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# Natural gas liquefaction using Nitrogen Expander Cycle – An efficient and attractive alternative to the onshore base load plant

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## ABSTRACT

Large scale liquefaction has traditionally been based on vapour compression cycles, using a mixed refrigerant or arranged as a pure component cascade. For marginal fields, offshore production and developments with production in the range of 3mtpa, the simpler nitrogen expander cycle is a serious competitor. For such developments, different engineering and safety requirements demand a different focus to maximising cycle efficiency.

By calculating the overall thermal efficiency, using identical and realistic conditions, for both a base load propane pre-cooled mixed refrigerant plant and an offshore sized dual nitrogen expander plant, a fair comparison has been made. The results show that by including the liquefaction cycle drivers in the efficiency considerations a more accurate picture is given. No significant difference in thermal efficiency between the thermodynamically efficient base load cycle using large industrial gas turbines and the dual nitrogen expander cycle utilising aero-derivative gas turbines was found. Furthermore, for marginal fields, maximising availability is economically superior to investing in minimisation of fuel gas consumption.

In summary, the nitrogen expander cycle can provide a safer, simpler, more reliable and less expensive solution for marginal fields with overall efficiency comparable to the most advanced base load liquefaction schemes currently in operation.

# Natural gas liquefaction using Nitrogen Expander Cycle – An efficient and attractive alternative to the onshore base load plant

The interest for application of offshore liquefaction plants is increasing as the industry becomes aware of the significant value of associated gas, untapped stranded and remote gas fields and excess pipeline gas. Several companies are at this moment racing to be the first to produce LNG offshore, presenting a variety of refrigeration technologies and potential train sizes. Whilst interest for offshore liquefaction increases, opinions regarding the liquefaction technology best suited to handle the challenging engineering and installation demands of an offshore facility are many and varying.

For many years gas expander cycles have suffered from a presumption in the industry of being less energy efficient than vapour compression cycles. This may indeed be the truth if one limits the comparison to only the core cycle thermodynamic efficiency at its optimum efficiency conditions. However, for marginal fields with production capacities in the range of 1.5 - 3mtpa, floating liquefaction using gas expander cycles have become a serious competitor to the well-established large scale base load liquefaction plants. This paper presents study results which show that the assumptions made with regards to gas expander cycles being less efficient than vapour compression cycles can be misleading, and demonstrates that for the efficiency of a liquefaction system to be relevant, both the liquefaction cycle drivers and the associated non-LNG liquid co-production should be included when comparison between cycles are made. Last but not least, it is shown that increased fuel consumption associated with lower efficiencies than the highest available will hardly affect the project economy in most cases.

## Selection criteria for offshore liquefaction plants

Offshore LNG plants have clearly different technical and safety challenges than well-established onshore plants. Restrictions concerning space and weight, and potential future re-location will force engineers to overcome the technical challenges and design a plant prioritising high inherent safety, high availability, flexibility for changing feed gas composition and more frequent start and stops compared to onshore plants.

Onshore LNG facilities are today characterised by high total production capacities typically producing 3 – 8 mtpa per train. Potential offshore LNG plants are planned in small to medium train sizes, typically 0.5 – 3 mtpa, with a few exceptions.

### Gas expansion cycles

For small to medium sized liquefaction plants, gas expansion cycles show great potential generally, and especially for offshore facilities. A nitrogen gas expansion cycle has the advantage of using a non-flammable single phase refrigerant, which makes the cycle robust to motion and easy to start up and operate, whilst at the same time providing a high inherent level of safety. The main disadvantage of a gas expander cycle is lower thermodynamic efficiency and larger volumetric flow rates of refrigerant, compared to a vapour compression cycle.

### Vapour compression cycles

In a vapour compression cycle the refrigerant is continuously undergoing phase transition throughout the cycle. Vapour compression cycles used for large scale natural gas liquefaction exclusively use hydrocarbons as refrigerant, either as pure components in separate cycles arranged as a cascade, or as mixtures arranged in one or more separate sub-cycles. It is also common to use multistage single component pre-cooling of a multicomponent vapour compression cycle. Vapour compression cycles have the advantage of having high thermodynamic efficiency; however, optimum efficiency often requires that the operation of the cycle and the composition of the refrigerant are tailored according to the actual feed gas composition. On the negative side, the refrigerant cycle will constitute a large on-site inventory of flammable refrigerant at high pressures, which results in safety challenges. The use of both vapour, liquid and 2-phase flows in the same cycle will cause the design of a compact offshore process plant to become challenging.

