Introduction
With the LNG sector set for unprecedented growth, but with gas prices globally under pressure from both low oil prices and a very competitive supply situation, project developers are looking for innovative and cost effective ways to get their gas to market, both quickly and efficiently. Although historically the industry has stuck closely to the tried and tested traditional methods of producing LNG by land based liquefaction and storage with accompanying marine facilities, more and more projects are considering new alternatives, and many are actively pursuing floating concepts, built in shipyards, and moved into position where needed. The key question for the industry is how the economics of these novel projects will compare to more traditional approaches. To make informed decisions Natural Gas resource holders, investors and regulators need an understanding of the nature, costs and cost drivers of Floating Liquefied Natural Gas (FLNG) technology.

FLNG: Costs and Cost Drivers
Fundamental project decisions (onshore vs. offshore LNG, project feasibility) are being progressed on a limited understanding of FLNG development costs. Indeed, some feasibility studies have excluded FLNG cost altogether due to the lack of information. GCA has carried out a review of public domain cost information in order to bring some insight to the wide range of numbers quoted.

What is FLNG (and what isn’t)
There has been a tendency (outside of the industry) to attach the “FLNG” label to any technology that is associated with gas, and floats. This includes floating storage and regasification units (FSRU), LNG transport carriers, or floating LPG processing units (LPG FPSO). This article focusses only on those projects where natural gas is liquefied by cooling and is located on a floating vessel- Floating LNG. A list of some 25 current FLNG projects forms the basis of this study. These include some 20 projects in various stages of pre-FID development, 5 projects under construction, and none (as yet) in service.

Even among the “true FLNG” projects it is also important to recognize that this includes a wide variety of facility types, ranging from essentially liquefaction-only facilities limited to benign water environments, to fully-fledged gas pre-processing, liquefaction, storage and offloading facilities that can operate even in hostile environments. Think of it in terms of a minimal facilities shallow water Gulf of Mexico development versus a northern North Sea / Norwegian Sea integrated platform. A big variance in cost results!

FLNG Project Costs
A convenient benchmark to compare FLNG projects is the “$/TPA” (US dollars per tonne per annum liquefaction capacity) metric. Figure 1 provides a histogram of published data, with costs normalized to 2015 US $ by application of capital cost escalation metrics. This data set covers press releases from projects announced, project in construction, and quotes published by vendors with no associated project. Data is grouped into “Bins” of $500/TPA increments, from below $500 to above $4,000. The data average is just under $1,500/TPA, the median is just over $1,100/TPA, and ranges from $200/TPA to over $6,000/TPA.
Figure 1: Histogram of $/TPA Public Domain FLNG Data (as of October 2015)

Clearly such a wide range of results is of little practical use. However, examination of the maturity and scope of the project data in each Bin provides some insights.

Bin A (below $500/TPA) includes data from vessel construction and conversion contracts, some early low-end speculative estimates, and small capacity inshore (sheltered waters) liquefaction projects with limited storage. A number of the data refer to vessel construction or conversion contract awards and may therefore exclude other critical project costs such as transport and installation, supervision, or client supply of key components. It is likely that pre-conditioning of gas to conventional pipeline specification is not included in these costs.

Data in Bin B ($500 to $1,000/TPA) is dominated by information released by developers of FLNG concepts intended for lease, and early stage estimates of some of the projects currently in construction. These estimates are generally at a preliminary stage of project definition, and relate to FLNG vessels of smaller train capacity; and low weight, lower efficiency, refrigeration cycles.

Bin C ($1,000 to $1,500/TPA) is characterized by recent cost data on vessels of smaller train size, with Nitrogen Recycle refrigeration process. This process offers low specific weight, but is also of lower efficiency than (for example) Dual Mixed Refrigerant (DMR) processes. Nitrogen Recycle refrigeration processes have a relative process efficiency of 75, versus 100 from DMR, thus producing

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1 Natural Gas Liquefaction Technology for Floating LNG Facilities: Air Products and Chemicals Inc. 2013
proportionately less marketable LNG from any given quantity of feed gas. The Nitrogen Recycle process is also limited to a train size up to 1.5 MTPA. The LNG storage capacity of these vessels (177,000 m³) is sized to provide a full loading to the majority of LNG cargo vessels (120,000 to 140,000 m³ LNG, or 56,000 to 65,000 MT²).

