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Thermo-Economic Analysis of Combined Cycle Based Liquefaction Plants

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ABSTRACT

The Design of high thermal efficiency LNG liquefaction plants is of importance to minimize feed usage and to reduce CO_2 emissions. High efficiency becomes important in gas constrained situations where savings in fuel auto consumption of the liquefaction facility can be converted into LNG production. The imposition of a CO_2 taxes will further promote the need for higher energy efficiency. This paper will examine heat integrated combined cycle approaches applied to the ConocoPhillips Optimized Cascade® Process and will address both industrial and aeroderivative gas turbines. Aeroderivative engines offer very attractive efficiencies where comprehensive steam systems are not viable or desired by the end customer. When steam systems are acceptable, a combined cycle type liquefaction facility can be attractive in increasing the efficiency of a simple cycle plant. The paper will examine combined cycle /cogeneration configurations with respect to plant heat to power ratio. An evaluation of a range of technical options for heat recovery including the use of back pressure and condensing extraction steam turbines is first made. Finally conceptual designs for four combined cycle configurations are examined from a thermodynamic perspective.

1.0 INTRODUCTION

LNG train designs currently fall within four classes, having nominal capacities clustering around 1.5, 3.5, 5, and 8 million tonne per annum (MTPA). These designs may coexist in the coming years, as individual projects choose sizes that match their gas supplies, sales, and other logistical and economic constraints. The issue of selection of plant size is covered in a paper by Durr et al (2008), which treats commercial and technical issues. The thermal efficiency of an LNG facility depends on numerous factors such as gas composition, inlet pressure, and other factors such as the location of the loading dock relative to the liquefaction process which impacts the heat leakage into the cryogenic system. Gas turbine selection, the use of waste heat recovery, ship vapor recovery, and the power generation configuration, all have a significant effect on the overall thermal efficiency of the LNG process. Detailed discussions of LNG plant thermal efficiency have been made by Yates (2002) and Ransburger (2007) and studies on combined cycle approaches have been made by van de Lisdonk et al (2010), Tekumalla et al (2007) and Avidan et al (2003).

Market pressures for thermally efficient and environmentally friendly LNG plants coupled with the need for high plant availability have resulted in the world's first application of high performance aeroderivative gas turbines for the 3.7 MTPA Darwin LNG plant utilizing the ConocoPhillips Optimized Cascade® Process[1]. This plant implemented cogeneration by incorporating heat recovery units on four of the six mechanical drive gas turbines in refrigeration service (Meher-Homji et al, 2007). This paper focuses on a higher level of heat integration than that provided at Darwin LNG.

Specific plant and project drivers, operating conditions, project economics and other factors may dictate gas turbine solutions involving either aeroderivative engines or industrial gas turbines, and this paper examines the application of cogeneration (combined use of gas turbine heat and power) to attain efficient designs. Details regarding cogeneration system design may be found in Horlock (1997) and Kehkhofer (2007). Details pertaining to industrial and aeroderivative engines in cogeneration applications may be found in Jacobs and Schneider (2009).

A simplified process flow diagram of the ConocoPhillips Optimized Cascade® Process is shown in Figure 1. In this liquefaction process, multiple mechanical drive gas turbines drive refrigeration compressors that sequentially cool the feed gas until it liquefies at a temperature of -160°C. The applicability of aeroderivative engines to this process was covered in Meher-Homji, et al (2009).

[1] Optimized Cascade services are provided by ConocoPhillips Company, Phillips Technology Services Company and Bechtel Corporation via a collaborative relationship with ConocoPhillips Company. Optimized Cascade, the Optimized Cascade logo, ConocoPhillips and its logo are trademarks of ConocoPhillips Company. Bechtel and its logos are trademarks of Bechtel Group Inc

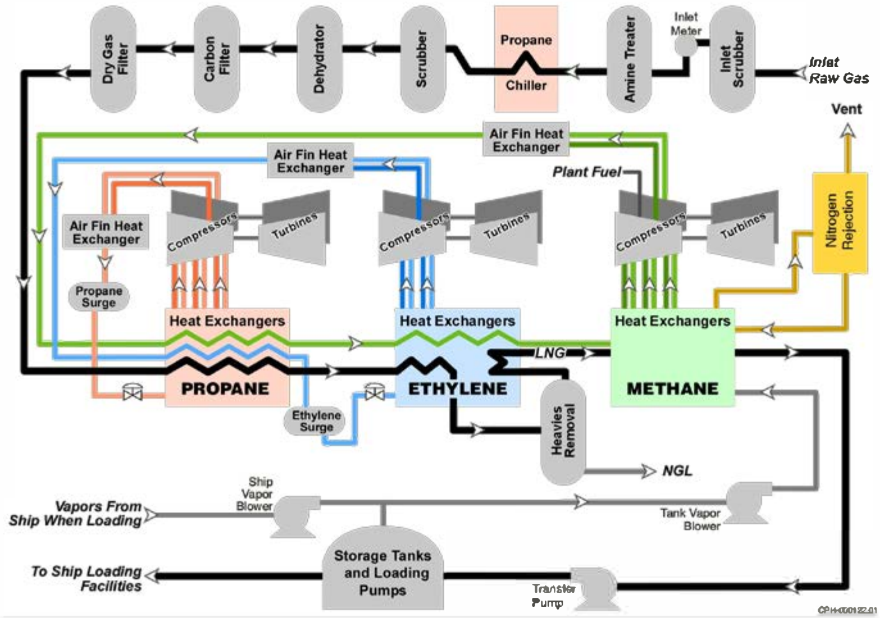


Figure 1. Simplified process flow diagram of the CoP Optimized Cascade® Process.

2.0 GAS TURBINE SELECTION AND SELECTION OF COMBINED CYCLE CONFIGURATION

A plot of thermal efficiency vs. specific work for a large population of aeroderivative and industrial engines is shown in Figure 2 (Meher-Homji et al, 2009). In this figure, the triangles indicate aeroderivative engines. The Pressure Ratio and Turbine Inlet Temperature (°C) is shown for each engine. Typical aeroderivatives used for LNG are clustered in the green ellipse and typical industrial units in yellow ellipse. Aeroderivative gas turbines achieve significantly higher thermal efficiencies than industrial gas turbines. The higher efficiency of an aeroderivative can result in a 3 percent or greater increase in overall plant thermal efficiency. Further, there is an improvement in plant availability as a result of the ability to completely change out a gas turbine gas generator (or even a complete turbine) within 48 hours versus 14 or more days that would be required for a major overhaul of an industrial gas turbine. A discussion of LNG gas turbine options is made in Meher-Homji et al (2007).