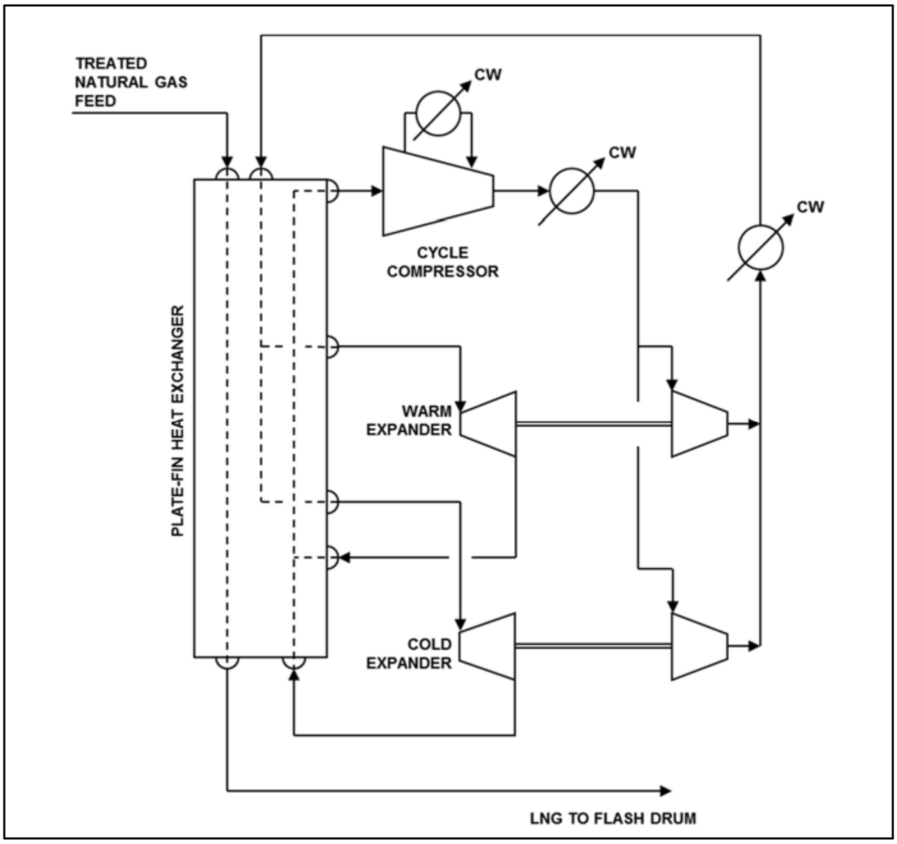


Figure 1 Typical flow scheme of a dual nitrogen expander cycle.

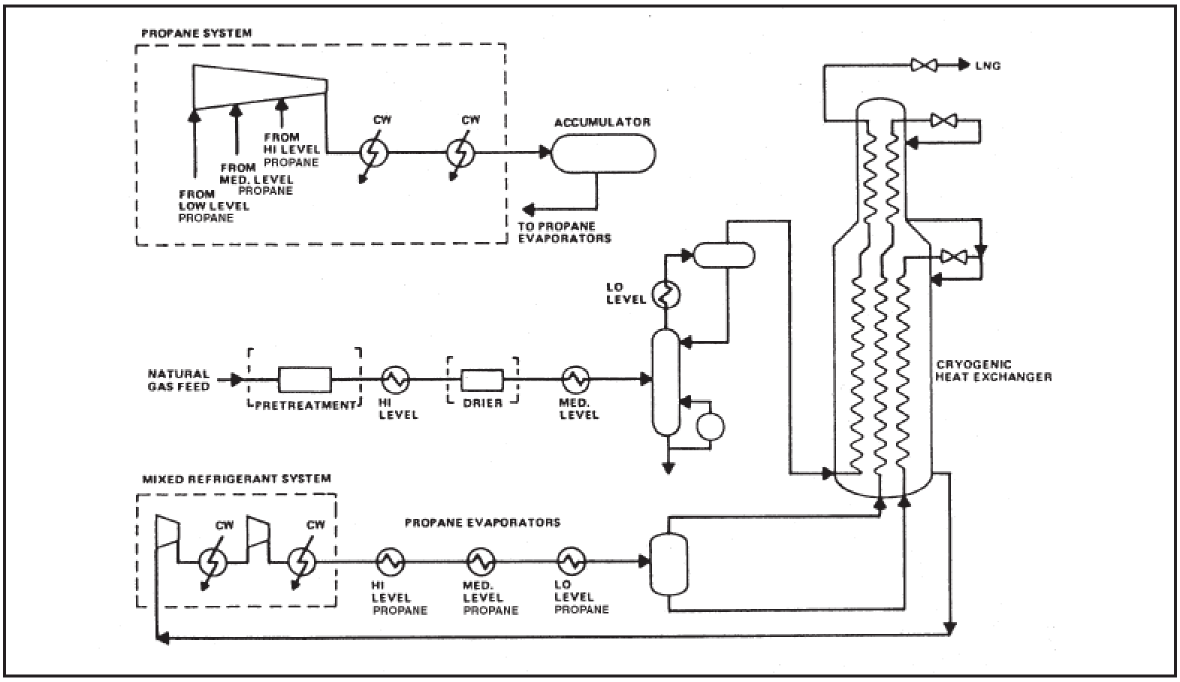


Figure 2 Typical flow scheme of a propane pre-cooled mixed refrigerant process [1].

## Liquefaction plant efficiency

In natural gas liquefaction there are at least three efficiency definitions that can be used to benchmark and compare different liquefaction technologies:

- Specific power consumption (kWh/LNG, or kWd/tonnes LNG)
- Thermodynamic efficiency
- Thermal efficiency

The calculated efficiency of a liquefaction cycle is highly influenced by where the boundary of calculations is set. Natural gas may undergo energy consuming compression upstream liquefaction, or a potential high liquid bi-production may need power for stabilisation and recycling. Because of the large influence the boundary lines hold, the scope included in the efficiency calculations should be clearly stated when numbers are published. Unfortunately, numbers are often compared on unequal terms.

