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Optimal Sizing of Small Scale Liquefied Natural Gas Storage using Numerical Cascade Pinch Analysis

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Increasing demand for liquefied natural gas (LNG) at the inaccessible area through pipeline has provided a solid platform for the emergence of new small scale LNG (ssLNG). The key challenges related to the ssLNG business are relatively expensive supply chain due to the diseconomy of small scale and meeting the security of supply and demand with limited supply alternatives available. Nevertheless, the market has increasingly become the preferred delivery method for natural gas (NG) because LNG can be produced at remote locations and distributed to end-users conveniently. To date, extensive works with a variety of objectives have been developed in an attempt to optimise the ssLNG supply chain in terms of conversion, transportation, and utilisation yet an optimal synthesis of LNG for small scale market has not been adequately investigated. The activity of loading and unloading of LNG in supply port terminals needs sufficient capacity of LNG storage tank. Designing an adequate capacity is necessary in order to secure reliable supplies of LNG as well as to offset fluctuations in the supply and demand of LNG. This work aims to ease industrial planner to design an optimal capacity of ssLNG storage by implementing a well established numerical cascade approach based on Pinch Analysis technique and proposed a new numerical approach of small scale LNG-Storage Cascade Analysis (ssLNG-SCA). Based on the proposed tool, the minimum amount of LNG supply for operation has been reduced from 2,100 m^3 to 1,400 m^3 due to the stored amount of excess LNG supply (700 m^3) during start-up with the existence of ssLNG storage tank. The developed ssLNG-SCA in this work shows a significantly reduced storage capacity from 24,000 m^3 to 6,300 m^3 thus eliminate the need to provide for a larger and higher price of LNG storage tank. The storage offers delivery of NG to virtual trading hubs to meet end-user demand which inaccessible to the high-pressure pipeline.

1. Introduction

Worldwide energy demand is driven by few factors but the key drivers for energy demand are rapid economic development and population growth. Exxon Mobile (2016) stated that the world’s population will raise 25 % and reach up to 9 billion by 2040 and thus the Gross Domestic Product (GDP) will have more than doubled. The significant part of this growth creates a need for affordable, efficient and reliable energy for the next 20 years (Exxon Mobile, 2016). The coal remains as the main primary energy source with a share of 42 % while NG accounts for 21 % share in the global energy demand (Sevik, 2015). The energy from fossil fuels will continue to rise for about 75 % by 2050 including the share of NG (Reilly et al., 2015). NG is the cleanest burning hydrocarbon and most hydrogen-rich among all of the hydrocarbon energy sources. As global energy demand growth is rapidly increasing, NG plays a pivotal role as one of the main energy supply that is abundant and accessible virtually over the world. NG also plays a significant role in delivering cleaner air quality concerns and facilitating climate change objectives. The earth has an enormous amount of NG but stranded far from where the resources are needed and is transported through a fixed network of pipelines. Exxon Mobile (2016) reported that 40 % of the growth in global energy demand are projected to be met by NG by 2040. According to Rahim and Liwan (2012), Malaysia now owns the most extensive NG pipeline networks in Asia since completion of project multi-phased Peninsular Gas Utilization (PGU) in 1998. Malaysia owns gas processing plants that are located in the East Coast of Peninsular Malaysia and the system overall comprises of six gas processing plants including producing methane, ethane, propane, butane, as well as condensate.

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Increased pipeline infrastructure enables the development of gas fields located near the pipeline routes which may otherwise be uneconomical to develop in isolation. Therefore NG is transported in liquid form of LNG where the pipelines are unfeasible to transport NG over long distances to the end consumers located far from the NG network.