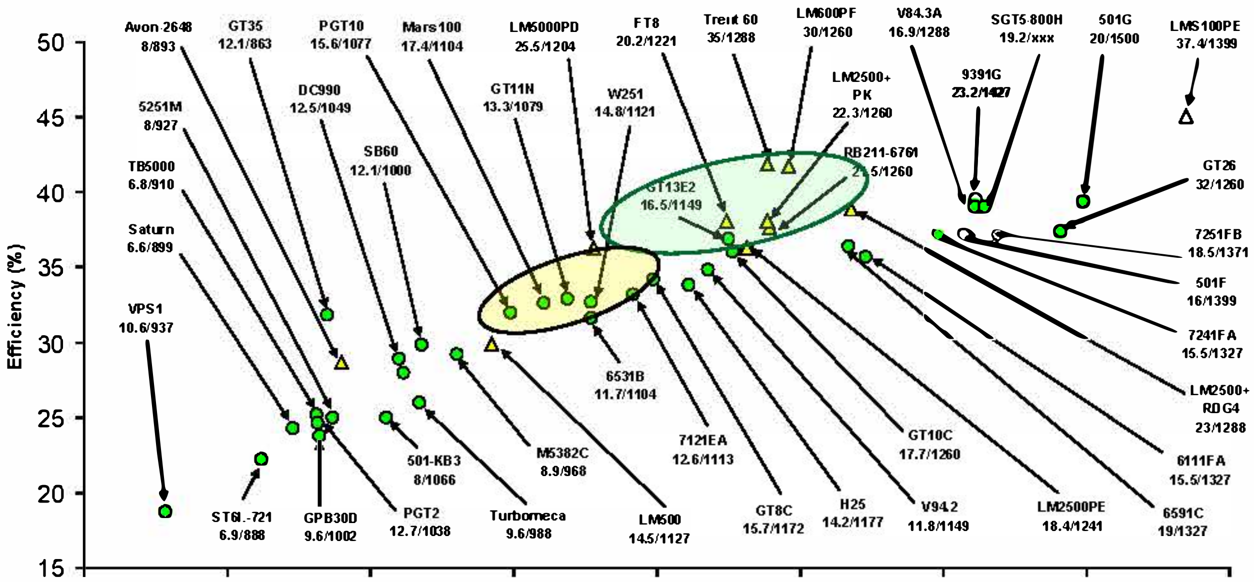


Figure 2. Specific work vs. efficiency for selected engines with associated PR/TIT(°C).

It is often said that there is a convergence of gas turbine technology between industrial and aeroderivative engines. This may be true if advanced industrial turbines are being considered (where the specific work of the engines tend to converge) but in examining common industrial gas turbines used in LNG service (Frame 6B, Frame 7EA, and Frame 9E), these machines tend to operate at a significantly lower pressure ratio and turbine inlet temperature and consequently at lower thermal efficiency. In a situation where simple cycle LNG solutions are desired, the higher thermal efficiency of the aeroderivative makes them more attractive. While aeroderivative engines operate at high thermal efficiencies, they generally operate at high pressure ratios resulting in their having lower net work ratios compared to traditional older industrial gas turbine. The net work ratio is an important parameter that governs both power lapse rate with ambient temperature and also the susceptibility and sensitivity to fouling as discussed in Meher-Homji et al (2009). The net work ratio is defined as the output work of the gas turbine divided by the total turbine work. In high pressure aeroderivative engines which are optimized for higher efficiency, this ratio tends to be lower than industrial machines, making them drop off in output more rapidly with an increase in ambient temperature than traditional industrial gas turbines.

In a combined cycle/ cogeneration context, the thermal efficiency of the engine is of importance as described in Table 1. This table provides an example of the heat recoverable from an unfired heat recovery unit. For example, for an aeroderivative engine with a thermal efficiency of 41%, work output will be 41% of the fuel LHV. The available exhaust energy will be 100-41-1 = 58. Assuming a heat recovery unit efficiency of 70% the steam energy content will be 40.6 indicating a heat to power ratio of 0.99. For an industrial gas turbine with a thermal efficiency of 35% the corresponding heat /power ratio would be 1.46.

Table 1. Gas Turbine Thermal Efficiency and its Impact on Steam Generation (Unfired Heat Recovery Unit). Energy Values are referenced to GT Fuel LHV Energy.

	Aeroderivative Gas Turbine	**Industrial Gas Turbine**
Energy In (Fuel LHV)	100	100
GT Thermal Efficiency	41	35
GT Energy Losses	1	1
Available Exhaust Energy	58	64
HRSG Efficiency	0.7	0.8
Steam Energy Content	40.6	51.2
Heat/ Power Ratio	0.99	1.46

In the overall LNG chain, liquefaction contributes the largest CO_2 footprint (mainly due to the refrigeration drivers and power generation) and accounts for 80% of the CO_2 emission in the LNG supply (Rabeau et al, 2007). Consequently, any ability to reduce CO_2 in the liquefaction plant will have a major impact on overall green house gasses. In simple cycle applications, the reduction by using aeroderivative engines can be between 25-30% compared to traditional industrial gas turbines. A detailed paper by Rice (1987) provided a detailed treatment of the thermodynamics of cogeneration.

Heat Integration and Cogeneration

Each specific LNG project must take a number of factors into consideration to determine the extent of heat recovery that should be utilized based on the cost of energy, CO_2 penalty costs and other project drivers. The use of heat integration has been addressed by van der Lisdonk et al (2010), Kart et al (2005) and Phillips and Solis (2004).

Process heat is typically needed for:

- Acid Gas Removal Unit (AGRU) for solvent regeneration - this is a major user of process heat. The energy consumption for the AGRU could span the range of 2-20% of the overall plant energy demand. Recovered energy could be utilized for AGRU regenerator reboiler duty requirements. The amount of process heat required is a strong function of the CO_2 content in the feed gas to the plant. It is not uncommon for large multi train facilities with high CO_2 content to have heat requirements around $400MW_t$

- Incremental LNG Production (if additional helper motors or steam turbines are to be used) - these are commonly applied to single shaft industrial gas turbines that need a device for starting. For example, a Frame 7EA gas turbine may have a starter helper in the size range of 15-20 MW_e. In the past this starter helper has typically been a variable frequency drive (VFD) motor, though back pressure steam turbines can easily be used thus enabling the possibility of a cogeneration solution.
- Electrical Power Generation- if this is based on steam turbines (or a standalone combined / cogen cycle). The complexities, integration and startup issues have to be carefully studied and weighed in this decision
- Regeneration for dehydration.
- Fuel gas heating
- Stabilization and fractionation of liquids

To summarize, the extent of heat integration (and its associated complexity and cost) have to be carefully weighed against a simpler aeroderivative based solution, which itself can be further enhanced in terms of thermal efficiency if a cogeneration / combined cycle is considered. In any event, whether industrial or aeroderivative engines are considered, combined cycle / cogeneration solutions can enhance efficiency.