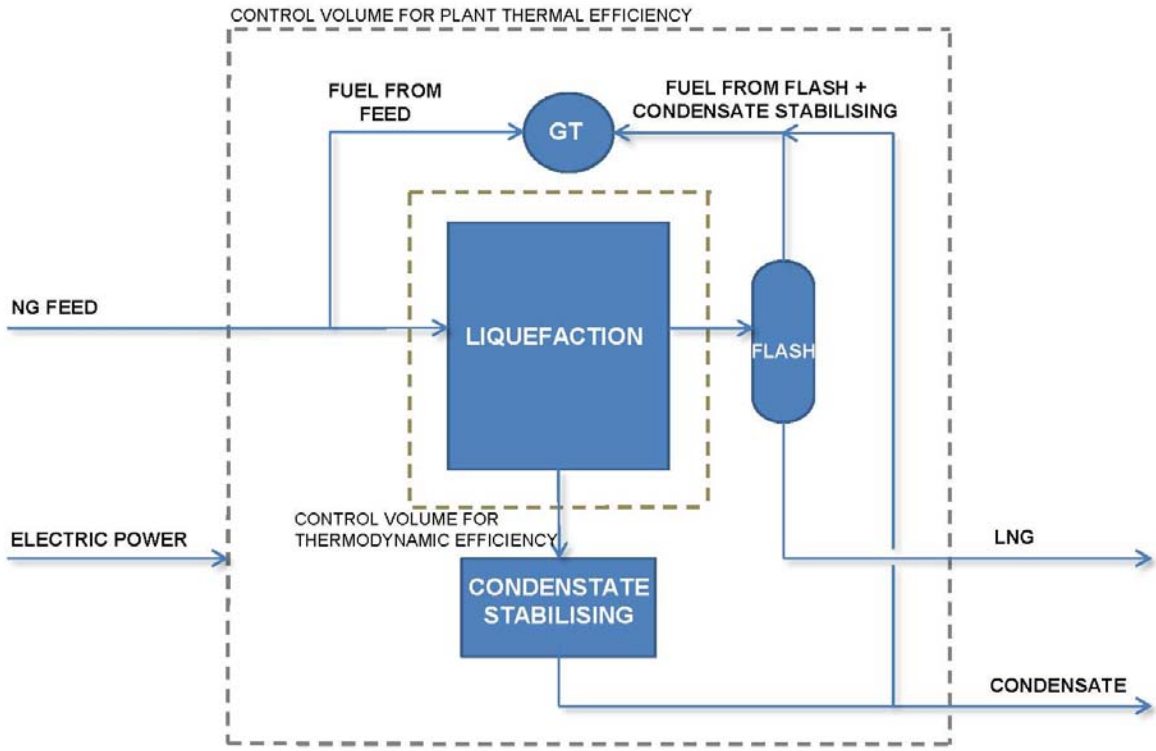


Figure 3 Figure demonstrating theory behind thermal and thermodynamic efficiency calculation.

### Specific power consumption

Specific power is the most common representation of a liquefaction cycle's efficiency. The specific power is defined as the ratio of the total axle work of the compressors to the amount of produced LNG. Specific power is strongly dependent on ambient conditions and other prevailing liquefaction conditions. As such, in order to be comparable, specific power figures must be supported by the liquefaction conditions and the ambient conditions. [2]

$$Specific\ Power = \frac{W_s}{\dot{m}_{LNG}} \quad (1)$$

Where:

$W_s$= Total axle work for refrigeration compressors, [kW]
$\dot{m}_{LNG}$= LNG rundown production after end flash, [Kg/h]

## Thermodynamic efficiency

Thermodynamic efficiency is defined as the exergy change (minimal amount of work needed to cool the natural gas to a desired temperature) to the total axle work of the compressors. The refrigeration temperature span of the cycle must be minimised to be able to maximise the thermodynamic efficiency. For a natural gas liquefaction plant, where the refrigerant must remove heat within wide temperature ranges, heat must be extracted at a highest possible refrigerant temperature at any stage in order to maximise the efficiency as per Equation (2).

$$\eta_{thermodynamic} = \frac{\Delta B}{W_s} = \frac{\Delta H - T_0 \Delta S}{W_s} \quad (2)$$

The change in exergy is the minimal amount of work needed to cool natural gas to desired temperature,

Where:

**η** = thermodynamic efficiency
ΔH or Δh = Intensive or extensive change in enthalpy [KJ/kg or KJ/h]
ΔB or Δb = Intensive or extensive change in exergy [KJ/kg or KJ/h]
ΔS or Δs = Intensive or extensive change in entropy [KJ/kg or KJ/h]
Ws = Total axle work for refrigeration compressors [kJ/Kg] or [kJ/h]
T0 = Cooling medium temperature [K]

Thermodynamic efficiency is, in contrast to specific power, independent of ambient conditions and is therefore a more preferred representation of the inherent efficiency of a cooling cycle. It is claimed to be the optimal for comparison of a liquefaction cycle`s isolated efficiency, but does not provide a representative picture of the complete liquefaction system or installation’s ability to produce LNG with minimum loss of energy. Unfortunately, data on a liquefaction cycle’s thermodynamic efficiency is rarely seen in the public domain, if any information at all. [3]

## Thermal Efficiency

Thermal efficiency is defined as the ratio between heat flow of the valuable products of the system and the heat flow of feed stock fed into the system. Provided that the heat flow is considering usable energy, and that fuel for the liquefaction cycle drivers is taken from within the considered system, the heat flows can be represented by the Higher Heating Value (HHV) of the valuable products to the Higher Heating Value of the natural gas feed. The thermal efficiency is affected by the cooling cycles` thermodynamic efficiency, but also by various other factors as gas composition, amount of bi-product liquids (condensate/NGL), and the efficiency of the power generation for the cooling cycle compressor.

$$\eta_{thermal} = \frac{HHV\ Product}{HHV\ Feed} = \frac{HHV\ Product}{HHV\ Product + HHV\ Fuel} \quad (3)$$

The setup can be used to estimate the entire plants` thermal efficiency, where all energy and power consumers are considered in the calculation. However, for benchmarking and comparison of liquefaction cycles, the evaluation can be limited to comprise only the power consumption required to operate the liquefaction cycle. [2] [4]

Assuming that natural gas is used as fuel in power generation, thermal efficiency expresses how much of the feed is recovered as product, and how much is lost during processing. **Therefore, thermal efficiency is the most optimal representation of the entire liquefaction system efficiency.**

## Impact of bi-produced liquids on efficiency

Frequently liquid bi-products are produced in addition to LNG production. The liquid bi-products extracted as part of the liquefaction cycle are usually recovered in the higher temperature ranges of the liquefaction process, but will inevitably consume parts of the available refrigeration duty and thereby decrease liquefaction efficiency in line with the definitions above.