Pinch Analysis (PA) has broadened a long way beyond the original studies to predict the performance of a process prior to the actual synthesis and design. It is best to be used at the preliminary design stage to assist in the decision-making process. Depending on the application, Pinch Analysis technique is further developed in targeting method for hybrid power systems comprising of renewable energy sources by using Power Pinch Analysis (PoPA) (Wan Alwi et al., 2012). The PoPA technique is implemented to target minimum outsourced electricity as well as the amount of excess electricity. Mohammad Rozali et al. (2013) developed a new numerical method in PoPA known as Power Cascade Analysis (PoCA) and Storage Cascade Table (SCT) which complement the graphical tools of PoPA. These techniques can be utilised to target minimum outsourced electricity and the amount of excess electricity for storage during start-up and normal operations. Besides, the tools can determine the amount of transferrable power, maximum storage capacity for off-grid systems (e.g. battery), the outsourced electricity needed at each time interval and the time interval where maximum power demand occurs. Esfahani et al. (2015) further modified PoPA technique into new numerical and graphical Extended-power pinch analysis (EPoPA) for optimal design of renewable energy systems with battery and hydrogen storage (RES-BH). Elmi et al. (2016) later further the concept and proposed an innovative power storage technology power to gas using PA that incurs considerable power losses compared to other storage technologies. Meanwhile, Mohammad Rozali et al. (2017) have developed a new framework for cost-effective design of Hybrid Power System (HPS) integrated with a cost-screening tool known as Systematic Hierarchical Approach for Resilient Process Screening (SHARPS). Othman et al. (2016) developed Gas System Cascading Analysis (GASCA) based on Time Based Pinch Analysis (TBPA) concept that can facilitate biogas supply-demand chain as well as targeting optimal storage capacities of anaerobic digestion (AD) and biogas. Recently, Jamaluddin et al. (2018) have developed an optimal design of trigeneration integrated with an energy storage system based on PA technique.

To date, extensive works with a variety of objectives have been developed in an attempt to optimise ssLNG supply chain as reported recently in Bittante et al. (2018) to aid decision making on tactical aspects in the design of LNG logistic chains. Koza et al. (2017) developed Mixed Integer Programming (MIP) for LNG infrastructure and tanker fleet sizing problem. Later, Mikolajková et al. (2018) developed Mixed Integer Linear Programming (MILP) for gas supply to a local market combination of pipeline and truck investment operation costs. Reported publications mostly focus on optimisation of ssLNG supply chain, analysis and enhancement of LNG plants that failed to grasp the targeting for optimal synthesis of ssLNG sizing storage. The activity of loading and unloading of LNG in supply port terminals need sufficient capacity of LNG storage tanks. Designing an adequate capacity is inevitable to secure reliable supplies of LNG as well as to counteract fluctuations in LNG peak demand by industry. This work aims to develop a planning tool based on PA analysis technique for targeting an optimal capacity of ssLNG storage. This work is expected to facilitate an industrial site planner to target an optimal capacity of ssLNG storage at an early stage of planning.

2. Problem Statement

The economy of how big the scale plays an important role in LNG logistics. In traditional infrastructure, large scale is more conventional where LNG is delivered and regasified for injection into the NG transmission grid. Larger liquefaction plants, carriers and terminals contribute to a lower unit cost. To serve end-users in remote places where traditional infrastructure cannot be reached, facilities that serve small capacities that would be regarded as small scale LNG (ssLNG) has emerged. The conventional base-load LNG business is mainly consisting of a liquefaction plant, transport, regasification, and end-users. Meanwhile, ssLNG can be sourced from an existing conventional scale of LNG facility, such as the liquefaction or regasification facility, or a small scale liquefaction facility itself. The end-customers can also be served from the larger storage facilities or the small terminals. It typically serves a wider range of end-users than the conventional value chain. Figure 1 shows an illustrated diagram for small scale LNG market supply consisting facilities of LNG import terminal, ssLNG carrier, ssLNG storage and distribution to the end-consumers. For transportation, ssLNG carriers are defined as vessels with LNG storage capacity of less than 30,000 m^3. The typical range of SSLNG storage capacity is between 500 m^3 to 5,000 m^3. For small scale supply chain, the LNG is shipped from the large scale supply terminal to consumers via ssLNG carrier and being stored in ssLNG storage. The storage is enabled to store LNG in small quantity for NG usage in off-grid locations or areas with no high-pressure pipeline.