Bins D, E, and F ($1,500 to $3,000/TPA) includes the large capacity, high efficiency, remote offshore FLNG vessels designed to handle extreme weather conditions and a wide variety of reservoir fluids. The cost data may also include first phase drilling and subsea development costs, and (in some cases) full cycle project costs including all wells required for full field development. These developments are typically based on high efficiency DMR refrigerant cycles, and have LNG storage volumes to allow full loading of an LNG carrier plus additional volumes in case of offloading delays (220,000 m³). Additionally, these vessels may include full gas pre-conditioning, LPG extraction, and condensate stabilization and associated storage. Clearly, for comparability, these costs must be adjusted to account for the upstream project scope.

Bins G, H, and I (above $3,000/TPA) include early stage (or out of date) estimates for the full project scope. In some cases, the cost benchmark is based on LNG capacity only, ignoring the condensate and LPG capacities but including the associated costs.

This review shows public domain FLNG cost data to be a mixture of component costs, FLNG vessel costs, and part- or full-cycle project costs. Hence, the data has a very wide range. It is crucially important when comparing costs to understand technically what is being compared as well.

**FLNG Facility Cost Drivers**

Even when focusing on just the cost of an FLNG facility and excluding the project costs associated with reservoir development (drilling, subsea architecture, risers, and shore base), there still remains a large scope for variability in project cost and unit cost.

The block diagram in Figure 2 illustrates the functionality that might be found in a typical full-scale LNG plant, with additional blocks related to an offshore FLNG vessel.

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² 1 m³ of LNG is equivalent to 0.465 tonnes
All these processes are likely to be found in a full-scale FLNG development such as those in Bins D, E, and F above. However the processes circled (in red), mounted on an inshore-moored barge receiving pipeline quality gas from an onshore supply, would also be characterized as an FLNG development (Bin A). Clearly, the functionality of the vessel in addition to the core liquefaction capability is a key cost driver. A study by KBR\(^3\) (based on onshore LNG, but nevertheless illustrative), indexing a minimum scope “base” plant at 100, shows construction costs approaching a 300 index, driven mainly by the process complexity illustrated above.

As noted when discussing smaller train size (Bin C), the choice of liquefaction technology will affect the vessel weight, cost, train capacity, and process efficiency. Lower efficiency processes also tend to have lower specific weight (i.e. tonnes of process equipment per TPA LNG capacity). A nitrogen recycle process requires 87% of the equipment weight required for an equivalent capacity DMR process, but delivers only 75% of the capacity. These process weight savings will have knock-on effects in vessel size and costs.

Feed gas composition and variability will impact the process functions required. H\(_2\)S removal, CO\(_2\) & other inert gas removal, mercury removal, gas dehydration, and condensate separation & stabilization may all be found in the “high cost” FLNG projects (Bin D and above), but are excluded from the scope of the lowest cost developments.

Product storage and offloading rate is another key differentiator between projects. Shell's Prelude FLNG provides 220,000 m\(^3\) of LNG storage together with 216,000 m\(^3\) of condensate and LPG storage. Some

\[^3\] KBR Paper PS4-1 “LNG Liquefaction- Not All Plants are Created Equal”
small, inshore moored concepts provide limited on board storage but rely on an adjacent, permanently moored LNG FSO. The available storage volume obviously affects the size of cargo vessel the development can service but also impacts system availability and operational continuity in cases where offloading disruptions occur.

System availability and facilities lifetime impact costs and economic performance on many levels. The consequences of an unplanned process shutdown to an FLNG development in terms of re-start time, contractual penalties, and lost production provide a strong incentive to aim for high reliability when overall economic performance is considered. Equipment sparing, storage capacity, offloading rate, vessel motion characteristics, mooring design, and vessel fatigue life all contribute to the overall uptime and cost of an FLNG vessel.