In those cases where the liquefaction plant produces significant amount of secondary liquid product, e.g. condensate or LPG, and where the separation of these liquids is partly of fully assisted by refrigeration duty from the main liquefaction cycle, the bi-produced liquids should be considered in the efficiency calculation. There are many ways to assess the produced bi-products in efficiency calculations. One can:

- Choose to neglect it as a product
- Exclude it from the natural gas feed
- Include it as a valuable bi-product along with LNG

How the bi-products are considered may affect liquefaction cycle efficiencies significantly, but how it is best handled will depend on the overall processing scheme.

In a case with relatively low or moderate bi-product flow rates, and where downstream processing of the bi-product will not require an extensive amount of additional power, the bi-products can be included as a valuable product without significant impact on efficiency. For thermal efficiency this can be shown according to Equation (4).

$$\eta_{thermal} = \frac{HHV\ LNG + HHV\ Condensate}{HHV\ Feed} \tag{4}$$

However, in cases with high production of liquid bi-products, considering the bi-products in the efficiency calculation will give a larger impact on efficiency and potentially overestimate the efficiency.

In order to ensure a reliable comparison of liquefaction cycles when the upstream conditions are unequal, as is often the case, **overall plant thermal efficiency is the most truthful frame of reference** as it accounts for the entire plant energy consumption and potential heat recovery applications, and reflects the value of products in relation to the value of the feed.

## Drivers of liquefaction cycles

Compressors in natural gas liquefaction plants are historically driven by industrial gas turbines or electrical motors. Large scale liquefaction plants are almost exclusively powered by gas turbines, with only the Snøhvit liquefaction plant in Hammerfest, Norway considered to be an exception.

## Industrial gas turbines

Industrial gas turbines are so far the most used drivers for LNG plant compressors. They are well tested and come in various sizes with ISO ratings up to 130 MW, and thermal efficiencies typically between 28 and 38%. On the negative side they are large and comparatively difficult to maintain and operate due to their size. Power output decreases moderately with falling temperature, 0.7% / °C. [2]

## Aero-derivate gas turbines

Aero-derivative gas turbines are developed from aircraft engine technology. They have a higher thermal efficiency than industrial gas turbines, typically up to 42%, and have typically improved reliability and availability compared to industrial gas turbines. The power output ceiling for available aero-derivative gas turbines is much lower than the limit for industrial gas turbines, so multiple gas turbines/compressors in parallel may be installed to achieve required power demand. However, they require less maintenance downtime and have a much reduced footprint and weight compared to equivalent industrial machines. They are simple in operation and well suited to the demands for the oil and gas industry, which is why they are the preferred type of gas turbine for power generation offshore. There is also a growing interest for use of aero-derivative gas turbines for onshore liquefaction. Aero-derivative gas turbines typically require higher fuel gas quality than industrial machines with power output decreasing typically with 1.2% / °C. [2]

## Steam turbines

Steam turbines have been applied as drivers in early base load liquefaction plants, but are uncommon today. The steam and associated cooling medium system require a large space, are generally complex and the simpler arrangements provide relatively low efficiencies. They have the advantage of being reliable and highly flexible in accepting varying and low quality fuels, but do not offer “free” additional heat.

## Electric motors

Electric motors theoretically can be made large, but very few references above 50MW can be found. The larger motors require a complex electrical system for start-up and control. They offer a high thermal efficiency, but there may be substantial losses related to the associated power control system, transmission grid and generator. Electrical drivers have less maintenance demands than gas turbines, and as such their availability is higher. Their power output does not decrease with ambient temperature.

In a liquefaction plant, electric motors can get power from an electrical power grid, or from site located generators, which again can be driven by gas turbines or steam turbines, resulting in a lower overall efficiency compared to gas turbines with direct compressor drive.

# Comparison of thermal efficiencies for a base - load liquefaction cycle using industrial gas turbines and medium scale cycle using aero-derivative gas turbine

A theoretical study was done in order to simulate, optimise and compare two fundamentally different liquefaction systems, subject to identical conditions and machinery efficiencies. The following liquefaction cycles were reviewed:

- A propane pre-cooled mixed refrigerant cycle utilising two industrial gas turbines GE Frame 6 and Frame 7
- A dual nitrogen expander cycle utilising one LM6000 aero-derivative gas turbine

The cycle configurations may deviate from commercially available cycles, but are assumed to be representative within reason for this purpose.

## Conditions and assumptions

The following process parameters were specified as constant and identical for principally equivalent equipment and operations:

*Efficiencies of the following equipment:*

- Compressors
- Expanders

*Pressure drops:*

- Heat exchangers
- Principal piping segments

The following assumptions and simplifications were made:

- Ambient conditions were assumed such that process cooling to 25°C would be feasible without refrigeration.

- Natural gas was assumed to be pre-treated and enters the liquefaction plant at 65barg and 25°C. The dry gas composition in % mole fractions is listed in Table 1.

- Heavy hydrocarbon separation was integrated as part of the liquefaction cycle and identical for both cases.

- For simplicity, ISO rated power output for gas turbines were used. No turbine de-rating and losses were considered, this is ideal and affects the resulting production capacity figures, but the results will indeed be comparable. See Table 3 for gas turbine details.

