**Supplementary Information File 2.**

**For**

**A Systematic Review of the Sustainability of Global Liquified Natural Gas Industry: A 10-years Update**

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1. Acronyms

|  |  |
| --- | --- |
| BOG | Boil-off Gas |
| CH4 | Methane |
| COx | Carbon oxides |
| CO | Carbon mono-oxide |
| CO2 | Carbon dioxide |
| CNG | Compressed Natural Gas |
| GTL | Gas to Liquid |
| GHG | Greenhouse Gas |
| IEA | International Energy Agency |
| IMO | International Maritime Organization |
| ISO | International Organization for Standardization |
| LCA | Life Cycle Assessment |
| LCSA | Life Cycle Sustainability Assessment |
| LNG | Liquefied Natural Gas |
| MR-LCSA | Multiregional life cycle sustainability assessment |
| NGL | Natural Gas Liquid |
| NGVs | Natural Gas Vehicles |
| NOx | Nitrogen oxides |
| PM | Particulate Matter |
| SDGs | Sustainable Development Goals |
| SI | Supplementary information |
| SOx | Sulfur Oxide |
| TLCAM | Tsinghua-LCA Model |
| UK | United Kingdom |
| US | United States |
| UNDP | United Nations Development Programme |
| WCED | World Commission on Environment and Development |
| WSSD | World Summit on Sustainable Development |
| WTW | Well-to-Wheel |

1. Further Literature Review
   1. *Transportation of LNG product*

Transportation of LNG starting from the manufacturing facility to the end-user location has been a challenge because of the possibility of changing the LNG back to the gas phase. For this purpose, pipelines are the most preferred mode of transporting liquid gas from one point to another. The demand for LNG in remote places in the 1960s necessitated the design of a suitable and safe way of transporting LNG. However, using pipelines to transport LNG to remote areas was considered either economically infeasible or technologically impractical [1]. The use of pipelines in the transportation of LNG is recommendable for a distance of approximately 2,000km. When the distance exceeds 2,000km, there is a significant increase in the costs involved [2]. However, the benefits associated with the use of LNG mean that there is a need for effective ways of transporting it from one place to another. Among the benefits that are related to the use of LNG is less emission of sulfur oxide (SOx), nitrogen oxides (NOx), and carbon oxides (COx) in comparison with other alternatives (e.g., diesel) [3,4].

LNG is known as a green source of energy for the future. The life cycle analysis of Greenhouse Gas (GHG) emissions of LNG illustrates much better improvement than other fuels. There is a clear and positive relationship between LNG and sustainable development referred to the advantages in reducing the environmental footprint, promising future in safety and social respects, and the flexible and available solutions for many uses globally along with renewable energy sources.

Unlike pipelines, LNG cargoes have the benefit of flexibility. They can be used to access any part of the nation, thus enabling the supply of the commodity to respond to changes in demand [5]. However, the supply of LNG has often been hindered by the difficulty of selecting the most appropriate supplier. There are various models for determining the suitable suppliers that have been used in multiple sectors. There is one approach that involves four steps. The first step of this model consists in defining the objectives that need to be met by the supplier. The second step consists of developing selection criteria, which entails the identification of the traits that an organization will be seeking in a supplier. The third step involves the qualification of suitable alternatives with reference to the criteria developed in step two. The final stage is the selection of suppliers. The criteria commonly used in selecting an appropriate supplier are delivery cost, quality, and flexibility [6,7]. The risks that are supposed to be taken into consideration include availability and stability. Furthermore, there are also commercial, political, and geographical risks that should be considered [8,9].

* 1. *Emissions of LNG against coal and oil*

The energy industry has often been under scrutiny for its impact on the environment. Industries' influence on the surrounding environment is not entirely attributed to the nature of combusting the fuels. Other processes such as production, exploitation, and transportation of energy sources have been confirmed to have an effect on the ecosystems and the environment [10]. The mainstream of the energy that is consumed globally comes from sources that are not environmentally sustainable. Fossil fuel, which is the most demanded of the available sources of energy, has the highest level of threat to the environment [11]. The carbon dioxide (CO2) produced after the combustion of fossil fuels causes harm to the environment by causing global warming [12]. However, the carbon monoxide (CO) produced after the combustion of fossil fuels should be of more significant concern. CO is a colorless, scentless, and tasteless gas that is poisonous. A slightly above 0.5% CO concentration can kill a person after just 15 minutes of breathing [13,14].

