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DOES (TRAIN) SIZE REALLY MATTER?

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The LNG industry has long embraced the notion that, for export facilities, bigger is better. Large trains take advantage of economies of scale to achieve the lowest CAPEX for a given facility size – right? Through changes in execution planning (e.g. modularization) and changes in plant location (e.g. LNG in North America), the bigger is better premise held strong…until the threat of LNG oversupply happened.

Almost without warning, new project concepts entered the development queue with proposed small and midscale plant designs touting potentially much lower costs per tonne than any of the recent large scale facilities. Even in a buyer's market, what has fundamentally changed? Have our traditional assumptions been totally wrong or has cost per tonne obscured our way of thinking about train size? Are there other factors and project drivers that can lead to a different train size selection?

This paper addresses the advantages and disadvantages of trains of varying capacities for various facility sizes. It will cover the impact on such areas as:

- Technology selection
- Packaging & Modularization
- Construction/CAPEX
- Operations and maintenance
- Plant efficiency and emissions
- Safety
- LNG sales, marketing, and financing

All of the criteria above play important roles in the decision making process for an optimal train configuration and associated infrastructure. Who knows, maybe a new understanding of these factors will lead in a different direction than we thought possible in the past.

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INTRODUCTION

The premise of this paper is based on a common debate held in many forums, across numerous contexts, and over many generations: does size really matter? In the context of the LNG industry, the premise refers to liquefaction train size to achieve a certain facility size and the resulting project economics (often capital cost divided by annual production capacity, shortened to US$/tonne); therefore, the resulting question remains: Does train size really matter?

Instilled in our minds and hearts since youth, we've often been led to believe that "bigger is better". As we have matured, many things still seem to be best presented when delivered on a large scale. Through education, we learn some basic economic theories where we are introduced to the concept of *economies of scale*. When "bigger is better" is framed by the theory of economies of scale, our previous assumptions appear to be validated. As is the case with many theories, there are often exceptions to what appear to be well validated rules. Therefore, is there a valid counterargument to "bigger is better"? Is there a way to offset or negate the size advantage?

There are many interesting counterintuitive examples in the world of sports. In basketball, size (height) is often a great advantage, but there are notable examples of effective basketball players that are excellent shooters or have quickness that towering individuals may not possess. In Major League Baseball, the 2017 American League Most Valuable Player was the 5'-6" tall Jose Altuve and the runner up was 6'-10" Aaron Judge [Ref 1]. While size remains an obvious advantage in the sport of Sumo wrestling, there are other sports examples where being large scale is a disadvantage, such as in gymnastics, diving and horse racing. Even an economy class airplane seat is a distinct disadvantage to people of significant size, whereas first class accommodation may be ineffective for a child.

Anecdotes aside, this paper is not intended to analyze the fundamental theory of economies of scale; however, this paper does intend to discuss the differences of planning and designing large LNG plants with large trains versus large LNG plants consisting of small and mid-scale trains to achieve a low installed unit cost (US$/tonne). At this point in the LNG project development timeline, the debate continues on the influence of LNG train size on capital cost (CAPEX) and unit cost. Until there are a sufficient number projects built to fully compare and contrast the economic views, the debate will continue.

PURPOSE – WHY THE DEBATE ON SMALL VS LARGE TRAINS?

The purpose of this paper is quite simple, yet multilayered. When surveying the landscape of potential LNG projects, there are examples of all shapes and sizes of project definition with little correlation of one plant to another (even those within geographical proximity to each other). There are proposed large facilities with large trains, large facilities with small trains, small facilities with small trains, as well as other combinations of train size and facility size. For reference, the November/December issue of LNG Journal [Ref 2] lists forty projects as either proposed or in EPC. There are actually well over forty projects in various states of development, illustrating an ample but crowded field of projects vying for attention and investment. What can we deduce from this list of potential projects?

Scanning the proposed LNG list, the facility sizes range from 2.0 to 27.0 Mt/a (often informally written as MTPA). Corresponding train sizes are 0.25 to 7.0 Mt/a. Since this paper is technically-focused and not purely commercial, the selection of total facility size involves many economic and strategic factors that are beyond the scope of the "bigger is better" premise. For reference, these factors may include global supply/demand, asset/reservoir size, long term capital expenditure/planning, corporate strategies, partnership factors, etc. While the range of facility size is wide, as shown in Table 1, this paper is primarily interested in the decision behind train sizing for projects that have roughly the same facility size.

Note the largest planned train size (7.0 Mt/a) is twenty-eight times the capacity of smallest train (0.25 Mt/a). For a facility size above 5-7 Mt/a (which could be configured as one large train), the range of available train size options poses the question of how a project determines the best train size for their facility size and location. For a 15 Mt/a facility, a project could build two of the largest trains (at 7.5 Mt/a), three large trains (at 5 Mt/a), five modestly size trains (at 3 Mt/a), fifteen small scale trains (at 1 Mt/a) or an extreme thirty to sixty of the smallest units (0.5 Mt/a and below). With so many choices, how do projects make the optimal decisions that affect billions of dollars of investment?

