Drive your LNG project to success with optimal machinery selections from Air Products of US

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Integration of rotating equipment into the liquefaction process is a key component in the design of a liquefied natural gas (LNG) facility. Decisions on the choice of drivers as well as the arrangement of drivers and compressors in the liquefaction process will impact the plant performance as well as other aspects of the project, such as turndown, efficiency, and maintenance.

Selecting the liquefaction process cycle is another key component. There are many driver options along with a number of possible configurations and liquefaction cycle options. This paper will discuss these options and outline a work process for selecting designs that best achieve the project requirements.

Fundamentals

Various considerations need to be taken into account when designing an LNG plant. Of these, two fundamental ones are the process cycle and machinery selections. Much of the plant performance and process efficiency depend on these two selections.

Once the process cycle is chosen, the machinery selection is the next critical step in natural gas liquefaction process design. This includes choosing the right driver for the process as well as an acceptable machinery configuration.

The refrigerant compressors increase the refrigerant gas pressure while the drivers provide power to the compressors. Multiple compression stages, such as low, medium, and high pressure stages with optional inter-cooling, may be present.

These compressor stages may be present in single or multiple casings. Machinery selection has two components:

- **Driver selection** - Drivers provide

power to the refrigerant compressors. The most common types of drivers are gas turbines (industrial and aero-derivative), steam turbines and electric motors. The driver selection determines how much power is available to drive the compressors.

- **Machinery configuration** - This determines which rotating bodies are on a drive train. At a minimum, there will be a driver and a compressor, but there may be multiple compressors and sometimes an additional starter/helper motor. The machinery configuration determines how the available power is divided among the various compressors.

The liquefaction process cycle directly impacts the process efficiency and determines the required power for the facility. Therefore, the machinery and process selections are intertwined and must be evaluated together.

Optimal machinery and process selections lead to improved plant performance and are critical for successful LNG projects. In this paper, the authors present a methodology for making the right machinery selections in concert with the process selections.

Background

Figure 1 shows a general schematic of a precooled natural gas liquefaction facility. Feed natural gas from the pipeline passes through a pre-treatment system where acid gases, water, and mercury are removed.

The natural gas then enters the Natural Gas Liquids (NGL) rejection unit, where C2+ components are removed. The NGL-rich stream may be sent to a fractionation unit, where individual

components are separated for sale or used as refrigerant make-up in the facility.

The purified natural gas then enters an optional precooling system, where it is cooled to about -30°C to -60°C. It then enters the main exchanger where it is liquefied to produce LNG at a temperature of about -130°C to -150°C.

The LNG is reduced in pressure and passed through an endflash drum before it is sent to storage. Any endflash vapor generated is typically used as fuel gas. NGL extraction may be performed before liquefaction as shown, or may be integrated with liquefaction.

Integrated methodology

There is an increasing number of driver choices along with a number of possible configurations and liquefaction cycle options. Taken together, these options result in a large number of potential choices. Therefore, there is a need to

narrow down the choices to a few options that are worthy of detailed study.

Shown in Figure 2 is a flowchart of the key steps involved in a work process that may be used for quick screening of potential options with the project developers.

Also provided is a description of the work process along with a case study describing a typical effort.

Nominal design capacity

The liquefaction plant owner provides a desired nominal design capacity for the facility. This value is determined based on various factors such as available feed natural gas quantity, LNG demand, LNG export regulations, and financial decisions.

This value is usually measured in million metric tonnes per annum (MTPA) and takes into account the expected plant availability over the year.

Figure 2: Process Machinery Selections Flowchart

Figure 1: Block Diagram of Natural Gas Liquefaction Facility

Liquefaction cycle selection

Various considerations need to be taken into account while selecting the liquefaction cycle. Some of these are nominal design capacity, number of liquefaction trains desired, ambient temperature, plot space availability, and floating versus land-based application.

Key decisions to be made are whether to precool the natural gas and what refrigerants to use. Figure 3 (next page) shows typical capacity ranges of Air Products liquefaction cycles.

The number of liquefaction trains impacts the nominal train capacity desired. For instance, a 3 MTPA LNG facility could require a single train with the Propane Precooled Mixed Refrigerant (AP-C3MR™) process or two parallel trains with the Single Mixed Refrigerant (AP-SMR™) process.

The process cycle determines the process efficiency or refrigeration specific power as well as the number of refrigerant circuits.

