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A systematic review for sustainability of global liquified natural gas industry: A 10-year update

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ABSTRACT

This paper presents a comprehensive review and 10-years update of the sustainability research related to Liquefied Natural Gas (LNG) worldwide for the period between 2010 and 2020. Using the Scopus database, 467 articles, including journals, conference papers, and many other reports, were initially collected and screened. The filtered studies were categorized based on various factors such as author, year of publication, title, journal, method, country studied, analyzed system, the scope of the analysis, and period. It was found that only 168 (36% of the whole) studies have investigated the LNG sector's sustainability impacts with a detailed analysis. The collected literature was studied and categorized based on a proposed criterion. The findings showed that approximately 7 out of 46 countries performed such a massive number of LNG studies with a focus on LNG industries and sustainability. Moreover, it is observed that sustainability analysis research in LNG production concentrates mainly on the national level with 48% and the global level studies were found to be around 40% of total studies. The review also showed that there is no holistic life cycle environmental, economic, and social impact assessment for the LNG industry considering the entire value chain activities from gas extraction/processing to final consumption. This review finally discussed the lessons learned from the literature reviewed and industry best practices and several practical industry-specific policies are presented to enhance the long-term sustainability of LNG in support of sustainable development globally.

1. Introduction

The World Commission on Environment and Development (WCED) was formed to promote developmental approaches that are attentive to both the existing and future needs globally in 1987. The report was dubbed 'Our Common Future.' It was in this report that the phrase "sustainable development" was first used formally. According to this report, development can be categorized as sustainable if it meets the present needs without harming the capability of upcoming generations to satisfy their necessities. The 2002 World Summit on Sustainable Development (WSSD) borrowed heavily from the concept of sustainable development as defined by WCED. WCED asserts that sustainable development comes in three forms: economic development, environmental development, and social development [1].

Sustainability should be at the core of development. Various factors make the sustainability of high relevance in the energy sector. Sustainability is a significant factor for the energy division because of the prevalence of the demand for energy, the relevance of the energy sector to the economy, and the impact of processes that are associated with production and use on the environment of the world. Concerning the Sustainable Development Goals (SDGs) plan by 2030, numerous goals are directly or indirectly affected by the lengthy processes associated with LNG's processing, importation, exportation, and logistic activities.

Regarding the Paris Agreement, which was aimed at promoting the stabilization of global temperature in accordance with the SDGs framework that was brought in place by the United Nations Development Program (UNDP), natural gas can be considered a suitable transition source of energy. Its low carbon emission implies that when it is used together with a renewable source of energy, there will be a significant improvement in the programs that aim to reduce global warming [2].

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Abbreviations

BOG	Boil-off Gas
EUA	European Union Allowances
GHG	Greenhouse Gas
HDVs	Heavy-Duty Vehicles
IEA	International Energy Agency
IMO	International Maritime Organization
LCA	Life Cycle Assessment
LNG	Liquefied Natural Gas
MCDM	Multiple-criteria decision making
NGL	Natural Gas Liquid
NGVs	Natural Gas Vehicles
PM	Particulate Matter
SDGs	Sustainable Development Goals
SI	Supplementary Information
UK	United Kingdom
UNDP	United Nations Development Program
US	United States
WCED	World Commission on Environment and Development
WSSD	World Summit on Sustainable Development

1.1. Economic growth

The global energy demand has constantly been increasing. Projections show that the demand will grow around 1.2% on average because of factors such as the increase in the population [3]. In addition, the demand is expected to continue growing due to the growth of the middle class, increasing demand for natural gas industrial and domestic uses, declining indigenous production in Europe, and rising EUA prices coincide with the rise in the demand for natural gas and its liquified form as LNG. Currently, the reasons for traditional fossil fuels' commercial usage are relative to their cost, high energy density, and ease of transportation of these fuels. 85% of the global commercial needs for energy are provided by fossil fuels. However, LNG is still a fossil fuel; it can be acceptable in the transition towards sustainability. Therefore, it can be a fuel that drives countries towards sustainable development. The use of LNG is projected to increase over the next two decades significantly. Such an increase will decrease the dependency on other traditional fossil fuels [4,5].

It is projected that, in the next century, the demand for energy in China will be more than any time earlier [6,7]. Globally, the use of automobiles leads to more than 50% of the global energy demand. The increase in the number of vehicles in developing economies is likely to lead to a significantly higher increase in demand for energy as compared to what will be experienced in developed economies. With such expectations, LNG will be a more sustainable alternative to make sure that economic development is fueled sustainably [8].

The supply of LNG has been increasing at a considerably high rate. The world is experiencing what could be termed and the semi-biggest escalation in LNG stock in history. Escalation of LNG supply globally is highly attributed to the expansions that have been experienced in the US and Australia. The International Energy Agency (IEA) expects that by 2023 the gas liquefaction volume will have increased. This is backed by the recently recorded increase in the supply of LNG in economies such as the US, Australia, and Qatar (see Fig. 1).

There have been changes in decisions concerning the investment in the energy sector based on opportunities, attractive and green trading, and worldwide needs in general towards a more sustainable and reliable source of energy. Previously, energy projects were characterized by offtake projects that involved buyers who were eligible to credit products. However, the investment decisions that have been made recently were more reliant on the strength of the equity of sponsors such as Shell, Qatar Energy (known earlier as Qatar Petroleum), Mitsubishi, and Petronas. The markets that have been warming up to the concept of natural gas in its liquid form are lower as far as the credit quality hierarchy is concerned [9,10].

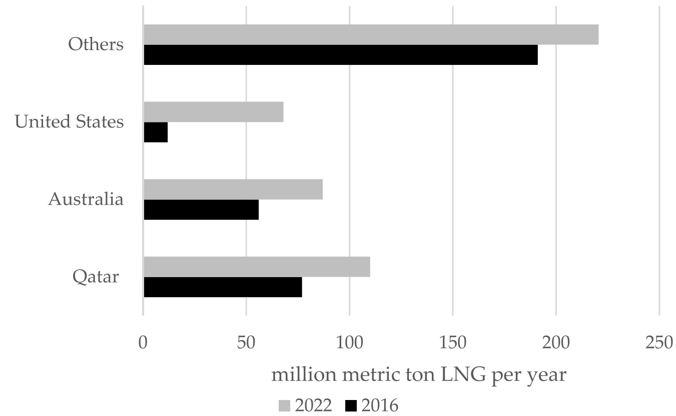

Fig. 1. Global LNG supply growth 2016–22 [11].

One of the advantages associated with the LNG is that there are more than 600 times a decrease in the resultant volume [12] not to eliminate the associated cost of energy. Moreover, another advantage is that natural gas (in a liquefied form) can be transported worldwide and not only specified at fixed locations (use of fixed pipelines). Furthermore, due to the increase in LNG demand, regasification capacities significantly increased in the last decade.

Activities related to the handling of liquid gas are, in many ways, similar to the activities associated with handling oil. Furthermore, there has been a notable expected decrease in the lump sum costs associated with LNG production throughout the liquefaction process. This is an implication that the competitiveness of LNG has increased over the recent past. Therefore, natural gas and LNG can be suitable alternative energy sources, especially when political instability threatens the production and transportation of oil. Therefore, the demand for LNG is likely to increase faster as compared to the demand for gas in general [5].

