OpenWater Energy Newsletter

February 2022

Decarbonising Floating Oil & Gas Facilities

Part 2 - Floating Liquefaction (FLNG) Vessels

1. Introduction

The objective of this newsletter is to discuss the options available to decarbonise a large FLNG vessel. This is the second paper in the Decarbonisation series, following our January 2022 newsletter which discussed similar options for a large FPSO.

Since the two newsletters target different audiences, Part 2 is written as a stand-alone document. Readers of both will therefore notice some overlap, which is intentional and shows the synergy between the two products. A glossary of terms is included in section 8.

Typical FLNG vessels, like the new Coral Sul FLNG below, have multiple sources of environmental emissions. Technology exists to significantly reduce these emissions, and pressure is now mounting to do so for several reasons.


Courtesy: Eni

Firstly, there is Environmental, Social, and Governance (ESG) pressure from stakeholders to reduce the environmental impact – both from internal stakeholders (staff) and external stakeholders (host governments, shareholders, media, and the public). Secondly, Financial Institutions are becoming more selective in the projects they finance (due to their own ESG pressure) and are likely to favour those which can show low carbon footprints. Thirdly, the application of a Carbon Tax, either imposed externally by local authorities or internally as a project sanction test, will also drive projects towards lower emissions.

For all these reasons, the various technologies to reduce emissions are growing in importance, and we expect these to be widely applied soon.

2. Baseline

To help illustrate the potential to decarbonise, we have calculated the baseline emissions from a typical FLNG. We selected a generic design of 3.0 MTPA capacity using SMR technology and 3% CO_2 in the feed gas as a Reference Case, and we have illustrated the main sources of emissions from this type of unit in **Figure 1** (see page 7).

We have then calculated the total CO_2 equivalent emissions for this Reference Case FLNG, using GWP to convert hydrocarbon emissions back to CO_2e, and applied vendor data for fuel demand. We found total CO_2 equivalent emissions are around 1.30 MTPA at full capacity, which is broken down as shown in **Figure 2** below.

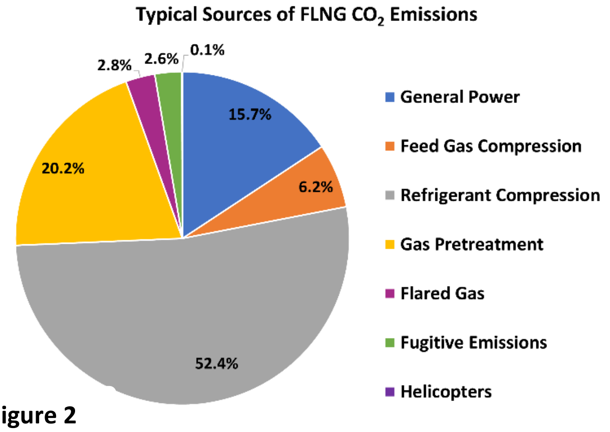


Figure 2

The main sources of emissions are the gas turbine drivers for the refrigeration compressors and the power generators. In this Reference Case, we have assumed three LM2500+G4 gas turbines for power generation (3 x 50%), and three LM6000PF+ gas turbines for direct drive of the refrigeration compressors (3 x 33%). The CO_2 in the exhaust gas from these 6 machines represents over 75% of the total FLNG annual emissions. For these calculations, we used data published by SINTEF. (Ref 1)

We have included in our Reference Case a feed gas compressor, driven by an electric motor, to boost feed gas pressure to that required for the liquefaction process. On some fields, this may not be required, at least in early field life. Hence, we show the results with and without this feed gas compression power demand.

The next largest source of emissions is the CO_2 vented from the gas pre-treatment unit. Assuming 3% CO_2 in the feed gas, around 750 t/d of CO_2 must be removed from the incoming gas before liquefaction. This CO_2 is typically vented to the atmosphere on existing FLNGs.

Gas flaring, venting and fugitive emissions may contribute around 5% to the annual emissions, assuming that the plant is reliable and has a low frequency of process upsets and trips. Normally only a small flow of purge gas and pilot gas will be burned. But during the periodic process upsets, plant trips and subsequent restarts, or preparation of equipment for maintenance, significant amounts of gas may be flared for short durations. Moreover, flare tips are typically around 98% efficient, so there will be a small amount of methane slip to the atmosphere, which is important due to the high GWP of methane.

