Optimize LNG Liquefaction Operations through Proper Refrigeration Compressor Driver Selection

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Abstract

Natural gas liquefaction is an energy-intensive process. As a result, there is significant opportunity for operators to benefit by selecting the appropriate equipment for their specific LNG application. First, and perhaps most importantly, cleaner LNG solutions minimize greenhouse gas emissions. This is an important consideration, as we expect excessive emissions will eventually incur financial penalties. Secondly, reducing power consumption during the liquefaction process can be a source of substantial financial return.

The liquefaction island of a plant is simply a large refrigerator that consumes abundant energy to bring natural gas to approximately -163°C. Liquefaction can occur through various processes, and although not all offer the same efficiency, each has its own advantages that make it more or less suitable depending on project objectives. The choice of what driver configuration to use for liquefaction has lasting effects throughout the life of an LNG facility. Because of this, an adequate amount of time and effort should be put into evaluating options to ensure the optimal selection is made.

This paper reviews equipment configurations that can be used to drive main refrigeration compressors for given liquefaction processes and discusses the relative benefits of each. It focuses on the power consumption of the main refrigeration island, and compares 10 main driver solutions. It also provides recommendations from an OEM perspective.

The driver solutions discussed in this paper include designs that are currently being used in liquefaction facilities throughout the world, as well as ones that have not yet been widely implemented. Depending on the requirements of an operation, other configurations not included in this paper may warrant consideration.

Keywords: LNG, liquefaction, refrigeration compressors, natural gas liquefaction
1. INTRODUCTION

In recent decades, the use of liquefied natural gas (LNG) as a clean burning alternative to coal and crude-derived fuels such as gasoline and diesel has grown substantially. Despite the relatively weak short-term outlook, which is largely a result of slumping commodity markets, the global demand for LNG is expected to grow 4-6% annually through 2030 [1]. Moreover, in addition to the more than 100 million tons per annum (MPTA) of production capacity currently in post-FID or under construction across the globe, an estimated 65 MPTA will need to be added in order to meet projected demand by 2025.

In the coming years, enhancing LNG production by improving efficiency, reducing energy consumption, and minimizing emissions will play a critical role in increasing the viability of LNG as a fuel source throughout the world. The liquefaction island of an LNG plant is responsible for refrigerating natural gas to approximately -163°C. The process itself typically accounts for anywhere from 30 – 40% of the total cost to deliver LNG to market — making it an area where operators can achieve significant savings through optimization and proper equipment selection.

When designing an LNG facility, determining the optimal configuration of equipment and refrigeration cycle for liquefaction requires careful consideration of a number of variables, including gas composition, production volume, ambient temperature, weight and size limitations, reliability, safety, maintainability, etc. Operators today have their choice from a wide range of cycle options (single mixed refrigerant, double mixed refrigerant, nitrogen expansion, double nitrogen, etc.), all of which have different compression requirements. After a specific refrigeration cycle has been selected, a key decision that must be made is the mechanical driver configuration that will be used to drive refrigeration compressors. Each configuration presents its own unique advantages, disadvantages, and subsequent trade-offs with regards to CAPEX, OPEX, maintenance, emissions, efficiency, and availability. Selecting the option that will provide the most value to an LNG facility is largely dependent on project-specific objectives.

The goal of this paper is to help operators better understand driver selection by examining the performance of 10 different configurations that can be used for liquefaction. In addition to providing an overview of the different types of drivers (e.g., electric motors, gas turbines, steam turbines, aero-derivative turbines), the study included in section 4 of this paper will quantify the performance of each configuration with regards to capital investment, OPEX, loss of production from scheduled and unscheduled shutdown time, fuel consumption, emissions, and opportunity for incremental increases in production.
2. THE IMPORTANCE OF DRIVER SELECTION

Because liquefaction islands are typically designed to the limits of the available refrigeration compressor drivers in order to maximize train capacities, selection of driver type and configuration will have a significant impact on the overall performance, efficiency, and profitability of an LNG plant. It’s important that the decision regarding what type of driver configuration to implement is made in the earliest possible phase of the project timeline. This is largely due to the fact that as the schedule progresses, it becomes increasingly difficult and costly to make design changes. Poor scope definition and equipment selection during preliminary design phases will also increase the likelihood of running into issues during installation and commissioning, as well as when the plant comes online.