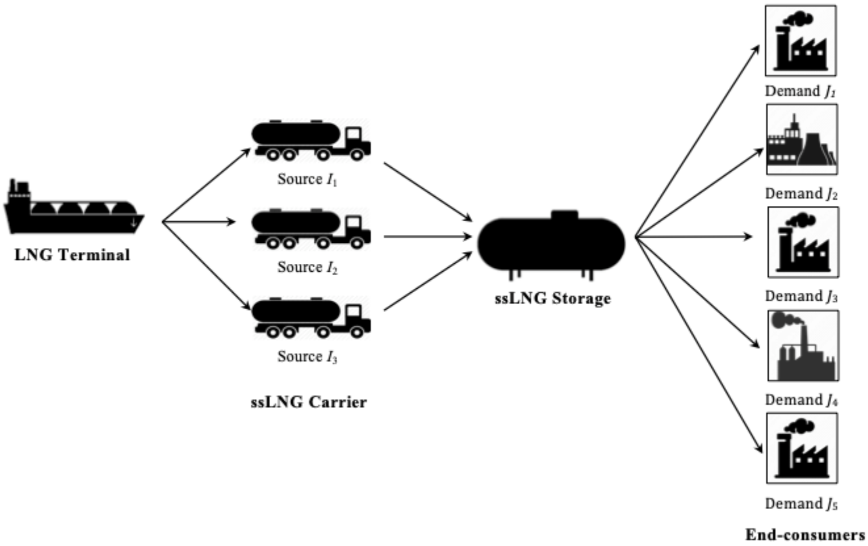
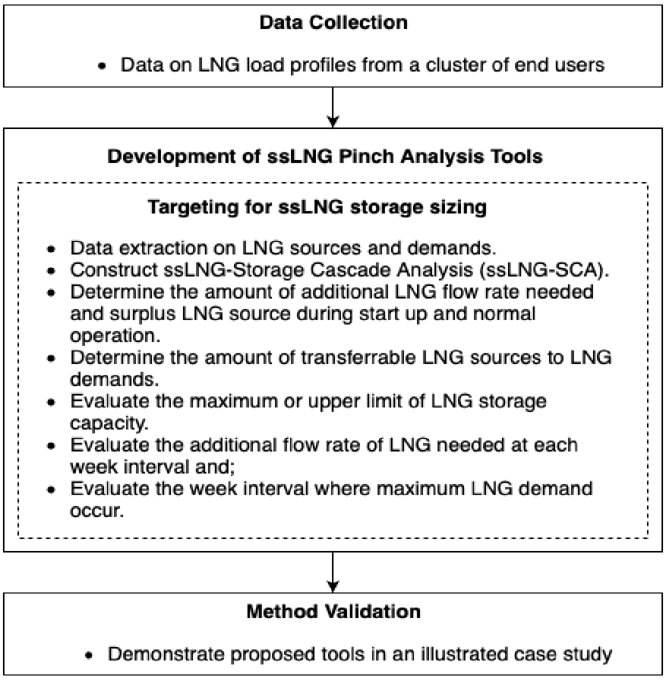


Figure 1: Overview illustrated diagram for small scale LNG market supply chain

The problem definition for this work as follows:
Given a new small scale LNG market that needs to develop a ssLNG terminal which acts as a supply port for a set of sparsely distributed receiving end-users with given demands. The potential of ssLNG terminal to supply to the location located far from the NG network has remained unexplored. Besides, an optimal synthesis on the ssLNG storage sizing has not yet been investigated. The activity of loading and unloading of LNG in ssLNG supply port terminal need sufficient capacity of ssLNG storage tank. Designing an adequate capacity of ssLNG storage is necessary to secure reliable supplies of LNG as well as to offset fluctuations in the supply and demand of LNG. Therefore, this work aims to design an optimal capacity of ssLNG storage at ssLNG terminal to meet the LNG demands.

3. Methodology

Figure 2 illustrates an overall flow chart for the development of ssLNG-SCA.



Data Collection

- Data on LNG load profiles from a cluster of end users

Development of ssLNG Pinch Analysis Tools

Targeting for ssLNG storage sizing

- Data extraction on LNG sources and demands.
- Construct ssLNG-Storage Cascade Analysis (ssLNG-SCA).
- Determine the amount of additional LNG flow rate needed and surplus LNG source during start up and normal operation.
- Determine the amount of transferrable LNG sources to LNG demands.
- Evaluate the maximum or upper limit of LNG storage capacity.
- Evaluate the additional flow rate of LNG needed at each week interval and;
- Evaluate the week interval where maximum LNG demand occur.