LNG Export Projects

Country	Location/Project	Project Developers	Planned Start Up	Number of Trains	Capacity In MTPA
AUSTRALIA	Pluto LNG expansion	Woodside	2021+	2	10.0
	Prelude FLNG	Shell, Inpex, Kogas CPC	2018	1	3.5
CANADA	Bear Head LNG, Nova Scotia	LNG Ltd.	2024	4	8.0
	Goldboro LNG, Nova Scotia	Pieridae Energy	2024	2	10.0
	Kitimat LNG, BC	Woodside, Chevron	2024	2	10.0
	LNG Canada, BC	Shell, Mitsubishi, Kogas, PetroChina, Petronas	2024	2	12.0
	Melford LNG project, Nova Scotia	H-Energy Hiranandani Group	Studies		
	Kwispaa FLNG, Vancouver	Steelhead LNG	2024	4	12.0
	Vancouver Tilbury	WesPac Midstream	2021	1	3.25
	Woodfibre LNG, Squamish	Pacific Oil & Gas Co	2020	2	2.1
EQ.GUINEA	Equatorial Guinea Fortuna FLNG	Ophir, Golar LNG, GEPetrol	2020+	1	2.0
INDONESIA	Sengkang LNG	Energy World Corp.	2018	4	2.0
MALAYSIA	Rotan FLNG (Sabah)	Petronas, Murphy Oil	2019	1	1.5
MOZAMBIQUE	Area 1 Onshore	Anadarko Petroleum and partners	2023+	2	10.0
	Area 4 Onshore	Eni and partners	2023+	2	10.0
	Area 4 FLNG	Eni and partners	2019	1	2.5
NIGERIA	NLNG Train 7	NNPC, Shell, Eni, Total	2022+	1	7.0
PAPUA NEW GUINEA	Elk-Antelope LNG	Total, ExxonMobil Oil Search, Petromin	Studies		
RUSSIA	Sakhalin II expansion	Gazprom, Shell, Mitsui, Mitsubishi	2021	studies	
	Vladivostok LNG	Gazprom, Itochu, various	2023+	2	10.0
USA	Alaska LNG Nikiski	Alaska Gasline Development Corp.	2023+	3	20.0
	Annova LNG, Brownsville	Exelon Corp.	2023+	6	6.0
	Cameron LNG, Louisiana	Sempra, Total, Mitsui, Mitsubishi	2019	3	14.95
	Commonwealth LNG, Louisiana	Commonwealth LNG LLP	2022	8	9.0
	Corpus Christi Liquefaction, Texas	Cheniere	2019	5	22.5
	Delfin LNG, Louisiana	Delfin, Hoegh	2021	3	9.0
	Driftwood LNG, Louisiana	Tellurian Investments	2022	6	26.0
	Elba Island, Georgia	Kinder Morgan, EIG Energy	2018	10	2.5
	Freeport LNG, Texas	Freeport LNG	2018	4	20.4
	Galveston Bay LNG	NextDecade	2023+	6	27.0
	Golden Pass, Texas	Qatar Petroleum, ExxonMobil	2021	3	15.6
	Jordan Cove, Coos Bay	Pembina Corp.	2024	2	7.8
	Lake Charles, Louisiana	Shell, ETE	2024	3	15.0
	Magnolia LNG	Louisiana LNG Ltd.	2023+	4	8.0
	Port Arthur LNG	Sempra	2023+	2	10.0
	Rio Grande LNG	NextDecade	2023+	6	27.0
	Sabine Pass LNG, Louisiana	Cheniere	2018-19	2	9.0
	Texas LNG Brownsville	Chandra, Meyer, Samsung, others	2023+	2	4.0
	VG LNG (Cameron Parish)	Venture Global	2021	5	10.0
	VG LNG (Plaquemines)	Venture Global	2021	10	20.0

Table 1. LNG Export Projects from LNG Journal, Nov/Dec 2018 (Potential and in EPC)

While LNG project delivery history is young compared to that of chemicals, oil, and other fuels, it is still a mature business with many project successes. If the LNG industry is as mature and well defined as we think it is, why is there little to no alignment on train size and why do some current projects appear to deviate from proven experience? There is so much variance in terms of configuring LNG projects, we continually are asked the question if certain projects are right or wrong. Both small and large trains can be technically “right”, but can both choices be executed as planned and hit their cost and schedule targets?

A potential reason behind the misalignment on train size selection is that new LNG projects (a.k.a. greenfield or newbuild) are often ranked using unit cost or US$/tonne. When projects are compared by unit cost, projects seeking outside investment must strive for the lowest unit cost in order to stand out from the dozens of other investment opportunities. As a result, the intense focus on US$/tonne, and the LNG market’s aspirational cost of US $500/tonne [Ref 3] may have resulted in configuring a new wave of projects based on a small train size; the resulting configurations and associated costs are then readjusted to justify these aspirational cost targets (without any historical benchmarks to dispute the economics). In addition to cost targets, there are other supporting technical and execution factors that currently appear to positively support the wide range of train sizes.

Continuing to rephrase the size argument, this debate is also addressing if sticking with train size based on economies of scale captures the most value (lowest cost and fastest schedule) versus new ways of configuring trains based on site specific project execution. Historically, the LNG industry has grown based on bespoke LNG projects with little synergy among different projects other than commonly used process technologies, equipment, and key service providers. While there have been examples of train duplication with certain train sizes (e.g. P.T. Badak, Malaysia, NWS, Nigeria, Qatar, Cheniere, etc.) many of these same facilities embraced increased train sizes in subsequent expansions.

A strong counterargument to economies of scale is the idea that large facilities can be built in numerous parcels of capacity if done so in a cost efficient and effectively repetitive manner resulting in either a lower overall CAPEX or greater net project value. Similar to economies of scale, this idea is referred to as economies of unit scale. Due to the potential for success for energy and infrastructure projects, there is significant research in applying economies of unit scale in the nuclear and power generation industries [Ref 4 & 5]. For LNG, the key is in understanding the characteristics of small scale trains in order to evaluate if the industry is approaching a tipping point in economies of scale (i.e. trains becoming too large). Conversely, site-specific civil and infrastructure issues often still most influence project cost; as a result, train size is merely a required decision point in the long journey of planning and developing a natural gas megaproject.

For simplicity, this paper segregates train sizes into two groups, large scale (LS) and small scale (SS). Large scale trains will be defined as those above 3 Mt/a in capacity. While it is well understood that there are benefits to the mid-scale range (1 to 3 Mt/a), trains in this size range can exhibit characteristics of both large scale and small scale and would complicate the discussion. In addition, the micro-scale range (below 0.25 Mt/a) is also worth discussion in a later edition of this paper. This paper will identify benefits from the mid-scale range when appropriate, but will stick to the theme of multiple small trains versus few large trains to fulfill an overall plant capacity. Support infrastructure outside the train (e.g. gas conditioning, refrigerant and LPG processing, and storage and loading) is not considered in this paper to allow clear focus on the strategies of large scale versus small scale.

GLOSSARY

For ease of reading, we will use the following terminology for the remainder of the paper:

- CAPEX Capital Cost
- EOS Economy (or Economies) of Scale
- EOUS Economy (or Economies) of Unit Scale
- EPC Engineering Procurement and Construction
- FEED Front End Engineering Design (pre-FID work)
- FID Final Investment Decision
- LS Large Scale (trains larger than 3 Mt/a)
- MCHE Main Cryogenic Heat Exchanger
- MMSCFD Million Standard Cubic Feet per Day (English unit of measure)
- Mt/a Million Metric Tonnes per year (Metric unit of measure)

- NPV Net Present Value (a Measure of Profitability)
- OPEX Operating Cost
- SIMOPS Simultaneous Operations
- SMR Single Mixed Refrigerant (process technology)
- SS Small Scale (trains less than 3 Mt/a)

BIG IS BEAUTIFUL

FOLLOWING THE TREND

History has shown that the LNG industry, with very few exceptions, has embraced EOS from the very first projects through 2015. As shown in Figure 1, LNG projects consistently contained larger and larger trains, regardless of facility size, to chase the benefits of EOS. Interestingly, the trend toward large trains held constant even for plants with only one train for its total capacity (e.g. Darwin LNG, EGLNG, SEGAS LNG, and Peru LNG). There are many publications that have covered the merits of LNG train economies of scale (e.g. Ref 6), so this paper will consider future projects and/or project drivers that may lead to different project decisions other than EOS.