1.2. Environmental impacts

It is projected that the increase in global carbon emission between 2005 and 2030 will be 30%. This projection was made with consideration of factors such as the expected growth in energy effectiveness and the usage of more sustainable sources of energy [3,4]. Therefore, there would be a need for more to be done for the projected increase in demand to meet sustainability. The use of LNG is among the viable alternatives while considering the usage of more sustainable sources of energy [13]. LNG utilization can reduce the number of overall greenhouse gases (GHG) that are emitted into the atmosphere; however, methane slip remains an area of concern that requires further technical solutions towards sustainability. Using LNG to power vehicles contributes to both energy diversity and security. The fact that most of the fuel produced globally is used for automobiles is an implication in which the usage of Natural Gas Vehicles (NGVs) has become revolutionary [4].

The use of a mix of renewable and non-renewable energy sources has been a norm in most countries. However, the possibility of using natural gas has not been exploited as much as it is supposed to be. The efficiency of natural gas should be the primary selling point. For instance, natural gas produces less than half the emission that is produced by coal. In several nations, particularly in Asia, the energy of different natures is used in mixed along with renewables based on the availability of the sources. In which natural gas, occasionally is taking place. The governments use this way to satisfy the need for energy and reduce emissions to meet environmental limitations and minimize human health impact. The overall advantage becomes a 40% reduction in emission as well as GHG minimization [9].

Natural gas utilization as a significant source of energy can be economical. This is regarding the amount of time and financial resources that would be used in responding to the resultant emissions. For example, when there is a change from using coal to using natural gas, there is a consequent 73% decrease in the amount of carbon that is emoted. Therefore, natural gas is the most preferred non-renewable energy source if factors such as efficiency, environmental benignity, and cost-effectiveness are considered. As far as long-distance transportation and expected shipping volume are concerned, transportation in the form of LNG by road is more practical than when gas is transported in the gaseous state using pipeline systems [4,9].

Strezov and Cho (2020) studied a power generation facility's direct emissions, midpoint, and endpoint impacts. Brown coal was determined to have the highest global warming impacts, which were over 40% higher than hard coal's. Brown coal has a very high natural moisture content, which decreases the energy efficiency of its combustion when compared to black coal, resulting in higher GHG emissions. Brown coal emitted 1223 kg CO_2eq, and hard coal emitted 879 kg CO2eq, both greater than the norm. The lowest GHG emissions from fossil fuel energy generation methods came from gas-fired power plants, with 515 kg CO_2eq. With 91, 54, and 37 kg CO2eq, respectively, the GHG emissions from landfill gas, sewage gas, and bagasse generation were the lowest as renewable energy sources [14].

It is concluded that natural gas found the lowest GHG impact compared with other fossil fuels for the power generation case in Australia.

1.3. Research goals and structure

The goals of this novel study include the below:

1. Illustrate the previous studies related to sustainable energy sources, including the LNG manufacturing process chain and supply chain.
2. Address the primary uses of LNG as a product worldwide and the sustainability of this product from economic, environmental, and social perspectives.
3. Study and address the lesson learned from experience and current development in the literature and industry best practices.

This research is organized as charted: Section 1 is a general introduction including the economic growth of fossil fuels and environmental impacts, Section 2 illustrates a comprehensive review from the literature on the LCA of the LNG industry, and LNG worldwide uses in Section 3. Section 4 covers the lesson learned and recommendations, and research conclusions in Section 5.

2. Literature review

2.1. Sustainability of LNG industry: a global review

A review of the literature is carried out with the intent of investigating the application-based and methodological gaps. Filtering and specific keywords were used for the purpose of reviewing literature from the Scopus database. A structured review consisting of 4 phases was used. The first phase entails a general search of the literature to identify the total number of articles that were focused on the sustainability of the development of LNG industries. The keywords: sustainability, sustainable, liquefied natural gas, and LNG were used in the first phase to search articles that were published between 2010 and 2020. The first phase led to the retrieval of 467 documents. The accessed literature materials included journal articles, books, conference papers, and letters. After identifying the total number of literature materials that were based on this study's topic, a search was narrowed down to those found on macro-level estimations for the LNG sector. The list of these studies is available in the supplementary information (SI) file No. 1. The use of automatic filtering made it possible for the narrowing down to be based on the sector at large. Most of the studies that were identified focused on specific traits of the LNG industry, and thus, there was no focus on macro-level sustainability development estimations. As a result, there was a need to carry out a comprehensive review in phase 2 and manually filter the materials that were not within the scope of this study. The primary focus of the paper is the suitability of the developments in the LNG industry. Therefore, there was an exclusion of life cycle assessment-based environmental focusing on biofuels, technical and design studies, and materials based on risks and safety issues of LNG production.

Table S1 avails details of the studies that were excluded and the reasons behind their exclusion. In phase three, there was an inclusive review of 168 literature materials [15–180]. In this phase, the sources were categorized based on various factors such as author, year of publication, title, journal, methodology, country studied, analyzed system, the scope of the analysis, and period. Table S2 in the SI No.1 file gives comprehensive details of the categorization of the sources. After the narrowing down had taken place, there was a detailed analysis of the 168 literature materials. Table 1 present the bibliometric analysis of the LNG and its relevant sustainability studies between 2010 and 2020.

The visualized form of the results from the bibliometric analysis can be found in Fig. 2 for various studies based on the year. There has been a noticed increase in the studies recently, and that provides evidence on the importance of using LNG fossil fuel sustainably in the coming future.

The bibliometric analysis results are analyzed in-depth and illustrated more in Fig. 3 for the various studies conducted for the last ten years based on the scope margin, country, and systems. If all the samples of the studies were focused on the field of LNG sustainability overview, the number of micro-level studies would be just 36% of the total studies. Of the 36% of the studies, the results revealed that an averagely of 7 nations were close to 46 other nations of the research that had been undertaken about the suitability of the LNG industry. The 7 nations claimed almost half of the studies that had been undertaken concerning the suitability of the LNG industry. More deals can be found in Fig. 3a. As seen in Fig. 3b, most of the studies (48%) undertook an analysis at the national level. (40%) of the studies took place at the global level with a focus on manufacturing and production of LNG.

City-level and regional-level studies accounted for 5% and 7% of the reviewed studies, respectively. Fig. 3c reveals that 29% of the reviewed materials focused primarily on the general energy sector. The general energy sector is followed by the LNG sector specifically with 19%, LNG fueled ships with 15%, and the LNG industry with 13%.

For top-down methods, we see that most of these studies cover the review and analysis part of the LNG industry, LNG sector, and energy sector in general. The energy sector can be defined as any energy trading and business, including LNG and other energy supply industries. It is considered the broader sector among the other systems. The LNG sector in this review covered the LNG trading and business that include all the stages of natural gas extraction, liquefication, regasification operations, and the supply chain. The process of LNG manufacturing is considered here as the LNG industry. Also, many studies were found illustrating the life cycle assessment of LNG utilization either in power generation, fueled ships and vehicles, and aircraft. However, after a comprehensive literature review by the research team, no complete life cycle sustainability assessment for the LNG industry (from extraction until customer use) has been found. Further consideration on the LNG transportation, sustainability, and associated emissions are illustrated in the SI file No. 2.