Method Validation

- Demonstrate proposed tools in an illustrated case study

Figure 2: Methodology for development of cascade Pinch Analysis

For the development of small scale LNG-storage cascade analysis (ssLNG-SCA), the concept of numerical cascade Power Pinch Analysis introduced by Mohammad Rozali et al. (2013) is adapted and modified depending on the application and further proposed as ssLNG-SCA. The cascade technique can be used for (1) Targeting the minimum flow rate of LNG supply and surplus of LNG flow rate from during start-up and normal operation, (2) The transferrable LNG flow rate of LNG sources to LNG demands, (3) The upper limit of storage capacity, (4) The additional LNG flow rate needed at each day interval and (5) The day interval where maximum LNG demand occurs. The numerical technique will facilitate prompt calculation and accurate distribution of LNG sources as well as the calculation of storage sizing at the site. The selection and matching of the sources and demands corresponding to the storage sites are often an issue of optimisation due to various constraints i.e., storage capacity availability, location of the source and storage availability, and time source and storage availability. These problems can be solved with pinch technology that can provide visual insight at early stage of planning.

4. Small Scale Liquefied Natural Gas-Storage Cascade Analysis (ssLNG-SCA)

The Pinch Analysis in this work is constructed using numerical technique by extracting at first, data on ssLNG sources and demands followed by the development of ssLNG-Cascade Table (ssLNG-CT) and finally ssLNG-Storage Cascade Table (ssLNG-SCT). Table 1 shows data extraction on ssLNG sources and demands which illustrates LNG supply and demand flow rate for four weeks within a month with an assumption of 28 d storage followed by Table 2a and 2b that tabulate findings for ssLNG-storage cascade analysis (ssLNG-SCA).

Table 1: Data extraction on ssLNG sources and demands for Case Study 1

Week	Source, S_i (m^3)				Demand, D_j (m^3)				
	S_1	S_2	S_3	S_4	D_1	D_2	D_3	D_4	D_5
1	6,000				900	1,700	800	1,000	800
2		6,000			1,500	1,100	1,200	900	1,800
3			6,000		1,100	1,300	1,200	1,500	1,500
4				6,000	1,500	1,100	1,400	900	1,000

Following are generic steps to construct Table 2a and 2b. Starting with column 1, the days are arranged in ascending order from ‘0 day’ to ’28 d’. The duration between two-day intervals are tabulated in column 2. Next, the LNG sources and demands flow rate are tabulated corresponding to the day interval as in column 3. The total ∑ flow rate for LNG sources and demands in column 4 and 5 for each day interval is obtained from Eq(1) below.

$$\Sigma\, Flow\ rate\ LNG\ Source\ or\ Demand\ = Flow\ rate\ LNG\ Source\ or\ Demand\ \times\ \Delta d \tag{1}$$

The net LNG flow rate surplus (+) or deficit (-) in column 6 is obtained from Eq(2) below. A positive net LNG flow rate indicates that LNG sources are sufficient for LNG demands thereby allowing surplus LNG in the storage. Meanwhile, a negative value denotes that deficit LNG sources in fulfilling the requirement of LNG demands. Therefore, to counteract this LNG deficit, additional LNG supply is needed.

$$Net\ Flow\ rate\ LNG\ surplus\ or\ deficit = \ \Sigma\, Flow\ rate\ LNG\ Source - \Sigma\, Flow\ rate\ LNG\ Demand \tag{2}$$

The LNG cascade table starting from column 7 until 10 to determine the overall surplus LNG for storage and additional LNG supply needed for start-up by cumulating the net LNG flow rate surplus or deficit acquired in column 6. At this stage, by assuming that there is no additional LNG supply (0 m^3), the net LNG flow rate is cumulatively cascaded from day 0 to day 28 (from earlier to later day intervals). Column 7 is an unfeasible LNG cascade since it contains few negative LNG flows indicated that the net LNG flow rate is cascaded from a later to an earlier day interval. Following this, a feasible mass load cascade is further generated in column 8 by cascading down the absolute value of the largest negative LNG flow (-2,100 m^3) in column 9 to the net LNG flow rate in column 6. The first value (2,100 m^3) in column 8 gives the minimum additional LNG supply needed for current month during start-up while the last value (700 m^3) gives the excess LNG supply for storage during start-up that is also indicates that this value can be used to reduce the amount of additional LNG supply needed during operation. Therefore, 700 m^3 of excess LNG supply for storage at the end of start-up is cumulatively cascaded to the operation from ‘day 0’ to ’day 28’ in column 9. The excess LNG brought from start-up is insufficient to cater the net LNG deficits during operation thereby resulting an infeasible cascade with negative LNG flows. To obtain a feasible cascade in column 10, the absolute value of the most negative flow (-1,400 m^3) in column 9 is added with 700 m^3 excess LNG supply stored from start-up and cumulatively cascaded down to the net LNG flow rate in column 6 again to yield 1,400 m^3 additional LNG supply needed during operation and 700 m^3 available excess LNG supply for storage.

