HOW THE RIGHT TECHNICAL CHOICES LEAD TO COMMERCIAL SUCCESS

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ABSTRACT

For many years, the industry has focused on large baseload plants built on land. Recently, more attention is being given to FLNG and smaller train sizes. These new plant types have different requirements and weightings for reliability, operability, efficiency and capacity. These new inputs affect the technical decisions, including their interactions. This paper will discuss what key features of large baseload plants should be retained and which should be modified to optimize CAPEX and OPEX, and will show how the right technical decisions ultimately lead to commercial success.

Among the most important considerations are

- The number of refrigerant loops: single vs. multiple
- Types of refrigerants: pure or mixed components, and proper component selection
- Compressor drivers: industrial gas turbine, aero-derivative, and electric motor

The correct choices are interdependent and very project specific. In particular, this paper will focus how to make the correct choices for the smaller land based or FLNG plants currently under consideration.

INTRODUCTION

The past decade has seen a significant growth in the number and variety of LNG plants being developed. To design the optimum plant, many technical choices must be made early in the project. Wise choices will set the course for a successful project; poor choices can significantly reduce the profit from the plant. This paper outlines and gives items to be considered when making the key technical choices in this new environment.

Previously, the industry focused on large baseload plants (typically larger than 2 mtpa), almost all of which were in tropical locations [1]. While the industry still is building this type of baseload plant, some different plants types are being built or considered:

- Baseload plants in temperate or arctic climates,
- Baseload plants with modular construction for offshore structures or difficult construction environments,
- Smaller plants (<1.0 mtpa), where the CAPEX/OPEX tradeoff shifts when compared to past baseload plants, and
- FLNG (Floating Liquefied Natural Gas) plants.

When building a plant today, new technology has expanded the options for many choices. Also, the new variety of plants yield different answers to some of the old choices. To build the optimal plant, these new constraints and considerations must be carefully considered. Using previous experience, intuition, and go-bys will not be adequate.

This paper defines many of these technical choices. It lists the alternatives and the implications of making these choices, primarily from the viewpoint of the liquefaction unit. The knowledge of these implications will help to choose the proper technical solution. While specific guidance is given wherever possible, the paper focuses on the questions to be asked and the decision-making process rather than giving final answers. It recognizes that individual projects may have different specific requirements that lead to different conclusions.

The LNG Process

Figure 1 is a block diagram of an LNG Liquefaction Train. A pipeline from the gas wells feeds the train. Impurities are removed from the feed gas, including (a) sulfur compounds and CO_2 in the Acid Gas Recovery Unit (AGRU), (b) water in molecular sieve driers, and (c) mercury by adsorption beds. The sweet stream then goes to NGL rejection, where C_2+ components are removed. The amount removed depends on the NGL production requirements and the need to meet LNG product specifications, including heating value. A small portion of the natural gas is taken as fuel (called Fuel From Feed-FFF), and the remaining stream is then cooled and liquefied in two stages: first by the precooling refrigerant, and then by the main refrigerant. The LNG is then reduced in pressure in the Endflash drum. The remaining low pressure cold LNG is sent to storage. The Endflash Vapor is compressed and sent to the fuel header, where it is mixed with any FFF. The refrigeration unit compresses and circulates the refrigerants to the precooling and liquefaction units.

In this paper, we use the term “unit” to describe an individual block in Figure 1; for example, LNG is liquefied in the “Liquefaction Unit”. Then entire collection of units composes the “LNG train”. In most LNG locations, two or more trains are installed. They generally are independent, but they may share one or more common units, such as fractionation, storage or utilities. In this paper, we will use the term “facility” to refer to a single geographic location, which may contain one or more trains.

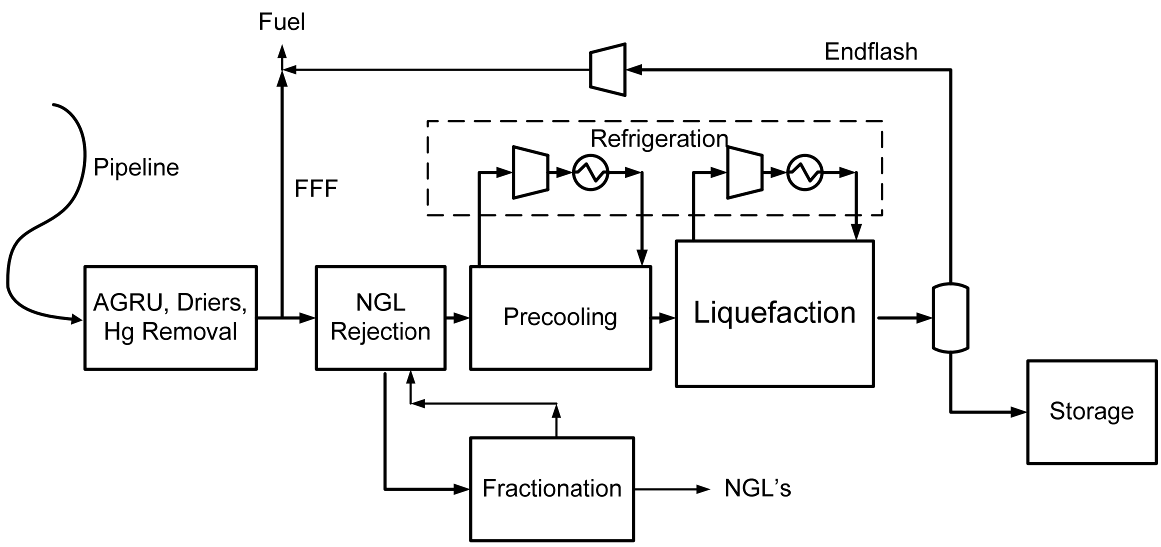

Figure 1 - LNG Train

KEY TECHNICAL CHOICES

As a project is developed, the developer must make several technical choices. Seemingly minor technical decisions can impact the commercial aspects of a project, and ultimately will affect the overall project profitability. It is critical to *consciously* make these decisions and understand their technical and financial impacts on the project. These key decisions are

- What main refrigerant?
- What precooling refrigerant?
- What type of driver for the refrigerant compressors?
- What is the best liquefier pressure?
- What cooling medium should be used?
- Integrated or front end NGL recovery?
- What is the right amount of endflash?
- What unit limits the production?