Finally, we have included emissions from helicopters for the crew transportation to and from the vessel. However, in comparison to the above emissions, these are not significant.

We have not included in this analysis inert gas blanketing for condensate storage tanks, since at very low liquid production rates this is negligible. Nor have we included emissions to sea, since the produced water discharges from an FLNG vessel are also typically minimal.

3. Pathways to Decarbonise FLNGs

We have grouped the various technology initiatives available to reduce emissions into five broad categories, shown below in ascending order of cost and effort to deploy. These are discussed in more detail in the following section and are illustrated in **Figure 3** (see page 7).

For each, we include an indication of the Technology Readiness Level (TRL) for the application of this technology. This is based on the API 17N (Ref 2) seven-point gate system, where TRL1 is a new conceptual idea and TRL7 is when new equipment has been proven in service for at least 3 years. The TRL shown is our view of the application of the technology to FLNG service, which may differ from wider industry applications.

Table 1

Category	Technology Options	TRL for FLNG Application
Optimisation	• Improved Efficiency • Better control of turbine fouling losses • Better O&M Procedures – reduced flaring • Digitalisation • Optimised Logistics	7 7 7 7 7
Flare & Vent	• Reduced Fugitive Emissions – IR Cameras • Closed Flare – Eliminate routing flaring • Eliminate CO_2 venting from pre-treatment	7 7 7
Liquefaction Process	• Select a low specific power demand process, such as DMR	6
Fuel Demand	• Combined cycle power generation • Renewable energy power import • Power import from shore • Battery Energy Storage System (BESS)	7 4 7 6
Exhaust Gas	• Pre-combustion CC(U)S – Hydrogen fuel blending • Post combustion CC(U)S	3 3

4. Technology Options

4.1 The simplest pathway to reduce emissions is through optimisation of the current facilities, without any major hardware change. The options available include the following.

a) **Improved Efficiency.** By running the main machines (compressors and pumps) at the highest possible efficiency points, power demand can be reduced, with an equivalent reduction in CO_2 emissions. Examples could be optimising compressor recycle flows or avoiding shared load between two parallel machines (each operating at sub-optimal conditions).

Using high-efficiency air inlet filters on gas turbines to reduce losses from compressor fouling (Ref 3) can also be highly beneficial.

b) **Digitalisation.** The use of advanced Digital tools and AI can improve plant uptime and reduce the number of process upsets, trips, and restarts, reducing the amount of gas flared. An Onshore Support Centre manned by Engineers with access to live plant data and advanced AI tools can support the offshore crews to ensure that machinery is running as close to the optimum efficiency points as possible, reducing power consumption and fuel demand, as discussed above.

c) **Better Operations & Maintenance procedures.** Plant trips and restarts are the major sources of gas flaring. Operating procedures can often be optimised to reduce the amount of flaring, such as by better consideration of the timing of the well opening sequence and the compressor restart procedures. Dynamic simulations can be used to test alternative restart scenarios and develop robust procedures to minimise flaring.

Selecting a refrigeration gas turbine driver that will allow the liquefaction plant to restart from full settle-out pressure, without the need to dump refrigerant inventory, is critical for low emissions.

Procedures for the preparation of equipment for maintenance can often be optimised to reduce the quantity of gas to be flared or vented, such as by partial depressurisation through the process train before final depressurising to flare.

d) **Optimised Logistics.** By optimising logistics planning for the crew, vendor assistance, catering provisions, production chemicals and spare parts, it may be possible to reduce the number of helicopter and supply boat trips needed per year, so reducing emissions (and cost). Digitalisation should also reduce the required number of crew, and the number of visits needed by vendor technicians, so again reducing emissions related to travel.

The above four items should be considered as routine operations and maintenance management, but it is important to ensure that these basic steps are achieved before considering more complex solutions.

We estimate that emissions may be up to 5% higher than the baseline level if the plant is being run with sub-optimal conditions.

4.2 Flare, Vent and Fugitive Emissions

Estimating the quantity of Fugitive Emissions is difficult. An interesting study was published in 2019 which investigated the fugitive emissions from 8 North Sea oil and gas installations and found these to average 36 kg/hr (Ref 4). Since our Reference Case FLNG has topsides around four times the size of an average North Sea platform, we have assumed a value of 144 kg/hr for our analysis.