- The product specifications used are listed in Table 2.

- Heat for condensate stabilisation was assumed as “free” due to being provided from waste heat recovery.

- Power for end flash gas re-compression and condensate stabiliser overhead re-compression is generated at 40% efficiency.

**Table 1 Composition of dry natural gas.**

| Gas Compositions (dry basis) in % mole fractions | |
|---|---|
| Nitrogen | 0.37 |
| CO2 | 0.19 |
| Methane | 90.15 |
| Ethane | 5.75 |
| Propane | 1.93 |
| i-Butane | 0.40 |
| n-Butane | 0.47 |
| i-Pentane | 0.2 |
| n-Pentane | 0.14 |
| n-Hexane | 0.15 |
| Benzene | 0.0090 |
| n-Heptane | 0.13 |
| n-Octane | 0.0075 |
| n-Nonane | 0.0026 |
| n- Decane | 0.0017 |

**Table 2 Assumed product specifications used in both simulation cases.**

| LNG Specification | | |
|---|---|---|
| Max HHV (GHV) | [Btu/scf] | 1140 |
| Max C5+ | [ppmv] | 1500 |
| Max N2 | [vol%] | 1.0 |
| Max Benzene | [ppmv] | 1.0 |
| **Condensate Specification (40 °C storage temperature)** | | |
| Max TVP @ Storage temperature | [bara] | 0.95 |
| Max RVP @ 100 deg F (37.8°C) | [psia/bara] | 12/0.827 |

**Table 3 List of gas turbines used in the study [5].**

| Manufacturer | Series | Gas turbine | ISO Rated Power (*) [MW] | Efficiency [%] | Weight (**) [tonnes] | |
|---|---|---|---|---|---|---|
| General Electric | | LM6000 | 43.7 | 41.9 | 31 | Aero derivative |
| General Electric | Frame 6 | MS6001B | 43.5 | 33.3 | 96 | Industrial |
| General Electric | Frame 7 | MS7001EA | 87.3 | 33.1 | 121 | Industrial |

(*) Values are based on mechanical drive at ISO conditions.

(**) GT skid without enclosure

## Simulation and optimisation method

Each refrigeration cycle was built and optimised in AspenTech HYSYS. Starting points for optimisation were based on available literature and in-house knowledge. An optimisation method developed in-house was used to seek a combination of process variables providing the highest available efficiency for each cycle. A final step of optimisation was completed using the HYSYS Optimiser.

## Results

Table 4 presents the results of the study, and since all liquefaction conditions are identical, a valid comparison can be made for the two liquefaction cycles.

- Thermodynamic efficiency calculated based on inner control volume of Figure 1
- Thermal efficiency calculated based on outer control volume of Figure 1, including power for end flash gas and stabiliser overhead re-compression
- Specific power consumption calculated by only considering liquefaction cycle compressors

The liquefaction cases had only a small bi-production of secondary liquids which could be stabilised into condensate. The thermodynamic and thermal efficiencies presented below are not considering this liquid, in that the respective heat flows and enthalpy and entropy flows were excluded from the natural gas feed upstream liquefaction. The effect of considering the bi-produced liquid is discussed later.

**Table 4 Comparison of key parameters from the optimised simulated propane pre-cooled mixed refrigerant cycle and the dual nitrogen expander cycle.**

| | Unit | Propane pre-cooled mixed refrigerant cycle | Dual nitrogen expander cycle |
|---|---|---|---|
| Gas turbine | [-] | LM7001EA and MS6001B | LM6000 |
| Average thermal efficiency of driver | [%] | 33.2 | 41.9 |
| Production capacity per train | [mtpa] | 4.35 | 1.11 |
| Thermodynamic efficiency | [%] | 40.9 | 28.8 |
| Specific power consumption for liquefaction cycle | [kWh/Kg LNG] | 0.243 | 0.345 |
| **Thermal efficiency** | **[%]** | **94.7** | **94.3** |

As one can see from the table there are significant differences in inherent efficiency between the two cycles. The propane pre-cooled mixed refrigerant cycle has a lower specific power consumption and higher thermodynamic efficiency than the dual nitrogen expander cycle. However, because of the fundamental differences of the driver efficiencies, the resultant difference in the liquefaction cycles thermal efficiency is insignificant.

*Impact of bi-produced liquids on efficiency:*

Above, the bi-produced liquid amount was small and the effect on the efficiencies was assumed to be minor.

In order to see if this assumption is valid, the efficiencies were re-calculated considering the liquid bi-product.

- Thermodynamic efficiency considering enthalpy and entropy of the non-stabilised liquid bi-product
- Thermal efficiency considering condensate as a product

The numbers presented in Table 5 below display the impact of bi-produced liquids on thermal and thermodynamic efficiency for the dual nitrogen expander cycle. It can be seen that the efficiency increases slightly, but due to relatively low bi-product flow rate the impact is not significant. However, care must be taken when comparing liquefaction cycles where the amount of bi-produced liquid is higher.

**Table 5 Impact of bi-produced liquids on thermal efficiency for the dual nitrogen expander cycle.**

| | Unit | Excluding bi-produced liquid | Including bi-produced liquid |
|---|---|---|---|
| Thermodynamic efficiency | [%] | 28.8 | 31.4 |
| Thermal efficiency | [%] | 94.3 | 94.4 |

## Liquefaction efficiency and effect on project economy

As pointed out above, the thermal efficiency is the most sensible way to compare different liquefaction technologies. Furthermore, it has been highlighted that only the overall plant efficiency will provide a true picture of the fuel consumption. In such case, energy used for pre-treatment, NGL and condensate plant, utility systems, marine systems and domestic power and heat must be taken into consideration.