In addition to CO and CO2, oil and coal combustion releases particles of dangerous SOx and NOx into the environment. When natural gas is compared to both coal and oil, it is noted that the production of SOx is reduced to almost zero. The production of NOx is reduced with a percentage of around 75-80, particulate matter reduction close to the percentage of 99, reduction of sulfur oxides (SOx) emissions relatively close to 100 percent, and last but not least, 70 percent less in GHG emissions [14,15] as mentioned in Table 1.

Table 1. Comparison of LNG, Oil, and Coal emissions[[1]](#footnote-1) [16].

|  |  |  |  |
| --- | --- | --- | --- |
| **Pollutant** | **LNG** | **Oil** | **Coal** |
| CO2 | 117,000 | 164,000 | 208,000 |
| CO | 40 | 33 | 208 |
| NOx | 92 | 448 | 457 |
| SOx | 1 | 1112 | 2591 |
| PM | 7 | 84 | 2774 |
| Mercury | 0.000 | 0.007 | 0.016 |

When LNG goes through combustion, the production of SO2 and its elimination seizes to be a cause of concern. There is also a significant decrease in the quantity of CO2 that is emitted into the air. Therefore, it is advisable consuming the LNG instead of other fossil fuels (e.g., oil and coal) to be encouraged. Evidence can prove that LNG is an eco-friendly energy source based on the significant decrease of the GHGs produced when used instead of oil and coal [15,17].

Concerns regarding the environmental effects of the development and operation of ports have been on the increase, especially because of the emergence of energy conservation and climate conservation as global agendas. As far as sustainable development is concerned, ports' existence should be anchored on the management of three bottom lines: economic progress, environmental sustainability, and wellbeing of the society. Therefore, the development of suitable ports marketing plans that fulfill the three bottom lines should be used in guiding ports towards the type of development that can be categorized as sustainable [18].

* 1. *LNG as an alternative for transportation*

The road transport network has been acknowledged as a unique contributor to air pollution worldwide because of the level of energy intensity associated with road transport. This is a factor that should be taken into consideration by governments and other stakeholders when formulating strategies and programs that are aimed at making transport more sustainable. Therefore, the use of alternative greener energy sources should be one of the approaches used in making road transportation greener. The alternatives that can be considered include using electric cars or cars that run on more sustainable fuels (e.g., natural gas, biofuel, and liquefied petroleum gas). The lack of sufficient details on the techno-economic viability of these alternatives is a foremost stumbling block in the pursuit of a higher level of sustainability in road transportation [19].

Because of the sustainable nature of the combustion of natural gas, heavy-duty vehicles powered by LNG can effectively reduce the amount of carbon footprint that results from road transportation. It will also reduce the number of resources that will have to be channeled towards emission control. Furthermore, ships that use LNG have also been observed to have higher efficiency levels than the alternatives available in the market because of the dependence on natural gas. LNG represents 7% of the demand for natural gas globally [20].

LNG definitively can show a considerable role in the reduction of GHG emissions into the atmosphere. Its comparison with commonly used alternatives, such as oil and coal, tells a lot about what will occur when natural gas completely replaces oil and coal [21-24]. Using heavy-duty vehicles (HDVs) that LNG powers as an alternative to diesel-powered ones can lead to a 10% reduction in the resultant carbon emission [4,25].

A research that was undertaken on the lifecycle of a system using LNG and one using coal reveals that the system that depends on coal has a rate of emission that is 161% higher than the system that uses LNG. The study also reveals that the cleanest that a system using coal can be will still lead to an emission rate that will be 73% higher than the emission rate that is observed in a system using LNG. Notably, some costs are associated with making a system that is powered by coal as clean as possible [26].

The Life Cycle Analysis (LCA) conducted in China considers a combination of data on the real-time consumption rate for diesel and LNG. There was also the consideration: HDV population data for both diesel and LNG and the database for Tsinghua-LCA Model (TLCAM) precisely for the situation in the country. From such an analysis, it was observed that diesel use resulted in a significantly high carbon emission rate. Given the fact that the use of LNG has been on the increase in China, the increase in the LNG HDV population is an indication that there is a likelihood of a significant decline in the contribution of road transport to carbon emission in the future [27-29].

Among the studies that have been undertaken in China in relation to energy efficiency and suitability is the availability of technological resources that would support the use of natural gas for powering automobiles. Such analysis focused on the comparison of six possibilities: electricity, methanol, hydrogen, Compressed Natural Gas (CNG), Gas to Liquid (GTL), and LNG using various dimensions [30].