2.2. LNG process and supply chain

Fig. 4 depicts a flow block schematic of the LNG process chain for this review. The divisions are classified into natural gas drilling and exploration, followed by gas treatment and acid gas removal to meet the feed specification of the liquefaction unit. Then, the liquefaction process will

Table 1
Bibliometric analysis of the LNG industry and sustainability studies in between 2010 and 2020.

ID	Authors	Year	Country	Method	Analyzed system	Scope	Period
1	Koilo V. [15]	2020	Norway	The twofold model was proposed, Sustainable Development Index (SDI), and mathematical modeling	LNG Fueled Ship	National, Global	Multi Years
2	Ji C., El-Halwagi M.M. [16]	2020	US, China	A bottom-up emission inventory model and shipboard Automatic Identification System (AIS)	LNG Fueled Ship	National, Global	Single Year
3	Yuanqi S. et al. [17]	2020	China	National energy network	LNG Sector	National, Global	Multi Years
4	Luo Z. et al. [18]	2020	China	A hydrogen energy cost model	Energy Sector	National	Multi Years
5	Rao A.G., Yin F., Werij H.G. C. [19]	2020	Netherlands	Various options f or energy carriers in aviation	Aircraft	Global	Multi Years
6	Li J. et al. [20]	2020	China	Global natural gas resources status, trade pattern, and development trend	LNG Sector	National	Multi Years
7	Jiao J., Huang Y., Liao C. [21]	2020	China	Quantitative analysis model based on the Long-range Energy Alternatives Planning (LEAP) framework	Energy Sector	City	Multi Years
8	Maksakova D., Popov S. [22]	2020	Russian Federation	A model of national gas infrastructure creation	Energy Sector	National, Regional, Global	Multi Years
9	Lachkov G. [23]	2020	Russian Federation	The efficiency of gasification evaluation	Energy Sector	National	Multi Years
10	Arefin M.A. et al. [24]	2020	Bangladesh, Australia	Overview of the LNG as a potential fuel for diesel engines	Energy Sector	Global	Single Year
11	Laribi S., Guy E. [25]	2020	Canada	Niche analysis approaches such as the multilevel perspective model (MLP)	LNG Fueled Ship	National	Multi Years
12	Al-Breiki M., Bicer Y. [26]	2020	Qatar	Examine the effects of BOG economically in production and transportation phases	LNG Transportation	Global	Single Year
13	Allahyarzadeh-Bidgoli A., Dezan D.J., Yanagihara J.I. [27]	2020	Brazil	An automated optimization procedure is performed for commonly used MPFHE	LNG Industry	Global	Single Year
14	Kharlamova T., Kharlamov A., Gavrilova R. [28]	2020	Russian Federation	Sustainability of the world market the Fourth Industrial Revolution brings.	LNG Sector	Regional	Multi Years
15	Najm S., Matsumoto K. [29]	2020	Saudi Arabia, UK, Japan	Examining the impact of renewable policies on international trade in LNG among 1359 trading partners during the period 1988–2017	LNG Sector	Global	Multi Years
16	Kumar V.V., Shastri Y., Hoadley A. [30]	2020	India, Australia	A modeling approach to quantify the economic and environmental impacts of natural gas utilization	LNG Sector	National, Global	Multi Years
17	Barone G. et al. [31]	2020	Italy, Canada	TRNSYS software is adopted for analyzing the energy system of a moving ship	LNG Fueled Ship	National, Global	Single Year
18	Lasemi M.A., Assili M., Hajizadeh A. [32]	2020	Iran, Denmark	Integrated scheduling for fuel dispatching and the generation planning of the power system comprising multi-fuel-fired thermal power plants and hydro units	Energy Sector	Global	Single Year
19	Yao B. et al. [33]	2020	UK, Saudi Arabia	Emerge is in hydrogen energy as a sustainable vector for our future energy needs	Ecosystem Impact	Global	Single Year
20	Kusuma J., Artana K.B., Dinariyana A.A.B. [34]	2020	Indonesia	Two scopes of research, first determining the supply and demand of natural gas in Java Island, and then market analysis	LNG Sector	National	Single Year
21	Daryanto, Maulana M.A., Kurniawan F. [35]	2020	Indonesia	Ship to Ship (STS) LNG transfer activity	LNG Terminal and Ship	Global	Single Year
22	Sherry L., Thompson T. [36]	2020	US	Physics of AIC formation and RF	Aircraft	Global	Single Year
23	Vaferi M., Pazouki K., Van Klink A. [37]	2020	Belgium, UK, Netherlands	Analytical model for conversion from HFO to LNG dual-fuel engine in a fleet with three sizes of vessels	LNG Fueled Ship	Global	Single Year
24	Ayou D.S., Eveloy V. [38]	2020	United Arab Emirates	Multi-generation concepts combining low-to-medium grade environmental or waste heat utilization, and waste cryogenic cold recovery, are investigated	LNG Industry	Global	Single Year
25	Malik S. et al. [39]	2020	United Arab Emirates, US, Singapore, Japan	The 4-As methodology attempts to measure and illustrate the change in energy security graphically	Energy Sector	National	Multi Years
26	Zhang X. et al. [40]	2020	China	Driving Cycle and Establishment of Emission Inventory	Ecosystem Impact	City	Single Year
27	Al Marzooqi M., Ahmad S.Z. [41]	2020	United Arab Emirates	Gas Project	Energy Sector	National	Multi Years
28	Budiyanto M.A. et al. [42]	2020	Indonesia	Optimize LNG distribution using small-scale LNG carriers and carry out an economic analysis	LNG Transportation	National	Single Year
29	Zhang L., Bai W. [43]	2020	China		LNG Sector	National	

(continued on next page)

Table 1 (*continued*)