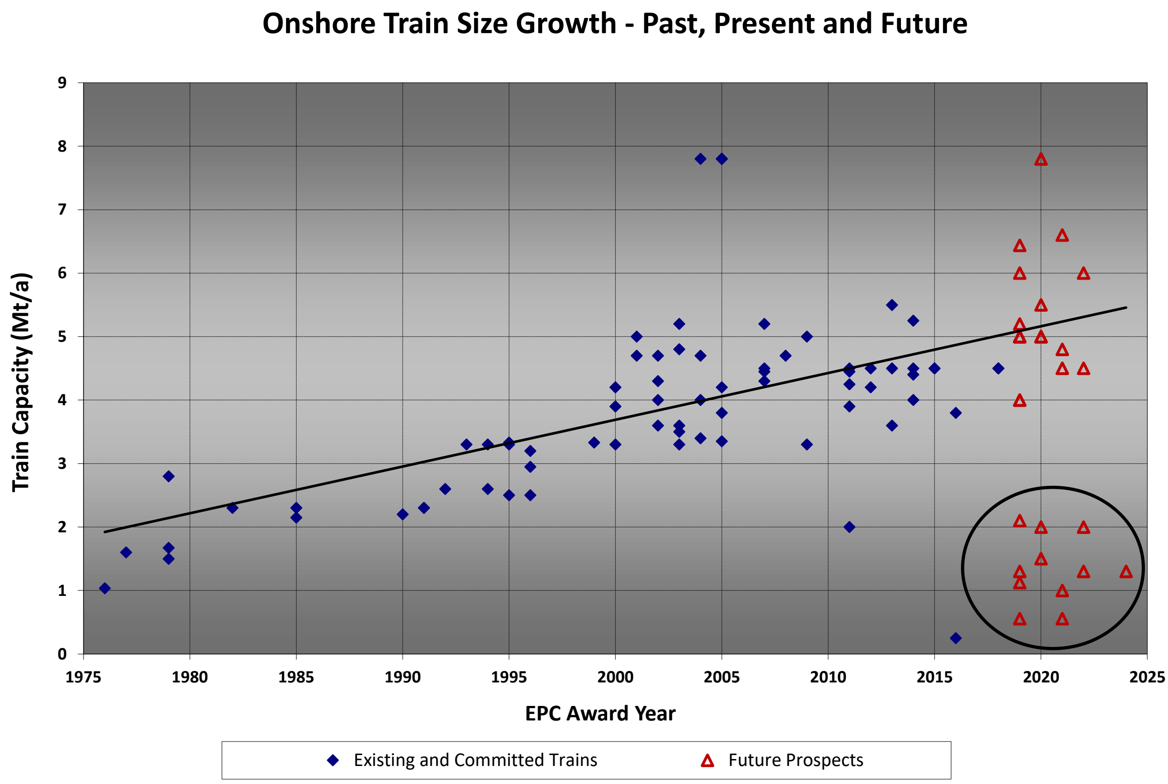

Figure 1. LNG Train Size over Time and Future Diversification

Referencing back to Figure 1, there remain several planned projects that embrace EOS even for one or two train grassroots facilities. The most recent example to reach FID is LNG Canada, which is a planned two train facility using large trains above the current trend at 7 Mt/a [Ref 7 & 8]. Other projects using large trains include prospects in every region of the world, including Canada, Mozambique, Russia, Tanzania, and the USA. It is interesting to consider the potential configuration issues that may influence a decision away from the trend – i.e. from near the trendline to either the largest LNG trains or to the SS range as shown in the bottom right quadrant of Figure 1.

EOS STILL HAS ISSUES TO CONSIDER WHEN SELECTING TRAIN SIZE

For completed projects included in Figure 1, the notable exceptions to the trend are the 7.8 Mt/a Qatargas/RasGas LS trains and the 2.0 Mt/a single SS train at Donggi Senoro LNG. Noting that the single train facility at Donggi Senoro was never expanded, it can be assumed that the single SS train size was well suited to the commercial parameters of the project and its owners. On the other hand, although the train configurations in Qatar are again proposed for future expansion (duplication at same train size in 2020 and beyond), the configuration was never repeated at another global location; therefore, one may ask if there is a point when a train may become too large, even when the largest train sizes should drive down unit cost (US$/tonne) considering the EOS philosophy.

The configuration for the LS trains in Qatar is based on the AP-X® liquefaction process technology offered by Air Products and Chemicals, Inc. (APCI). Along with the project sponsors and EPC contractors, APCI has commercially proven the AP-X® process and has continued to improve and reconfigure their design to offer up to 10 Mt/a in a single train [Ref 9]. From a recent publication, APCI believes in the economics of the upper end of this capacity range (from the process technology perspective) and has invested to prepare for this future. Since the final project EPC costs for these largest trains are not publicly disclosed, it is unclear if these projects achieved the lowest US$/tonne based on the largest train size ever built. Perhaps the technology to support the largest EOS trains was selected based on other influential criteria. Due to the many factors involved in establishing a plant configuration (not just US$/tonne), it is likely that the selection criteria was more complex than just unit cost.

From the EPC contractor perspective, project costs tend to increase as equipment sizes become too large to competitively procure economically, require parallel equipment due to manufacturing limitations, or have increased complexity that results in losing EOS [Ref 6]. Prior to the commercialization of AP-X® technology, the maximum size of the MCHE (coil wound or cold box), the complexity of the refrigerant compression equipment, or limits on pipe diameter were points to consider when determining the maximum train size. For many of the projects shown in Figure 1, even those above the trendline, the proven limits on equipment often set the expectations on train EOS.

In summary, what is clear from Figure 1 is that there two distinct sides of the LNG train size debate; LS versus SS. The industry may be witnessing an inflection point where EOS appears to have limitations as we approach a certain train size. Like many debates, there are notable benefits and constraints on both sides.