A final cost driver, common to all floating facilities, is mooring design. The projects included in this review range from small barges moored in sheltered waters to world-scale 600,000 tonne facilities permanently moored to withstand Category 5 cyclone conditions. Mooring designs include jetty mooring, spread-moored, external turret, and internal turret. The reported cost of the turret in Shell’s Prelude development exceeds the total facility cost of the smallest developments in this review.

In summary, there are trade-offs between cost (and unit cost) with functionality, capacity, reliability, and process efficiency.

**Other Considerations**

Project assessment includes many other aspects beyond cost and capacity. FLNG developments may differ in certain aspects to more conventional projects (e.g. an onshore LNG option).

The environmental footprint of an FLNG development, *assuming equivalent process efficiency*, is arguably less than an onshore plant. Of course no land is required for the FLNG vessel, no loading jetty, and no pipelines or shore approach. Furthermore, there is less likelihood of urban development near to the facility. Logistics support for FLNG is likely to be supply boat and helicopter based, whereas an onshore facility might be serviced by road and fixed wing aviation.

As an immature technology, experience suggests that cost predictability and cost control of FLNG developments will be an issue, at least with the early projects. This will require greater levels of contingency in time and budget, together with strong client project supervision. In turn this will pose increased risks to project finance providers, limiting the level and restricting the sources of financing that can be expected.

By analogy with the evolution of the FPSO industry, FLNG does offer the opportunity for new commercial structures in LNG. There has already been development of “spec” FLNG vessels, with a business model to lease these to resource holders and accelerate development cycles.

Although difficult to place a dollar figure on mobility, FLNG facilities offer one major advantage over traditional approaches, as a result of them having the potential for relocation. This could be as a result of planned events, such as multiple smaller fields/reservoirs, or unplanned events such as local political
risk, disappointing reservoir performance or market conditions. For investors, this can represent a significant area of risk reduction with a potential commensurate adjustment to the cost of finance, or at least a mitigation of the technical risk premium mentioned above.

Finally, local content must be considered. However, these days both onshore and offshore project developments depend strongly on modular fabrication in yards remote from the project site. The host country’s capability to fabricate and deliver these modules is critical from a local content perspective. Although the near-term focus tends to be on the local content of project development, the long term prize lies in the local component of the operational support and economic multiplier effect during the decades of project operation.

Future Trends
The evolution of the FPSO industry since the first (IOC-sponsored) developments in the 1970s to the current day offers a model for the future direction of FLNG. Figure 3 compares the time on station of FPSO’s currently in service, with the early growth of FLNG facilities under construction or in planning.

Figure 3: FPSO and FLNG Growth Trends

There is a clear similarity in the growth curves, typical of the trajectory of technology adoption in oil and gas. On this analogy, what trends might be seen in FLNG?

*Reduction in unit development costs.* As more yards develop the capability to build FLNG units, supply chains evolve, and technology becomes established, unit costs (in real terms) are likely to fall.

*Easier finance.* Technical maturity and project experience will build the confidence necessary for project finance to become available. This, in turn, will bring FLNG developments within the reach of the smaller player.
Leasing. Vessel owners will begin to offer FLNG capacity on a leased basis. This trend is already emerging.

Commercial innovation. Other commercial structures will evolve to match project development risk with FLNG ownership risk.

Technology innovation. Developers will continue to explore other options to new build. Vessel owners are already converting LNG carriers to FLNG. Conceptual designs for a higher capacity, twin-hull design, based on two LNG carriers, have also been considered. Variety in vessel capacity, cost, capability, and specification will continue to emerge.

Unplanned outcomes. Inevitably, with any new technology development, some projects will not go according to plan. There may be economic shortfalls due to cost overruns, technical failures, or market conditions.

Conclusions
With an understanding of the technology choices and cost drivers behind FLNG projects, it is possible to make sense of the limited financial information offered in the public domain. Although the uncertainty range around FLNG costs will remain wide until the experience base develops, understanding is now at the stage where a more detailed appreciation of the requirements of each particular project can be used to prepare screening level estimates in support of concept selection.