ID	Authors	Year	Country	Method	Analyzed system	Scope	Period
				Risk Assessment and use of Fuzzy AHP-TOPSIS			Multi Years
30	Seithe G.J. et al. [44]	2020	Norway Greece	A "Well-to-Propeller" Life Cycle Assessment of maritime transport	LNG Fueled Ship	Regional	Single Year
31	Ayou D.S., Eveloy V. [45]	2020	United Arab Emirates	Sustainable district cooling	LNG Regasification	Global	Single Year
32	Litvinenko V. [46]	2020	Russian Federation	Analyze the consistency of criticism towards HCR	LNG Sector	National, Regional, Global	Multi Years
33	Phu N.M., Thao P.B., Truyen D.C. [47]	2020	Viet Nam	Aspen HYSYS-based performance simulations for LNG-fired power plants	LNG Regasification	Global	Single Year
34	Smajla I. et al. [48]	2020	Croatia	Analyses the possibility of establishing a regional gas hub.	LNG Terminal	Regional	Multi Years
35	AlNouss A., Al-Sobhi S.A. [49]	2020	Qatar	Aspen HYSYS	LNG Industry	Global	Single Year
36	Meenakshi Sundaram A.C., Karimi I.A. [50]	2020	Singapore	A comprehensive evaluation of the existing LNG bunkering protocol using a Unisim Dynamic Simulation (DS) model	LNG Transportation	Global	Single Year
37	Al-Haidous S., Govindan R., Al-Ansari T. [51]	2020	Qatar	A multi-objective mathematical model for shipping fleet scheduling, routing, and delivery for sustainable LNG supply chains.	LNG Transportation	Global	Single Year
38	Boahen K.Y., Oppong R. [52]	2020	Ghana	Assessment of Natural Gas Infrastructure Development	LNG Sector	National	Multi Years
39	Köhler J. [53]	2020	Germany	MATISSE-SHIP model for illustrative long term scenarios of technical change in shipping	LNG Fueled Ship	Global	Multi Years
40	Al-Breiki M., Bicer Y. [54]	2020	Qatar	Mathematical calculation of BOG	Energy Sector	Global	Single Year
41	Al-Haidous S., Al-Ansari T. [55]	2020	Qatar	Life cycle assessment	Energy Sector	Global	Single Year
42	Yoon S., Oh J.-S., Kim J.-K. [56]	2020	South Korea	Process simulation	LNG Sector	Global	Single Year
43	Iannaccone T. et al. [57]	2020	Italy	Overview and sustainability assessment	LNG Fueled Ship	National	Single Year
44	Stokes D.M. et al. [58]	2019	Canada	socio-economic analysis	LNG Industry	City	Multi Years
45	Wu B. et al. [59]	2019	China	"cradle to grave" life cycle assessment (LCA)	Energy Sector	Global	Single Year
46	Jovanović F. et al. [60]	2019	Croatia	Overview	LNG Terminal and Ship	Global	Single Year
47	Łaciak M. et al. [61]	2019	Poland	Review and analysis	LNG Industry	Global	Single Year
48	Włodek T. [62]	2019	Poland	Review and analysis	LNG Industry	Global	Single Year
49	Qyyum M.A. et al. [63]	2019	South Korea, Saudi Arabia	Review and analysis	Energy Sector	Global	Single Year
50	Baldi F., Brynolf S., Maréchal F. [64]	2019	Switzerland, Sweden, Italy	Review and analysis	LNG Fueled Ship	Global	Single Year
51	Pizzol M. [65]	2019	Denmark	LCA and Monte Carlo simulation	LNG Transportation	National	Single Year
52	Viertl B., Guccione D. [66]	2019	Germany	Review and analysis	Energy Sector	National	Single Year
53	Karnauskaite D. et al. [67]	2019	Lithuania, Denmark, Germany	Setting Indicators and Indicator-Based Sustainability Assessment	Energy Sector	National	Single Year
54	Gounni A., Rais N., Azzouzi Idrissi M. [68]	2019	Morocco	Simulation of Urban Mobility	LNG Fueled Vehicles	National	Single Year
55	Salmi H.A., Khan F.R. [69]	2019	Oman, Malaysia	Survey	LNG Sector	National	Multi Years
56	Deja A. et al. [70]	2019	Poland	Review and analysis	LNG Fueled Vehicles	National	Single Year
57	Kanbur B.B. et al. [71]	2019	Singapore	Life-cycle-based enviroeconomic and life-cycle-integrated thermoeconomic assessment (LCiTA) models	LNG Sector	National	Single Year
58	Choi D.S. et al. [72]	2019	South Korea	Emission calculation	Energy Sector	National	Multi Years
59	Navas-Anguita Z., García-Gusano D., Iribarren D. [73]	2019	Spain	Review and analysis	LNG Fueled Vehicles	National	Multi Years
60	Hansson J. et al. [74]	2019	Sweden	MCDM	LNG Fueled Ship	National	Single Year
61	Iannaccone T., Landucci G., Cozzani V. [75]	2018	Netherlands, Italy	Review and analysis	LNG Fueled Ship	Global	Single Year
62	Al-Sobhi S.A. et al. [76]	2018	Qatar, India, United Arab Emirates, Canada	Aspen Plus simulation	Energy Sector	Global	Single Year
63	Bicer Y., Dincer I. [77]	2018	Qatar, Turkey, Canada	Life cycle environmental impact assessments	LNG Fueled Vehicles	Global	Single Year

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Table 1 (*continued*)

ID	Authors	Year	Country	Method	Analyzed system	Scope	Period
64	Yoon B., Shin J., Lee S. [78]	2018	South Korea	K-TOL for strategic technology planning	LNG Terminal and Ship	Global	Single Year
65	Lee S.H., Seo Y.K., Chang D. J. [79]	2018	South Korea	Aspen HYSYS	LNG Sector	Global	Single Year
66	Azad A.K. et al. [80]	2018	Australia, Bangladesh	Environmental review	Energy Sector	National	Single Year
67	Pope J. et al. [81]	2018	Australia, South Africa, UK	Environmental Impact Assessment	LNG Industry	National	Single Year
68	Li L. et al. [82]	2018	China	Review and analysis	Energy Sector	National	Multi Years
69	Yang J. [83]	2018	China	Macro-economic and environmental review	Energy Sector	National	Multi Years
70	Strantzali E. et al. [84]	2018	Greece	Multicriteria evaluation model, PROMETHEE and Simos approach	LNG Sector	National	Single Year
71	Matsuzaka K. [85]	2018	Japan	Review and analysis	LNG Transportation	National	Single Year
72	Ullah K. et al. [86]	2018	Pakistan	MCDM	LNG Fueled Vehicles	National	Single Year
73	Son H. et al. [87]	2018	South Korea	Environmental review	LNG Industry	National	Single Year
74	Cooper J., Stamford L., Azapagic A. [88]	2018	UK	LCA, LCC, MCDM	Energy Sector	National	Single Year
75	Castán Broto V. [89]	2018	UK	Review and analysis	Energy Sector	National	Single Year
76	Kurle Y.M., Xu Q., Palanki S. [90]	2018	US	Process simulation using Aspen Plus	LNG Terminal	National	Single Year
77	Pfoser S., Schauer O., Costa Y. [91]	2018	Colombia, Austria	Technology acceptance model (TAM)	Energy Sector	Regional	Multi Years
78	Ren J., Lützen M. [92]	2017	Hong Kong, Denmark	Novel multi-criteria decision-making method with Dempster-Shafer theory and a trapezoidal fuzzy analytic hierarchy process	LNG Fueled Ship	Global	Single Year
79	Raghoo P., Surroop D., Wolf F. [93]	2017	Mauritius, Germany	Techno-economic analysis	Energy Sector	Global	Single Year
80	Gao J., You F. [94]	2017	US	A novel mixed-integer nonlinear fractional programming model	Energy Sector	Global	Single Year
81	Benham C.F. [95]	2017	Australia	Environmental impact review	LNG Sector	National	Single Year
82	Sharma A., Strezov V. [96]	2017	Australia	LCA	LNG Fueled Ship	National	Single Year
83	Yan J. et al. [97]	2017	China, Sweden, Singapore, Italy	Review and analysis	Energy Sector	National	Single Year
84	Köppel W., Ruf J., Graf F. [98]	2017	Germany	Review and analysis	LNG Fueled Vehicles	National	Single Year
85	Strantzali E., Aravossis K., Livanos G.A. [99]	2017	Greece	Multicriteria decision making model, PROMETHEE II, to	Energy Sector	National	Single Year
86	To W.M., Lee P.K.C. [100]	2017	Macao, Hong Kong	LCA GHG	Energy Sector	National	Single Year
87	Osorio-Tejada J.L., Llera-Sastresa E., Scarpellini S. [101]	2017	Spain	MCDM	LNG Fueled Ship	National	Single Year
88	Hua J., Wu Y., Chen H. [102]	2017	Taiwan	LCA	LNG Fueled Ship	National	Single Year
89	Brooks P.M., Jedele T.K. [103]	2017	US	Academic analysis	Ecosystem Impact	National	Single Year
90	Ren J., Liang H. [104]	2017	China, Hong Kong	Fuzzy TOPSIS (Technique for Order Performance by Similarity to Ideal Solution).	LNG Fueled Ship	Regional	Single Year
91	Hao H. et al. [105]	2016	China	Review and analysis	LNG Fueled Vehicles	Global	Single Year
92	Cerf C. [106]	2016	France	Review and analysis	LNG Sector	Global	Single Year
93	Jiang Z. et al. [107]	2016	China	Review and analysis	LNG Sector	National	Single Year
94	Chen C., Li Y.P., Huang G.H. [108]	2016	China, Canada	Interval-fuzzy municipal-scale energy model	Energy Sector	National	Multi Years
95	van Bets L.K.J., van Tatenhove J.P.M., Mol A.P. J. [109]	2016	Netherlands	Socio-economic and political dynamics	LNG Sector	National	Single Year
96	Acomi N., Acomi O. [110]	2016	Romania	Overview	Energy Sector	National	Multi Years
97	Osorio-Tejada J.L., Llera-Sastresa E., Scarpellini S. [111]	2016	Spain	MCDM	LNG Fueled Ship	National	Single Year
98	Liu X., Schlake B.W. [112]	2016	US	Event chain	Energy Sector	National	Single Year