3.0 COMBINED CYCLE /COGENERATION CYCLES- SALIENT PARAMETERS FOR DIFFERENT CLASSES OF TURBINES

There are several approaches wherein steam derived from the mechanical drive gas turbines may be used to provide both power and heat for the LNG facility. The full utilization of heat enables a significant improvement of efficiency when low efficiency industrial gas turbine drivers are utilized. A discussion is made of different options relating to gas turbines and various cogeneration options has been studied by Meher-Homji et al (2009) and salient results are outlined here. The treatment focuses on thermodynamic parameters. Additional factors that have to be considered include:

- Plot plan impact- the location of the HRSGs, steam piping and condensers if condensing steam turbines are used
- Pressure levels and Piping considerations- integrating the liquefaction section and the power generation section will call for piping routing to the power block
- Design complexity- the design complexity has to be weighed against increased thermal efficiency
- Transient operation- consideration must be made of transient scenarios such as a liquefaction unit trip, or half plant trips [2]
- Electrical transient considerations
- Startup considerations- very often additional boilers or stand by gas turbine generators may be needed

Levels of Heat Integration

There are multiple levels that can be considered for heat integration in an LNG facility:

- Use of HRSGs coupled to gas turbines to provide process steam (no steam turbines)
- Use of HRSGs to provide process steam and also drive back pressure steam turbines. These turbines could be used for either power generation if aeroderivative engines are considered or as starter helpers if single shaft gas turbines are considered. If aeroderivative engines are used, then using the exhaust heat to produce power and process heat either using a back pressure or extraction condensing steam turbine, keeps the liquefaction block intact (driven totally by gas turbines).

[2] The Optimized Cascade Process can operate at part load with 50% of its refrigeration turbine drivers out of service due to the two trains in one configuration.

- Use of HRSGs to provide steam and condensing extraction steam turbines which can be used for either power generation or as mechanical drivers. For example in the Optimized Cascade® process, in a Two Propane+ Two Ethylene+ Two Methane configuration, steam generated by the four propane and ethylene drivers, can be used in condensing steam turbines to drive the two methane trains. This case is studied in the next section.

The current state of the art of combined cycles and cogeneration systems is very advanced, and several practical considerations can be leveraged successfully into LNG liquefaction plants. Bechtel's Oil and Gas and Bechtel's Power GBU has built over 100 large scale combined cycle and cogeneration facilities and a host of valuable information is available relating to the design and application of such plants. Narula and Zachary (2008) cover several aspects of this experience including experience with site performance of gas and steam turbines. While large scale heat integration is relatively novel in LNG liquefaction, a considerable body of design and operational experience exists in power and industrial cogeneration facilities.

Heat Recovery Steam Generator Considerations

HRSGs can be classified by the orientation of the exhaust gas flow which can be either horizontal or vertical. Typically designs in the USA have tended to be horizontal, while vertical designs are more common in Europe. Both designs offer certain advantages and disadvantages.

Horizontal HRSGs feature natural circulation and for LNG liquefaction service would typically be either one or two pressure levels. Advantages include reduced power requirements and no maintenance of circulating pumps and easier draining of the vertical tubes. A disadvantage is a larger footprint which can impact the LNG liquefaction block plot plan.

Vertical HRSGs are more suited to cycling designs and typically have less thermal inertia. These HRSGs occupy a smaller footprint and in some cases can be located above the gas turbine exhaust. In these arrangements, separate pumps typically assist circulation of the steam and water systems for each pressure level.

Once through steam generators (OTSGs) are becoming popular especially for areoderivative engines and smaller industrial turbines. In a OTSG, preheating, evaporation and superheating of the feedwater takes place consecutively with water being forced through the tubes by a boiler feed water pump. OTSGs do not have steam drums.

In order to increase the HRSG efficiency, it may be desirable to use multiple pressure levels for heat recovery, where the second pressure level produces steam at a much lower pressure than the HP steam level. Single pressure level systems could also be considered for simplicity. Duct firing to moderate levels (up to 800°C) [3] could also be considered to help in the additional generation of steam or to manage varying heat load requirements. Duct firing is very common place in power applications. Details relating to the optimization of HRSG designs may be found in Pasha (1991).

Back Pressure and Condensing Steam turbines.

Characteristics of back pressure steam turbines (BPST) compared to condensing steam turbines (CSTs) include:

- Simple configuration with few components
- Larger turbine than a CST for the same output
- The costs of expensive low pressure stages of the turbine are avoided
- Low capital cost compared to CST
- Reduced or even no need of cooling water

When used as a starter helper a back pressure steam turbine would be a better fit given its simplicity and ability to start rapidly compared to a condensing steam turbine. For power generation however, condensing steam turbines may be advantageous. If condensing extraction steam turbines are selected care must be taken to limit the extraction to a reasonable limit to avoid design complexities that would occur during off design operation.

[3] This level of duct firing would not call for special metallurgy.

Heat Requirements and Heat/ Power Ratio in LNG Liquefaction Facilities

The extent of process heat required is a strong function of the concentration of acid gas contaminants in the feed gas and the process heat required for the AGRU. The required process heat to power ratio for the facility is an important parameter and impacts the type of gas turbines selected and the heat recovery equipment and approaches used. Aeroderivative engines have higher thermal efficiencies around 40% and this means that the capability to raise heat in an *unfired* HRSG is lower than an industrial gas turbine commonly used in LNG mechanical drive service that have thermal efficiencies around 32-33%. Typical Heat/Power ratios for aeroderivatives are around 0.9- 1.0 while those for industrial engines are higher- around 1.4-1.5. These values are without supplemental firing and can be significantly increased by the use of supplemental firing.

Combined Cycle – Cogen Analysis

All cogeneration systems, if properly designed, save fuel energy, because they have higher efficiency than the efficiency of separate production of electricity and heat. To evaluate different types of cogeneration options, two types of gas turbines were selected that could be used for LNG applications. The LM6000PF was selected as a high efficiency aeroderivative and the Frame 6B was selected as a representative industrial gas turbine. The analysis was done considering a single gas turbine, recognizing that a LNG plant in the 4-5 MTPA range would consist of a total of 6 gas turbines, nominally in a 2+2+2 combination. The analysis below is to obtain an overview of the cogeneration / combined cycle capability of the two classes of gas turbines.

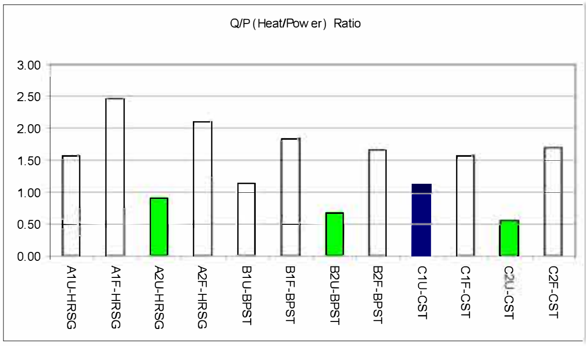
Three cases: A (HRSG only) B (Back pressure Steam Turbine), and C (condensing extraction steam turbine) have been considered with Frame 6B (designated as 1) and LM6000PF (designated as 2). The last letter in the case designator represents an unfired (U) or supplementary fired (F) case. In each case, a thermal design has been carried out using Thermoflow® software[4]. The goal of this analysis is to get a feel for the efficiencies of the various configurations and to see what types of heat to power ratios are attainable. Cases are defined in Table 2.