SMALL IS BOTH NEW & BEAUTIFUL

ECONOMIES OF UNIT SCALE

We could simplify this entire size argument and say that selecting train size is as trivial as buying a certain size of pizza and simply determining how many slices you want or need to serve; but these decisions are far more complicated than cutting up pizza, cake, or pies. Train configuration is not merely a process and mechanical discussion; train size, especially when moving from LS to SS completely changes the execution planning of a project. While EOS and LS trains have had many proven project outcomes, there have been notable economic challenges on recent LNG projects as well as other gas and infrastructure projects [Ref 10]. In projects that have experienced such challenges, the question remains whether or not the LS train size had significantly influenced project execution outcomes, leading to increased cost and schedule risk. Conversely, one must consider that other site related factors are responsible for these unintended project outcomes, and maybe a SS philosophy would still provide a degree of project certainty even if only on a percentage of the total project. As a result, if chasing EOS is not the guaranteed project solution, looking to EOUS may be of interest.

As previously stated, EOUS seeks to find economic gains (CAPEX and/or schedule) from the repeatability of multiple small units integrated over time to build up to a large overall plant capacity. This concept has already been applied in the nuclear and power generation industries [Ref 4 & 5]. For LNG facilities, the technical feasibility and constructability of a SS LNG train is not the question; the new strategy is that EOUS (many SS trains) is being applied for large facilities where two or more LS trains would be required to achieve the desired capacity. Some peripheral issues unrelated to CAPEX, including plant efficiency and the likelihood of fabrication repeatability are key to the full economic analysis and are discussed in later sections.

Another way of embracing the philosophy of LNG EOUS is with the ideas surrounding digital design and automation. If LNG plant configuration in FEED (i.e. design basis and engineering specifications) becomes a more perfect "science", the process could be automated; one could simply enter the design parameters and push a button to obtain the resulting high quality engineering data and deliverables with little effort. Continuing this analogy post-FEED, EOUS looks to achieve the same types of digital design gains through excellence in fabrication, logistics, integration, and construction. If the bits and pieces of the facility (modular or not) were automated or executed with repetitive precision, the resulting cost and schedule estimates can be realized with a high degree of certainty and result in lower costs than pursuing an EOS strategy.

TURNING ECONOMIC THEORY TO LNG REALITY

The results from the referenced economic studies show that the traditional reductions in capital costs achieved by scaling up in size are generally matched (or exceeded) by learning effects in a mass production process when scaling up in numbers [Ref 4, 5]. Like in many advanced applications, this theory is realistically achievable, but possibly only after many proven iterations (actual project experience) navigating through the difficult journey and hardships of learning the execution lessons. In essence, this philosophy of applying and learning lessons to improve the productivity of unit scale design suits the EOUS theory well, but has yet to be put into practice successfully. The LNG industry should proceed cautiously with these initial project delivery expectations.

Projects such as Tellurian's Driftwood LNG [Ref 11] and Venture Global's Calcasieu Pass LNG [Ref 12], although using different process technologies, are pursuing EOUS in order to forecast project delivery for their projects at or around an advertised cost of US $500/tonne. These two projects are both technically mature and are progressing along the project development path. Caution should be considered in the planning, design, fabrication and construction/installation phases of more complex multi-train applications for a first of a kind SS train delivery. Other projects from Table 1 are following a similar project development journey. When and if these projects actually deliver on their forecast of large grassroots facilities at a unit cost of US $450-550/tonne, which means not encountering difficult lessons along the way, SS may be able to compete with LS as the LNG trend of the future.

ISSUES FOR DISCUSSION (SS vs. LS TRAINS)

The following section includes project definition subjects that affect both SS and LS trains and should be included in the train size selection criteria. While covered at a high level, each of these areas not only influences the decision to select the train size, but also influences the implementation of the project EPC delivery, the long term maintenance & operations, and the overall project economics. The following topics are included in this section:

- Liquefaction Process Technology Selection
- Construction and Modularization
- Sacrificing CAPEX for OPEX?
- Safety

- Operational Flexibility and Maintenance
- LNG Sales and Marketing (Commercial)

LIQUEFACTION PROCESS TECHNOLOGY SELECTION

Liquefaction process technology choices for LS trains is well covered in previous conference literature. In short, LS trains employ pre-cooled technologies in order to deliver high process efficiency and reliability while capturing the highest net value via EOS. The LS process market share is dominated by APCI (multiple process cycles) and the ConocoPhillips Optimized Cascade® Process. There are other offerings in this family of pre-cooled technology, which are covered in other publications.

Technology Provider	Process Technology
Air Liquide	Smartfin™ + others
Air Products	AP-SMR™, AP-N™ + others
Black and Veatch	Prico®
BHGE	SCMR + others
Chart	IPSMR® & N_2
ConocoPhillips	Optimized Cascade®
Gasconsult	ZR-LNG™
Linde	Limum®3 + others
LNG Limited	OSMR®
Novatek	Arctic Cascade

Table 2. Partial Listing of Liquefaction Process Technologies Suited for EOUS

For SS trains, there are additional choices for liquefaction process technology. A partial list of liquefaction processes suitable for SS and mid-scale trains is shown in Table 2. Some process technologies that are identified as Mid-scale are included as they are also striving to achieve the fabrication and unit repeatability benefits of EOUS. While it is often advantageous to have multiple technologies to review, there is a resulting difficulty in how to make the liquefaction process technology selection for an individual project. Key areas of variation among these technologies are process complexity, cycle efficiency and proven installed applications.

Many SS technologies embrace a philosophy of simplicity (i.e. lack of process complexity and equipment count) which may result in low CAPEX trains, but also often result in lower process efficiency than LS trains. Stated another way, some SS technologies require more energy (fuel) per tonne of LNG than the optimized technologies for LS trains. High fuel consumption will result in a high OPEX which will affect the overall project economics (but not US$/tonne). Many of the technologies represented in Table 2 try to improve their overall efficiency with added features, but these technologies remain less efficient than those used for LS trains.

As far as SS technology features, some cycles employ gaseous and/or inert refrigerants which may enhance process safety while sacrificing efficiency. Some technologies have pre-cooling schemes which add complexity (and possibly cost), but significantly improve efficiency. Some technologies require a combination of their technology and self-fabricated cryogenic equipment (or the entire process plant) while others allow the freedom of global procurement. In summary, while all SS liquefaction technologies are technically qualified for use, the key to technology selection is to firmly establish a set of weighted technology selection criteria for evaluation. This evaluation should performed by an independent specialist considering all associated project execution drivers and constraints in order to make the best choice for the project. If the evaluation is performed by a company without design and EPC experience, there is potential to miss out on the key project execution constraints.