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Table 1 (*continued*)

ID	Authors	Year	Country	Method	Analyzed system	Scope	Period
99	Poyraz O.I., Keskin O., Unal R. [113]	2016	US	Review	Energy Sector	National	Multi Years
100	Schönsteiner K., Massier T., Hamacher T. [114]	2016	Singapore, Germany	LCA	LNG Fueled Ship	National	Single Year
101	Agbonifo P.E. [115]	2016	UK	Review and analysis	LNG Sector	National	Single Year
102	Sanavandi H., Ziabasharhagh M. [116]	2016	Iran	Optimization	LNG Industry	National, Global	Single Year
103	Elgohary M.M., Seddiek I.S., Salem A.M. [117]	2015	Egypt, Saudi Arabia	Review and analysis	LNG Fueled Ship	Global	Single Year
104	Dato' Wee Y.H. [118]	2015	Malaysia	Overview	LNG Sector	Global	Multi Years
105	Thunnissen S.K., Van De Bunt L.G., Vis I.F.A. [119]	2015	Netherlands	Review and analysis (BOOK)	Energy Sector	Global	Multi Years
106	Vleuten J.M., Bal F. [120]	2015	Netherlands	Alternative fuels selection	LNG Fueled Ship	Global	Single Year
107	Mering W. et al. [121]	2015	Qatar, India, Netherlands, South Korea, Iran, Russian Federation, Thailand Japan, Malaysia, France, Spain, UK, Germany	Review and analysis	Energy Sector	Global	Multi Years
108	Han Y., Shin H. [122]	2015	South Korea	Description	LNG Sector	Global	Single Year
109	Williams T. et al. [123]	2015	US, Qatar, Iran, Croatia, Algeria, Russian Federation Finland, France, UK, Germany	Review and policy implication	LNG Sector	Global	Single Year
110	Lammons R. et al. [124]	2015	US, Qatar, India, Netherland, Iran Algeria, Portugal, Thailand, Denmark, Austria, Sweden, Japan, Norway, France, Spain, Singapore, UK	Review and policy implication	LNG Sector	Global	Single Year
111	Al-Sobhi S.A., Elkamel A. [125]	2015	Canada	Process simulation using Aspen Plus	Energy Sector	National	Single Year
112	Ma J. et al. [126]	2015	China	Review standards and regulations	LNG Transportation	National	Single Year
113	Wang Q. et al. [127]	2015	China, Australia	Information Entropy Model and LMDI Model	Energy Sector	National	Multi Years
114	Tzannatos E., Papadimitriou S., Koliousis I. [128]	2015	Greece	Review and analysis	LNG Fueled Ship	National	Single Year
115	King G. [129]	2015	Australia	Review and analysis	LNG Sector	National, Global	Multi Years
116	Ren J., Lützen M. [130]	2015	Denmark	MCDM combining Fuzzy Analytic Hierarchy Process (AHP) and VIKOR	LNG Fueled Ship	National, Regional	Single Year
117	Mozgovoy A., Burmeister F., Albus R. [131]	2015	Germany	Review and analysis	Energy Sector	Regional	Single Year
118	Yannoulis P. [132]	2015	Greece	Review and analysis	LNG Fueled Ship	Regional	Single Year
119	Alahmad A.R., Bacani J., Deb K. [133]	2014	Qatar	Review and analysis	LNG Industry	City	Multi Years
120	Mirza M.B. [134]	2014	Qatar	Review and analysis	LNG Industry	City	Multi Years
121	Al-Sulaiti K.A., Subedar A.A. [135]	2014	Qatar	GHG accounting and reporting EU standards	LNG Industry	City	Multi Years
122	Deb K. et al. [136]	2014	US, China, Qatar	CALPUFF modeling for air quality	Energy Sector	City	Multi Years
123	Conroy T., Bil C. [137]	2014	Australia	LCC	Aircraft	Global	Single Year
124	Ikealumba W.C., Wu H. [138]	2014	Australia	Review and analysis	LNG Sector	Global	Multi Years
125	Xu H.J. et al. [139]	2014	China	Cascade recycling strategy	LNG Regasification	Global	Single Year
126	Rao A.G., Yin F., Van Buijtenen J.P. [140]	2014	Netherlands	Hybrid engine	Aircraft	Global	Single Year
127	Gudmestad O.T. [141]	2014	Norway	Review and analysis	LNG Extraction and Processing	Global	Single Year
128	Mozgovoy A., Burmeister F., Albus R. [142]	2014	Germany	Review and analysis	Energy Sector	National	Single Year
129	Ahmad M. [143]	2014	India	Review and analysis	LNG Fueled Ship	National	Multi Years
130	Pereira S.R., Fontes T., Coelho M.C. [144]	2014	Portugal	LCA	Aircraft	National	Single Year
131	Nwaoha C., Wood D.A. [145]	2014	Thailand, UK	Review and analysis	Energy Sector	National	Multi Years
132	Uday T. [146]	2014	US	Review	Energy Sector	National	Single Year
133	Lim K.E.W., Bil C. [147]	2014	Australia	Review and analysis	Aircraft	National	

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Table 1 (*continued*)