It is beyond the scope of this paper to cover all of the topics in complete detail. Cooling Medium, NGL recovery, and endflash are covered only briefly in this paper, and will be addressed in more detail in later papers.

DEFINITIONS

Before answering these questions, some basic terms need to be defined.

Specific Power

Specific Power measures the thermodynamic efficiency of the precooling, liquefier and refrigeration blocks in Figure 1. It is computed as

$$W_s = \frac{kW_{ref}}{LNG} \tag{1}$$

Where

W_s = Specific Power for liquefier, kwh/tonne

kW_{ref} = total gas hp for refrigeration compressors[1], kW

LNG = LNG rundown production after any endflash, tonne/hr

The Specific Power primarily measures the thermodynamic efficiency of the process, with lower Specific Power indicating a higher efficiency. W_s is also affected by the feed conditions and the liquefier equipment design. Higher pressure drops, higher temperature approaches and lower compressor efficiencies all increase W_s. However, the compressor driver efficiency is not included.

Autoconsumption

The autoconsumption is the percent of the feed fuel value which does not end up in the LNG or NGL product; it is the percent of the feed which is used to provide thermal or mechanical energy, or is lost as part of the processing. Note that it does not include inerts or rejected impurities, such as N_2, CO_2, H_2S or other sulfur compounds.

$$A = \left(1 - \frac{LNG + NGL}{F}\right) \times 100 \tag{2}$$

Where

A = autoconsumption, %

LNG = HHV LNG rundown production after any endflash, MW

NGL = HHV of all saleable C_2+ hydrocarbon products, MW

F = HHV of Feed to LNG train, less impurities (e.g., CO_2, H_2S), (MW)

Autoconsumption is affected by several things, including heat rate (i.e., specific fuel consumption) of the compressor drivers, liquefier Specific Power, utilities used by other facility units, etc. Autoconsumption is also known as “thermal efficiency”.

Note that Equation (2) applies only when all of the facility utility needs are supplied from the feedgas. For example, if the refrigerant compressors are driven by electric motors, where the

[1] For the C_3MR process, this is the sum of all propane and MR compressor gas horsepower.

electricity comes from an outside power grid, Equation (2) above would imply a very low autoconsumption. In such cases, the autoconsumption equation should be changed to ensure a useful comparison.

WHAT MAIN REFRIGERANT?

Probably the most important choice in the LNG train is selecting the main refrigerant. This refrigerant cools and liquefies the natural gas, typically from about -35°C to between -145 and -165°C. Selecting main refrigerant is critical to determine the Specific Power, and it sets much of the equipment and piping configuration and size. There are several choices for the main refrigerant, described briefly below. Following the precooling refrigerant section, Table 1 gives the relative Specific Power of each precooling/main refrigerant combination.

Mixed Component Refrigerant (MR)

With MR, the main refrigerant is typically a mixture of C_1, C_2, C_3 and N_2, although it can contain butanes and ethylene. The composition is selected to minimize the temperature differences between the hot and cold streams in the main exchanger, which decreases Specific Power, W_s. Nearly 90% of the world's baseload LNG is produced at facilities using MR as the main refrigerant.

The strengths of MR are summarized below:

1. Much of the heat transfer occurs by boiling the refrigerant. The heat transfer coefficients are very high, which allows efficient heat transfer equipment.
2. The refrigerant fluid density is high, because it is partially or completely liquid in much of the process. The higher density results in more compact piping and equipment.
3. Processes using MR have the lowest Specific Power, because they have the smallest temperature approaches within the liquefier [2]. As discussed below, this gives MR refrigerants smaller compressor/driver size for a fixed production, or increases production for a fixed compressor/driver set.
4. Only one compressor string is needed for the main refrigerant. The compressor string typically has one or two intercoolers to improve efficiency, and in some cases, has two casings.
5. Good operating flexibility is easily obtained by changing the MR composition and inventory. This can be tuned in the field to match changes in feed gas conditions, ambient temperatures, production objectives, uncertainties in design, etc. The hydrocarbon MR components are typically present in the natural gas feed, and can be provided by the fractionation unit. The only exception is N_2, which is provided from the onsite N_2 utility system. [3]

Items to be considered when using MR main refrigerants are

1. The refrigerant enters the exchanger as a two phase stream, and must be evenly distributed within the exchanger to give proper heat transfer. There are well proven methods and equipment to do this for land-based plants.

2. Because of the liquid distribution issues in point 1 above, and because much of the heat transfer is by boiling liquid, special considerations are needed for FLNG applications. To predict the effect of various sea states on heat transfer performance, Air Products has developed mathematical models that have been validated with large scale experiments

Pure Component Cascade (PCC)

The feed is cooled with three separate refrigeration loops, each containing a relatively pure fluid. In each loop, the low pressure gas phase refrigerant is compressed, cooled, and condensed. The pressure of the liquid is reduced, and it then evaporates to provide refrigeration. The first loop uses pure propane at 3 or 4 pressure levels. This is followed by 2 or 3 stages of ethylene cooling, which is then followed by 2 or 3 stages of cooling with methane. Each stage has a separate temperature level, progressively colder. The final methane loop and can be either closed or open. In an open loop, N_2 and methane are used as the refrigerant.

Note that with the Pure Component Cascade process, propane must be used. It is not feasible to have a PCC process without precooling.

The strengths of Pure Component Cascade main refrigerants are

1. Much of the heat transfer occurs by boiling the refrigerant. The heat transfer coefficients are very high, allowing good efficient heat transfer equipment.
2. The refrigerant fluid density is high, because it is partial or completely liquid in much of the process. The higher density results in more compact piping and equipment.
3. The Specific Power is worse than MR refrigerants, but better than gas expansion refrigerants (see below).