CONSTRUCTION AND MODULARIZATION

Often, SS train configurations are planned with modular design and execution in mind; but similar to the experience with LS trains, not all modularization is equal. LS trains have progressed down a modular execution path for many years, generally driven by site constraints and available skilled labor. Some may argue that due to the historic location of global LNG projects, modularization is the default project execution strategy unless proven otherwise. LS trains are often modularized out of necessity (cost of labor, productivity factors, site-related construction laydown issues, etc.), while SS trains have the opportunity to capture both the benefits of LS experience as well as the EOUS by the potential repeatability of fabrication. Although more than a dozen LNG project sites have high levels of process plant modularization, these projects have had vastly different module execution strategies and various degrees of technical and commercial success.

The premise behind SS and LS modular execution is similar with respect to economic and schedule drivers. The intent is to reduce site labor and overall construction and installation costs by placing work in fabrication yards where you maximize labor productivity and fabrication efficiency. Net site construction activities involve module integration in lieu of piece by piece (stick build) plant assembly, resulting in reduced site construction personnel.

It often takes a substantial greenfield LNG production capacity to make the economics of the necessary offsite, utilities, and associated infrastructure costs look competitive. Many SS trains are needed to have the equivalent LNG capacity of two or three LS trains. Due to the simplicity of the liquefaction process and the partitioning of a large facility into many SS trains, the overall plot for SS LNG is likely larger than the equivalent capacity using LS trains. In challenging areas of construction execution, including the cost of land, restrictions on land usage, as well as site preparation costs, the management of the overall plot is a substantial project expense. Noticeable variation in modularization strategies include determining the module count, size and weight constraints for shipping and handling, site access and MOF constraints, and limitations of fabrication shops. All of these elements help establish the module configuration for a train.

Modularization is not new to SS LNG execution. Some SS trains have mature modular configurations that have been constructed and installed. However, many of the proposed SS plant designs have yet to be fabricated on a grand scale in order to obtain the EOUS necessary to drive unit cost lower than LS trains. Some SS designs have embraced a small scale truckable modular philosophy, with excess of 100 modules per SS train. These modules may be easy to fabricate and transport, but require significant logistics and integration effort to assemble and commission at site. As an example, a 10 Mt/a facility with 20 trains at 0.5 Mt/a per train may have over 2,000 modules using a small module philosophy. Increasing the size to 10 modules per train would still result in over 200 modules to fabricate, transport, integrate, commission and test.

For SS projects, chasing the economics of repeatability will require finding a reputable module yard (or multiple yards) and driving excellent productivity without learning difficult lessons in fabricating multiple process units over long periods of time. These lessons can include difficulties with late engineering (requiring rework in the module yard or construction site), defects in manufacturing affecting multiple trains, material management issues, system preservation, transportation, security control, difficulties in site integration (fit and hook up), or other operational challenges. These issues tend to arise when placing the entire LNG process facility scope in the responsibility of a fabrication yard.

A large module strategy would reduce the module count per SS train, but fabrication, transportation, or logistics issues will become critical factors in project execution. Regardless of the train size, LNG trains need to develop the proper balance of modularization (count, size, and weight) to allow for global competitiveness in fabrication while monitoring the resulting logistics and site-specific constraints required to integrate, commission, and operate the facility. The true modular cost of delivery is also dependent on any global tariffs that may affect the expected price.

While modularization offers potential benefits, it also has its risks. First, this approach requires an incredible amount of structural steel simply to fabricate the module structure. The structure must be designed not only for site conditions, but also for potentially severe conditions experienced during ocean transportation. Next, material handling and logistics costs need to be considered since all materials must first be shipped to the module fabrication yard and then the finished modules must be shipped to site. Finally, the sequencing of module fabrication, transportation, and integration is of critical importance to the project execution plan.

Typically, the modules are planned to arrive for integration at site in a particular order. If the module fabrication sequence gets out of order due to delays (for any number of reasons), it will have a significant impact on the construction effort. In some cases, modules are shipped incomplete to adhere to tight shipping and logistics plans. Consequently, the rest of the work must be completed at site, at high cost and low productivity, which defeats the whole purpose of module fabrication. These risks must be weighed carefully against the potential benefits to determine whether a modularized approach is the best solution for a given LNG facility.

SACRIFICING CAPEX FOR OPEX?

One of the most attractive attributes of the LNG unit cost metric is its simplicity: CAPEX per tonne of total LNG capacity. When comparing one plant to another using only CAPEX (even within the LS or SS family of train sizes), there are many other variables deemed to be irrelevant to the comparison. Some of those variables include:

- Liquefaction process efficiency (specific power)
- Total plant efficiency (autoconsumption or fuel gas use)
- Plant Availability (scheduled and unscheduled downtime)
- Maintainability (including capital and operating spares)
- Turndown capability (and efficiency at turndown)
- Ease of operations (operability)
- Environmental Considerations (emissions and impurities)

While all these variables are important, two interesting items that influence both CAPEX and OPEX are the liquefaction cycle efficiency and the total plant efficiency. Many publications have been written on the subject of both liquefaction process efficiency and overall plant efficiency [e.g. Ref 13]. When taking an overall life-cycle or NPV analysis, we should balance CAPEX and OPEX, but when your only evaluation metric is CAPEX, you can *intentionally sacrifice* OPEX (and long term economic value) for reduced CAPEX.

As stated in a previous section, LS trains have optimized process schemes and often employ gas turbines to power the refrigeration compressors using the feed gas as fuel. SS trains often use simple process schemes and have a lower process efficiency (represented by high refrigeration energy needed to convert gas into LNG) than LS designs. As a result, SS trains will often consume more fuel, have higher overall emissions, and cost more to run (per ton of product) than LS trains. If SS configurations are electric motor driven plants, the added OPEX cost of imported electric power or the CAPEX of self-generated electricity will be significant. A project's OPEX cost has often been completely ignored in the race to achieve the lowest US$/tonne, but has a significant effect on the overall project economics. While LS trains can also sacrifice CAPEX for OPEX in their plant configurations, the transfer of expense to OPEX cost has been common for SS trains that are electric motor driven and rely on process technologies that require more energy to covert gas to LNG.