The questions that arise are: what is the cost of fuel gas and how is the fuel contributing in the net present value calculation? How much extra investment cost would be reasonable to consider for lower feed gas shrinkage?

For a stranded gas field developed with a single liquefaction plant for processing all recoverable reserves, the value of the fuel will be equal to the sales value of LNG at the end of the production time. Assuming that only highly efficient drivers are being used, the most efficient liquefaction process will give typically 30% lower fuel consumption than the less efficient gas expander cycles. This difference corresponds to typically 2-3 % of the plant total feed gas flow.

In order to explore the effect on the economy of an offshore LNG project, simplified present value calculations were carried out. The following assumptions were used:

- Reserves: 2.5 TCF
- Gas price paid by the project: 0 (stranded gas)
- Asian market LNG sales price: 13 USD/MMBtu
- Liquefaction floater CAPEX: 1000 USD per ton per annum (tpa) (ship + plant)
- Subsea CAPEX: 500 MMUSD
- OPEX and other cost: 3% of initial CAPEX per year
- Reference liquefaction efficiency: 94.4% thermal efficiency for nitrogen expander plant
- Fuel consumption, other users: 2%

The internal rate of return was set to 15%, which is somewhat higher than used in many oil projects. However, the technical and commercial risks for an offshore liquefaction project are considered to be higher than for a traditional oil project, and support for 15% can be found, e.g. in reference [6].

The reserves of 2.5 TCF will nominally give a production time of around 25 years, using a liquefaction plant with nominal capacity of 2 mtpa. This figure will change slightly depending on feed shrinkage due to fuel consumption, and availability. An initial CAPEX for the liquefaction plant of 1000 USD per ton per annum is in the lower range of recently published costs for offshore liquefaction projects [7].

## Constant design production capacity

The first scenario is for plants of identical production capacities. Results are shown in Figure 4 and Figure 5. The reference case, a dual nitrogen expander plant with thermal efficiency of 94.4%, will provide a production time of 24 years and an overall project present value of 4550 MMUSD. The availability is assumed to be 95%. A development based on a 30% more efficient technology, and identical capacity, availability, and capital cost, would give 6 months longer production time due to reduced feed shrinkage, and an overall project present value of 4566 MMUSD. **The additional economic value of 30% better efficiency is thus only 0.4% over the field lifetime.**

The additional 0.5 years of production is actually only worth 17 MMUSD in an overall project economic perspective. Subject to these constraints and assumptions, clearly there should not be much incentive to invest more CAPEX in order to boost efficiency, if this was required to achieve the higher efficiency.

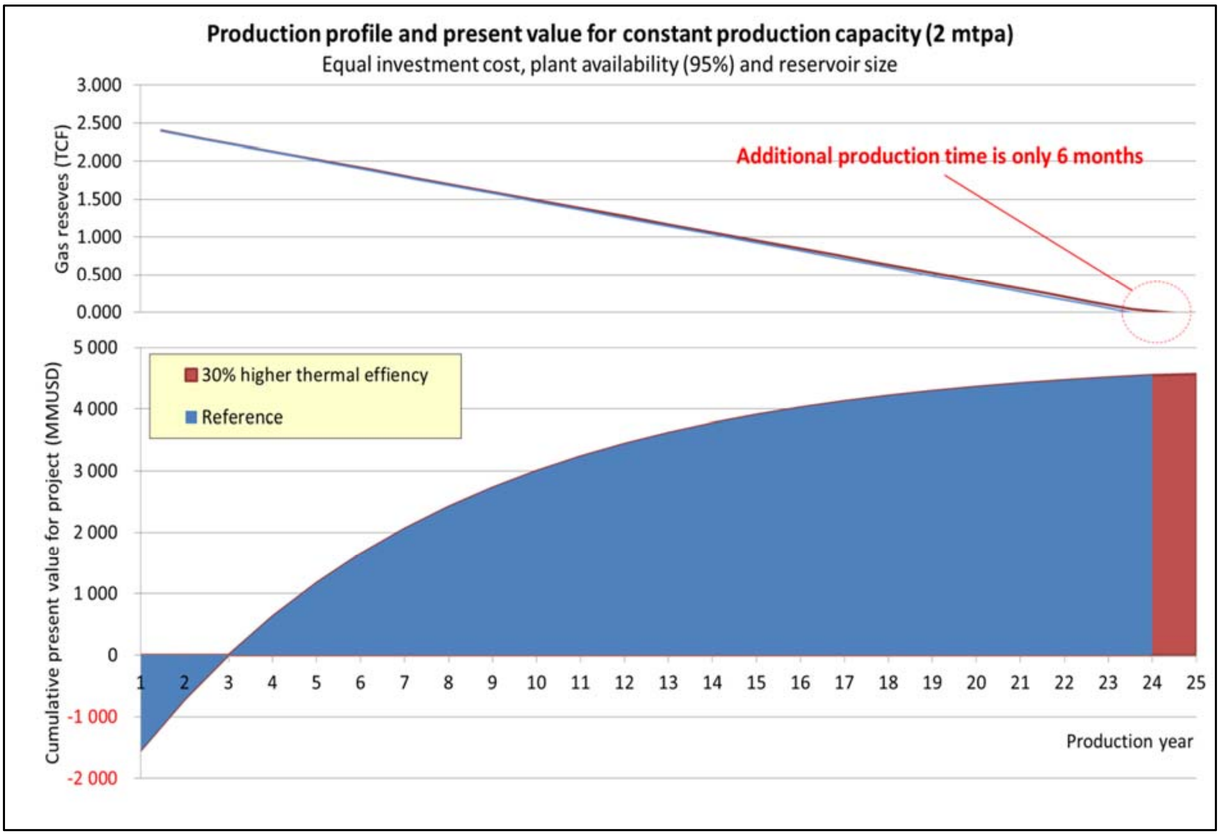


Figure 4 Production profile and present value for constant production capacity.