Items to be considered when using PCC main refrigerants are

1. Two main refrigerant compressor duties (CH_4 and ethylene) are typically needed, so an extra refrigeration loop is needed when compared to MR; in addition, a third propane precooling loop is needed.
2. Because the PCC uses pure components, the cooling curves cannot be as tight as with an MR refrigerant. This gives a higher mean ΔT, which results in a somewhat higher Specific Power [2].
3. The PCC process is more sensitive to changes in the cooling medium temperature.
4. Often ethylene is used as one of the refrigerants. This is typically not available from the natural gas feed, and must be imported.
5. As with MR, the refrigerants enter the exchanger as a two phase stream. The liquid must be evenly distributed within the exchanger to give proper heat transfer. There are well proven methods and equipment to do this for land-based plants.
6. As with MR, special considerations are needed to ensure proper liquid flow distribution and heat transfer for FLNG applications.

Gas Expansion

Gas expansion uses an all gas refrigerant, either CH_4 or N_2. The refrigerant is compressed, cooled, and then expanded through a turboexpander to reduce its temperature. The cold gas is warmed, which cools the incoming feed.

The strengths of gas phase main refrigerants are

1. Processes with gas phase refrigerants tend to have simple operation, because there is only a single vapor phase.
2. The gas phase refrigerant is typically either CH_4 or N_2. If N_2 is used, it is inert, which can be an advantage for some FLNG applications, where some operators prefer minimize flammable refrigerants, particularly C_3.
3. The single vapor phase is insensitive to motion, a consideration for FLNG applications
4. The Specific Power is not very sensitive to changes in cooling medium temperature.

Items to be considered when using gas phase main refrigerants are

1. The refrigerant is gas phase. Gas phase refrigerants have the following issues:
    a. The vapor phase density is significantly lower than the other refrigerants.
    b. The heat transfer coefficients are approximately 5 to 30 times lower for a single phase vapor than a boiling liquid.
    c. The single phase heat capacity is 4 to 6 times lower than the latent heat of boiling fluids, which results a significantly large refrigerant flowrate for the same LNG production.

   These factors combine to make either make the piping and equipment significantly larger or to increase the Specific Power of a gas phase refrigerant. In practice, the optimum usually is a combination of the two.
2. The Specific Power is relatively high, because the gas phase processes are not very efficient.
3. The refrigeration is generated with a turboexpander, so there is an extra rotating equipment item.

WHAT PRECOOLING REFRIGERANT?

The train Specific Power can be improved significantly by using a precooling refrigerant. This refrigerant cools the natural gas feed and the main refrigerant to approximately -25 to -45°C. The benefit of precooling is that the main refrigerant is optimized to provide refrigeration at a very cold temperature. It is somewhat inefficient to use this very cold refrigeration to cool the feed from ambient to -25 to -45°C; it is more efficient to use a refrigerant tailored to cool over this temperature range.

What is also often not appreciated with precooling refrigerants is that they also reduce the main refrigerant circulation flowrate, and hence reduce the size of the main refrigerant compressor and heat exchangers. Because the precooling refrigerant reduces both the CAPEX and OPEX of the main refrigerant system, it is almost always justified for facilities over 1 to 2 mtpa, even accounting for the CAPEX of the precooling system and the extra operating complexity.

Using precooling refrigerants is further justified when one realizes that as the plant size goes above 2 mtpa without precooling, the main refrigerant flowrates become so large that parallel compressors and wound coil heat exchangers are needed. Therefore, for plants over 2 mpta, because two refrigerant compressors are needed in any case, it is better to use one compressor for the main refrigerant and the other for the precooling. This eliminates the need for parallel exchangers and also significantly reduces the facility Specific Power. Precooling thus saves both CAPEX and OPEX.

Propane

Propane is by far the most commonly used precooling refrigerant. It is readily available, because it is present is almost all natural gas feeds, and its physical properties are ideally suited for cooling over the desired temperature range. Note that the Pure Component Cascade Process has Propane as its first refrigerant, so it has precooling "built into" the overall process.

The advantages of propane are

1. It is a very simple system to operate. The propane system runs like a utility and "takes care of itself", requiring almost no operator attention.
2. Propane is almost always available from the LNG feed stream, and can be provided onsite from the fractionation unit.
3. It is well proven, with over 90% of the world's LNG is produced in facilities using propane precooling.

Items to be considered when using propane precooling refrigerant are

1. The typical precooling temperature approximately -35°C, depending on the system design. Historically, this cannot be made lower, because operators prefer not run the propane system in vacuum, due to safety concerns.
2. When the cooling medium temperature becomes cold, propane precooling requirement is less, because the precooling temperature range decreases. That is, if the cooling medium is 40°C, the precooling range is 80°C (+40 to -40°C). If the cooling medium is 5°C, then it reduces to 45°C (+5 to -40°C). The lower temperature range utilizes the precooling refrigerant less, making the precooling less cost-effective. This is an important design consideration when the cooling medium changes temperatures significantly over the course of a year, particularly when using air cooling in arctic or temperate climates.
3. Some shipboard operators have a preference to avoid pure propane on an FLNG vessel. In these applications, other precooling refrigerants must be used.

Mixed Component Refrigerant (MR)

The precooling MR is a mixture of C_1, C_2, C_3, and in some cases C_4. The composition is selected to minimize the temperature differences between the hot and cold streams. This has been used in some baseload LNG facilities.

The advantages of MR precooling refrigerant are

1. It is a flexible precoolant. By changing the composition, the cooling curve and final temperature can be adjusted to account for different operating conditions. This is more important when the cooling medium seasonal temperature varies significantly, e.g., using air cooling in arctic locations.
2. The MR components are almost always available from the LNG feed stream, and can be provided onsite from the fractionation unit.
3. The composition and or pressures can be adjusted to give colder precooling than C_3. This makes it easier to shift the refrigeration load to precooling if the cooling medium becomes colder.
4. The precooling MR composition can be adjusted to not use propane, when this is an operator's preference (as in some FLNG applications).

Items to be considered when using an MR precooling refrigerant are

1. The MR refrigerant system is somewhat more complex to operate than propane.
2. The experience base with MR precooling is much less, with currently only a few operating facilities.
3. Because the MR refrigerant is two phase when introduced into the heat exchange, it has the same issues as the MR main refrigerant, namely
    - Liquid distribution within the heat exchanger
    - Some sensitivity to motion when used in shipboard (FLNG) applications.