SAFETY

All LNG projects, regardless of process technology or train size, go through a rigorous process and safety hazards evaluation. This analysis leads to several design benefits offered by SS trains. First, the emergency flare capacity scales primarily to individual train capacity, so smaller trains will reduce the flare size and resulting flare plot area. Second, the process hazard analysis will look at individual events that could release hydrocarbons to the surrounding environment. The relatively small refrigerant inventories of SS trains reduces the size of these potential releases. Finally, the individual train refrigerant inventories can lead to a reduction of onsite refrigerant storage and again reduce the risks due to an accidental hydrocarbon release.

Separate from safety in design, the issue to highlight with respect to safety and train size is the simultaneous operations (a.k.a. SIMOPS) taking place. This condition occurs by having one or more functional SS trains in close proximity to other trains in construction or commissioning. SIMOPS occurs when construction takes place in close proximity to a commissioning or operating process area of an existing facility such that there are heightened risks to those involved [Ref 14].

While large facilities that are constructed with LS trains have to account for the concept of SIMOPS, the situation is exacerbated when there are more SS trains in the same plot that would accommodate few LS trains. One of the main commercial goals of the SS philosophy is to progress in commercial operations (albeit at small capacity) more quickly than with a LS design. As a result, a large construction workforce, commissioning workforce, and the owner's operations team will face the challenges of working near an energized hydrocarbon facility. All teams will interact with a live construction site and all the hazards associated with heavy construction. SIMOPS can certainly be accommodated in the construction execution plan, but SIMOPS adds execution and safety risk to the construction, commissioning and operating personnel.

OPERATIONAL FLEXIBILITY AND MAINTENANCE

As mentioned in the CAPEX vs. OPEX section, if the initial project development goal is to achieve the lowest US$/tonne, elements such operational flexibility, turndown, maintenance, or even plant efficiency should not matter – but they certainly do matter. One of the major selling points of SS trains is operational flexibility – the ability to run a large LNG complex and each train at many different production rates in an efficient manner. This section will briefly review some of the expected operational traits of LS and SS trains.

LS trains have operational flexibility, but are primarily designed to operate at maximum design rates with high process efficiency. It is incorrect to assume that LS trains cannot operate in turndown mode [Ref 13]. The main issue with LS trains is that fuel consumption remains relatively constant when using gas turbine drivers at reduced production rates. Modifications to the base LS configuration (e.g. parallel compression) can allow for greater flexibility and improved efficiency at reduced production rates. Regardless of LS liquefaction process technology, LS trains can be safely operated in turndown mode, but may result in a higher OPEX per unit of product.

From an EPC perspective, sponsors of large facilities configured with SS trains seem to be as interested in turndown capability as much as the full design rate. In other words, large facilities with SS trains have the inherent flexibility to simply shut down trains with varying LNG demand. This scenario is similar to how many regasification facilities operate, where vaporization capacity is built in increments (e.g. 100-200 MMSCFD) and can be tailored to immediate gas demand. The only difference in the analogy to regas is that liquefied LNG can be stored long-term, whereas vaporized LNG is delivered based on immediate demand needs outside the regas facility.

As a result, a 10 Mt/a facility comprised of 0.5 Mt/a SS trains has at nineteen different efficient facility production capacities when operating at least one train at design rate. Furthermore, each train has a turndown capability where the facility can pinpoint their production capacity to meet expected demand (if less than the maximum design capacity). Again, it seems the operational flexibility at turndown rates (regardless of the CAPEX or US$/tonne to build the entire facility) is as important as the overall economics at full production rate. The North American tolling model is the likely reason to configure facilities in this way.

The tolling model is one of the reasons why operational flexibility is a key design criteria for new SS based facilities. In the tolling model, the facility owner does not own the natural gas to be liquefied; the gas is sourced and purchased on the open market based on a known index like the US Henry Hub. As a result, in times of high gas prices, it may be advantageous to not produce LNG at full design rates. Additionally, different customers for the facility may have different pricing structures such that some customers want LNG at any price while other may be selective in when they want LNG based on the source gas cost.

From the maintenance perspective, SS trains require much more routine maintenance than LS trains based simply on the increased equipment count (affecting frequency of maintenance and unscheduled intervention) versus LS trains. To the positive, SS trains are often based on electric motor drives, which eliminates one of the primary maintenance intervals for LS gas turbine driven plants. On the other hand, maintenance for SS trains can be routinely planned with ample plant capacity remaining on-line, causing little disruptions when high production is required. The net result of this flexibility is a higher production availability (limited days with significant production downtime) but the total annual production is expected to be similar to that when using LS trains. Although production availability is a key feature for SS designs, trains that are motor driven with imported power must rely on the stability of an electrical network that is outside the influence of the LNG facility. As more plants are designed to be electric drive with imported power (e.g. Freeport LNG), the issues regarding stability of the electric grid will be fully understood.

The number of operations and maintenance staff is also affected by a SS vs. LS configuration. Total operations and maintenance personnel does not scale linearly with site equipment count, but having many LNG trains to monitor will require more operations support than for a LS facility. In areas of high labor cost, the professional staff headcount (operators, supervisors, managers, etc.) will have an effect on plant OPEX. Handling of spare parts will also be incrementally higher with a SS configuration, but highly customized and difficult to obtain spares (e.g. large compressor rotors) will not be required.

In sum, the issues of operational flexibility is an important issue for facilities designed with SS trains. Large scale trains are primarily interested in running at full design rate and are interested in operational flexibility when off-design operating scenarios occur. The question that comes to mind from this debate is: why spend all this CAPEX to worry about excessive turndown and low production rates? This new design criteria of a wide range of operational flexibility has crept into LS train design and appears to be here to stay.

LNG SALES, MARKETING, AND FINANCING (COMMERCIAL)

While this paper is not commercially focused, issues such as LNG sales, marketing, and financing play a part in the SS vs. LS debate. The EOUS theory is well suited to a phased CAPEX approach when configuring a large LNG facility. Building up capacity in several EPC phases using groups of SS trains (hopefully backed by long term sales contracts) may be more easily financed than two or more LS trains that are perfectly balanced with the overall storage and infrastructure costs. In other words, the initial SS project FID may require a lower initial CAPEX than that for a traditional LS configuration. Once a SS project has achieved initial sanction, the expansion capital needed to maximize use of the storage and marine infrastructure may be more easily sourced than the initial financing.