In general, there are four different driver options that can be used for LNG liquefaction. They are as follows:

**Steam Turbines** - Steam turbines offer excellent reliability, as well as flexibility with regards to the type of fuel gas they can accept. However, they typically have poor thermal cycle efficiency and require a large footprint. They also often require a dedicated steam/water network, which can increase project complexity and drive up costs. The use of steam turbines as a driver for liquefaction operations over the past two decades has decreased significantly, though they may be an effective option in applications where minimizing downtime is the primary objective.

**Heavy-duty Gas Turbines (HGDT)** – Heavy-duty gas turbines have been the most widely used driver for liquefaction operations over the last 20 years. Thermal efficiency of HDGTs ranges from 30 – 38%, although that number will decrease as ambient temperature rises. One of the primary advantages of HDGTs is that they are available in a wide range of sizes/capacities, which allows operators to design fit-for-purpose trains to maximize efficiency. One of the key drawbacks of heavy-duty gas turbines is that they have a high specific fuel consumption, which leads to increased emissions. Single-shaft HDGTs are also limited with regards to torque and speed variation, and often have extensive maintenance requirements.

**Aero-derivative Gas Turbine (ADGT)** – In recent years, aero-derivative gas turbines have become an increasingly popular driver option for liquefaction in both onshore and offshore applications. In addition to being lightweight and relatively easy to replace, AGDTs provide a number of advantages over industrial gas units, including a higher thermal efficiency (40-43%) and lower emissions. Furthermore, they can be started from a refrigerant compressor settle-out condition, thereby eliminating the need to reroute (or flare) a large portion of the refrigeration gas medium from the compressor system. AGDTs also don’t require large starter motors like single-shaft HDGTs. Because they don’t have
the power output of an industrial gas turbine, multiple AGDT driver configurations typically have to be used in parallel to meet the production requirements of mid-to-large-scale liquefaction operations. In many instances, this can be beneficial as it provides operators with the flexibility to shut down turbines while maintaining partial production.

**Electric Motors** - Electric motors offer a number of advantages compared to gas and aero-derivative turbines, particularly with regards to availability. When power supply is generated from a renewable source, they also produce fewer emissions. Electric motors are an attractive option in applications where uptime is paramount; however, they do require a significant up-front investment in connecting to a dedicated power source, which increases scope complexity and presents risks related to grid stability. Electric motors are also typically sized to meet specific production requirements and provide limited opportunity for increased production as a result of site temperature variation, which is an inherent advantage of the gas turbines. For these reasons, their use as a dedicated driver solution for refrigeration operations is uncommon.

The following section of this paper will provide a quantitative analysis of 10 different driver configurations for LNG liquefaction.

**3. LNG LIQUEFACTION DRIVER PERFORMANCE STUDY**

This study compares ten (10) different driver configurations that can be used for liquefaction operations in nine different performance areas, including CAPEX, loss of production due to scheduled shutdown, loss of production due to unscheduled shutdown, fuel consumption, OPEX, potential for incremental production, emissions (potential CO₂ tax), optimized production rate, and total cost (OPEX + CAPEX).

Configuration 1 is a heavy-duty gas turbine driver solution. Because some variation of this configuration can be found in many LNG liquefaction operations across the globe, it will serve as the base case for the study. Configurations 2 – 10 represent additional driver solutions that are currently being used throughout the industry, as well as ones that have not been widely implemented but may be particularly advantageous for operators to consider depending on the requirements of their operation. The configurations will be compared on the basis of the production rate that Configuration 1 can achieve, which for the purposes of this study was set at 8.6 MTPA. Because the various solutions are not consuming the same electrical power, the power plant cost will be added to the CAPEX evaluation. For instance, the HDGT in Configurations 1 and 2 requires a starter-helper motor. It is therefore necessary to consider it in the evaluation.
Diagrams of each configuration, along with details regarding individual designs are included on the following pages. Page 12 of this paper contains a table summarizing the results of the 10 Year Net Present Value (NPV) analyses. Assumptions made for the study are as follows:

- Gas price 2.5$/Mbtu ($=USD)
- LNG price 6$/Mbtu (314$ / T)
- Average gas 52.32 Mbtu/tonnes of LNG
- APC C3 MR process with an assumed power requirement of 0.24 KW per Kg of LNG
- Site rating for the turbine 30
- 120/260 mm H2O inlet exhaust losses for gas turbine performance
- 10% turbine aging and fouling
- CAPEX exclude civil work and spare parts
- Scheduled maintenance based on published information
- CO2 emission 55 Kg/Gigajoules
- 20.8 Euro per tonne of CO2
- $/Euro exchange rate 1.08
- NPV base on 10% financial rate
- 10 MW of electrical power is required for every MPTA of incremental production

Fig. 1 Configuration 1 (Base Case) –Heavy Duty Gas Turbine (HDGT)

**Configuration 1 details:** This configuration features a total of four mechanical drives and three power generating drives. To achieve production of 8.6 MPTA, two configurations operating in parallel are required. The power plant configuration includes two operating turbines and one redundant turbine (2+1 arrangement).
Configuration 2 details: This configuration features a total of three mechanical drives and four power generating drives in a 3+1 arrangement. To achieve production of 8.6 MPTA, three configurations operating in parallel are required (helper motor is producing 23.3 MW). This solution features the same number of turbines as Configuration 1. It does not offer incremental production and may require an oversized power source to ensure grid stability.

Configuration 3 details: This configuration features a total of four mechanical drives and four power generating drives in a 3+1 arrangement. To achieve production of 8.6 MPTA, two configurations operating in parallel are required (helper motors are producing 20 MW each). This solution offers 28.8% incremental production when compared to Configuration 1 and may require an oversized power source to ensure grid stability.

Configuration 4 details: This option features a total of eight mechanical drives and three power generating drives in a 2+1 arrangement. To achieve production of 8.6 MPTA, four configurations operating in parallel are required. This solution offers 28.5% incremental production when compared to Configuration 1.
**Configuration 5 details:** This configuration features a total of 10 mechanical drives and four power generating drives (four propane compressors and six MR compressors in a 3+1 power generation arrangement). To achieve production of 8.6 MPTA, four configurations operating in parallel are required. This solution offers 9% incremental production when compared to Configuration 1. ExxonMobil uses a variation of this configuration with a 30 MW Class ADGT at the Papa New Guinea (PNG) LNG plant.

**Configuration 6 details:** This configuration features a total of 12 mechanical drives and five power generating drives in a 4+1 arrangement. To achieve production of 8.6 MPTA, six configurations operating in parallel – which can be grouped into three sets of two – are required. This solution offers 10% incremental production when compared to Configuration 1.
Configuration 7 details: This configuration features a total of six VSDs and eight HDGT power generating drives (the same class HDGT used in Configuration 1). To achieve production of 8.6 MPTA, two sets of three of the configuration above as well as six power-generating HDGTs operating in parallel are required to provide the electrical power. Each configuration includes six operating turbines plus one idle turbine, and one redundant turbine to ensure grid stability (6+1+1 arrangement). This solution offers no incremental production when compared to Configuration 1; however, it is the most reliable solution, as VSDs require very little maintenance.

![Configuration 7 Diagram](image)

Fig. 8 Configuration 8 – SGT-750 Industrial Gas Turbine

Configuration 8 details: The SGT-750 gas turbine is a lightweight, high-efficiency industrial turbine that is still relatively new to the industry. It features a total of 10 mechanical drives (five configurations operating in parallel) and five power generating drives. To achieve production of 8.6 MPTA, the SGT-750 turbine has to be configured in a similar manner to that in Configuration 5 (4+1 arrangement). This solution offers 6% incremental production when compared to Configuration 1. It also offers a similar level of reliability as Configuration 5.