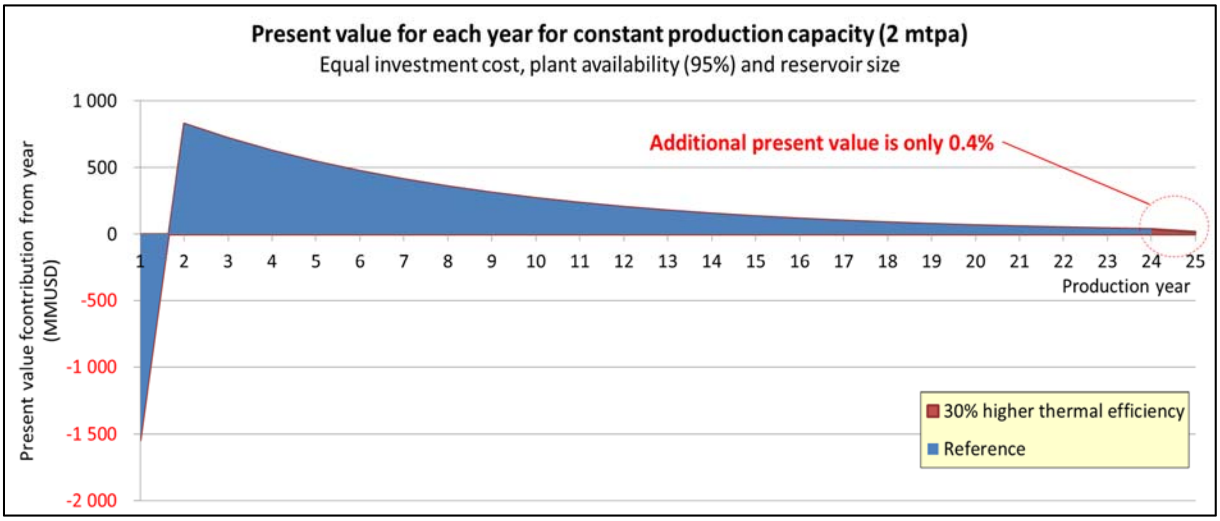


Figure 5 Cumulative present value for constant production capacity.

## Constant feed flow

A relevant scenario would be that of fixed plant design feed flow; this could be due to design limitations of wells, subsea installations and flow lines, or any upstream processing facility, e.g. an oil/gas/water separation platform or FPSO.

If the liquefaction installation total feed flow is limited, the scenario would be that the less efficient plant will have slightly less LNG production, as it consumes more of the feed. Subject to equal availability, the production time will be exactly the same for the two alternatives, as the reservoir flow will be identical. The 30% more efficient plant will produce an equivalently larger product flow due to less fuel consumption, and generate more revenue over the entire production period. For a feed flow equivalent to 2 mtpa, **the present value of the extra revenue for the efficient plant will only be 2.1% larger.** Furthermore, only 4% additional CAPEX for the liquefaction floater (plant + ship) can be justified for additional investments required to achieve 30% extra efficiency. The present value for the project is shown in Figure 6.

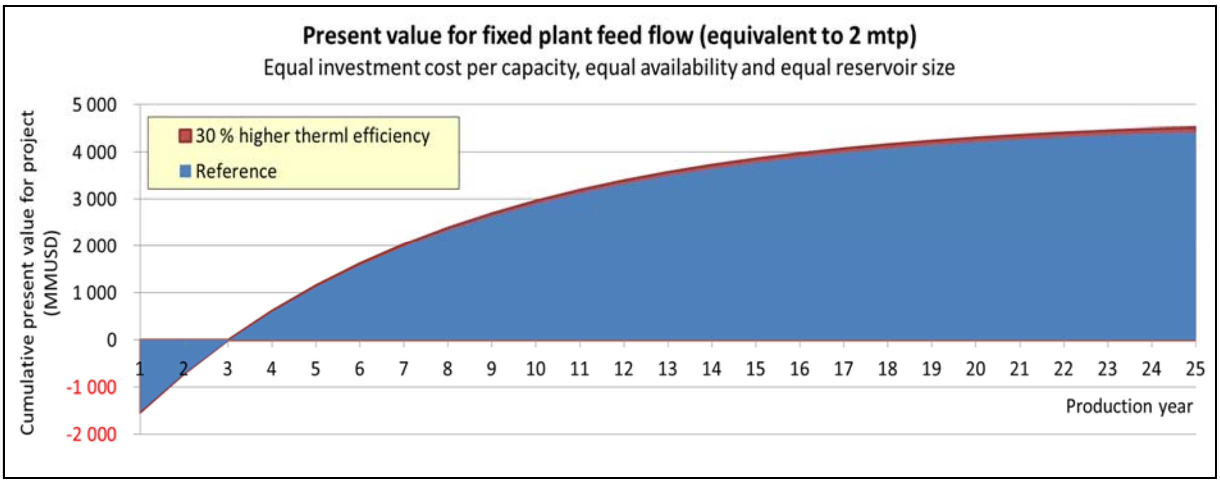


Figure 6 Cumulative present value for constant feed flow to liquefaction installation.

## Availability

The availability will affect the present value of the project, in that it affects the revenue for each year of production. Reduced availability also extends the production time, such that the last part of the reserves will be sold later and generate less present value.