* 1. *LNG storage*

To achieve the appropriate storage of LNG, many aspects shall be determined. One such factor is whether the storage intends to serve the gas shortage experienced during winter. The other factor is the supply of baseload gas of the vessel that is used for long-distance shipment. In addition to the needed installations that are aimed at reducing possible losses from vaporization, it is advisable for the cargo that carries the LNG not to be in contact with the structure of the ship. This is because mild steel is vulnerable to brittleness when the temperatures get below 223K. Therefore, allowing the contact can lead to disastrous occurrences. There is a possibility of the evaporation kept to levels as low as 0.1% daily as long as there is sufficient installation of the tank, especially considering all the safety measures. 0.3% boil-off can result from re-liquefaction facilities that are installed in sea-going vessels [31].

At the on-shore, the storage of LNG can be done using double-walled metal tanks. Such tanks are not similar to the tanks that are used while LNG is in ships. The inner wall should be made of either nickel steel or aluminum. Additionally, concrete tanks that are attached to the ground can be contracted for the same purpose. Underground spaces that are specifically designed for the storage of LNG can be an alternative. The main advantage that is associated with the use of in-ground tanks is that there is no need for containment dikes. Such an advantage stands regardless of whether the tank is built from concrete or natural substances. The use of above-ground tanks can be recommendable because there is an ease in controlling heat leakage. Above-ground tanks are also easier to repair as compared to underground ones [31].

* 1. *LNG Sustainability*

The effect of the LNG usage on the environment in relation to diesel's impact can be determined by applying a Well-to-Wheel (WTW) assessment. The WTW is relaying on real-world HGVs drive cycles for it to be effective in such an analysis. The analysis is supposed to be complemented by the determination of the costs associated with ownership in both cases. The methods can be validated using practical case studies that have been undertaken in further portions of the world, such as the United Kingdom (UK). According to the findings from the UK, LNG vehicles recorded a lower energy efficiency compared to diesel ones. As a result, around a 7 percent rise in cumulative GHG emissions. Nevertheless, there is a possibility that the emission will be reduced by 13% as soon as the LNG comes level with the diesel ones in relation to energy efficiency. The findings from this study lead to the conclusion that there would need to be a noteworthy rise in the efficiency of vehicles based on LNG for them to have the impact that the usage of LNG is supposed to have on the environment from a theoretical point of view [32].

Most of the studies on LNG that have been undertaken have focused on economic and environmental impacts. Very few studies have reviewed the social impact of LNG. The main issues that are associated with the social sustainability of LNG are health, safety, employment, local communities, public participation, resources, and infrastructure. A Life Cycle Assessment (LCA) can be used in the evaluation of the social impacts of LNG. The LCA results can be used in affirming the assumption that the production and use of LNG can lead to various social benefits such as the provision of employment opportunities and financial gain by local governments through the collection of revenue [33].

Notably, some social barriers need to be overcome in the production and use of LNG. The obstacles include the lack of public support, traffic, noise, conflict in relation to land use, a strain of infrastructure, and the accessibility of regulatory resources. Furthermore, there is no sufficient evidence to link the use of LNG with energy security. LNG can only enhance energy efficiency if its production volume goes through a significant increase. Such information is relevant to various stakeholders, including policymakers, scholars, and other LNG stakeholders [33].