ID	Authors	Year	Country	Method	Analyzed system	Scope	Period
							Multi Years
134	Robinson D.R. [148]	2014	US	GHG review and reduction	LNG Industry	Regional	Single Year
135	Albacete L.I. [149]	2013	Belgium	Overview	LNG Industry	Global	Single Year
136	Hubert C., Ragetly Q. [150]	2013	France	Overview	LNG Industry	Global	Single Year
137	Hoagie M. et al. [151]	2013	US, Australia	Prediction of withdrawal rates and time	LNG Extraction and Processing	Global	Single Year
138	Osborne D.G. et al. [152]	2013	US, Australia, Germany	Academic analysis	Ecosystem Impact	Global	Single Year
139	Burston M. et al. [153].	2013	Australia	Review and analysis	Aircraft	National	Single Year
140	Senthamaraikkannan G., Chakrabarti D., Prasad V. [154]	2013	Canada	Overview	LNG Fueled Ship	National	Single Year
141	Yang D., Peng X., Xu Y. [154]	2013	China	Review and analysis	LNG Sector	National	Single Year
142	Tzannatos E., Nikitakos N. [156]	2013	Greece	Review and analysis	LNG Transportation	National	Single Year
143	Balyan A.K. [157]	2013	India	Review and analysis	Energy Sector	National	Multi Years
144	Burel F., Taccani R., Zuliani N. [158]	2013	Italy	Statistical analysis	LNG Terminal	National	Single Year
145	Goncalves C.J. [159]	2013	US	Analysis of current natural gas in the US	LNG Industry	National	Multi Years
146	Attanasi E.D., Freeman P.A. [160]	2013	US	Review analysis	LNG Sector	Regional	Multi Years
147	Wang X., Economides M.J. [161]	2012	US	Calculations and estimations applied to an underground natural gas	LNG Industry	Global	Single Year
148	Kini S., Van Duker J., Hayes B. [162]	2012	US	Community Development Support Plan	LNG Industry	Global	Single Year
149	Hamdani S.A. [163]	2012	Venezuela	Review and analysis	LNG Sector	Global	Single Year
150	Zihang F., Kun S., Tongwen S. [164]	2012	China	Review and analysis	LNG Terminal	National	Single Year
151	Zhang C., Peng S. [165]	2012	China	Energy comparison	Energy Sector	National	Multi Years
152	Beckwith J.A. [166]	2012	Australia	Strategic environmental assessment and decision-making	LNG Sector	National, Global	
153	True W.R. [167]	2012	US	Review and policy implication	LNG Industry	National, Global	Single Year
154	Nicotra A. [168]	2012	Germany	Review and analysis	Energy Sector	Regional	Multi Years
155	Liu S. et al. [169]	2011	China	Pipeline engineering	LNG Transportation	Global	Multi Years
156	Stougie L., Van Der Kooi H. [170]	2011	Netherlands	LNG evaporation Techniques selection. Environmental, economic, and social aspects of its sustainability.	LNG Regasification	Global	Single Year
157	Kortenaar M. et al. [171]	2011	Netherlands	LCC	LNG Terminal	Global	Single Year
158	Kumar S. et al. [4]	2011	South Korea	Review and analysis	LNG Sector	Global	Multi Years
159	Kumar S. et al. [5]	2011	South Korea	Overview	LNG Sector	Global	Multi Years
160	Barclay J., Oseen-Senda K., Skrzypkowski M. [172]	2011	US	Magnetic liquefaction technology	LNG Industry	Global	Single Year
161	Hardisty P.E., Sivapalan M., Brooks P. [173]	2011	US, Australia, UK	Method and analysis	Energy Sector	National	Multi Years
162	Gangadharan P., Zanwar A., Lou H. [174]	2011	US	Aspen Plus software, comprehensive sustainability assessment, and Enhanced Inherent Safety methods	LNG Sector	National, City	Single Year
163	Haselip J., Al-Shafai N., Morse S. [175]	2010	Qatar, UK	Review and analysis	LNG Industry	City	Multi Years
164	Stougie L., Van Der Kooi H. J. [176]	2010	Netherlands	Review and analysis	Energy Sector	Global	Single Year
165	Shi G.-H. et al. [177]	2010	China	Overview on LNG	Energy Sector	National	Single Year
166	Zhang W. [178]	2010	China	Decision-making method	Energy Sector	National	Single Year
167	Tkalčič M., Špendl R. [179]	2010	Slovenia	Socio-economic impact assessment	LNG Terminal and Ship	National	Single Year
168	Boodoo C. [180]	2010	Trinidad and Tobago	Overview	Energy Sector	National	Single Year

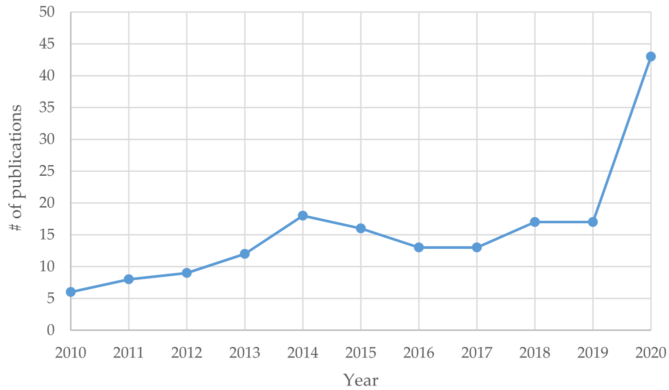

Fig. 2. Search results from SCOPUS (2010 until 2020).

take place for the main product; however, the other byproducts will be considered separately. The LNG final product is then stored in well-designed tanks and kept ready for loading into the various LNG carriers through LNG loading arms. The LNG product is then distributed overseas for the international customer based on the agreements, and regasification will be performed at the importing area for further industrial and domestic uses [181].

2.3. Research gap

Following a detailed review of the literature, it was found that many studies on the energy sources used around the world either for transportation, electricity generation, LNG transportation, etc. However, a rare number of papers cover LNG's life cycle assessment as a reliable, promising, and more environmentally friendly source of energy compared to other energy sources, and no study conducted the entire life cycle sustainability assessment from natural gas extraction until arrival to the end-user. Moreover, the economic, environmental, and social LNG impacts illustrate the better performance and less pollution to the environment significantly compared with other energy sources.

Furthermore, there is no comprehensive paper found offering or gathering the best practices related to LNG production and supply chain that covers the transportation, selecting supply option, designs of refueling station, energy security, LNG sustainability and safety, sustainable development strategy of LNG, policymakers' opportunities, and natural gas liquefaction design and optimization.