Table 2. Cogeneration Cases Evaluated.

CASE	Description A= HRSG only, B= BPST, C= CST
A1U-HRSG	Frame 6B with HRSG - steam for process
A1F-HRSG	Frame 6B with HRSG, with supplemental firing
A2U-HRSG	LM6000PF with HRSG- steam for process
A2F-HRSG	LM6000PF with HRSG with supplemental firing
B1U-BPST	Frame 6B with HRSG and BPST
B1F-BPST	Frame 6B with HRSG, and BPST with supplemental firing
B2U-BPST	LM6000PF with HRSG and BPST
B2F-BPST	LM6000PF with HRSG with supplemental firing and BPST
C1U-CST	Frame 6B with HRSG and CST
C1F-CST	Frame 6B with HRSG, with supplemental firing and CST
C2U-CST	LM6000PF with HRSG and CST
C2F-CST	LM6000PF with HRSG with supplemental firing and CST

The simulations were conducted for an ambient temperature of 26°C and typical site conditions. The heat/power ratios derived are shown in Figure 3. As expected, the aeroderivative solutions tend to have lower heat to power ratios (compared to industrial gas turbines) when no supplemental firing is used, but this difference diminishes when supplemental firing is used. The Combined Heat and Power (CHP) efficiency for the different configurations is shown in Figure 4.

[4] GTPRO® and GTMASTER® (www.thermoflow.com)



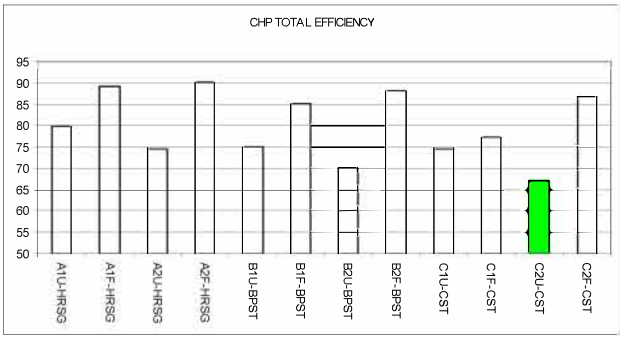
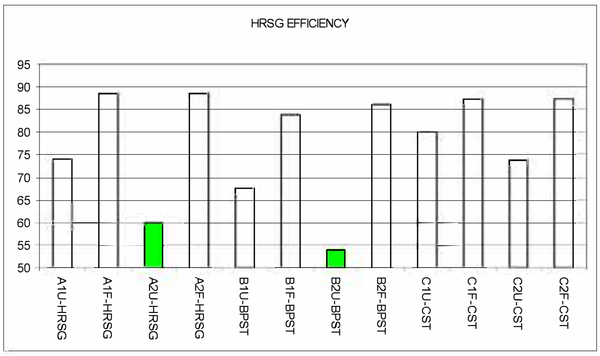


Figure 3. Heat / Power Ratio for Different Configurations   Figure 4. CHP Efficiency (%) for Different Configurations.

The HRSG efficiency for the different configurations is depicted in Figure 5. The HRSG efficiency is the ratio of the energy transferred to water and steam divided by the available sensible heat in the GT exhaust plus the LHV energy of supplemental firing if applicable. As expected, the lower exhaust temperature of an aeroderivative engine results in a lower level of heat recovery in an unfired HRSG, though with supplemental firing, both gas turbines types tend to have similar HRSG efficiencies. The CO_2 generated per MW-hr values are shown in Figure 6. As expected, the aeroderivative engines are superior, though supplementary firing increases the CO_2 generated in all cases.



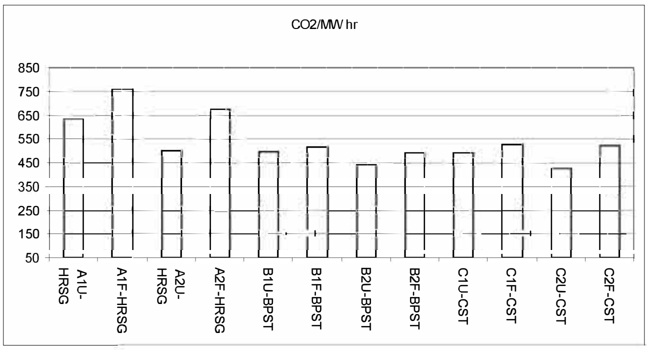


Figure 5. HRSG Efficiency (%) for Different Configurations.   Figure 6. CO_2/MWhr for Different Configurations.

A graph showing the power efficiency (power produced by the gas turbine and steam turbines) on a LHV basis is shown in Figure 7. In all cases the aeroderivatives power output efficiency is superior compared to an industrial engine.   In comparing this with Figure 4, it can be seen that supplemental firing increases the CHP efficiency, but as expected, the power efficiency drops.

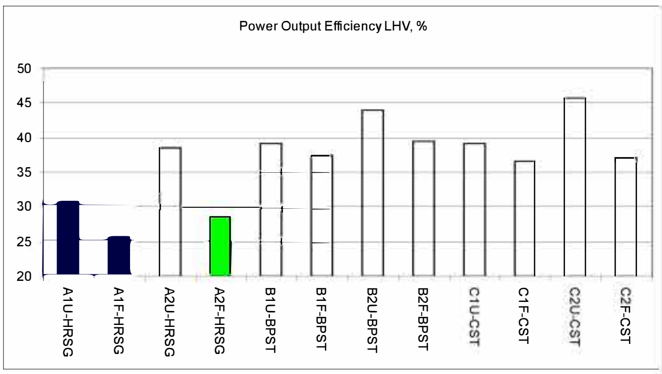


Figure 7. Power Efficiency for Different Configurations.

A better representation of the heat to power capability of industrial and aeroderivative engines is depicted in Figures 8 and 9 respectively. The CHP efficiency and power efficiency for different configurations using a Frame 6B industrial gas turbine is shown in Figure 8. For each configuration the two points on a line represent the situation with no supplemental firing and with supplemental firing[5]. The general trends and capability with respect to heat to power ratio are shown. As expected, as the CHP efficiency increases, the power efficiency drops. A similar graph for a LM6000PF is shown in Figure 9. It can also be seen that for small heat to power ratios, condensing extraction cycles fit well, and in situations with very large heat to power ratios, pure HRSG cycles fit. In the intermediate range, back pressure cycles are attractive. Low power to heat ratios tend to favor aeroderivatives.

An analysis of the pros and cons of different cogeneration variants with steam and gas turbines is presented in Kehlhofer (2007).