Piping flanges, valve stem seals, and instrument tubing joints are all possible sources of small gas leaks to the atmosphere. These may be too small to trigger the gas detection systems, but when accumulated they can be a significant source of fugitive methane emissions. Regular IR camera surveys should be performed to identify and repair any such sources of fugitive emissions. ATEX certified IR cameras are now widely available for this purpose (Ref 5).

A proven solution (TRL7) to routine gas flaring is the 'Closed Flare' design. This uses a high integrity valve or valves (with a bursting disc bypass) and a recycle compressor to return all purge gas, vented process gas and any gas leakage (such as from safety valves and blowdown valves) to the main process system. Only in case of a significant release of gas to flare, above the capacity of the recycle compressor, will the high integrity valve(s) open to release gas to the flare tips. This system has been widely used in Norway for many years but is less common in other locations (Ref 6).

4.3 Gas Pre-Treatment

Recovery of CO_2 from the gas pre-treatment system and disposal of this via a CC(U)S system has now been applied on some onshore LNG plants, such as Gorgon and Snøhvit, and is planned for others such as the Barossa gas feed to Darwin LNG.

Application of this technology to an FLNG is straightforward, so long as a CO_2 disposal location is available, such as a sequestration reservoir.

4.4 Liquefaction Process Selection

Considering the seven FLNGs currently operating, under construction or on standby, the liquefaction technologies used are shown in **Table 2** below.

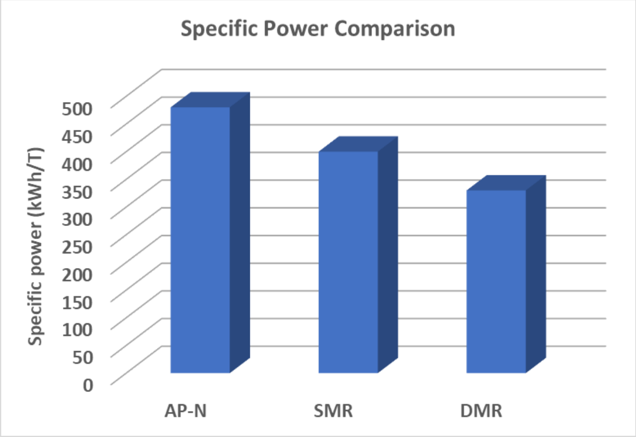
Liquefaction Process Type	Licensor	Installed Capacity (MTPA)	Vessels
Dual N_2 Expansion	**Air Products (AP-N)**	**2.7**	**PFLNG Satu, PFLNG Dua**
Single Mixed Refrigerant	**Black & Veatch (PRICO)**	**5.35**	**Tango, Hilli Episeyo, Golar Gimi**
Dual Mixed Refrigerant	**APCI DMR, Shell DMR**	**7.0**	**Coral Sul, Prelude**

Source: OWEL Research

Our Reference case is based on a generic Single Mixed Refrigerant (SMR) process, such as APCI's SMR, Black & Veatch's PRICO, Chart's IPSMR or Linde's LIMUM. This type of process is popular on FLNGs for its simplicity, having only a single refrigerant compressor per train.

LNG liquefaction process efficiency can be measured by the specific power demand per unit of LNG produced. However, the actual power demand for a project will depend on many variables - primarily the feed gas composition and the ambient temperature conditions.

Figure 4 below shows the range of Specific Power Demand (in kWh/t of LNG) for the three processes used so far on FLNG vessels, assuming tropical conditions for our Reference Case FLNG. We can see that SMR has mid-range efficiency, with AP-N requiring around 20% more compression power, and DMR around 20% less.



Source: OWEL Research

Many factors drive the decision on which liquefaction process to select for a project, including CAPEX, OPEX, reliability and safety. If we add to this Emissions, then we can see that switching from SMR to DMR on our Reference Case would have a significant impact on power demand for the refrigeration compressors, and hence fuel gas consumption and resulting emissions.

4.5 Reduced Fuel Gas Demand

To further reduce the FLNG fuel gas demand, three options are available.

Firstly, increasing the efficiency of the gas turbines, so that less fuel gas is required to deliver the same power. The most effective way to do this is to move from the traditional Simple Cycle, with typical peak efficiencies in the range of 35% to 40%, to Combined Cycle systems which have typical efficiencies between 50% and 60%.

Golar's Hilli Episeyo FLNG uses Heat Recovery Steam Generators (HSRG) on each of the refrigeration compressor exhausts to generate up to 40% additional power **(Ref 7)**. The steam system, therefore, covers the FLNG general power demand as well as the process heating. This arrangement is now TRL7, and the Golar Gimi FLNG is adopting a similar configuration **(Ref 8)**.