3. LNG uses in the world

3.1. Coal to gas-switch

Because burning natural gas in combined gas-fired power plants has shown to be more efficient and cleaner than burning other fossil fuels, such as coal, natural gas plays a vital role in electricity generation. Studies have found that when LNG is burned to generate energy, it releases about half the GHG emissions that coal does. When combusted in a new efficient natural gas power plant, natural gas releases 50–60% less CO_2 than a typical new coal plant. Natural gas would minimize CO2 emissions by 1200 Mt if it were used to replace all coal in power generation. The Asia Pacific has a lot of conversion potential. However, GHG emissions are a problem for the gas sector throughout its whole value chain's lifecycle. Some argue that upstream methane emissions and, in the case of LNG, the extra energy required for liquefaction reduce

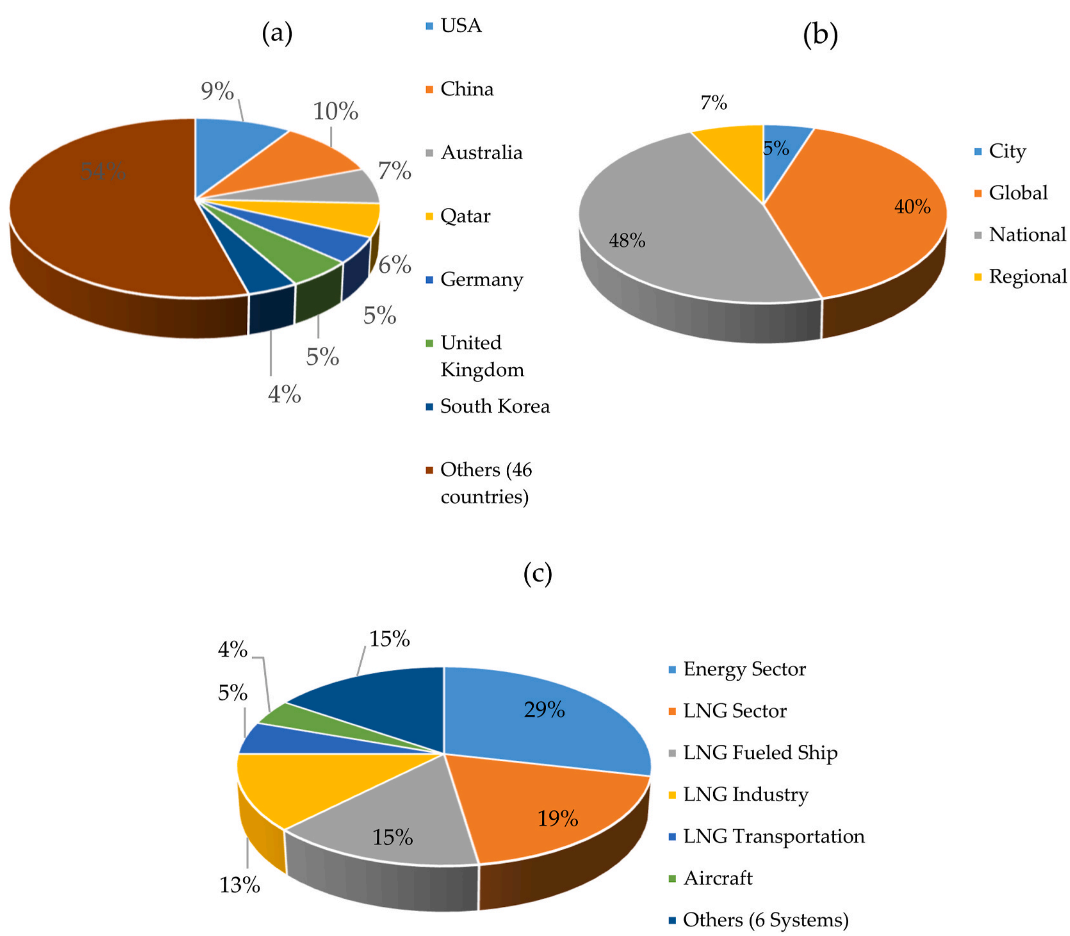

Fig. 3. Literature review analysis of nominated articles based on a) country, b) scope margin, and c) analysis performed.

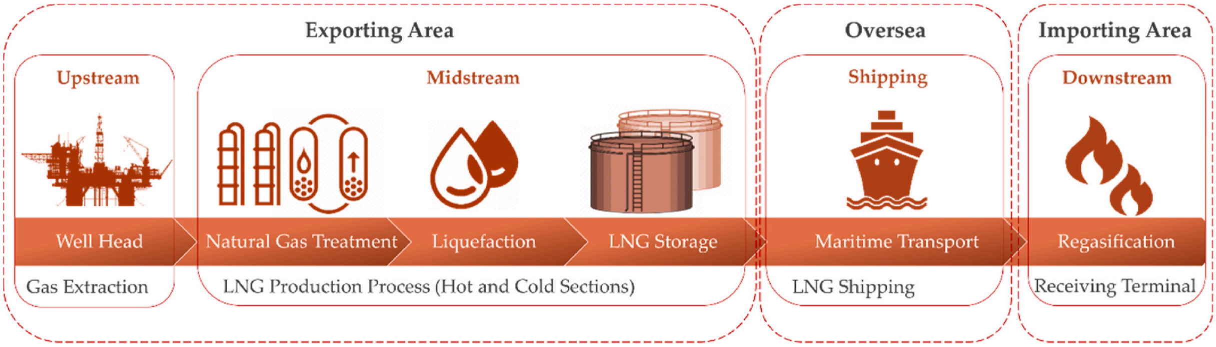

Fig. 4. LNG process chain.

or even negates gas's basic benefits [182].

Most of the world's countries have substantial reserves of natural gas. That abundance, combined with its low emissions and reliability, makes natural gas a building block of the easy power future and a cheap, and low-carbon energy preference for consumers at home and across the globe. Natural gas is used by residences for heating and cooking, the industry for manufacturing imperative merchandise as assorted as steel, scientific equipment, and fertilizer, and with the aid of grocery stores, lodges, and restaurants for heat, power, and dehumidification. Moreover, it is used by the automobile as a cleaner fuel and utilized utility to generate power as a reliable energy source with low emissions.

In addition to the numerous uses for natural gas, LNG in its liquid structure can be used in the marine and mining sectors as fuel. The beauty of LNG is that it enables herbal gas to be safely and economically transported to other countries considering the distance, bringing environmental benefits and more suitable exceptional of life. Most natural gas usage as fuel for transportation and electricity generation in addition to the heating sector, power generation, and chemical industry. The following are brief details for each use.

3.2. LNG used as a transportation fuel

Using LNG for transportation has significantly increased in various parts of the world over the past few years [183]. LNG is the most used source of energy that is categorized as a greener source of energy for powering Heavy-Duty Vehicles (HDVs) such as trucks and buses. Using LNG needs a storage facility that will ensure that low temperatures of $-162\ ^{\circ}C$ are maintained to make sure that it does not turn into gas [184, 185]. Additionally, vehicles running on LNG need to have a unique duel engine. Furthermore, their tanks should be made to match the conditions that LNG needs to be in for it to be useful in the production of energy. Such requirements have often made the use of LNG for transportation economically unsuitable.

LNG has higher thermal efficiency as compared to the other available alternatives, which allow meeting the energy needs with a reduced quantity of fossil fuel. Higher thermal efficiency is a desirable factor for energy-intensive industries. It also has lower specific energy as compared to other options such as oil and coal. Therefore, there is a possibility that technologies and innovations might make the use of LNG more energy efficient in the future. Many academics have focused on the use of LNG as oceanic energy because of the sulfur-based emission limits that the International Maritime Organization (IMO) introduced. The limits were aimed at reducing the extent to which the operation of ships leads to the emission of GHG [158,186].