HydroFluoroCarbon (HFC)

In some cases, it may be desirable to use a non-hydrocarbon precooling refrigerant. In these cases, R-410A is a good precooling refrigerant. It is a near-azeotropic mixture of R-32 and R-125. While it is a mixture of two components, it acts as a pure component, with physical properties well matched to provide good precooling.

The advantages of HFC precooling refrigerant are

1. HFC precooling is easy to operate, because it operates very similarly to propane.
2. It is environmentally friendly. R-410A's ASHRAE safety classification is A1[2]. It has zero ozone depletion.
3. It is readily available as the leading R-22 replacement.
4. In FLNG applications, some operators may prefer HFC precooling combined with N_2 gas phase expander main refrigerant, because these minimize flammable refrigerants.
5. Its properties are such that it can provide colder precooling than C_3. This makes it more efficient in colder climates or with large seasonal cooling medium variations.

[2] Class A signifies refrigerants for which toxicity has not been identified at concentrations less than or equal to 400 ppm; Class 1 indicates refrigerants that do not show flame propagation when tested in air at 21°C and 101 kPa.

Items to be considered when using HFC precooling refrigerant are

1. While HFC's have been used on large industrial scales, including LNG facilities, they have never been used in LNG applications as a precooling refrigerant. The first application will need a development program to identify and manage technical risks.
2. It would need to be imported for the initial charge and for any replacement. Therefore, losses must be kept to a minimum. (With modern seal technology, the compressor seal losses can be kept very small.)
3. The refrigeration circuit will require a relatively high design pressure to prevent venting any HFC refrigerant on shutdown. This will increase CAPEX.

REFRIGERANT SPECIFIC POWER

The most important single feature for a precooling/main refrigerant combination is its Specific Power, with lower being better. Table 1 below shows the relative Specific Power in a liquefier for various combinations of main and precooling refrigerants. Using any precooling refrigerant significantly reduces the Specific Power. (The choice between precooling refrigerants is made on criteria other than energy consumption, because all give about the same improvement.)

Table 1: Relative Liquefier Specific Power(1)

Main Refrigerant	Precooling Refrigerant(2)	
	None	C_3, MR, or HFC(3)
Gas Expansion	1.33	1.25
Pure Component Cascade	N/A(4)	1.1
Mixed Component	1.25 (SMR(5))	1.00 (DMR(6), C_3-MR(7), or HFC-MR(8))

Notes:

1. Each Specific Power is relative to the C_3-MR process.
2. It is possible to have a liquefier without a precooling refrigerant.
3. For a given main refrigerant, the *type* of precooling refrigerant does not affect Specific Power.
4. When using PCC Refrigerants, the process always has a precooling refrigerant as an integral portion of the process.
5. A process using mixed component main refrigerant which does not have precooling is typically called "Single Mixed Refrigerant (SMR)".
6. A process using mixed component main and precooling refrigerants is typically called "Dual Mixed Refrigerant (DMR)".
7. A process using mixed component main refrigerant which using C_3 precooling is typically called "C_3-Mixed Refrigerant (C_3-MR)".
8. A process using mixed component main refrigerant which using HFC precooling is typically called "HFC-Mixed Refrigerant (HFC-MR)".

WHAT TYPE OF DRIVER FOR THE REFRIGERANT COMPRESSORS?

There are several types of drivers available for the refrigeration compressors

- **Industrial Gas Turbines** – Most refrigeration compressor turbine drivers in the LNG industry are industrial types. Typical ISO ratings are 30 to 130 MW. Because these turbines come in only a few discrete sizes, the train is designed around the turbine power rating for maximum profit. Their thermal efficiency is acceptable, between 29 and 34%. (Efficiency is also expressed in heat rate, LHV of fuel/unit work supplied, and industrial turbines typically have ISO ratings between 7300 and 8600 BTU/hp-hr.) The gas turbine power output falls moderately with increasing ambient temperature, with the maximum power falling about 0.7%/°C.

  Industrial gas turbines come in both single and dual shaft design. When compared to the dual shaft design, the single shaft design is simpler with lower maintenance, but a lower operating speed range. The single shaft also requires a starter, which is either a separate turbine or motor. Once they are started, the starter turbine or motor can supplement the gas turbine power by acting as a helper motor.

- **Aero Derivative Gas Turbines** – These gas turbine drives were developed from aircraft engines. They are relatively lightweight, can be easily replaced with a spare unit within 48 to 72 hours, and have high efficiency, with ISO thermal efficiencies of 41% to 43% (equivalent to an ISO heat rating of approximately 6000 BTU/hp-hr.) One drawback is that they may require periodic boroscope inspections, requiring the train production to be reduced or stopped. These are currently in operation in one LNG plant [4], and they have been proposed for several others. As with the industrial turbines, the aero derivatives come in a few discrete sizes. The maximum power ratings are generally smaller than the Industrial turbines, so for baseload plants, multiple parallel compressors have been installed. Aero derivative turbines are dual or triple shaft designs, so they do not need a helper motor to start, and typically have a larger speed range, which can be up to 50 to 105% of nameplate. Aero derivatives are more sensitive to ambient temperature variations, with their output falling about 1.2%/°C.

- **Electric Motors** – The compressor is driven with an electric motor, and 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 very large, requiring expensive and complicated VFD drives for startup. The VFD drives give a wide speed range. Electric motors can be built in virtually any power rating; 65 MW are the largest motors demonstrated in LNG service to date. The maintenance requirements for electric motors are less than gas turbines, increasing plant availability by approximately 2% [5]. Electric motor output is not affected by ambient temperature. The thermal efficiency of electric motors themselves is very good, with 98 to 99% of the incoming electricity being converted to shaft power. However, the overall thermal efficiency needs to account for the electrical generator efficiency. Since electrical generation equipment is typically gas turbine drives, and the overall efficiency of the electrical generators would be less than the gas turbines.

- **Steam Drive** – Most of the earlier LNG baseload plants used steam drives; however, their use has become less common in the past 20 years. They also have a relative low thermal efficiency of approximately 24% (equivalent effective heat rate of approximately 10,200 BTU/hp-hr.) Depending on the facility design, the steam system and the associated cooling water system can be relatively complicated, resulting in higher CAPEX and OPEX. However, they have a wide variation in operating speed and they also can be built in virtually any desired power rating. They are affected by the temperature of the cooling medium used for the condenser. Typically, ambient air temperatures vary too widely, and water is used to cool the condenser. Steam turbines typically have a high availability, but the overall availability depends on the entire system, including the steam boilers.