![Configuration 8 Diagram](image)

Fig. 9 Configuration 9 – Small AGDT 30 MW Gas Turbine

Configuration 9 details: This configuration features a total of 15 mechanical drives and five power generating drives (six propane-HP MR and nine LP-MP MR). To achieve production of 8.6 MPTA, five configurations operating in parallel are required. Each configuration includes four operating turbines and one redundant turbine (4+1 arrangement). This arrangement offers 15% incremental production when compared to Configuration 1. It also requires the highest number of compressor casings.
**Configuration 10 details:** This configuration features a total of six mechanical drives and five power generating drives in a 4+1 arrangement. To achieve production of 8.6 MPTA, three configurations operating in parallel are required. This solution offers 2% incremental production when compared to Configuration 1; however, production can be increased through more chilling.

**4. SUMMARY OF 10-YEAR NET PRESENT VALUE ANALYSIS**

Table 1 below displays the results of a 10-year net present value (NPV) analysis conducted on each driver configuration. It also provides a cost summary per tonne before and after optimizing to achieve incremental production. Potential incremental operating income (OI) was calculated by evaluating the value of the incremental sales less the cost of the feed gas and less the cost of the fuel required to achieve that incremental production.

As seen in Table 1, each configuration presents its own unique advantages and disadvantages that will make it more or less advantageous depending on project objectives.

For instance, in applications where reliability is critical, Configuration 7 (VSD with HDGT) would be a suitable choice. This option, however, does not come without tradeoffs in the form of increased OPEX, CAPEX, and potential emissions taxes. It’s important to note that the higher costs associated with Configuration 7 can be reduced if power for the electrical motor is available from the local grid. In such cases, securing a competitive power supply contract from the utility company will be critical to maintaining low OPEX. Overall efficiency of the solution can be increased by using the large HDGT featured in Configuration 1 – where any excess power generated can be delivered to the local grid. Configuration 7 also has low maintenance requirements.

If the LNG operation is CAPEX driven, Configuration 1 (HDGT with no helper) may be the best option. Once again, however, an operator may want to consider that with Configuration 1, the loss of production as a result of scheduled and unscheduled shutdowns is significantly higher. There is also no opportunity for potential increase in incremental production. Configuration 10 (Industrial Trent Turbine with Inlet Chilling) also offers benefits with regards to CAPEX, but unlike the HDGT...
with no helper, it has significantly lower production losses from scheduled downtime and does allow for an approximate 10% increase in production if needed.

Configuration 4 (Industrial Trent Turbine) offers the lowest combined CAPEX and OPEX. It also provides the opportunity for increased production by using excess power generated by the turbine. Configuration 8 (SGT-750) offers comparable benefits to the Industrial Trent Turbine option; however, it does have a lower maintenance profile, making it an attractive option in applications where maintainability is critical.