Power requirement

Driver selection is directly impacted by the power required for the liquefaction process. Items that determine the required power are the liquefaction cycle, natural gas feed composition, pressure and temperature, ambient temperature and type of cooling medium (water or air).

The plant owner provides information on feed gas conditions and ambient temperature. Refrigeration specific power for the process is estimated based on the selected liquefaction cycle and is corrected for ambient temperature and feed gas conditions.

Refrigeration specific power

Refrigeration specific power measures the thermodynamic efficiency of the precooling and liquefaction processes shown in Figure 1.

It is defined as power required divided by LNG production. In the methodology described here, since the actual power required and production are not known, refrigeration specific power is estimated as follows:

$$ W = \frac{W_{ID}}{E_{BASE} \times f} $$

Where

W = Refrigeration specific power

W_{ID} = Ideal refrigeration specific power from energy balance

E_{BASE} = Base thermodynamic efficiency at standard conditions based on liquefaction cycle selected

f = Cycle specific correction factor for deviation from standard conditions to account for impact of ambient temperature, feed gas conditions and main exchanger outlet temperature

The refrigeration specific power primarily measures the thermodynamic efficiency of the process, with a lower value indicating higher efficiency. Based on the estimated refrigeration specific power, the nominal refrigeration power required for the process is determined as follows:

Where

$$ P_{nominal} = C_{nominal} \times W $$

$P_{nominal}$ = Nominal refrigeration power required

$C_{nominal}$ = Nominal design capacity

W = Refrigeration specific power

Driver selection

There are four main categories of drivers that may be used to drive the refrigerant compressors:

Industrial gas turbines - This is the most common refrigeration compressor turbine driver in the LNG industry. Typical ISO ratings are 30 to 130 MW. These turbines come in discrete sizes; so the train is typically designed to fully utilize the site-rated turbine power for maximum profit. Thermal efficiency is between 29 and 38 percent. The gas turbine power output falls moderately with increasing ambient temperature.

A rough estimate of this power reduction is 0.7 percent/°C. Industrial gas turbines come in both single and dual shaft design. In a single shaft gas turbine, the gas generator and power turbine are mounted on the same shaft whereas in a dual shaft gas turbine, the gas generator and power turbine are mounted on different shafts.

The single shaft design requires a relatively large starter motor, which is either a separate steam turbine or motor. Once they are started, the starter motor or turbine can supplement the gas turbine power available to the compressors by acting as a helper. Industrial gas turbines are often selected for land-based facilities. Major maintenance is performed every few years, requiring an outage that lasts for a few weeks.

Aero-derivative gas turbines - The selection of these drivers has increased in recent years especially for Floating LNG (FLNG) applications. They are relatively lightweight, can be easily replaced with a spare unit within 48 to 72 hours, and have a higher thermal efficiency of 41 to 43 percent. As with industrial turbines, aero-derivative turbines come in discrete sizes.

The maximum power rating is generally smaller than that for industrial turbines; so multiple parallel compressors may be required depending on the production required.

Aero-derivative turbines are dual or triple shaft designs and have a wider range of speed variation than single shaft industrial gas turbines. Multiple shafts reduce the required starting power, eliminating the need for a large starter motor and reducing suction pressure by venting refrigerant.

Aero-derivatives are more sensitive to ambient temperature variations, with their output power falling about 1 to 1.2 percent/°C. Aero-derivative turbines typically require internal boroscopic inspections once or twice a year, lasting one or two shifts.

Major maintenance is performed by removing the turbine and replacing it with a spare one over the course of a few days, and then rebuilding the unit offline.

Electric motors - For compressors driven by an electric motor, the electricity comes from either an external power grid or by generating power within the facility. The motors for a baseload LNG train would be large and may require a Variable Frequency Drive (VFD) for start-up.

VFDs are typically used to allow the compressors to be operated over a wide speed range. Electric motors can be built in virtually any power rating; 65 megawatts (MW) are the largest motors demonstrated in LNG service to date although larger ones are currently being built.

The maintenance requirements for electric motors are less than gas turbines, increasing plant availability by approximately 2 percent.

Electric motor output is not affected by ambient temperature. The efficiency of electric motors themselves is very good, with 97 to 98 percent of the incoming electricity being converted to shaft power.