Over the past 20 years, the vast majority of plants have been constructed with Industrial gas turbine drives. One plant has been built with aero derivative turbines, and one with electric motors, where the electricity is generated onsite by aero derivative gas turbine generators, with supplemental support from the external electrical grid. Table 2 summarizes the above comparison:

Table 2 – Comparison of Refrigeration Compressor Drivers

Driver	Industrial	Aero	Electric	Steam
ISO Thermal Efficiency	29 to 34%	41-43%	N/A(2)	24%
Heat Rate (BTU LHV/hp)	7,300 – 8,600	6,000	Gas Turbine + several percent(2)	10,200
Size	Discrete	Discrete (smaller max)	Variable	Variable
Shaft Type	Single and Dual	Dual and Triple	N/A	N/A
Speed range (1) (% nameplate)	SS: 95-102% DS: 50 to 105%	50-105%	20-100%	60-110%
Starters required(1)	SS -Y DS - N	N	N (VFD req'd)	N
Availability	Good	Good	Best	Depends on entire steam system
Amb T effect	Moderate	Large	Nil (w/ sufficient electricity supply)	Small (w/ water condenser)
CAPEX	Least	Least	Middle(3)	Highest

Notes:
1. SS = Single Shaft, DS = Dual Shaft
2. The heat rate depends on the heat rate of the electrical generation system. If electricity is generated onsite, then one must consider the type of turbines (aero derivative or frame), as well as the fractional load. (Low fractional load gives lower heat rates.)
3. Assumes onsite electrical generation via gas turbine generators

From the process perspective of the liquefaction unit, the key items are Efficiency (or Heat Rate), Size and ambient temperature effect. These can have a large impact on the overall train efficiency and production capacity. It is well worth spending time and effort to fully investigate the effect of possible drivers to ensure that the proper selection is made. In many facilities, the refrigeration compressor drivers are the limiting unit. In those cases, the train production will be very strongly affected by driver heat rate and the liquefier Specific Power.

WHAT IS THE BEST LIQUEFIER PRESSURE?

It is generally advantageous to have the liquefaction unit feed pressure to be as high as possible. This has two benefits:

- **Lower CAPEX -** The higher pressure feed has a higher density, so the equipment is smaller, or for the same size equipment, the production increases. However, this size reduction will be partially offset by the higher design pressure.
- **Lower OPEX -** It takes less energy to liquefy the feed. The overall power decreases as the feed pressure rises to approximately 70 bara. Above this pressure, the power saved in liquefaction only offsets the feed compressor power.

These benefits are quantified in Figure 2 below:

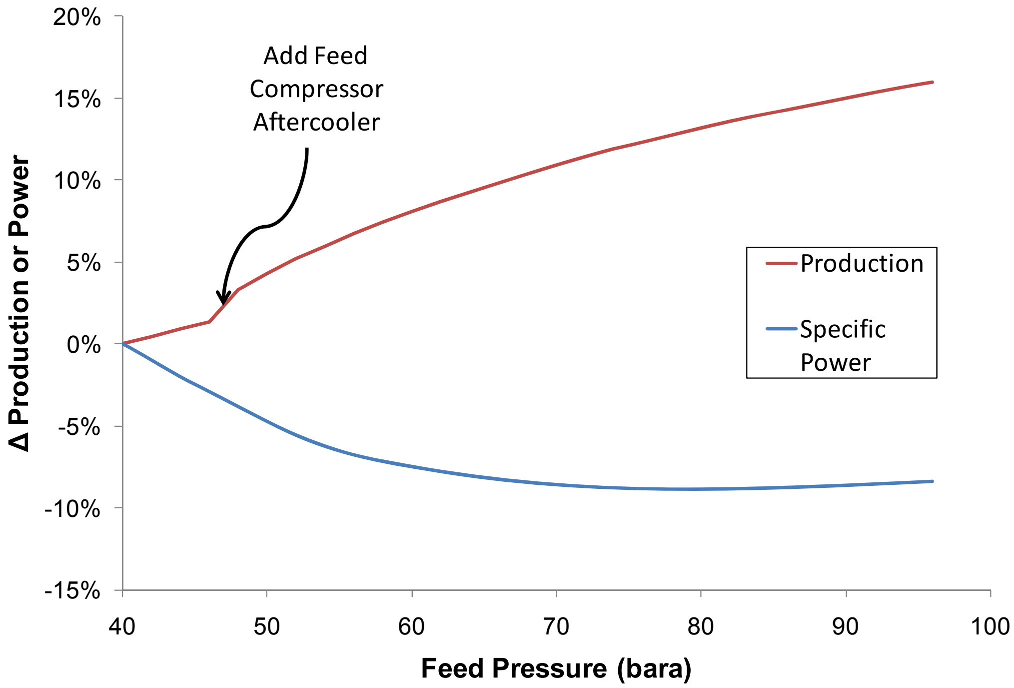

Figure 2 – Effect of feed pressure on Production and Specific Power

This curve shows that there are always process benefits to compressing the feed. Whether it is justified for a particular project should be evaluated for each case, based on the CAPEX required, as well as the operating complexity of the feed gas compressor. Note that in many cases, it is possible to continue to run the liquefier at a lower pressure if the feed compressor is lost, so adding the feed compressor does not dramatically reduce the train availability. (Figure 2 has a bump in the production curve when an aftercooler is added to the feed compressor.)

WHAT COOLING MEDIUM SHOULD BE USED?

The heat generated by the process must be rejected to the cooling medium. Most of the heat leaves through the compressor intercoolers, aftercoolers and the refrigerant compressors. LNG plants typically use one of three cooling media: ambient air, seawater, or water from an evaporative cooling tower. The vast majority of plants cool with either ambient air or seawater. In short, seawater gives colder process temperatures than air cooled plants by 5 to 10°C. Seawater cooling has smaller variations, both diurnally and season-to-season, which make the LNG liquefier easier to operate. However, an air cooling system itself is easier to operate and requires less maintenance. Seawater cooling systems require more maintenance and must be designed to meet the site specific environmental requirements.