Combined Cycle power generation is also starting to be used on major FPSO projects. Equinor's Johan Castberg FPSO, currently under construction, will be the first major FPSO project to deploy this **(Ref 9)** and will be followed by Equinor's Bacalhau FPSO for Brazil, and Santos' Barossa FPSO in Australia.

Although the CC power generation equipment is larger, more costly, and more complex than SC, it can reduce fuel gas demand by 30%, or more.

Secondly, to reduce fuel demand further, power import from an external source is needed – either from shore or from adjacent wind turbines. The shore power option has been applied to FPSOs in Norway, for example on the circular Goliat FPSO. But although the swivel technology for full HV power import through a conventional turret is qualified to TRL4, this has not yet been applied on a project at full scale. Hence, for FLNGs, power import from shore is most likely to be applied to units in spread moored or jetty-moored applications.

Equinor has pioneered offshore floating wind to partly power an offshore facility with the Hywind Tampen project, where the 88 MW of renewable power will feed the Gullfaks and Snorre platforms, meeting about 35% of their annual power demand (Ref 10). Several other projects are considering similar schemes, and with four leading FPSO contractors also investing in wind technology, we can expect to see this technique deployed soon to reduce FPSO emissions. This concept could be equally applicable to an FLNG vessel.

Finally, another technology available is the use of Battery Energy Storage Systems (BESS). This can provide a virtual 'spinning reserve' without the need to run a spare generator on shared load. Turbine efficiency drops quickly with part load, so sharing the load between multiple machines increases emissions. Using BESS as an alternative standby power source allows the generator(s) to be run closer to full load, and so closer to peak efficiency. Woodside installed the first offshore BESS rated a 1 MWh on the Goodwyn A platform, offshore Australia, in 2019. The objective was to allow the platform to run with three gas turbine generators, instead of four (Ref 11). Application on an FLNG should be no different to a platform, so we consider this to be mature at TRL6 (but not yet TRL7, since it is less than 3 years in operation).

4.6 Reduced CO_2 in Exhaust Gases

To reduce the CO_2 content of gas turbine exhaust streams, Carbon Capture & Storage (CCS) can be used in two configurations: pre-combustion and post-combustion.

4.6.1 Pre-Combustion CCS

As shown in **Figure 3**, Pre-combustion CCS takes a slipstream of fuel gas through a Hydrogen reformer process and blends the resulting H_2 product back into the main fuel gas stream. The reformer process includes a conventional CO_2 removal step, achieving very high recovery rates of CO_2, which can then be re-injected or exported along with the CO_2 recovered from the pre-treatment system. Many gas turbines are now able to run reliably with H_2 blended into fuel gas at rates from 10% to 100%, depending on the model. By blending say 30% H_2 into fuel gas, CO_2 emissions from gas turbines will be reduced by a similar amount.

An H_2 reformer unit with an associated CO_2 compressor could be modularised and readily integrated into new FLNG projects. Some process licensors have optimised Blue Hydrogen processes to be more suitable for modular construction, such as the Johnson Matthey LCH^{TM} process. (Ref 12).

4.6.2 Post-Combustion CCS

In comparison, post-combustion CCS suffers from more difficult challenges.

- Lower CO_2 recovery (80% to 90% maximum) (Ref 13).
- Solvent degradation issues from some flue gas components (Ref 14).
- Large and heavy equipment, difficult to marinize

These challenges have slowed the application of post-combustion CCS projects onshore, and even more so for offshore applications. For these reasons, we expect pre-combustion CCS to be more favoured for FLNGs.

5. Other Emissions

Essential and emergency diesel-powered generators are also a source of CO_2 emissions, but generally, their short-term intermittent use makes this insignificant.

The FLNG cooling water system will discharge a large amount of heat to the sea, but the maximum discharge temperature is usually closely regulated to minimise the environmental impact. Again, the environmental impact is generally insignificant in open water, although this could be a concern in an enclosed near-shore or at-shore environment. In such cases, air cooling can also be considered for lower capacity FLNG vessels.

6. Benchmarking

The emissions level for the Reference Case FLNG is calculated at 0.43 $tCO_2e/tLNG$ (or 0.41 t/t if no feed gas compression is required).