However, the overall thermal efficiency needs to account for the electrical generation efficiency and transmission losses. Since electrical generation equipment is typically gas turbine driven, the overall efficiency of an electrically driven liquefaction train may be less than a train having direct gas turbine drive. Higher efficiency is possible with a cogeneration design.
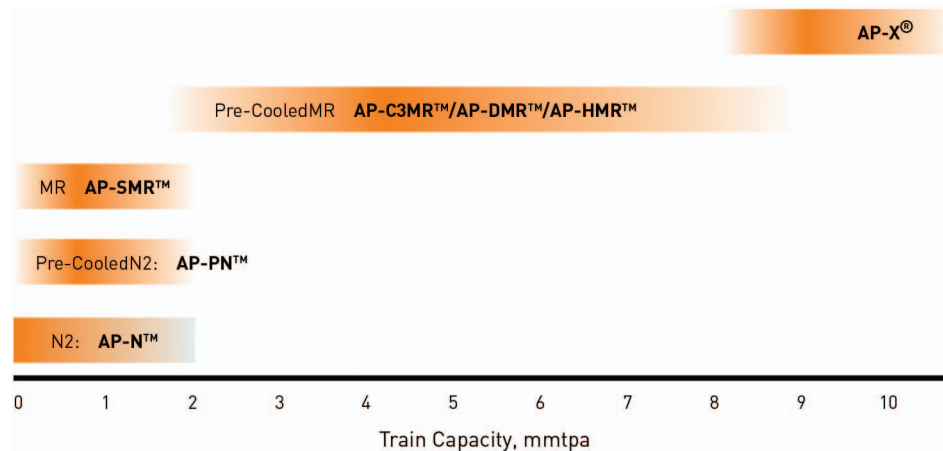

Figure 3: Air Products natural gas liquefaction cycles versus Train capacity

AP-X®

Pre-CooledMR AP-C3MR™/AP-DMR™/AP-HMR™

MR AP-SMR™

Pre-CooledN2: AP-PN™

N2: AP-N™

0 1 2 3 4 5 6 7 8 9 10

Train Capacity, mmtpa

Aero-derivation Gas Turbine (Picture Courtesy: GE Oil and Gas)

Natural Gas Liquefaction Facility. (Picture Courtesy of Segas)

Steam turbines – Most of the earlier LNG baseload plants used steam turbine drives. They also have a relatively low thermal efficiency of approximately 25 to 30 percent. Depending on the facility design, the steam system and the associated cooling water system can be relatively complicated, resulting in higher capital expenditure (CAPEX) and operating expenditure (OPEX).

However, they have a wide variation in operating speed and can be built in virtually any desired power rating. Steam turbine driven trains typically have high availability.

In summary, over the past 20 years, a vast majority of baseload LNG plants have been constructed with industrial gas turbines. Aero-derivative gas turbines are of increasing interest due to their high efficiency, suitability for FLNG application, maintenance requirements and other factors.

Driver Sets

A driver set comprises a driver type and quantity of drivers required.

There are multiple driver types within the industrial and aero-derivative categories from various manufacturers, each with a different power capacity and efficiency.

Based on the ambient conditions and de-rating factors, site-rated driver power is obtained for each driver type. For sparing reasons, the owner may choose to have all drivers of the same type. Inlet air chilling may be used with any of the driver types to increase the available power especially at high ambient temperature conditions.

For each driver type, the following ratio is calculated:

$$R = \frac{P_{nominal}}{P_{driver}}$$

Where

R = Ratio

$P_{nominal}$ = Nominal refrigeration power required

P_{driver} = Site-rated driver power

This ratio is then rounded up or down to whole numbers to obtain the quantity of each driver type required. Driver category and type should be chosen taking owner preference into consideration.

Capacity

For each driver set, the refrigeration power available and capacity are calculated as follows:

$$P_{available} = Q \times P_{driver}$$

$$C = \frac{P_{available}}{W}$$

Where

Q = Driver quantity

$P_{available}$ = Refrigeration power available

P_{driver} = Site-rated driver power

C = Capacity

W = Refrigeration specific power

The capacity is then refined by taking into consideration the fuel required to meet the fuel demand for the driver selected.

The next step is to evaluate whether the capacity is acceptable. If the capacity is not sufficient, then the driver quantity may be increased or the driver set may be eliminated. Once all the driver sets are evaluated in this manner, a list of possible driver sets is obtained.

Machinery Configurations List

Since electric motors and steam turbines can be built for a wide range of power ratings, machinery configuration options are fairly simple in those cases. The motors or steam turbines can be designed to provide the required power for each compression service. On the other hand,

aero-derivative and industrial gas turbines come in discrete sizes and only certain machinery configurations will be feasible. For the purposes of this paper, we focus primarily on machinery configurations involving industrial and aero-derivative gas turbines. However, similar configurations may be applied to any other driver type.