The LNG storage cascade table starts from column 11 until column 16. For start-up period, it is inevitable to evaluate the upper limit of storage capacity as well as additional LNG supply needed at different ranges of day intervals by cascading down column 11. The net cascaded LNG surpluses are tabulated in storage capacity (column 12) while net LNG deficits are tabulated in column 13 to indicate the additional amount of LNG supply required at a certain range of day intervals. For this case study, LNG deficit occurs between 7th and 21st-day interval which is -2,100 m^3 and LNG surplus cascade begin again at zero storage which gives last value available LNG surplus 700 m^3 to be stored for next operation period. The largest cumulative LNG surplus of 5,600 m^3 in column 12 denotes the upper limit of the storage capacity during start-up. For normal operation columns, it is also inevitable to evaluate the maximum LNG storage capacity for site storage and the additional LNG needed at different ranges of day intervals by cascading down column 14 starting from the amount of LNG stored from the previous start-up period which is 700 m^3. The net cascaded LNG surpluses are tabulated in storage capacity (column 15) while LNG deficits recorded in additional LNG needed (column 16). The largest cumulative LNG surpluses of 6,300 m^3 denote the upper limit of storage capacity during normal operation period whereas -1,400 m^3 denotes additional LNG needed during normal operation period.

From this analysis, the aim is not only to evaluate the upper limit of storage capacity but also to reduce the additional LNG supply needed with the existence of a storage tank. The ssLNG-SCA gives the amount of minimum LNG flow rate during start-up which is 2,100 m^3 and 1,400 m^3 during operation. The minimum supply amount for operation has been reduced from 2,100 m^3 to 1,400 m^3 due to the storage amount of excess LNG available (700 m^3) during start-up after integration. The ssLNG-SCA shows that the maximum storage capacity is 6,300 m^3. Instead of having a larger storage tank to cater a total of 24,000 m^3 for a month supply, this cascade analysis gives a significantly reduced storage capacity of 6,300 m^3. Most significantly, this analysis can eliminate the need to provide for a larger and higher price of storage tank as well as allow a more effective way to manage boil-off gas that is said to be inherent to the cryogenic storage.

Table 2a: ssLNG storage cascade analysis (ssLNG-SCA) for Case Study 1

1	2	3		4	5	6	7	8	9	10
							Start-up		Operation	
Day (d)	Δd	Flow rate LNG (m^3)		∑ Flow rate LNG source (m^3)	∑ Flow rate LNG demand (m^3)	Net Flow rate surplus/deficit (m^3)	Infeasible flow rate cascade (m^3)	Feasible flow rate cascade (m^3)	Infeasible flow rate cascade (m^3)	Feasible flow rate cascade (m^3)
		Source	Demand							
0							0	2,100	700	1,400 2,100
	7	6,000	5,200	42,000	36,400	5,600				
7							5,600	7,700	6,300	7,700
	7	6,000	6,500	42,000	45,500	-3,500				
14							2,100	4,200	2,800	4,200
	7	6,000	6,600	42,000	46,200	-4,200				
21							-2,100	0	-1,400	0
	7	6,000	5,900	42,000	41,300	700		Pinch		Pinch
28							-1,400	700	-700	700