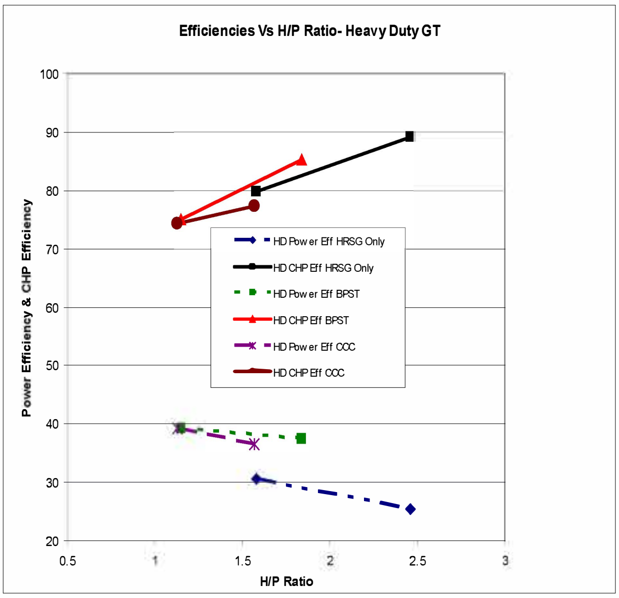


Figure 8 CHP and Power Efficiency (%) for Different Configurations with an Industrial Gas Turbine.

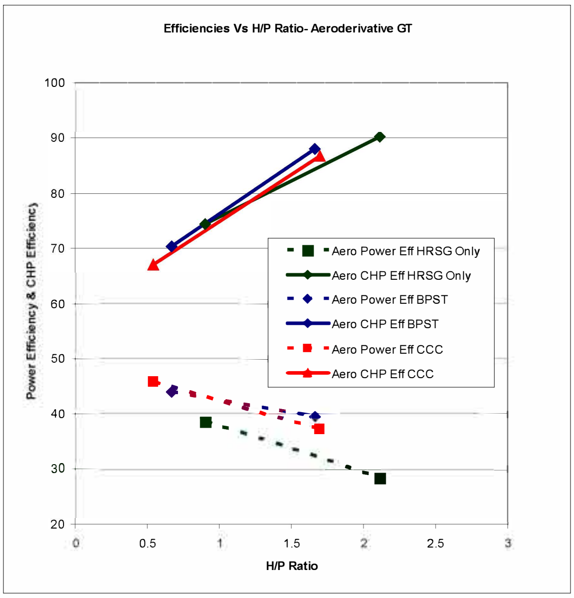


Figure 9. CHP and Power efficiency (%) for Different Configurations with an Aeroderivative Gas Turbine.

Heat Sink Options

Steam cycle heat rejection occurs at a temperature that is much lower than the temperature at which heat is added. A facility that dissipates heat at the lowest possible temperature will maximize cycle efficiency and minimize the amount of heat rejected. In cases where a condensing steam turbine is used for power generation, the heat dissipation (heat sink) scheme to the environment consists of a steam surface condenser and/or a wet or dry cooling water system. The heat sink option is often governed by factors such as site configuration, availability of water, and water disposal. The heat sink option selection process should be initiated in the early stages of project development to take this into account. Bechtel Power Corporation has done extensive studies relating to the optimal selection of heat sinks reported by Tawney et al, (2003).

Approaches used in combined cycles could be either "wet" or "dry" and for most LNG liquefaction plants, water is typically not available. Wet cooling technologies include once-through cooling or the use of a wet cooling tower. Dry Cooling Technologies include direct dry cooling system (air-cooled condenser). The advantages of this system are that water usage requirements are minimal and that no issues are associated with blowdown disposal and plume formation. The challenges of this design are higher installed costs, relatively higher noise emissions, and larger footprint. Other systems exist such as the Heller system and hybrid cooling technologies such as wet- dry cooling systems (wet surface air cooler).

5 For supplemental firing cases, a temperature of 700°C was used.

Exergy Considerations

The exergy is a measure of a substances ability to do work and provides a second law of thermodynamics perspective in analyzing a combined cycle. As proposed by Gulen (2010) concepts of Exergy Efficiency can provide a meaningful approach in the study of combined cycle and cogeneration plants as opposed to the traditional CHP efficiency which treats power and heat as equivalent but also ignore the variation in quality of the thermal energy output. An exergy analysis can identify locations of energy degredation and rank them in significance thus allowing one to focus on areas offering the greatest opportunity for improvement. Gulen's proposed definition is shown in equation below:

$$\eta_{CHP} = \frac{P + \sum_{i=1}^{N} \varepsilon_i \cdot E_i}{F}$$

Where,

P is the net power generated by the turbines in the plant
F is the total fuel consumed
E_i is the exergy of the individual product streams where there are N of them in a particular plant
ε_i is the efficiency of a practical device that convert E_i into power

The exergy approach while very elegant, has a somewhat limited value in design of combined cycle liquefaction plants as the plant will have specific requirements of steam which are required and having more "valuable" high pressure steam may not be appropriate. Also the special requirements of the heat to power ratio, and the fact that there are constraints relating to power (liquefaction power) may force the liquefaction combined cycle design in a certain direction. Exergy analysis does however provide valuable indications of where attention could be focused to improve design. For example with a condensing steam turbine, while the energy loss in the condenser maybe high, its exergy loss is small, and so spending money to improve the condenser (more heat transfer area etc) does not help.

5.0 LNG LIQUEFACTION COMBINED CYCLE CONFIGRATIONS

Four different conceptual combined cycle/cogeneration type configurations for the Optimized Cascade® Process have been studied and are outlined below. The object here is not to "compare" these cycles but to identify different conceptual approaches and layouts available. Three configurations (A, B and C) utilize aeroderivative engines, and concept D utilizes industrial turbines with back pressure steam turbines as the starter/ helper. The plants were designed for certain heat and power requirements, and the designs may vary considerably under different combinations of these parameters. Site conditions (mainly the ambient temperature) would also have an impact on the designs chosen as would specifics relating to the thermal loads. Practical and site considerations may dictate adjustments to the designs to account for redundancy in the power generation configurations, and site layout.

In all cases simulation runs were made to examine off-design conditions (different temperatures) and in some cases operating under deteriorated conditions was examined. With aeroderivative engines, the low exhaust gas temperatures allow moderate supplemental firing to be utilized without attaining high gas temperatures. This allows considerable flexibility for the cogeneration process.

The following assumptions were made:

- Normal ambient temperature considered= 27°C, sea Level, 60% RH, methane fuel
- Air cooled plant
- No fuel gas compressors are required for configurations A, B and D. For case C: (LMS100) a fuel gas compressor has been considered deriving feed from the methane refrigeration compressor.

- Typical inlet and outlet losses were considered.
- Thermal loads were considered at 30 MW_t/MTPA
- Operating electrical loads were assumed to be 7 MW_e/MTPA
- All heating was accomplished by steam, no hot oil was considered
- All gas turbines are DLE or DLN except the LMS100 which was considered to be water injected
- Back up boilers etc would have to be provided but these are not considered in the cycle considerations of the combined cycle or power blocks

The four configurations evaluated are represented in Table 3 and a depiction of performance is shown in Table 4.