There are multiple options available for the machinery configuration based on the quantity of drivers and the number of refrigerant circuits involved.

Presented here is a machinery configuration list with various arrangements for cycles with two refrigerant circuits: a precooling circuit and a mixed refrigerant (MR) liquefaction circuit.
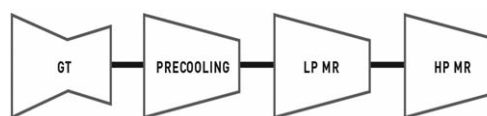
Similar methodologies may be applied to cycles with single or multiple refrigerant circuits as well as any other refrigerant type.

Only a limited set of configurations are shown here. However, similar methodologies may be applied to obtain other configurations including ones for more than seven drivers.

In each of the configurations shown, the location of each compressor casing on the train (if more than one casing is shown) may change depending on the compressor supplier's specific design. Also, starter/helper motors may be present and are not shown for clarity reasons.

Single Driver

1a. Single String of Precooling-MR: In this configuration, both the precooling and liquefaction compressors are driven by a single driver. As the power requirement changes for the different compressors, this configuration automatically balances the power consumption. For instance, as the ambient temperature decreases and the precooling compressor uses less power, more gas turbine power is available for the liquefaction compressors. Therefore, this configuration enables full power utilization.
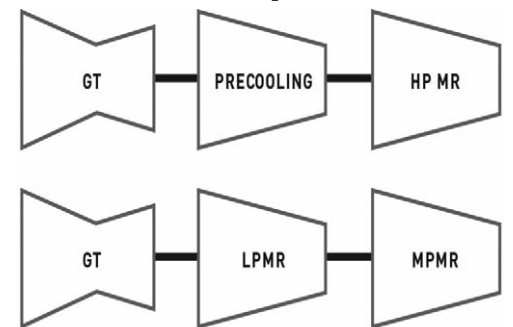

Two Drivers

2a. SplitMR® Configuration: In a precooled MR process (such as AP-C3MR™ process or AP-DMR™ process), the precooling compressor optimally consumes 25 to 35 percent of the total refrigeration power at typical ambient temperatures. If only two turbines are available, they are usually the same model based on spare and maintenance

considerations. Therefore, having one driver drive the precooling compressors and the other driver drive the liquefaction compressors leads to unutilized power at typical ambient conditions.
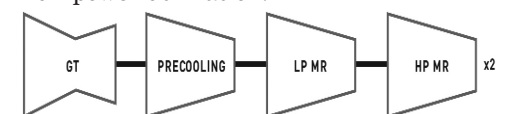
In the SplitMR® configuration, one driver drives the precooling and High Pressure (HP) liquefaction compressors while the other drives the Low Pressure (LP) and Medium Pressure (MP) liquefaction compressors.

As the ambient temperature decreases and the precooling compressor power requirement reduces, extra power is available and can be used for the liquefaction compressors. In other words, the SplitMR® configuration allows for automatic adjustment of the precooling and liquefaction power split as the ambient temperature varies and therefore enables full power utilization.
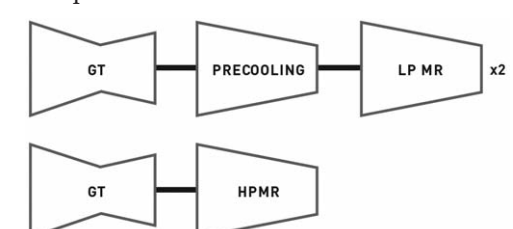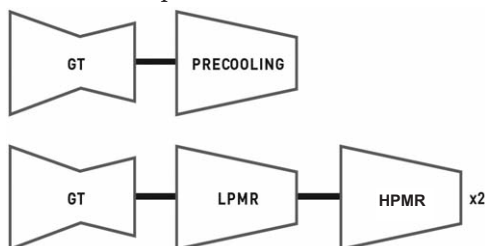

2b. Parallel: This configuration is a parallel version of 1a. There are two parallel strings, each with a single driver powering precooling and MR compressors.

This configuration can often provide higher plant availability and turndown efficiency. It also allows for automatic adjustment of the precooling and liquefaction power split as the ambient temperature varies and therefore enables full power utilization.