A phased CAPEX approach will also help to match the progression of signing LNG offtake agreements, especially in a tight LNG market. This feature was seen to be beneficial in the era of the LNG glut of 2016 where offtake agreements to underpin large trains were difficult to obtain. Signing up small parcels of LNG offtake to corresponding SS trains (even in a 1:1 customer to train ratio) may help to sanction the initial plant and make subsequent phases easier to implement than using the LS approach. As an added benefit, a phased CAPEX approach may also support incremental field development when liquefying gas from dedicated reservoirs.

If SS fabrication and delivery is successful, the schedule to produce the initial quantities of LNG (as opposed to LS trains) can have a significant benefit on the overall economics of a project. The combination of delayed cash expenditure and earlier initial revenues, if achieved in execution, are hard to resist for new entrants to the LNG market. These early initial revenues can also offset an unexpected increase in CAPEX over a LS configuration, especially when using high discount factors (cost of capital); however, the goal of SS train configurations are to achieve a lower US$/tonne than competing LS trains.

In sum, the financing required for greenfield LNG facilities is quite substantial and the marketing of offtake for large LNG facilities can be difficult in a tight buyer's market. A SS train and multi-train system approach may allow a faster initial project sanction than configuring a facility with LS trains. Subsequent expansions may be aided by early initial cash flows from operations or the ability to sign multiple offtake agreements after initial project sanction.

WHAT INFLUENCES THE DECISION MAKING PROCESS?

While there are benefits to both sides of the EOS and EOUS debate, how does one make a decision on train size for a large facility size? First of all, liquefaction train size is rarely in the EPC contractor's influence and control. The decision is properly made by the owner/operator who lives with the decision for the life of the facility. Experienced engineering contractors (who have delivered projects) are valuable in the liquefaction process technology and train size selection process, but the ultimate decision needs to be fully supported by the owner and any other project sponsors. Since the decision lies with the owner, it is extremely important to properly set the *weighted* evaluation criteria for each influential decision so that technology or execution bias does not creep in from third parties (non-owners) of the project. Giving weight to different parts of the decision is important; otherwise, simplified scoring does not focus on the areas of greatest influence.

When it comes to capacity (the denominator of US$/tonne), the project execution journey often starts with a target capacity and then moves to squeeze out additional capacity at a minimum design margin. In other words, this means increasing the guarantee capacity with minimal change to the design parameters. As a result, it is important that the train configurations (technology, major equipment, and hydraulics) have flexibility as the facility seeks to gain additional capacity along the journey to FID. In addition to capacity, the discussion of project cost always starts with CAPEX and later moves to life cycle cost – to capture the most value <u>after</u> the key project decisions are made. You can sacrifice OPEX for CAPEX initially, but life-cycle cost will usually dominate the commercial discussion.

Decisions aside, many publications continue to forget that LNG projects are major civil and infrastructure projects and that the liquefaction plant is a mere portion of the overall project cost. It is unreasonable to expect that liquefaction train size and technology would dominate the overall cost of the facility, but US$/tonne gets all the attention. In essence, that's why these debates are hard – the assumptions made in the technology and train size selection matrix are purely that, assumptions. Testing the economic theory when choosing SS/EOUS over LS/EOS often means reshaping the assumptions as projects are configured, constructed, and operated. In situations where people can easily change their minds over the course of a project, flexibility in the configuration is key.

DOES IT REALLY MATTER?

Until the first few large LNG facilities are built with SS trains, and the economics are verified and the lessons shared – size does not appear to really matter. If you plot the projects from Table 1 as facility size versus train size, you will see little correlation among project sponsors on how a facility size is subdivided into certain size trains. (Figure 2). As the industry stands today, without proof that EOUS unit costs are lower than the traditional EOS counterparts, this debate is one of several in a long list of polarized arguments [Ref 3]. So if size doesn't really matter, what does matter?

REALISTIC EXECUTION PLANS MATTER

One of the key assumptions from *Small Modular Infrastructure* [Ref 4] is that “a massively parallel production strategy is possible as long as there is no significant cost to combine the separate outputs into a single stream”. In applying this economic theory to LNG, this assumption implies that constructing, integrating and operating the SS modular trains does not add undue CAPEX or OPEX to the project. If we cannot presently distinguish a cost difference between using SS or LS trains, the true influence on the economics, and the ability to deliver cost certainty, lies in project execution.

Many of the characteristics of successful projects, and many more that lead to undesired outcomes are well documented by the company Independent Project Analysis (IPA). Published in 2011, the history and data delivered in *Industrial Megaprojects, Concepts, Strategies, and Practices for Success* [Ref 10] includes LNG experience and is a textbook in how not to execute megaprojects. A companion presentation is more aptly titled: *Why Large Projects Fail More Often, Megaproject Failures: Understanding the Effects of Size* [Ref 15].