Table 3. Four Configurations- Combined Cycle Liquefaction Schemes.

CONFIGURATION	Gas Turbines for Liquefaction	Power Plant Configuration (Operating load)	Thermal Load
CONFIGURATION A 2P+2E+2M Approximate MTPA≈ 5.x	4 LM6000PF + 2 Condensing Steam Turbines Propane – 2 x LM6000PF Ethylene- 2X LM6000PF Methane – 2 Condensing Steam Turbines	4 X Solar Titan130 and HRSGs	Steam from HRSGs from Power block
CONFIGURATION B 6 LM6000PF engines in 2+2+2 Configuration Approximate MTPA≈ 5.x	6 x LM6000PF Propane – 2 x LM6000PF Ethylene- 2X LM6000PF Methane- 2X LM6000PF	All Power derived from Condensing Steam Turbines using heat recovered from Refrigeration Drivers.	Steam from HRSGs and extraction from steam turbines
CONFIGURATION C 3 X LMS100 1+1+1 Configuration Approximate MTPA≈ 7.x	3 X LMS100 Propane – 1 x LMS100+ Ethylene- 1X LMS100 Methane- 1X LMS100	All Power derived from Condensing Steam Turbines using Refrigeration Drivers.	Derived from HRSGs directly and extraction from the CSTs
CONFIGURATION D 2X Frame 7EA +2 X Frame 6B Gas Turbines Approximate MTPA≈ 7.x	Propane and Ethylene- Frame 7EA+BPST (Helper starter)- two string Methane- Frame 6B +BPST – two strings.	Power derived from HRSGs of the Frame 6 Strings utilizing condensing steam turbines.	Derived from BPSTs .

Table 4. Salient Features of the Four Configurations

CONFIGURATION	A	B	C	D
	5.x MTPA	5.x MTPA	7.x MTPA	7.x MTPA
Total Number of Gas Turbines for Refrigeration block	4	6	3	4
Number of Gas Turbines for Power Block	4	0	0	0
Total Number of HRSGs Suplemental Firing	8 yes	6 yes	3 yes	4 yes
Power Generation Scheme	4 X Solar Titan130[6] with HRSGs	3 condensing steam turbines	3 condensing steam turbines	2 or 3 condensing steam turbines
Total Fuel In, kW	652694[7]	564121	878884	757271
Power Out (Electrical + Mechanical) [8]	256676	254845	343903	283231
Thermal Energy out, kWt	154026	156742	217984	212874
CHP Efficiency, %	63	72.96	64.9	70.97
Power efficiency, %	39	45	40	42.86
HRSG Efficiency, %	85.32 (Mech drive GT) and 89.19 (Power)	77.04	86.73	79.07 (Fr 7EA) 84.62% Frame 6
CO_2 kg/TPA	0.19	0.175	0.20	0.183

[6] The GT gen sets were operated at part load
[7] Includes an auxiliary boiler to make up thermal load required
[8] Gross power considered.

A cycle flow schematic for Configuration B is shown in Figure 10 and the combined cycle energy distribution is shown in Figure 11. An exergy analysis is shown in Figure 12.

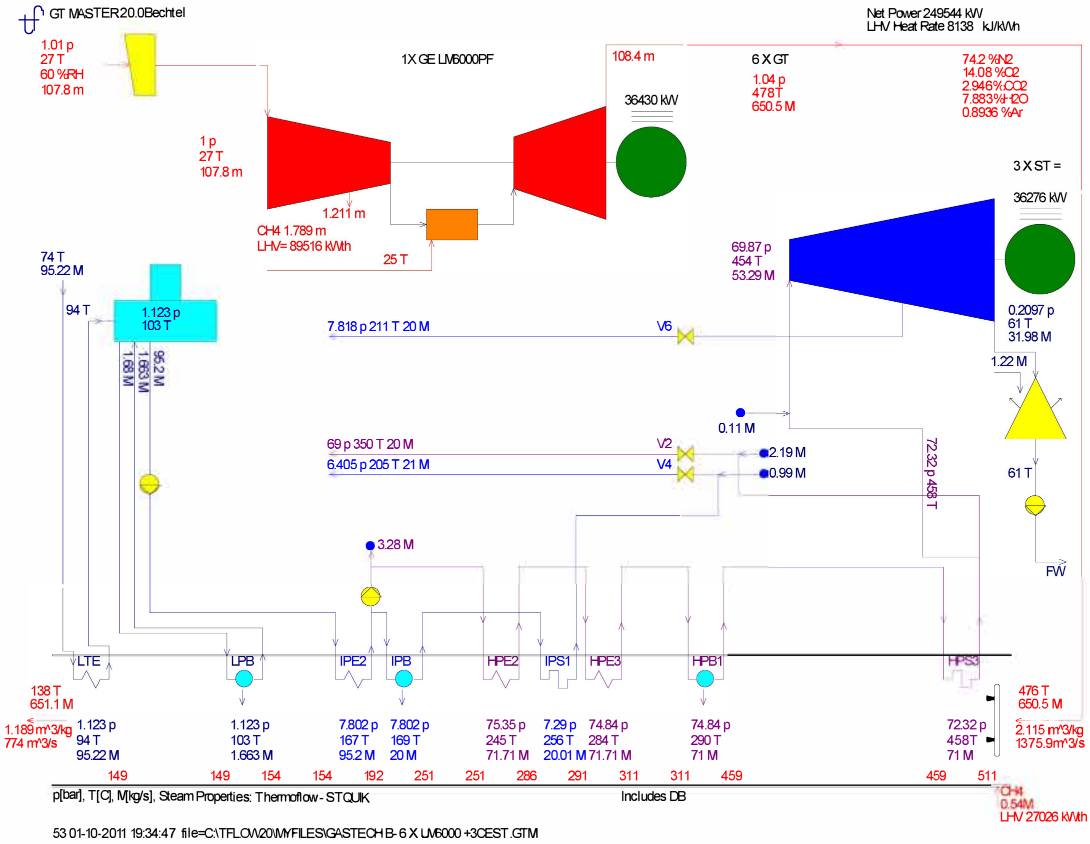


Figure 10. Cycle Flow Schematic of Configuration B.