Three Drivers

3a. Three Driver SplitMR® Configuration: This configuration is a three driver modification of 2a. Two drivers drive precooling and LP liquefaction compressors while the third driver is dedicated to the HP liquefaction compressor. This configuration allows for higher plant availability and automatic adjustment of the precooling and liquefaction power split as the ambient temperature varies and therefore enables full power utilization.
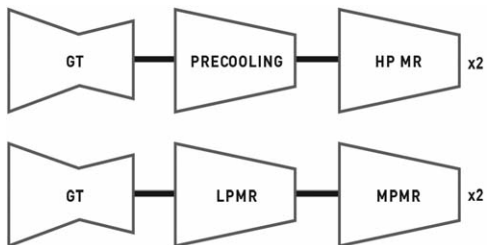
3b. Single Precooling String and Two Parallel Liquefaction Strings: In this configuration, the precooling refrigerant is driven by one driver while the liquefaction compressors are driven by two parallel drivers. For a typical liquefaction process using propane precooling, the optimal power split between the precooling and liquefaction compressors is about 1:2. Therefore, near optimal power split is achieved in this configuration at typical ambient temperatures.
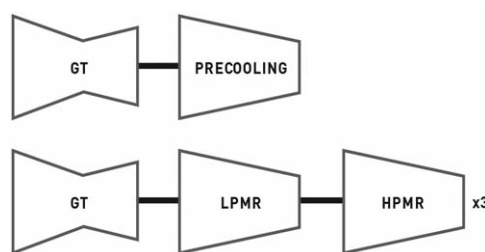

Four Drivers

4a. Parallel SplitMR® Configuration: This configuration is a parallel version of 2a and has all the benefits of the SplitMR® configuration (2a) as well as the parallel configuration (2b).
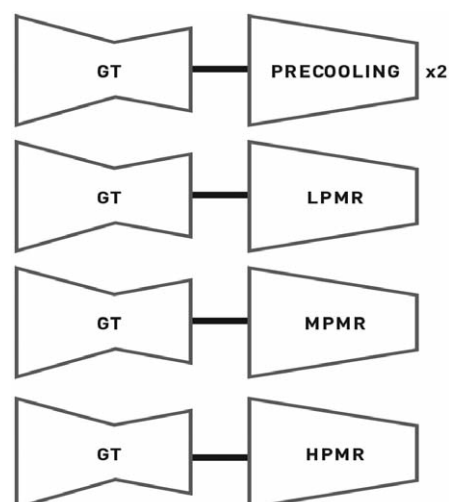

4b. Single Precooling String and Three Parallel Liquefaction Strings: In this configuration, one driver powers the precooling compressor while the other three power the liquefaction compressors.
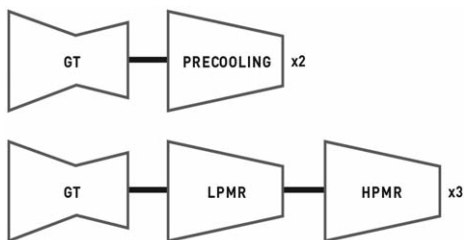

Five Drivers

5a. Parallel Precooling: This is a parallel configuration with two drivers driving precooling compressors and three drivers driving liquefaction compressors with LP, MP and HP stages of the MR machine on different strings.
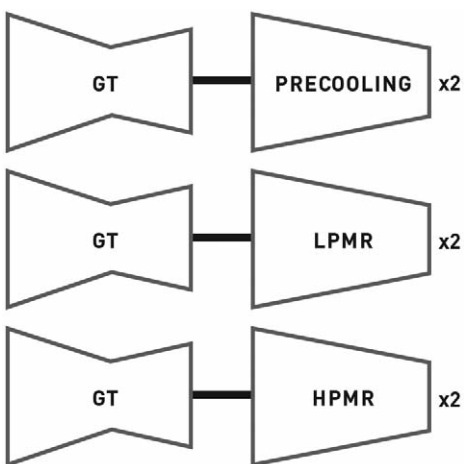

5b: Parallel with Identical MR Strings: This configuration is a variant of 5a with three identical MR strings and two identical precooling strings.
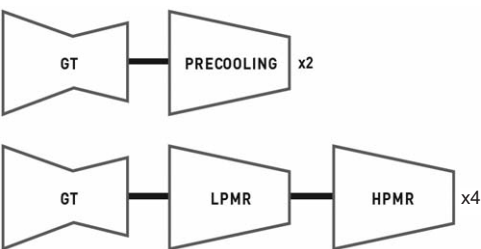

Six Drivers

6a. Parallel Dedicated Drivers: In this parallel configuration, two drivers drive precooling compressors while two drivers drive LP liquefaction compressors and two drivers drive HP liquefaction compressors. As in 3b, the power split between precooling and liquefaction compressors is 1:2 which is near optimal at typical ambient temperature.