Industry average levels for onshore LNG plants can range from 0.25 to 0.49 $tCO_2e/tLNG$, based on data presented by OIES (Ref 15). The range is due to the efficiency of the liquefaction plant, and the amount of CO_2 included in the feed gas, which is typically vented.

However, some onshore plants can achieve much lower levels, such as Snøhvit in Norway (0.21 t/t) and LNG Canada (0.16 t/t) (Ref 15). Both plants import hydroelectric power and use electric motor driven machinery. Snøhvit also has a CCS plant for re-injection of the CO_2 removed from the feed gas.

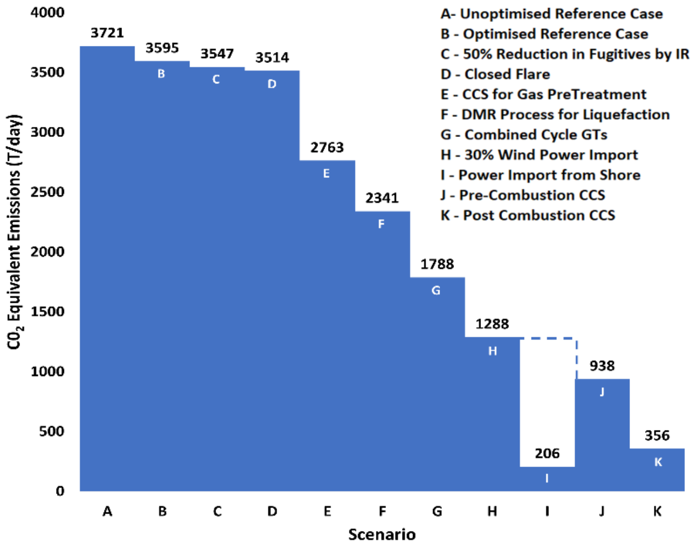
By implementing basic optimisations and the flare & vent system improvements, the carbon intensity of our Reference Case FLNG would reduce to between 0.41 t/t and 0.38 t/t. Re-injecting the CO_2 removed in pre-treatment would further reduce this to between 0.32 and 0.30 t/t. Adding Combined Cycle systems to the gas turbines would take this down to between 0.25 and 0.23 t/t (again with/without feed gas compression).

We have benchmarked this against Golar's Hilli Episeyo FLNG, using data published by Golar (Ref 16) which quotes a carbon intensity of 0.30 t/t. In their ESG report, Golar notes that this excludes the CO_2 vented from the gas pre-treatment system (Ref 17), so the quoted intensity fits well with our analysis.

7. Conclusions

The Reference Case FLNG emissions benchmark well with today's standard practice for onshore plants and FLNGs, but a range of proven technologies exist to reduce the emissions further, as summarised in **Figure 5**. Note that all options are applied incrementally in this analysis.

Figure 5 - Decarbonisation Options



From the Reference Case (point A on the chart), measures for optimisation, control of fugitive emissions, and switching to a closed flare all lead to relatively modest reductions in carbon emissions. But by implementing the deeper design change of CCS for the gas pre-treatment, an overall 25% reduction in carbon intensity can be achieved, to reach between 0.32 to 0.30 $tCO_2e/tLNG$ (with and without feed gas compression).

Moving from SMR to a higher efficiency liquefaction process, such as DMR, would reduce carbon intensity further, to between 0.27 and 0.25 t/t.

To go further, Combined Cycle Power Generation can be applied to both the main power generation and the refrigeration compressors, which would reduce the intensity to between 0.21 and 0.19 t/t, almost a 50% reduction from the base case. These solutions all have a low level of technology risk and would achieve a 'Best in Class' emissions intensity.

Importing Floating Wind power, at say 30% of the average total power demand, would reduce the carbon intensity to between 0.15 and 0.14 t/t, a reduction of around 65%.

To reduce emissions further, power import from shore is the most effective solution, but only if a green power source is available and it is technically feasible to cable this to the FLNG, depending on the distance from shore and water depth.