Table 1 10-year NPV Analysis

<table>
<thead>
<tr>
<th>Configuration</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
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<tbody>
<tr>
<td>Driver considered</td>
<td>HDGT split MR</td>
<td>HDGT 3(^\circ)33% with helper</td>
<td>HDGT split MR</td>
<td>Trent split MR</td>
<td>ADGT 40 MW Class split MR</td>
<td>Large ADGT 30 MW Class split MR</td>
<td>VSD</td>
<td>SGT/750 split MR</td>
<td>Small ADGT 30 MW class</td>
<td>Trent with inlet chilling</td>
</tr>
<tr>
<td>Capex in M$</td>
<td>500</td>
<td>575</td>
<td>536</td>
<td>586</td>
<td>622</td>
<td>569</td>
<td>614</td>
<td>515</td>
<td>637</td>
<td>504</td>
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<td>Loss of production due to schedule shut down M$</td>
<td>153</td>
<td>153</td>
<td>193</td>
<td>57</td>
<td>53</td>
<td>22</td>
<td>28</td>
<td>53</td>
<td>57</td>
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<tr>
<td>Loss of production due to unscheduled shut down M$</td>
<td>173</td>
<td>112</td>
<td>189</td>
<td>171</td>
<td>154</td>
<td>171</td>
<td>79</td>
<td>189</td>
<td>171</td>
<td>185</td>
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<tr>
<td>Cost for fuel consumed assuming value of fuel at LNG price M$</td>
<td>1223</td>
<td>1249</td>
<td>1272</td>
<td>954</td>
<td>1626</td>
<td>1074</td>
<td>1454</td>
<td>1080</td>
<td>1124</td>
<td>955</td>
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<tr>
<td>Opex Subtotal</td>
<td>1589</td>
<td>1554</td>
<td>1695</td>
<td>1183</td>
<td>1234</td>
<td>1289</td>
<td>1554</td>
<td>1297</td>
<td>1348</td>
<td>1198</td>
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<tr>
<td>Opex + Capex</td>
<td>2089</td>
<td>2129</td>
<td>2191</td>
<td>1768</td>
<td>1855</td>
<td>1866</td>
<td>2168</td>
<td>1812</td>
<td>1985</td>
<td>1702</td>
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<tr>
<td>Potential incremental oil linked to power available in M$</td>
<td>0</td>
<td>7</td>
<td>237</td>
<td>247</td>
<td>787</td>
<td>863</td>
<td>0</td>
<td>535</td>
<td>1273</td>
<td>639</td>
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<tr>
<td>Potential CO2 Tax M$</td>
<td>247</td>
<td>251</td>
<td>256</td>
<td>190</td>
<td>294</td>
<td>214</td>
<td>288</td>
<td>215</td>
<td>224</td>
<td>190</td>
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<tr>
<td>Optimized Production rate MTPA</td>
<td>8.6</td>
<td>8.6</td>
<td>11.1</td>
<td>11.1</td>
<td>9.4</td>
<td>9.5</td>
<td>8.6</td>
<td>9.2</td>
<td>9.0</td>
<td>9.5</td>
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<tr>
<td>Capex per tonne (based on 8.6 MTPA)</td>
<td>58</td>
<td>67</td>
<td>62</td>
<td>68</td>
<td>72</td>
<td>66</td>
<td>67</td>
<td>60</td>
<td>74</td>
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<td>Capex per tonne (with optimization)</td>
<td>58</td>
<td>67</td>
<td>48</td>
<td>53</td>
<td>66</td>
<td>68</td>
<td>71</td>
<td>56</td>
<td>64</td>
<td>53</td>
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<tr>
<td>Opex per tonne</td>
<td>164</td>
<td>180</td>
<td>192</td>
<td>137</td>
<td>143</td>
<td>150</td>
<td>180</td>
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<td>139</td>
</tr>
<tr>
<td>Capex and Opex per tonne</td>
<td>242</td>
<td>247</td>
<td>240</td>
<td>190</td>
<td>209</td>
<td>210</td>
<td>251</td>
<td>206</td>
<td>220</td>
<td>192</td>
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</tbody>
</table>

Overall, the theme that operators should take away from Table 1 is that every individual driver solution has its own merits. Therefore, when designing an LNG facility, the focus should not be on replicating a design from a previous plant or choosing the least costly solution, but rather on selecting the configuration that is most appropriate given the specific objective(s) of the project.
5. CONCLUSION

The liquefaction island of an LNG plant consumes a significant amount of energy. As a result, selecting the appropriate driver configuration for the process will play a critical role in the overall performance, efficiency, and profitability of a facility. In addition to production volume, feed gas composition, ambient temperature, weight and size limitations, and power availability, the optimal driver configuration to implement will largely depend on the philosophy of the operator, along with project-specific objectives. Although it is never too late to make process and/or equipment modifications, identifying what those objectives are early in the project timeline is critical due to the fact that as the project progresses the cost and difficulty of making design changes will increase.

Close collaboration between the supplier, EPC, and project owner is essential to making the optimal driver selection. In some instances, it may be advantageous to conduct two separate FEEDs (simultaneously) with two different EPCs, each of them implementing two different solutions with one OEM each. In such cases, evaluation criteria should be provided to the EPC. This will allow the integrated FEED team to select an arrangement that best aligns with project requirements in terms of CAPEX, OPEX, efficiency, reliability, maintenance, and emissions, thus increasing financial return and maximizing value throughout the life of the plant.
6. REFERENCES

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