This is a complicated topic, and is beyond the scope of this paper to address in detail. It should be addressed in detail for specific applications. However, when choosing the cooling system, do not overlook its impact on the liquefier performance.

INTEGRATED OR FRONT END NGL RECOVERY?

Almost all natural gas feeds remove C_2+ components for one or more of the following reasons:

- Reduce the product heating value to the customer's specifications
- Produce NGL byproducts for sale
- Provide makeup components to the refrigerant loop
- Remove trace components that could freeze in the LNG, such as benzene, toluene, and higher boiling hydrocarbons

There are two types of NGL recovery units: front end and integrated. They are distinguished by the condenser refrigeration source. In a front end unit, the refrigeration is provided by expanding all or a portion of the feed through a turboexpander. The distillation column runs at lower pressure. The overhead vapor is recompressed before being sent to the precooling or liquefaction units.

The discussion of which is preferred is beyond the scope of this paper, and will be addressed further in future papers. However, in many cases, an integrated NGL recovery unit is preferred, if all of the following items are true:

- The required C_2+ recovery is relatively low,
- There is sufficient C_2+ at the top of the NGL recovery column that the liquefier feed pressure is below critical, and
- The integrated unit allows the plant operator sufficient operating flexibility

If any of these are not true, then a front end NGL unit is generally the preferred choice.

WHAT IS THE RIGHT AMOUNT OF ENDFLASH?

The LNG leaving the liquefaction unit has two possible process configurations:

- **Subcooled Cycle -** The LNG is cold enough that no flash vapor is generated is generated in the storage tanks.
- **Flash Cycle** – Vapor flashes off as the pressure is lowered. As the vapor evaporates, it lowers the temperature of the remaining LNG. The flashing vapor provides cost effective refrigeration. The endflash vapor is compressed and sent to the fuel system.

Most LNG liquefaction units are Flash Cycles. The methodology for choosing between these is beyond the scope of this paper and will be addressed in future papers.

WHAT UNIT LIMITS PRODUCTION?

One of the most important choices to be made is what will be the limiting unit for the LNG Train. It usually comes down to which unit of Figure 1 has the highest CAPEX and OPEX combination. However, when making this choice, be aware of its implications, which are discussed further here.

Impact of Specific Power

For this analysis, it is assumed that the feed entering the LNG train either leaves as product or is consumed as fuel, that is,

$$P = NG - Fuel \quad (3)$$

where

P = LNG and NGL products, t/h

NG = Average feed to the liquefier, t/h

Fuel = Fuel consumed to drive the entire train, including compressor drivers, electricity and steam generation, etc. Also included are any small non-fuel losses, such as leaks, vents, etc.

The fuel use is therefore

$$Fuel = A + H \times W_s \times P \quad (4)$$

where

A = fixed fuel use, including electricity and steam generation, t/h

H = heat rate for gas turbine drivers, (t fuel)/(kwh driver power)

W_s = liquefier Specific Power, kwh/t LNG

This analysis uses the simplifying assumptions that (a) the liquefier compressors are driven by gas turbines, (b) the gas turbine heat rate is the same for all gas turbines, and(c) the fixed fuel consumption does not depend on feed rate. If any of these assumptions are not correct, the analysis can be made more detailed; however, the overall conclusions discussed below will not change significantly.

To make this analysis concrete, the parameters in Table 3 are used to study some specific cases in more detail:

Table 3: Parameters for Specific Power Study

Nominal Plant Size	3 mtpa
LNG cost	200 USD/tonne (4 USD/MBTU)
W_s	280 kwh/t
H	10,500 kj LHV/kw
Plant Availability	94%

With this background two cases are considered.

Upstream Operation Limited

An upstream operation limits the feed to the liquefaction unit. This can be the pipeline capacity, throughput limits on the AGRU, driers, or NGL units. Whatever the cause, the feed to the precooling and liquefaction sections is fixed; it cannot be increased.

For a fixed feed rate, about the best way to produce more LNG is to reduce fuel consumption by decreasing the Specific Power or gas turbine heat rate. Whatever is not consumed as fuel turns directly to the LNG product. No further equipment changes or investment are needed to the upstream systems. One can consider this "debottlenecking during design."

For the parameters in Table 3, a 10% improvement in Specific Power results in approximately 0.5% increase in production. This increases the plant revenue approximately $4 million per year. This would justify CAPEX of $10 to $20 million, depending on a specific project economics.

Refrigerant Compression Limited

The situation changes if the refrigerant compressors or their drivers limit LNG production. In this case, improving the Specific Power allows more feed to be processed for the fixed power available. For the case of Table 3, a 10% improvement in Specific Power results in 10% production increase, which boosts the revenue stream by $170 million per year. This would justify CAPEX of $0.4 to 1.0 billion. Some portion of this CAPEX would need to be spent to ensure that all upstream units (pipeline, gas treating, etc.) could deliver the 10% extra feed needed, in addition to whatever CAPEX is needed to improve the Specific Power.

Answer to the Question

This section asks "What unit limits production?" This simplified analysis shows that the answer to that question can have very significant implications on the project profitability. When an upstream unit is the limit, liquefier Specific Power improvements translate into extra production. When the refrigeration compressors limit, however, Specific Power improvements can justify significant CAPEX in upstream units.

So there is no one answer. The general lessons are

- the limiting unit in an LNG train should be chosen after careful analysis
- the liquefier should be optimized with this fact in mind
- doing this will can greatly improve the project economics

OVERCOMING MAXIMUM AVAILABLE DRIVER POWER

As just discussed, in many cases, the refrigerant compressor drivers set the train production. If more production is desired, the driver size must be increased. However, one drawback to gas turbines is that they are available in only a few discrete sizes. It can be a problem to match the desired production to the available gas turbines.

If it is desired to increase production above that available from a specific turbine, below are some of the most common options:

- **Install Helper Motor** – Installing a helper motor on the gas turbine allows extra power to be supplied to the compressor. This is relatively straightforward to do, particularly for industrial turbines, which already have an installed starter motor. Note that aero derivatives do not need a starter motor, so if a helper motor is needed, it must be installed for that purpose only.