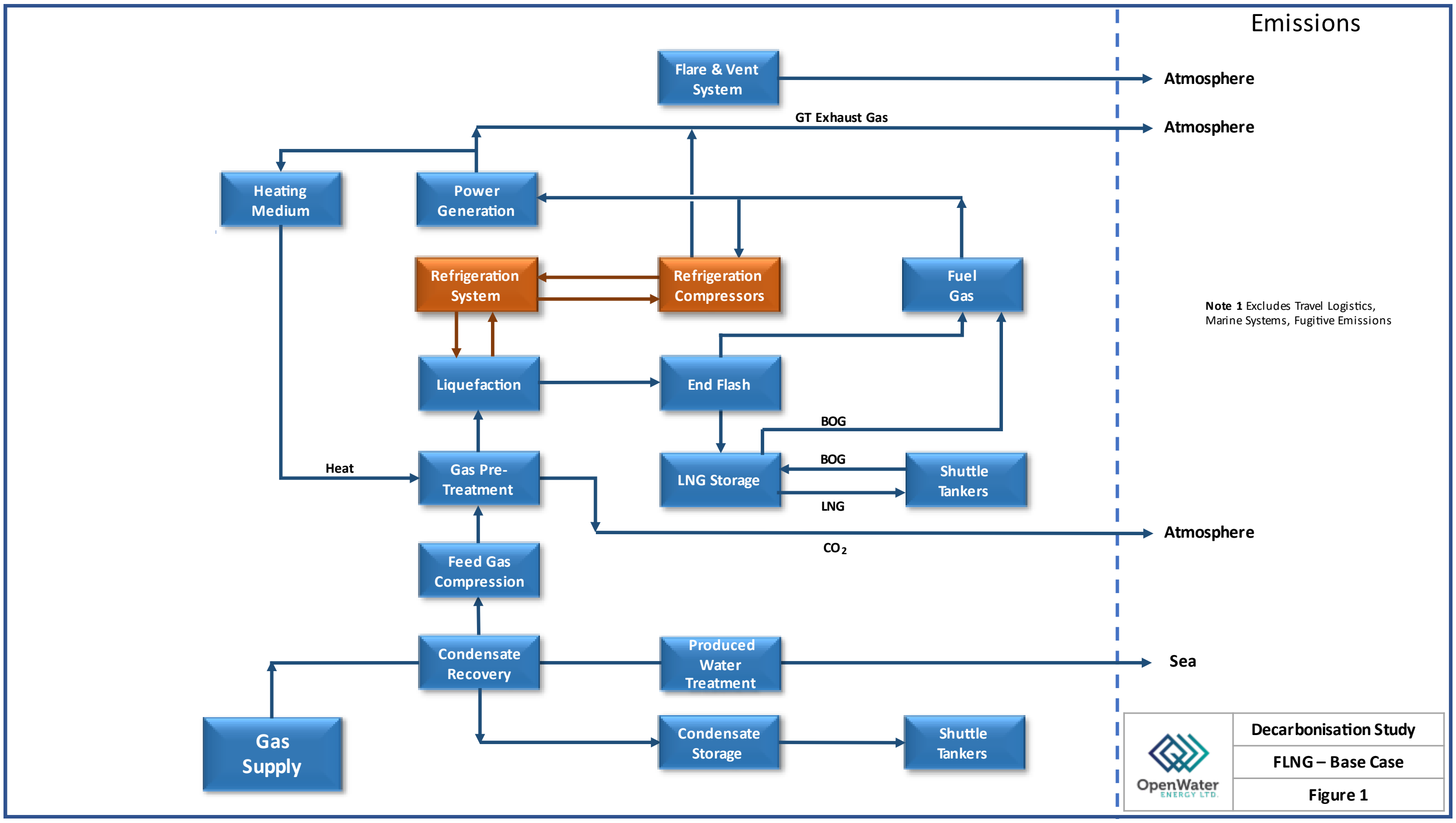
Alternatively, adding pre-combustion CCS to deliver 30% Hydrogen blended into the fuel gas is a promising alternative, although less mature. This would reduce the emissions intensity to between 0.10 and 0.11t/t, a total reduction of around 75%. The Sankey Chart in **Figure 6** (see page 8) shows the emissions abatement for this case.

The alternative of Post-combustion CCS may allow emissions reduction to reach around 90%, but again this is not yet mature technology for offshore applications and looks more difficult to implement.

The optimum choice of emission-reduction technologies for each FLNG will be a project-specific decision, depending on the field location and factors such as the emission intensity needed to secure project finance. The risk of deploying technology that is not yet mature should be balanced with the rewards of lower emissions, to manage total project risk exposure.