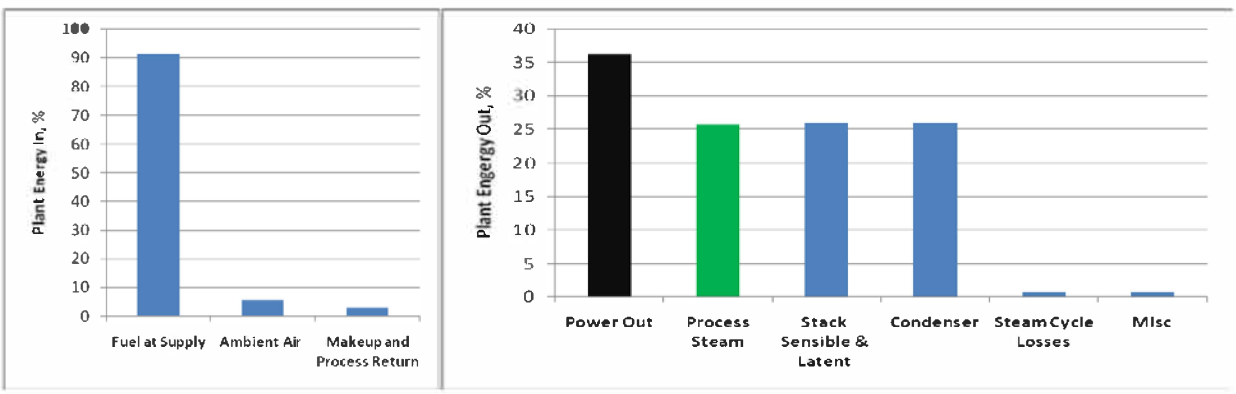


Figure 11. Energy Distribution- Configuration B: Plant Energy In and Out in %

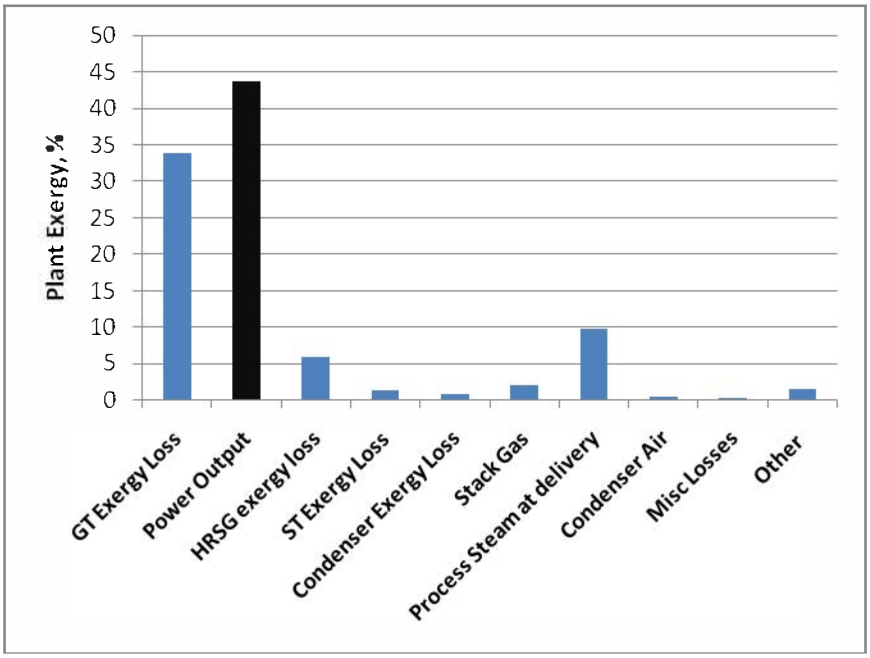


Figure 12. Cycle Exergy Analysis, % Distribution - Configuration B.

6.0 POWER AUGMENTATION

Power augmentation has numerous benefits for mechanical drive gas turbine applications and especially for the low net work ratio aeroderivative engines. These include a boost in LNG production throughout the year. Essentially, inlet chilling can remove or dampen the variability caused by climatic conditions. Evaporative cooling approaches can also provide significant boosts, especially at high temperatures when coincident relative humidities are lower. Evaporative cooling approaches have been utilized at Darwin LNG successfully for over four years. Inlet cooling improves the thermal efficiency of the gas turbine. LNG projects are now focusing on greater efficiency, and also the fact that a higher efficiency gas turbine operation results in a greener plant (lower specific CO_2 emissions)

If inlet chilling is utilized, there is considerable opportunity to optimize the process on line, as it is possible to shift cooling loads to the different compressor drivers by varying the gas turbine chilling water flow. Thus, the flexibility of the ConocoPhillips Optimized Cascade® process can be enhanced and optimized on line to reflect different operational conditions. For example, the effect of down time on a particular refrigeration compressor could be mitigated by minimizing the inlet temperature to its sister unit, thus allowing a greater flexibility in load shifting operations. This will lead to significantly higher plant availability and production efficiency. In the context of combined cycle type approaches, there is also a possibility of utilizing absorption type chilling.

7.0 ELECTRICAL POWER CONSIDERATIONS

Most cogeneration/ combined cycle schemes will involve the production of electric power with steam turbines. This is especially applicable in the case where aeroderivative engines are used that do not require starter helper devices (such as configuration B). It is very important that the overall design must be carefully integrated with the power generation electrical scheme and that this analysis be done during the early design phase. In addition to power generated by the steam turbines (derived from the liquefaction block cogeneration system), additional power may be needed depending on project specifics. Consequently the cogeneration steam turbines will have to be integrated with a conventional gas turbine or combined cycle power plant and also with power generation equipment that may be related to the liquefaction process such as gas expander driven generators or flashing liquid expander driven generators.

Some key issues that must be considered include:

- Electrical stability studies should be done to help minimize transient issues such as the starting of large motors, sudden loss of a generator set, and faults on synchronization busses.
- Electrical panel networks should be designed to ensure that generators share load changes properly, that hunting oscillations do not develop and that transient oscillations die away rapidly so that the frequency and voltage recover rapidly throughout the system.
- Definition of N+1 when there are a combination of steam turbines and other gas turbines is more complex and meeting the intent of spare capacity must be carefully analyzed.
- Definition and selection of the optimal size of the steam turbine generation unit. A decision should be made as to the optimal sizing and number of steam turbines from an electrical transient standpoint.

8.0 BENEFIT OF HIGH POWER EFFICIENCY- ECONOMICS

Several LNG projects are feed gas flow constrained. This situation occurs both on new projects being considered and also at existing LNG facilities. In these situations, any fuel consumption reduction due to higher thermal efficiency of the gas turbines means that this can be converted to LNG. Current projects and FEED studies value fuel at higher levels than a decade ago and many projects value the feed as the same as the LNG product (i.e., assume a supply constrained scenario). Given a gas constrained situation and the fact that fuel not consumed can be converted to LNG there are significant benefits in the order of hundreds of millions of net present value dollars by the use of high efficiency solutions. As NPV is a strong function of feed gas costs and LNG sales price, the present value is highly affected by the plants thermal efficiency especially when the FOB LNG costs are high as is the current market situation.