The economics of two similar plants with constant design capacity (2 mtpa) and investment costs, but different availability is shown in Figure 7. The availability reduction, from 95% to 93%, will give almost 3% less present value for the overall project. The reduction in initial liquefaction floater CAPEX (plant + ship) to justify this reduced availability is minimum 5%. Alternatively, you can invest maximum 5% more CAPEX to recover the availability. Hence, high inherent availability is important for the economy, since the project economy only allows for a relatively small additional investment to recover availability.

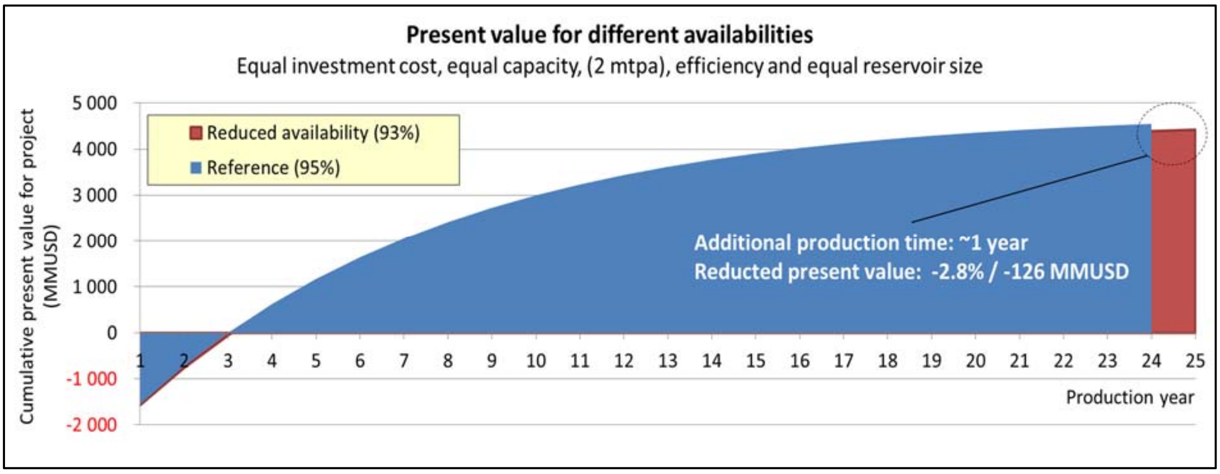


Figure 7 Cumulative present value for different availability.

## Plant capacity

From an economic perspective there will be no doubt that for a fixed size gas source, a higher production capacity will generate higher present value since the revenue will come earlier in the project.

The efficiency of the plant will contribute similarly also in case of higher plant capacity. It is often claimed that a higher cycle efficiency will allow for larger plant capacity for a given gas turbine driver. This may be indeed be true, however, this can only be used as a credible argument if the less efficient plant, e.g. the nitrogen expander plant, cannot be installed with a similar higher capacity by using more parallel trains or larger drivers, and to the same installed cost per capacity. Since most liquefaction technologies suitable for the small and mid-size range can consider multiple parallel trains, the economy vs capacity consideration reduces into a CAPEX consideration only.

# Emissions

The liquefaction cycle efficiency (thermodynamic or specific power) will not affect the plant emissions directly. Only when the driver or power supply is taken into consideration, the emissions to air can be quantified.

The thermal efficiency will be a suitable basis for qualitatively or quantitatively expressing $CO_2$ emissions. As demonstrated above, there will hardly be any significant differences in thermal efficiency between the base load cycle using a propane pre-cooled mixed refrigerant cycle driven by Frame type gas turbines, and the smaller nitrogen expander cycle driven by aero-derivate gas turbines. As such, there should principally not be any differences in $CO_2$ emissions between an on-shore base load development and one or more smaller floating liquefaction plants using nitrogen expander technology.

However; in the case where an efficient liquefaction technology, e.g. single or cascaded mixed refrigerant technology, is being applied at low to mid-scale, aero derivate gas turbines can be used. In this case there will obviously be reduced emissions of $CO_2$.

A true comparison of environmental impact, including $CO_2$ emission, can however only be achieved if the entire plant efficiency is taken into considerations. In most cases there will be significant contribution to the emissions from the related process systems, utilities, marine systems and domestic usage. These additional fuel consumers will reduce the differences between the state of the art efficient plant and the less efficient nitrogen expander plant, although not completely.

## Conclusion

The study shows that common assumptions made regarding vapour compression cycles being a better choice than gas expansion cycles for natural gas liquefaction with regards to effectiveness can be misleading. The results demonstrate that when the driver of a liquefaction cycle is included in the overall evaluation of the effectiveness of the plant, a simple and safe mid-scale dual nitrogen expander cycle utilising a highly efficient aero-derivative gas turbine can be an efficient alternative to large scale onshore base load liquefaction plants using large industrial gas turbines as drivers.

It is evident that plant overall thermal efficiency is the most accurate representation for comparing liquefaction cycles as both specific power consumption and thermodynamic efficiency can be misrepresentative due to unknown conditions for calculation.

Furthermore, it has been pointed out that for most scenarios the efficiency will hardy affect a project's overall economy, when considering present value. In fact it is more important for the project economy to strive for high availability than high efficiency. The main contributor to increased project economy will be the plant capacity. However; with scalable technology the capacity's contribution to project economy is more a capital investment consideration than an efficiency consideration.

Hence, provided that the capacity of each train is in the range of available equipment sizes for expander cycles, nitrogen gas expander cycles can provide a safe, simple, reliable and low cost offshore solution with overall efficiency comparable to state of the art base load liquefaction.

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