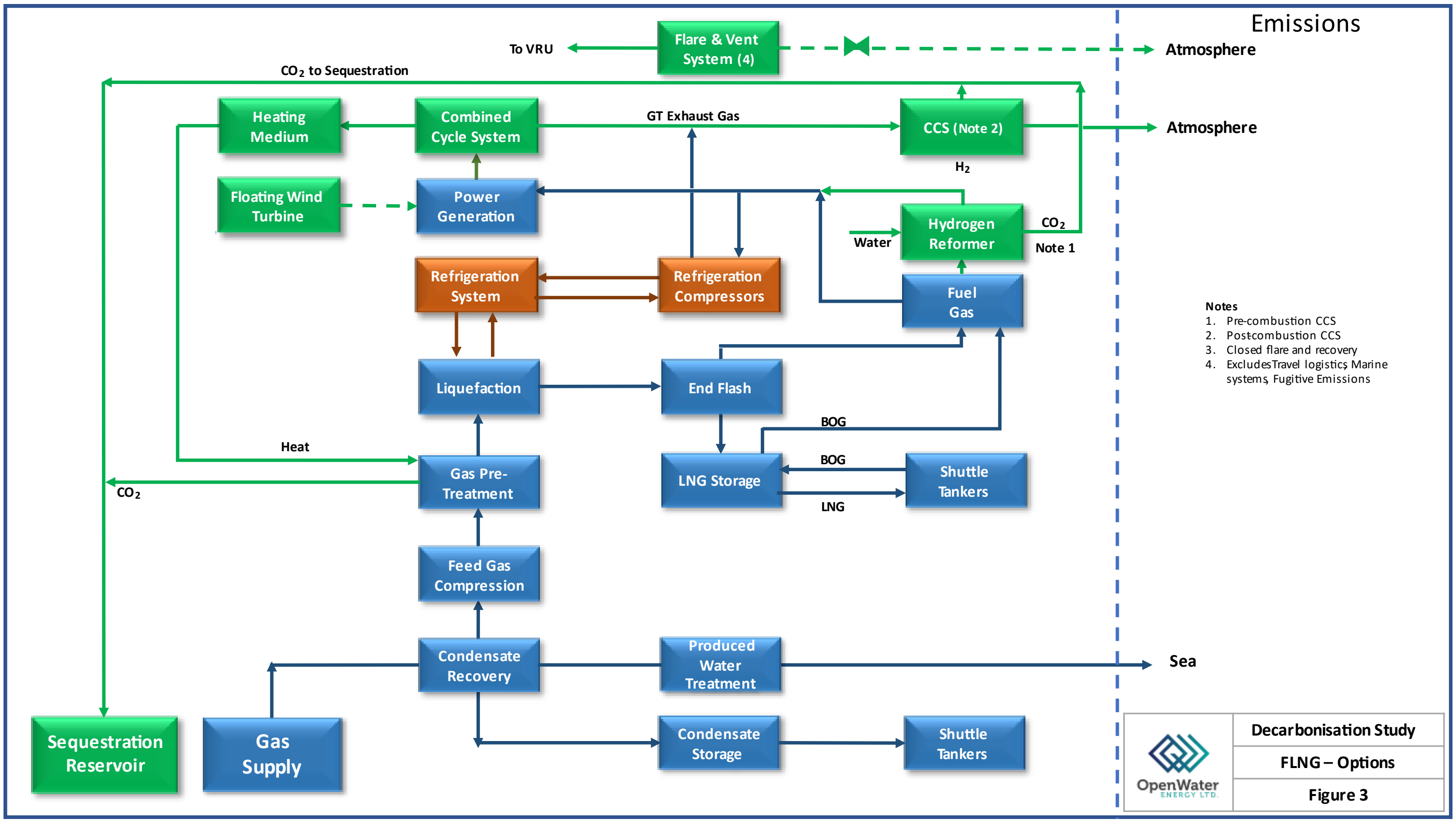
OpenWater Energy Ltd is pleased to be assisting Clients with these difficult decisions.