  A potential difficulty with helper motors is that they consume electricity. This may require installing extra electrical generation capability, and also running more generators if the electrical load is large. The autoconsumption may rise to generate this electricity, but this extra fuel can be supplied by increasing the facility feed flowrate.

- **Increase Feed Pressure** – Installing a feed compressor reduces the Specific Power for liquefaction. The same installed refrigeration driver power can then liquefy more feed and increase production. Note that in most cases, the overall facility autoconsumption will decrease with increasing feed pressure (see section "What Is the Best Liquefier Pressure?" above.)

- **Recycle endflash** – (See Figure 3 below.) Increasing the temperature of the LNG leaving the liquefier decreases the liquefier Specific Power, and allows more feed to be processed. However, this generates more endflash, requiring additional power the fuel gas compressor. The fuel gas compressor and liquefaction unit must have sufficient capacity to process the extra feed gas. In addition, a small booster compressor may be needed to raise the recycle stream's pressure from the fuel gas header to the feed pressure. While this will generally increase the autoconsumption slightly, it will allow for better use of the gas turbine drivers and increase the train production.

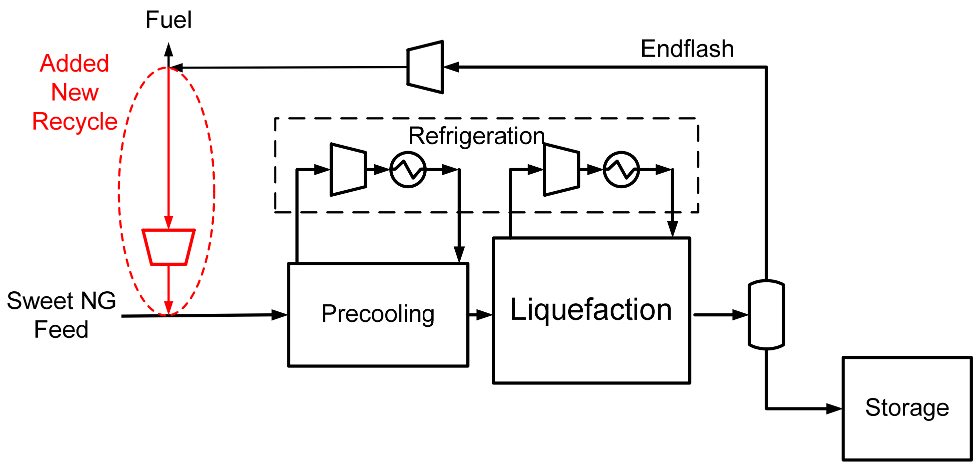

Figure 3 – Endflash Recycle

- **Parallel and Series Compressor Drivers** – Installing drivers in parallel will increase the refrigerant capacity. It is most common to install parallel units of equal size (e.g. 2 x 50% or 3 x 33%) to increase the flowrate, but this need not be the case. Also, it is possible to add drivers in series which will increase the available power primarily by increasing the discharge pressure.
- **Split Compressor Duties Among Drivers** – In a precooled cycle, the precooling and main refrigerant duties may not split equally. For example, if the precooling power is 1/3 and main refrigerant power is 2/3 of the total installed duty, is possible to place the one casing of the main refrigerant compressor on the precooling turbine. This will split the refrigeration power evenly, (50%/50%) and allow more production from the same overall installed gas turbine power [1].

Summary – Increasing Available Refrigeration Driver Power

One can see that while these options should be considered during the pre-FEED project phase to ensure that that the proper equipment and equipment configuration are selected. Consider both the base design point and any potential off-design points. Identifying the limiting unit and building in appropriate flexibility allows one to make the right technical choices. These will increase facility production for minimal CAPEX, and thereby significantly increase the project revenue stream.

CASE STUDIES

The most visible technology development in the past 20 years has been that single LNG trains have increased in size, from under 3 mtpa to nearly 8 mtpa in a single train. This has primarily been accomplished by developing and applying larger compressors, drivers and heat exchange equipment. While some large facilities are still being developed, there are few gas reserves that can support trains of 8 mtpa or more. The future direction is that more and more gas reserves are being found further offshore and new LNG markets are being developed inland in countries like China. Therefore, in the future, LNG plant technology is taking a new path, requiring different technical choices and decisions when compared to the traditional land-based baseload LNG facilities.

Two very different LNG applications are FLNG facilities and smaller facilities of less than 1 mtpa. Case studies on these plants show how some of the choices described above can be made, and how the proper choice is necessary for commercial success.

Case Study 1a – FLNG with N_2 Expander Process

Consider the case where a project would like to develop a nominal 2 mtpa FLNG. Aero derivatives are chosen, because they are lighter and can be quickly changed out for maintenance. The General Electric LM6000 ISO rating is 43 MW, and two turbines are used to supply the refrigeration power.

The train uses an N_2 expander process, with no precooling, based on the desire for a simpler process. For this study, the availability is somewhat arbitrarily chosen to be 92%. The Specific Power is estimated to be approximately 370 kwh/t.

These parameters result in a train that produces 1.49 mtpa of LNG.

Case Study 1b – FLNG with DMR Process

The same basic parameters as case 1a are used, except this time, MR is chosen as the main refrigerant, because of its high efficiency and proven track record. The precooling refrigerant is also MR, which allows all of the precooling to be done in a single exchanger, and the precooling exchanger footprint is smaller [6]. The use of two MR refrigerants gives this process the name “Dual Mixed Refrigerant (DMR)”. The refrigeration compressors are still driven with two LM6000 drivers. The availability is kept at 92%, and the Specific Power of this process is approximately 280 kwh/t, which is 33% better than the simple N_2 expander. Using the simplified methods from above, this train would produce 2.03 mtpa of LNG.

Discussion of Case Study 1a and 1b

The basic idea of these two cases assumes that the largest portion of the CAPEX for an FLNG goes into the subsea pipeline and ship. It also assumes that deckspace is limited, so the main units (i.e., compressor drivers) are fixed and kept the same for both cases. These two cases then compare the effect of changing the liquefaction process. The primary effect would be a very different Specific Power, which results in a very different production. Cases 1a and 1b are summarized in Table 4 below. Note that at a typical LNG price of $200/t, the more efficient DMR process would deliver about $99 million more per year in gross revenue.