Table 2b: ssLNG storage cascade analysis (ssLNG-SCA) for Case Study 1

11	12	13	14	15	16
Start-up			Operation		
Net Flow rate surplus/deficit (m^3)	Storage capacity (m^3)	Additional LNG needed (m^3)	Net Flow rate surplus/deficit (m^3)	Storage capacity (m^3)	Additional LNG needed (m^3)
				700	
5,600	5,600		5,600	6,300	
-3,500	2,100		-3,500	2,800	
-4,200		-2,100	-4,200		-1,400
700	700		700	700	

5. Conclusion

NG is a vitally important source for industry. Currently the accessibility of NG through NG pipeline network is very limited thus ssLNG is becoming attractive to supply NG and meet industrial NG demand throughout the year even though the NG pipeline infrastructure does not exist. A new technique to estimate ssLNG sizing storage using the numerical approach of Pinch Analysis has been successfully developed. The technique will help the industrial planner to determine the amount of transferrable LNG from sources (terminal) to demands (off-grid LNG pipeline), the optimal storage capacity of ssLNG, the amount of LNG needed by industry at different period, and LNG peak demand by the industry. This work is expected to be extended with the development of optimisation model to integrate the logistic network of ssLNG supply and optimal storage sizing to satisfy the demand and ensure the ssLNG remain competitive.

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References

Bittante A., Petterson F., Saxen H., 2018, Optimization of a small-scale LNG supply chain, Energy, 148, 79-89.

Elmi E.A., Er-rbib H., Bouallou C., 2016, Power-to-Gas Storage Optimization Through Power Pinch Analysis, Chemical Engineering Transactions, 52, 1213-1218.

Esfahani I.J., Lee S., Yoo C., 2015, Extended-power pinch analysis (EPoPA) for integration of renewable energy systems with battery/hydrogen storages, Renewable Energy, 80, 1-14.

Exxon Mobile, 2016, The Outlook for Energy: A View to 2040, Exxon Mobile Corporate Headquarters Texas <https://cdn.exxonmobil.com/~/media/global/files/outlook-for-energy/2016/2016-outlook-for-energy.pdf> accessed 30.06.2019.

Jamaluddin K., Wan Alwi S.R., Manan Z.A., Klemeš J.J., 2018, Pinch Analysis Methodology for Trigeneration with Energy Storage System Design, Chemical Engineering Transactions, 70, 1885-1890.

Koza D.F., Ropke S., Boleda Molas A., 2017, The Liquefied Natural Gas Infrastructure and Tanker Fleet Sizing Problem, Transportation Research Part E: Logistic and Transportation Review, 99, 96-114.

Mikolajková M., Saxén H., Petterson F., 2018, Mixed Integer Linear Programming Optimization of a gas supply to a local market, Industrial & Engineering Chemistry Research, DOI: 10.1021/acs.iecr.7b04197.

Mohammad Rozali N.E., Wan Alwi S.R., Manan Z.A., Klemeš J.J., Hassan M.Y., 2013, Process integration techniques for optimal design of hybrid power systems, Applied Thermal Engineering, 61, 26-35.

Mohammad Rozali N.E., Wan Alwi S.R., Ho W.S., Manan Z.A., Klemeš J.J., Mustapha N.N., Rosli M.H., 2017, A new framework for cost-effective design of Hybrid Power Systems, Journal of Cleaner Production, 166, 806-815.

Othman M.N., Lim J.S., Theo W.L., Hashim H., Ho W.S., 2016, Optimisation and targeting of supply-demand of biogas system through gas system cascade analysis (GASCA) framework, Journal of Cleaner Production, 146, 101-115.

Rahim K.A., Liwan A., 2012, Oil and gas trends and implications in Malaysia, Energy Policy, 50, 262-271.

Reilly J., Paltsev S., Monier E., Chen H., Sokolov A., Huang J., Ejaz Q., Scott J., Morris J., Schlosser A., 2015, Energy and climate outlook: perspectives from 2015. MIT Joint Program on the Science and Policy of Global Change. <http://globalchange.mit.edu/files/2015% 20Energy> accessed 30.06.2019.

Sevik S., 2015, An analysis of the current and future use of natural gas-fired power plants in meeting electricity energy needs: the case of Turkey, Renewable Sustainable Energy Review, 52, 572-86.

Wan Alwi S.R., Mohammad Rozali N.E., Manan Z.A., Klemes J.J., 2012, A process integration targeting method for hybrid power systems, Energy, 44, 6-10.