Figure 1



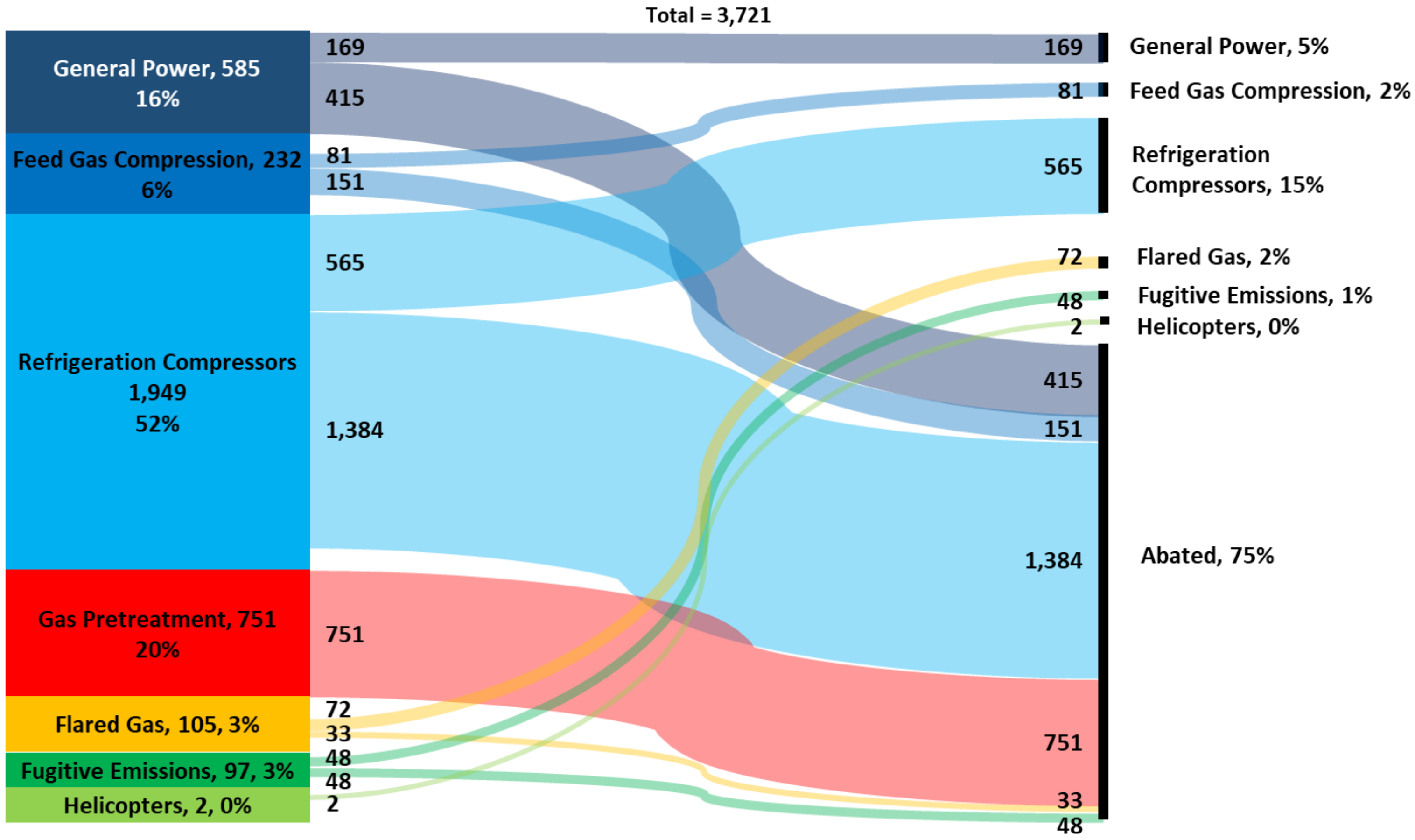
Note 1 Excludes Travel Logistics, Marine Systems, Fugitive Emissions

Figure 3



Notes
1. Pre-combustion CCS
2. Postcombustion CCS
3. Closed flare and recovery
4. Excludes Travel logistics, Marine systems, Fugitive Emissions

Figure 6 - Sankey Chart for Abatement – Scenario J



8. Glossary

ATEX	Appareils destinés à être utilisés en Atmosphères EXplosibles
BOG	Boil Off Gas
CC	Combined Cycle (Gas Turbine)
CC(U)S	Carbon Capture, (Utilisation) and Storage
CO_2e	CO_2 Equivalent
ESG	Environmental, Social, Governance
FPSO	Floating Production, Storage and Offloading Vessel
FLNG	Floating LNG Liquefaction vessel
GWP	Greenhouse Warming Potential
MTPA	Millions of Tonnes Per Annum
SC	Simple Cycle (Gas Turbine)
TRL	Technology Readiness Level, per API 17N

9. References

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17	https://www.golarlng.com/~/media/Files/G/Golar-Lng/documents/golar-lng-methodology-statement.pdf	Golar LNG	2022	Website