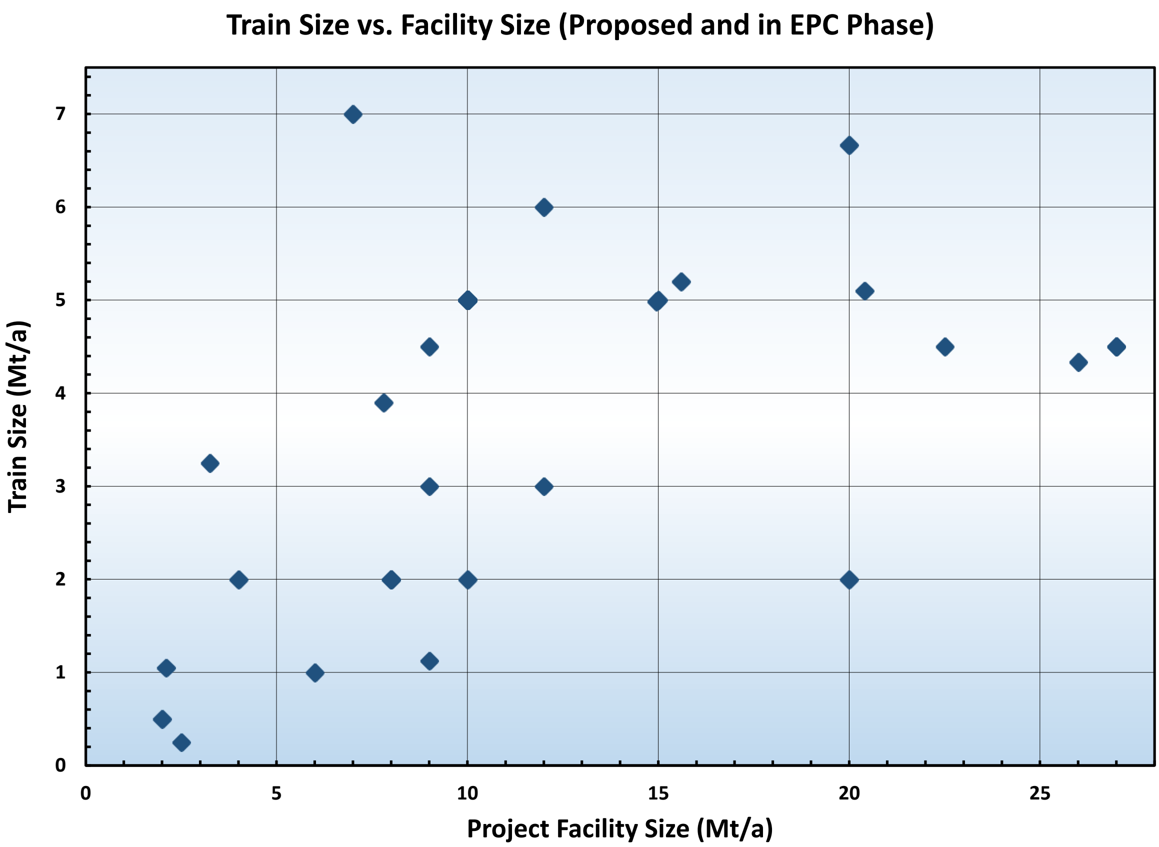

Figure 2. Train Size vs. Facility Size (Data from Reference #2)

We are back to the theme of size. However, the IPA uses size to mean the magnitude of the project spend, not simply the size of the LNG trains. While the case histories in the reference by IPA discuss the application of prototype technology, the significant lessons really involve project execution and especially those regarding schedule:

- Schedule pressure dooms more megaprojects than any other
- Projects routinely skimp on the front end – “speed kills projects”
- Taking risks with megaproject schedules is a fool’s game

The combination of reconfiguring large LNG facilities with SS trains and the drive for schedule optimization and early revenue from operations should be planned very carefully. Not only is there schedule pressure, these projects are also often bid lump sum. While the EOUS theory seeks to gain schedule advantages over EOS, one area that may have significant schedule risk is the commissioning, startup, and performance testing of multiple LNG trains within a facility.

It is clear that SS trains have the potential for capturing long term cost and schedule efficiencies in repeatability, lessons learned, and continuous improvement in manufacturing. However, if the execution plans are unrealistic, it is difficult to see how these opportunities are well captured for the first projects targeting EOUS. It should not be underestimated that the migration from LS to SS is a huge change in project execution strategy and is not to be undervalued. In essence, the LNG industry is parking decades of experience in train configuration and execution and reinventing itself in order to improve the project outcome. This type of strategy is thoroughly addressed by IPA.

CONCLUSION – DOES LNG TRAIN SIZE REALLY MATTER?

From an argumentative perspective, both sides of this discussion have valid points to sell the benefits of either SS or LS trains. The arguments rely on the economic theory and pre-FID estimating assumptions while the final results are based on the actual project conditions and the outcome of the project execution plans. Those execution plans heavily influence whether or not the assumptions, and the resulting unit cost, will come out as predicted.

Even at the end of our journey, one can say that “size does not really matter” as the train size is simply one of the many decisions required to achieve a particular result – a large quantity of LNG produced at an expected unit cost of production. What is of most interest today is that SS trains have yet to fully test the EOUS theory, the validity of the assumptions, or gather enough data to determine if the resulting unit cost of LNG is better than that achieved by LS trains and EOS.

When deciding the best way to configure LNG capacity, one must realize that every project has different characteristics that results in a unique project execution journey. While projects could be configured in multiple ways, the technical and commercial risks associated with different configurations for a given site are not the same. With the desire to rack and stack projects based on unit cost, one must evaluate the risks and probability of executing the project successfully more so than the estimated unit cost. A high risk project may double in cost in the EPC phase whereas a low risk project can be completed on time and on budget.

Another way of viewing past and future projects is that some projects that are delivered above US$ 500/tonne are still commercially successful. In addition, while the estimated cost at FID (e.g. EPC contract price) is often publicized, the final facility cost (either the final EPC cost or total owner’s cost) is not often public record. As a result, every LNG project does not have a publicly vetted account of how the execution either matched or strayed from the estimates at sanction.

While there is no clear winner, this paper looked at some of the issues when configuring large LNG plants with either LS trains or SS trains. Looking forward, it would be ideal if an LNG plant configuration could capture all the benefits mentioned throughout this paper: the benefits of standardization and repeatability (EOUS) as well as energy efficiency and lessons learned through history (EOS). Even better, these benefits would hold when given realistic schedules resulting in projects being delivered as promised.

As we stand today, LNG project execution history cannot prove with high confidence that EOUS can beat EOS. It may seem that for some pre-FID opportunities, there may not be much of an estimated CAPEX difference between the two strategies. Cost estimates made in a highly competitive environment fall within an expected band of estimating accuracy; if the schemes weren’t viable, they wouldn’t have been supported during FEED, but each scheme will carry different risks. One recent project (not yet sanctioned) conducted a FEED design competition based on both SS and LS trains where the SS scheme is the preferred solution.

One of the key attributes for EOUS is “mass produced and modular”. SS plants are currently modular, but they are not cost effectively mass produced. It will take many project iterations to get today’s SS offerings to a level of being mass-produced at a significant cost advantage. LS configurations are proven and reliable, but still rely on an achievable execution plan in order to deliver on expectations. When looking long term, EOUS can be realized when the manufacturing becomes precise and the risks and uncertainties have been mitigated for each unit or subsequent project.

One final conclusion from this dialogue is that US$/tonne is not a good key performance indicator (KPI) of the health of a project. The recent advances in digital delivery, real time performance monitoring, and predictive analytics show that well-developed KPIs can give insight as to the health of a process, system, or entire facility. The LNG industry needs a better KPI than US$/tonne to compare the health of LNG projects in the pre-FID phase. Although unit cost can show that a project needs to improve, it does not have well defined limits to determine if a project configuration, CAPEX, and OPEX is healthy or not. The variability in infrastructure costs and execution strategies lead to faulty assumptions of which projects will be successful prior to sanction versus those who may not have fully priced the risks.

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