The present value of converting fuel into LNG for a nominal 5 MTPA plant is shown in Figure 13 for a range of driver efficiencies between 33% and 50% as compared to base case of 30%. For example the base case would represent a simple cycle configuration with say a Frame 5D driver. Results are provided for a range of FOB LNG prices ranging from $1 to $5 per MMBTU. Feed gas is assumed fixed at $0.75 per MMBTU which a very conservative (low) assumption given values being used in current economic studies for LNG facilities under development. The availabilities have been adjusted with the aeroderivative solution being 1% higher than the Frame solution and combined cycle solution has an availability reduction of 2%. It is important to note that the sensitivity of the results to availability is considerable. The present value of the gross margin (defined as LNG revenue less feed gas cost) is calculated over a 20 year life and a discount rate of 10%. The strong influence of driver efficiency is evident from the graph. While not shown, there are also fuel savings derived by higher efficiency systems. At low values of fuel feed cost, the benefits of a higher efficiency obviously diminish, and with higher fuel costs, the benefits of higher efficiency grow significantly.

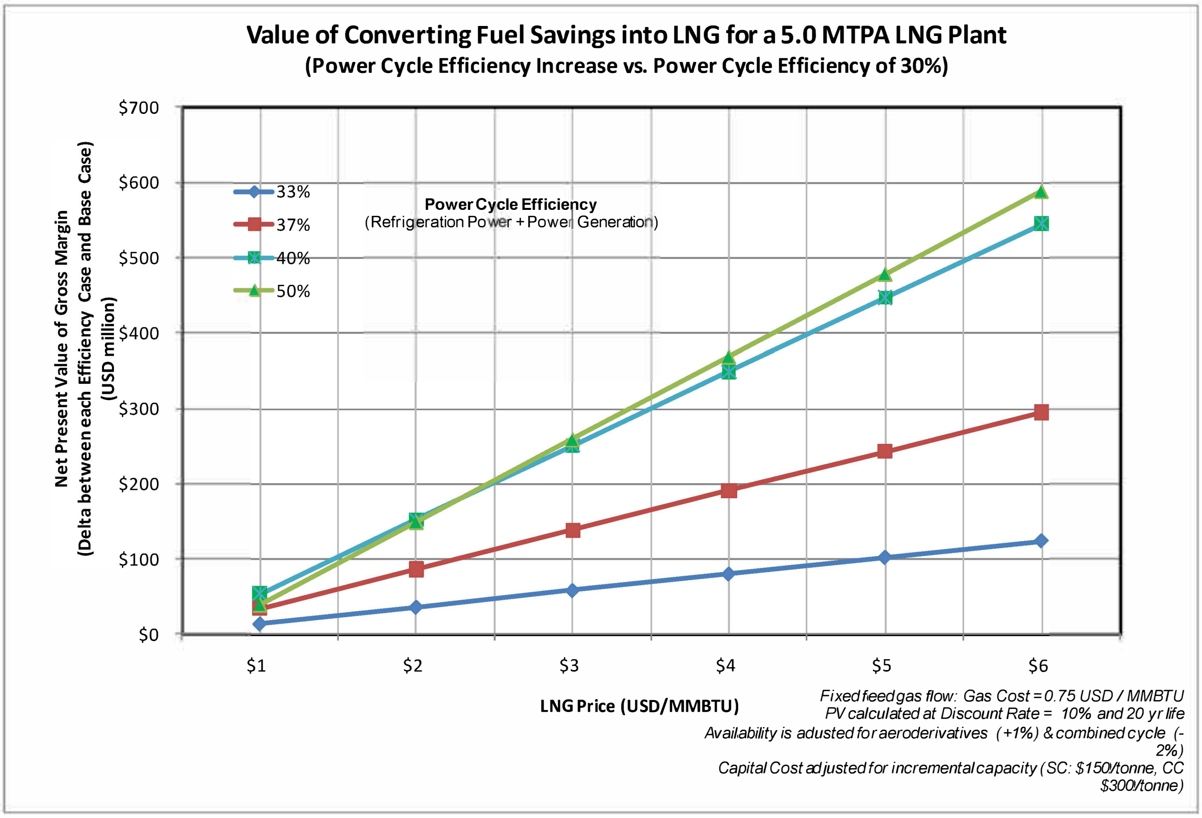


Figure 13. Value of Increased Power Cycle Efficiency.

9.0 SUMMARY

There are several approaches and concepts by which combined cycle / cogeneration approaches can be integrated within the ConocoPhillips Optimized Cascade® Process, using either industrial or aeroderivative engines. The combined cycle/ cogeneration approach enables a significant improvement in efficiency and a reduction in CO_2 emissions. If for some reason steam systems are not desired or are not viable, then high efficiency aeroderivative engines can provide a high level of efficiency even in simple cycle. The efficiency can be further enhanced by the addition of a combined cycle to provide power and heat. While some conceptual designs have been provided, specific designs would have to be formulated to match specific site requirements. With aeroderivative engines, power augmentation approaches are attractive and can consist of either evaporative approaches or inlet chilling. The design of the combined cycle liquefaction facility must incorporate these considerations at the outset.

Based on unfired designs, the heat to power ratio is lower (0.8 to 1.0) with aeroderivative engines and higher (approximately 1.5) with industrial engines. While this ratio is mainly dependant on the gas turbine thermal efficiency, it will also depend on the mode of heat recovery, and the number of pressure levels used to extract heat. For very large heat to power ratios, a simple heat recovery boiler can be used with no steam turbine. It is generally good practice to design a GT–HRSG (no steam turbine) system with supplemental firing for controllability at off design conditions of varying steam demand. The design of the heat and power system needs to match the process requirements that are driven by gas composition, site considerations and owner requirements.

For low heat to power ratios, the highest efficiency will be derived by the use of a condensing extraction steam turbine. For intermediate ranges of heat / power ratios which are typical of LNG plants, back pressure steam turbines look attractive. Steam can be generated at high pressure and then expanded through a back pressure steam turbine. Back pressure steam turbines allow fast startups and avoid the use of expensive condenser systems. The avoidance of air cooled condensers associated with condensing steam turbines can result in significant plot size reduction.[9] The use of supplemental firing, makes aeroderivatives and industrial engines relatively close in terms of the overall heat to power ratios and also in terms of CHP efficiency.

Regardless of the cogeneration scheme dictated by thermodynamic efficiency considerations, practical considerations relating to the plot plan, operational complexity, startup considerations and transient behavior must be evaluated in making a proper economic decision. Operational issues may dictate the need for standby boilers and standby gas turbines depending on the configurations implemented. Electrical system considerations and integration must be considered during the design phase.

NOMENCLATURE

AGRU	Acid gas removal unit
BPST	Back Pressure Steam Turbine
CC	Combined Cycle
CHP	Combined Heat and Power
CST	Condensing Steam Turbine
DBT	Dry Bulb Temperature
DLE /DLN	Dry Low Emission
GT	Gas Turbine
H/P	Heat (Steam) / Power Ratio
HRSG	Heat Recovery Steam Generator
HP	High Pressure
kW_t	Thermal Energy, in kW
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
MP	Medium Pressure
OTSG	Once Through Steam Generator
PR	Pressure Ratio
RH	Relative Humidity
TIT	Turbine Inlet Temperature
VFD	Variable Frequency Drive

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[9] Most LNG liquefaction facilities are air cooled as water availability is typically a constraint.

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