6b. Parallel Dedicated Drivers for Precooling with MR in Series: In this configuration, two drivers drive precooling compressors as in 6a. However, instead of having the LP and HP stages of liquefaction on separate drivers, they are on the same driver. This allows for adjusting the power split between the stages of liquefaction. As in 3b, the power split between precooling and liquefaction compressors is 1:2, as is required for near optimal design.

Machinery Configuration Selection

For each driver set selected, based on the quantity of drivers, candidate machinery configurations are selected from this list. Each configuration is then evaluated by taking into account various factors such as feasibility, reliability, industry references and owner preferences. A list of acceptable configurations with different driver types, quantities and configurations is then obtained.

This sets the stage for the Study Phase or Pre-FEED phase of the LNG Project where detailed simulations are developed to model the available power, machinery configurations, feed conditions and fuel balance to determine accurate specific power and capacity values along with a basis for estimating equipment cost. The final selection is then used during the FEED (Front End Engineering Design) Phase of the project.

Case study: This case study illustrates the use of the work process shown in Figure 2. In this case, the owner specified a nominal design capacity of 5.4 MTPA. The liquefaction cycle selected for this project is the Air Products Propane Precooled Mixed Refrigerant (AP-C3MR™) process.

Based on the ambient temperature, process cycle and feed gas conditions, refrigeration specific power is estimated and the total power required for the target capacity is estimated as 180 MW.

Over 20 driver types and corresponding driver sets are evaluated and five driver sets are short-listed since they provide close to the estimated power requirement of 180 MW. Listed in Table 2 are the five driver sets with driver types, quantity of drivers required, refrigeration power available, fuel consumption, capacity, and machinery configuration options for each.

Note that the refrigeration specific power for aero-derivative turbines is slightly higher than for industrial turbines because the lower fuel requirement for aero-derivatives requires deeper cooling in the main exchanger to suppress endflash and meet the fuel balance.

Of these five driver sets, the capacity of the option using six aero-derivative D turbines is 5.0 MTPA which is lower than the target capacity of 5.4 MTPA, so it was eliminated.

The facility owner would like a parallel configuration to improve turndown efficiency. Therefore, the three configurations highlighted in bold face in Table 2 are selected for detailed evaluation in the Study Phase of the project.

Conclusions

Selecting an appropriate liquefaction process cycle, refrigeration compressor drivers, and their configuration are key components in natural gas liquefaction process design. These decisions are closely inter-linked and directly impact the overall plant performance, efficiency, and profitability.

Various considerations such as nominal design capacity, ambient temperature, feed conditions, turndown capability requirements, owner maintenance philosophy as well as project-specific requirements need to be taken into account while making these selections.

The step-by-step methodology presented in this paper provides a fast and efficient way to select an appropriate liquefaction cycle, evaluate numerous driver sets and machinery configurations, eliminate unsuitable ones, develop a manageable number of process-machinery selections for detailed evaluation, and set the stage for the Study/Pre-FEED Phase of the project.

A thorough assessment of the available process and machinery options early on in the project provides valuable insights, enables making the right technical choices and is critical for LNG project success. ∎

TABLE 2: DRIVER SETS AND MACHINERY CONFIGURATIONS					
Driver Type	Driver Quantity	Refrig. Power Available, MW	Estimated Fuel Consumption percent of Feed	Capacity, mtpa	Machinery Config.
Industrial Turbine A with Helper	2	180	8.1%	5.4	2a or 2b
Aero-derivative Turbine B with Helper*	3	185	6.5%	5.4	3a or 3b
Aero-derivative Turbine B	4	182	6.5%	5.4	4a or 4b
Aero-derivative Turbine C	5	184	6.6%	5.4	5a or 5b
Aero-derivative Turbine D	6	169	6.9%	5.0	6a or 6b

*Aero-derivative gas turbines typically do not use helper motor, although it is feasible.

References

1. W. P. Schmidt, C. M. Ott, Y. N. Liu, W. A. Kennington, "How the Right Technical Choices Lead to Commercial Success", LNG 16, 2010.