™ plant configuration comprises all systems typically needed for a small-scale LNG business like pre-treatment, liquefaction, LNG storage and off-loading, utilities and infrastructure.

In the liquefaction section, the core of an LNG plant, the pre-treated gas is pre-cooled, liquefied and subcooled in a plate-fin heat exchanger by a very efficient improved version of Linde’s proven single mixed refrigerant process LIMUM. This closed cycle refrigeration system provides cryogenic temperatures by two staged compression followed by Joule-Thompson expansion and liquid evaporation of the mixed refrigerant. Energy efficiency is similar to competing two-staged MR-processes, approximately 5 to 10% higher than single-staged processes (like e.g. PRICO) and 20 to 30% higher than nitrogen expander plants. Whereas Linde can offer nitrogen expander plants, too, the design of a mixed refrigerant compressor, for the given capacity range, is considered simpler and more robust than large compander machines or split compressors and expanders respectively. The LIMUM process also has a lower equipment count than any competing process of same efficiency, which demonstrates that lowest investment cost can well be made compatible with lowest operating cost.

The refrigerant compressor can either be driven by an electric motor, which is typically the most economic option where adequate power supply from local grid is available, or by a gas turbine. Due to the limited
availability of very small gas turbines, this setup can only be provided for production capacities above 125,000 gpd.

Whereas coil-wound heat exchangers are applied in all large-scale plants, PFHE offer some benefits favouring their use for small-scale LNG plants:

- Very good heat transfer characteristic and therefore higher process efficiency
- Simpler manufacturing process and therefore lower investment cost

One of their downsides is limited acceptable operating pressure (approx. 900 psi), which is typically not an issue for small-scale LNG plants normally working off pipelines with pressures in that range. The maximum achievable capacity of a PFHE plant is approximately 900 gpd due to the maximum PFHE block size, which is limited by the manufacturing facilities and mechanical design as well as practical limits for arranging parallel PFHE blocks.

Based on experience, some Clients select the CWHE not only above but also well below this limit due to the advantages of this type of heat exchanger:

- Very robust design, allowing for quick load changes
- Part load capability down to approx. 30%

Whichever heat exchanger design the clients prefer, Linde can provide impartial, professional consulting since both types are manufactured internally based on own technology. Taking advantage of more than 30 years’ experience in building LNG plants around the world and also recently operating small-scale LNG plants, the StarLNG™ design is not only optimised for low CAPEX but also for simplicity, reliability and robustness in order to guarantee minimum life cycle cost and hence an overall optimum investment for our clients.
6 WHAT LNG STORAGE SOLUTION IS BEST?

Linde Engineering is one of few companies worldwide experienced in building and hence qualified in offering all types of LNG storage tank technologies typically applicable for small-scale LNG plants:

- flat bottom tanks
- spherical tanks
- bullet type tanks

Decision about which storage tank type should be selected will mainly be based on the following requirements:

- storage volume
- storage pressure
- storage safety

It is a common approach in small-scale LNG plants to design the storage volume for 3 to 10 days of plant production in order to provide adequate buffer and flexibility to the downstream supply chain. Depending on the resulting storage volume, the tank types can typically be applied economically in accordance with Figure 4.

In principal, bullets can be arranged in farms of multiple units, removing any capacity limit for this tank type in theory. In practice, economic limits will rule out this technology when larger storage volumes are needed.

Depending on storage pressure, selection may be narrowed down to the following:

- Atmospheric
- Pressurized (typically 30 to 40 psig)

The option for pressurized storage is somehow novel to the LNG business, since storage tank and LNG carrier technology sized for traditional world-scale LNG import / export business gave no other technical option. For small-scale LNG business however, pressurized storage can feature significant savings in CAPEX as well as energy consumption (OPEX), because natural gas liquefies at approximately -272 F (-169C) at ambient pressure, but already at 231 F (146 C) at 35 psig. This saving can only be capitalized on, when also the entire downstream distribution chain up to the end consumer is designed and operated at elevated pressure – a condition that can typically be met by small-scale LNG scheme downstream equipment like LNG road tankers, small-size LNG carriers (IMO-tanks), bullet satellite stations, etc.
With safety in focus, a range of storage tank solutions has been analysed within StarLNG™ not only for economic, but also for safety aspects. Depending on storage tank safety design, the following scenarios could occur in the unlikely event of a catastrophic tank failure:

<table>
<thead>
<tr>
<th>Safety Class</th>
<th>Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low integrity</td>
<td>uncontrolled LNG spill to the environment</td>
</tr>
<tr>
<td></td>
<td>uncontrolled vapour release to environment</td>
</tr>
<tr>
<td>Medium integrity</td>
<td>LNG spill into secondary impoundment,</td>
</tr>
<tr>
<td></td>
<td>uncontrolled vapour release to environment</td>
</tr>
<tr>
<td>High integrity</td>
<td>No LNG spill to the environment, controlled</td>
</tr>
<tr>
<td></td>
<td>vapour release to environment</td>
</tr>
</tbody>
</table>

Now, the higher and less controlled the LNG spill and evaporation to the environment, the higher the hazard of resulting fire or explosion as was seen at the catastrophic Cleveland, OH, accident in 1944, which set the starting point of safe storage tank design considerations.

The safety classification, applied to actual storage tank types, is displayed in Figure 5.
Today, low integrity storage tanks, like e.g. bullets without any external impoundment (note: their outer shell is typically made of carbon steel that will fail from brittle fracture when being exposed to cryogenic liquid issuing from an inner tank leakage) are limited by codes like NFPA 59A or EN1473 for relatively small storage volumes below the typical requirements of small-scale LNG plants only. Medium integrity designs are typically a good compromise between safety and economy in remote areas where no nearby population...
will be exposed to the inherent risk. High integrity solutions are selected when LNG plants are constructed close to populated areas.

7 KEEPING CONSTRUCTION COST AND RISK AT MINIMUM

Linde is a globally renowned EPC contractor with experience in both stick-built and modularized construction strategies:

— “Stick-built” means materials are delivered to site with low degree of prefabrication for installation. This strategy provides minimum transportation cost and issues as well as low overall EPC cost on construction sites with moderate labor cost, good labor qualification/efficiency and favorable ambient conditions.

— In case site conditions are not favorable, modularization is the alternative strategy, reducing on-site construction work by supplying highly prefabricated assemblies. This strategy requires a compromise to be found between maximized prefabrication on one hand and transportation cost/feasibility on the other hand; the larger and more complete the module is built, the lower the on-site hook-up cost, but the higher the transport cost, up to a point where transport becomes impractical. Designing modules for minimum transportation cost as an alternative model (e.g. by choosing a standard container dimensions envelope) will not result in an overall economic optimum either, as this will entail a very significant hook-up cost on site.

Linde Process Plants, Inc. has long experience in executing EPC projects with a modular construction strategy, and typically manufactures the process modules in-house. The advantage of having capability to assume responsibility for the entire EPC scope is that the cost of the total EPC project can be minimized and not just the delivery cost of the modules for which the client gets penalized later during transportation or construction.

Based on the comprehensive construction and modularization experience, a road transportable, generic module concept has been developed for StarLNG™ to serve markets with high on-site construction cost. The StarLNG™ 3D-CAD model provides a typical modularization compromise optimum, targeting minimum hook-up work and moderate crane lifting capacities on site while facilitating road transport, possibly involving escorts or special permits. To facilitate transportation in more restricted conditions, the module concept allows for breaking down one process module into two smaller transport units where needed.

The final decision on optimum construction strategy can only be taken individually for each project under consideration based on the specific site conditions and the available access roads or waterways.

8 SERVING THE ENTIRE LNG VALUE CHAIN

The Linde Group as a whole is committed to provide further value to any small-scale LNG scheme project from the pipeline to the end consumer, e.g. with equipment supply like:
— LNG regasification Units
— LNG Import Terminals
— Integrated LNG/NGL solutions
— LNG/CNG fuel stations and dispensers
— LNG road tankers

The Linde Group also provides further value by owning and operating LNG plants (BOO) with LNG product supply to client, offering e.g.:

— more than a century of experience in producing and distributing liquefied gases
— operating experience with LNG plants and LNG import terminals
— experience with remote-operated (LNG) plants
— experience with marine LNG bunkering
— truck LNG refuelling expertise