1. References
2. Khalilpour, R., Karimi, I.A., 2011. Selection of liquefied natural gas (LNG) contracts for minimizing procurement cost. Ind. Eng. Chem. Res. 50, 10298-10312.
3. Dobrota, Ð., Lalic, B., Komar, I., 2013. Problem of boil - off in LNG supply chain. Trans. Marit. Sci. 02, 91-100.
4. Pfoser, S., Schauer, O., Costa, Y., 2018. Acceptance of LNG as an alternative fuel: determinants and policy implications. Energy Policy 120, 259-267.
5. Stefano, P.D., Femia, A., Luzzati, T., 2001. Natural gas, cars and the environment. A (relatively) clean and cheap fuel looking for users. Ecol. Econ. 38, 179-189.
6. BP Energy Outlook 2017 Edition. <https://www.bp.com/content/dam/bp/pdf/energyeconomics/energy-outlook-2017/bp-energy-outlook-2017.pdf>. (Accessed 4 December 2017).
7. IGU (International Gas Union), 2017. World Energy Report, the World Depends on Natural Gas.
8. Thanaraksakul, W., Phruksaphanrat, B., 2009. Supplier evaluation framework based on balanced scorecard with integrated Corporate social responsibility perspective. In: Proceedings of the International MultiConference of Engineers and Computer Scientists (IMECS 2009), Hong Kong Vol. II, March 18 - 20, Hong Kong.
9. Stegen, K.S., Palovic, M., 2014. Decision-making for supplying energy projects: a four-dimensional model. Energy Convers. Manag. 86, 644-652.
10. Strantzali, E., Aravossis, K., Livanos, G. A., & Nikoloudis, C. (2019). A decision support approach for evaluating liquefied natural gas supply options: Implementation on Greek case study. *Journal of cleaner production*, *222*, 414-423.
11. World gas intelligence; 2009;6:8.
12. Energy and ecology November 2007. www.our- nergy.com/energy\_and\_ecology.html
13. Weisser D. A guide to life cycle green house gas (GHG) emissions from electric supply technologies. Energy 2007;32:1543–59.
14. Anthea M, Hopkins J, Laughlin Mc CW, Johnson S, Warner MQ, La Hart D, Wright JD. Human biology and Health Englewood Cliffs, New Jersey, USA, Prentice Hall, ISBN 013981176-1; 1993.
15. Dominguez ED, Ruiz MT, Rubio J, Andres de S. Equality of in vivo and in vitro oxygen binding capacity of hemoglobin in patients with serve respiration diseases. Br J Anesth 1981;53:1325–8.
16. Tamura I, Tanka T, Kagajo T, Kuwabara S, Yoshioka T, Nagata T, et al. Life cycle CO2 analysis of LNG and city gas. Appl Energy 2001;68:301–19.
17. Rellán, A. G., Brea, C. V., & Bugallo, P. B. (2018). Towards sustainable mobile systems configurations: Application to a tuna purse seiner. *Science of The Total Environment*, *631*, 1623-1637.
18. Zhang N, Noam L. A Novel near zero CO2 emission thermal cycle with LNG cryogenic exergy utilization. Energy 2006;31:1666–79.
19. Lam, J. S. L., & Li, K. X. (2019). Green port marketing for sustainable growth and development. *Transport Policy*, *84*, 73-81.
20. Navas-Anguita, Z., García-Gusano, D., & Iribarren, D. (2019). A review of techno-economic data for road transportation fuels. *Renewable and Sustainable Energy Reviews*, *112*, 11-26.
21. Oregon LNG <http://www.oregonlng.com/lng_enviro.php>.
22. Seatrans LHK. The LNG future seen from a ship owner. Magalog conference 16 January 2007.
23. Hekkert MP, Hendriks FHJF, Faaij APC, Neelis ML. Natural gas as an alternative to crude oil in automotive fuel chains well-to-wheel analysis and transition strategy development. Energy Policy 2005;33:579–94.
24. Hondo H. Life cycle GHG emissions analysis of power generation systems: Japanese case. Energy 2005;30:2042–56.
25. Kannan R, Leong KC, Osman R, Ho HK. Life cycle energy, emissions and cost inventory of power generation technologies in Singapore. Renew Sustain Energy Rev 2007;11:702–15.
26. Arteconi A, Brandoni D, Evangelista D, Polonara F. Life cycle green house gas analysis of LNG as a heavy vehicle fuel in Europe. Appl Energy 2010;87(6):2005–13.
27. Graham LA, Rideout G, Rosenblatt D, Hendren J. Greenhouse gas emissions from heavy-duty vehicles. Atmos Environ 2008;42:4665–81.
28. Life cycle assessment of GHG emissions from LNG and coal fired generation scenarios: assumptions and results. Fair Lakes Court, Fairfax, VA-22033348 USA, 3 February 2009.
29. Andress D, Nguyen TD, Das S. Reducing GHG emissions in the United States transportation. Energy Sustain Develop, in press. doi:10.1016/j.esd.2011. 03.002.
30. Song, H., Ou, X., Yuan, J., Yu, M., & Wang, C. (2017). Energy consumption and greenhouse gas emissions of diesel/LNG heavy-duty vehicle fleets in China based on a bottom-up model analysis. *Energy*, *140*, 966-978.
31. Hao, H., Liu, Z., Zhao, F., & Li, W. (2016). Natural gas as vehicle fuel in China: A review. *Renewable and sustainable energy reviews*, *62*, 521-533.
32. Kumar, S., Kwon, H. T., Choi, K. H., Lim, W., Cho, J. H., Tak, K., & Moon, I. (2011). LNG: An eco-friendly cryogenic fuel for sustainable development. *Applied energy*, *88*(12), 4264-4273.
33. Langshaw, L., Ainalis, D., Acha, S., Shah, N., & Stettler, M. E. (2020). Environmental and economic analysis of liquefied natural gas (LNG) for heavy goods vehicles in the UK: A Well-to-Wheel and total cost of ownership evaluation. *Energy Policy*, *137*, 111161.
34. Cooper, J., Stamford, L., & Azapagic, A. (2018). Social sustainability assessment of shale gas in the UK. *Sustainable Production and Consumption*, *14*, 1-20.

1. (in PPB Btu of Energy Input) [↑](#footnote-ref-1)