Table 4 – Comparison of Case Studies 1a and 1b

		Case 1a (N_2 Expander)	Case 1b (DMR)
Main refrigerant		N2	MR
Precooling refrigerant		none	MR
Ref compressor drivers		LM6000	LM6000
ISO rating	MW	43	43
Derate for site conditions		0.82	0.82
Number		2	2
Total available power	MW	70.5	70.5
Spec power	kwh/t	370	280
Autoconsumption	%	Base + 1.6%	Base
Plant Availability		0.92	0.92
LNG Production	mtpa	1.54	2.03
LNG Price	$/t	200	200
Revenue	$m/yr	base	Base + $99m

In this study, the primary difference is obviously the large production increase of 32%. Note that the production increase is primarily due to the lower specific power. The lower specific power also reduces the autoconsumption 1.6%, so that less feed is needed, so the upstream equipment could be made incrementally smaller, as well as upstream OPEX would be decreased

Another interesting observation from this exercise is that *when the refrigerant compressor drivers are the limiting component, changes in Specific Power are equivalent to changes in availability*. That is, decreasing Specific Power by 1% and increasing availability 1% give identical yearly production. For the processes described here, the DMR and N_2 expander processes would produce the same 1.54 mtpa if the DMR process had an availability of 70%.

Having said that, we recognize that availability and Specific Power are clearly not completely equivalent. If an availability decrease of 1% (3.5 days) occurs all at one time, this will be a significant portion of the time to fill a ship, and might result in delaying a product shipment. An increase of 1% in specific power would decrease the production rate by 1%, resulting in 1 to 4 more hours to fill a ship. What is important to recognize is that from a high level perspective, seemingly small increases in specific power are very significant, and could have similar financial implications for a project.

The reader should not conclude from this study that the DMR process is necessarily the best process for all FLNG applications. The N_2 cycle production could be increased with larger (or more) compressor drivers. It may also be that the plant operator's preference is to eliminate the hydrocarbon refrigerants and replace them with inert N_2. What this case study shows is that selecting the refrigerants—and the Specific Power that is implied by the selection—is very important. Specific Power does not just reduce the fuel consumption—it can also have a large impact on production, particularly when the limiting unit in the train is the compressor drivers. The higher production allows a relatively fixed capital investment to be spread across a larger production, lowering the unit cost. These all combine to show that process performance, expressed as Specific Power, has a significant impact on the financial performance of an FLNG facility.

Case Study 2a

Air Products is currently providing technology for a mid-size liquefier, which will produce 0.4 mtpa of LNG. Some key parameters of this train are

- The feed is coming from a natural gas pipeline, so the feed is not limited. However, the plant must produce 0.4 mtpa.
- The compressors are driven with electric motors, powered from a national grid. The electric motors allow any size driver to be selected.
- The small plant size gives a stronger emphasis on reducing CAPEX, even if efficiency is sacrificed.
- There is no need for fuel gas, so the process is subcooled with no endflash.

Based on these parameters, the main refrigerant was chosen to be Mixed Component (MR), without precooling, making this an SMR process.

Case Study 2b

As an alternative, the standard C3MR process was compared. This is to determine if the extra efficiency of the C3MR process would support the additional CAPEX.

Discussion of Case Study 2a and 2b

The production is fixed in both cases at 0.4 mtpa. The two cases are compared in Table 5 below. One common feature is that there are no breakpoints in the available compressor or driver sizes. Adding incremental capacity only adds incremental cost.

Table 5 – Comparison of Case Studies 2a and 2b

		Case 2a (SMR)	Case 2b (C3MR)
Main refrigerant		SMR	MR
Precooling refrigerant		None	C3
Ref compressor drivers		Electric	Electric
Refrigerant compressors		1	2
Spec power	kwh/t	363	290
Ref Comp Power	MW	16.2	13.0
LNG	mtpa	0.40	0.40
Power cost	$/kwh	0.04	0.04
Power Cost	$m/yr	Base	Base - $1.1

The differences between these two cases can be summarized as

- The SMR process has one large compressor, while the C3MR process has two significantly smaller compressors.
- The total consumed power of the SMR process is 3.2 MW more than the C3MR process. At USD 0.04/kwh, this is about $1.1 million more per year.
- While this additional power cost is clearly significant, it would not be enough to justify the extra compressor and precooling equipment, which is estimated at USD 6 million.

Therefore, the SMR process is the most economical for this case study, and is the correct process choice of this small LNG facility.

Comment on Case Studies

These studies are admittedly simplified to illustrate some important points in making the right Technical Choices. For a true project, many more factors should be examined to make all of the decisions and ultimately define the train. The case studies of this paper were chosen to highlight some key points, which hopefully the reader finds useful.

CONCLUSIONS

This paper gives the important key technical decisions that should be made when selecting an LNG liquefaction process. It gives possible alternatives for each decision, and discusses the implications of the possible choices. For an actual project, the specific circumstances will have to be used to make the final choices. It is critical to carefully examine the parameters for a project, and consciously make the key technical choices. Arbitrary choices based on intuition or simple comparison to past projects can reduce the project’s overall profitability—or even impact its financial feasibility.

General statements that can be made are

- It is important to carefully choose the constraints and/or limiting unit of the LNG project. Choosing these will have significant implications for other technical choices and decisions.

- Specific Power of the liquefaction train is always important. Lower Specific Power reduces equipment size and increases production. It becomes even more important when the refrigeration compressors are the limiting unit.

Two cases studies are presented that cover two developing trends in LNG liquefaction. The first is a nominal 1.5 to 2 mtpa FLNG, which shows that lower Specific Power dramatically improves the project economics. Interestingly, for the constraints of that case, better Specific Power did not reduce fuel consumption; rather it dramatically increased LNG production. The second case was a mid-size plant, 0.4 mtpa. At this smaller size, the different inputs led to a very different conclusion; the simpler process with higher Specific Power was the most economic choice.

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