3.3. Electricity production

LNG can also be used in the production of electricity. Using LNG's cryogenic energy in the production of electricity has been addressed in various studies [92–95]. Some studies suggest that the introduction of a Rankine and Braytone combination cycle, with CO_2 as a working fluid. Further heating source is needed and can be obtained by burning CH_4 in the presence of oxygen leading to the production of gases with large quantities of carbon dioxide. When heat is transmitted to the LNG that is undergoing evaporation, the resultant process is irreversible [187–190]. LNG has turned out to be a primary source of transportation energy in Japan. Such a development has led to a significant reduction in carbon emission. The same benefits could be achieved if LNG were used in the production of electricity.

3.4. Other domestic uses of LNG

There are many other uses of natural gas. It is used for houses and commercial buildings. It can be used for heating, air conditioning, food cooking, lighting, etc. LNG is also applicable in the production of fertilizers and increasing in popularity as far as household activities such as cooking and heating are concerned [191–194]. Furthermore, it is used as an industrial utility for heating, firing, flare systems, steam generation, and cooling in some cryogenic industries [195].

3.4.1. Heating use

Residential and commercial uses of natural gas account for more than a third of total consumption in the US, as gas is utilized in buildings for space and water heating as well as cooking. In 2013, natural gas was used to heat around half of all US residences, and 70% of all new homes were built using gas heating systems. Home furnaces can achieve an efficiency of more than 90%. Building efficiency improvements are typically regarded as the most cost-effective technique to minimize natural gas consumption [196].

3.4.2. Chemical industry use

According to studies that have recently been undertaken, LNG can be used for feedstock for chemical, power, fertilizer [197], and petrochemical plants. Huge business organizations using a large amount of energy are gradually opting for LNG at the expense of coal. LNG can potentially replace naphtha as a preferred source of energy for industries [4].

Chemical techniques based on methane activation are becoming more economically viable as methane is the principal component in LNG. Methane is currently converted into bulk chemicals in the industry via an indirect process. Methane is converted to syngas at a high temperature, and the syngas is then utilized to manufacture a variety of hydrocarbons or alcohols using various catalysts types. Lowering the reaction temperature for the transformation of methane into chemicals would be beneficial because the process is energy-intensive and expensive. The direct conversion of methane to derivatives is feasible, and methanol is one of the final products from the syngas reaction [198].

4. Lessons learned and recommendations

From the review, there are many lessons learned in addition to the other studies and reviews from the literature. This review highlights and combines the most relevant lessons of LNG as sustainable fuel to allow readers, researchers, and interested parties in the LNG sector to understand how suitable LNG is as an energy source. Furthermore, recommendations are based on this review paper and other gaps and areas of concern. The following are the main lesson learned from several perspectives and disciplines.

4.1. Challenges for using LNG as a transportation fuel

Despite the increase in the use of LNG for powering automobile, several numbers of challenges that hinder the utilization of LNG in NGVs globally. These challenges include [4]:

1. The relatively low number of worldwide regulations for NGV leads to various gaps in global standards. The lack of global regulations and standards is an obstacle to the production and use of LNG equipment.
2. Countries have non-uniform policies and national interests about energy for transportation and the legal passage of either pipeline or sea routes within each country's boundaries. This is a factor that limits the improvement of different types of NGVs in countries where the LNG markets would be strong.
3. Producers of HDVs and machines are yet to adapt their products to use LNG. The LNG-powered HDVs and machines that are available in the market are few. This is a factor that limits the increase in reliance on LNG fuel.
4. The systems installed in HDVs, and machines operate differently, especially with the need for LNG to be availed in varying pressures. This is an implication that the development of LNG fueling stations is a complex endeavor.
5. The inconsistency of the quality of LNG and biogas fuels is a concern that needs to be addressed. Different importers would request various product specifications and purities of the final LNG product and biogas that may impact the process's consistency and maximize the production rate.

For LNG to be normalized as fuel for automobiles, there is a need to establish global regulations for NGV and the development of more infrastructure [4].

Aseel et al. (2021) discovered that, although traveling the same distance and utilizing the same fuel type, the Q-Max vessel emits more carbon emissions than the Q-Flex. Because of the relevant carbon content in the fuel, the kind of fuel has a major impact on emission values. When comparing the two conventional fleets, the one that is just running on LNG only emits fewer emissions than the one that is running on dual-mode [199]. Also, the associated human health impact is relatively linked with air emissions. Accordingly, a decrease in air emissions leads to less human health impact [200].

4.2. Selecting the LNG supply option

One of the primary obstacles that are associated with the use of LNG is the determination of the most appropriate exploration terminals in different countries. It is appropriate for the most accurate decision support model to be used as far as this type of decision-making is concerned. The options that involve the optimization of green logistics should always be considered. Kumar et al. [201], researched various multiple-criteria decision-making (MCDM) techniques. The work focused on renewable energy applications and prospects in this area. Promethee II, Weighted Sum Model, Weighted Product Model, ELECTRE, TOPSIS, MAUT, and AHP are the main methods that can be used for the evaluation of all the options available. The methods could be different from one potential supplier to another based on various factors such as supply economics, the sustainability of the supply and demand network, and the possibility of supplies being available in the future. The process of evaluating the available alternatives should entail ranking the preferred scenarios. This approach assesses future consortiums possible [202,203].

4.3. Designs of LNG refueling stations

There is a possibility that LNG can be used in the place of diesel in HDVs, trains, and ships. However, the release of methane into the atmosphere due to LNG usage is a major environmental concern. Methane is a greater threat to the environment than CO_2 as far as climate change is concerned. Storage, transportation, and distribution of LNG contributed to the emission of methane. Some of the constraints that shall be highlighted and considered while designing LNG fueling stations include the management of Boil-off Gas (BOG), vehicle fueling flexibility, and the minimization of the heat transfer between dispensers and the storage tanks. Most of the existing LNG fueling stations lack BOG management systems [204–207]. Thousands of LNG barrels are delivered by road in the US for different clients to meet the demand for public cars. The delivery is made via small-scale LNG filling stations, which allow better flexibility and reliability [208].

4.4. Energy security of LNG

The difference between the pursuit of stability and stability of energy supply does not affect the energy security that is associated with the use of LNG. Researches over the past 20 years have furtherly provided a new provision to the issue of energy security. The added dimensions include environmental and technological dimensions. Therefore, the inclusion of new dimensions is a sign of national interest in making sure that there is energy security [209–211].

Energy security management is essential as energy trading in the world is increasing across countries and regions. For that, long-term agreements and measures shall exist in addition to reliable and accurate strategic and business planning.

4.5. Sustainability and safety

Sustainability has three primary pillars: financial stability, social protection, and environmental responsibility. Therefore, safety is an important starting point when it comes to the operationalization of sustainability [212]. Experts and industries often acknowledge the link between sustainability and safety. However, this link has also been disregarded at operational and strategic levels. The major reason for the link being disregarded is that there is a lack of safety culture. There seems to be a void in terms of safety culture globally. It has not developed to the levels that it is expected to have grown by now. Safety is only considered to be necessary after an accident has taken place. Risk management and minimization can have many benefits for the organization. The absence of the safety culture has led to a situation where the benefits associated with sustainability and safety can hardly be realized. There is a need for highly structured empirical research to be undertaken to strengthen the link between sustainability and safety at operational and strategic levels [212].

4.6. Sustainable development strategy of LNG

There are new factors that are of influence the production, demand, and importation of natural gas globally. Some of the suggestions on strategic actions that can be taken to encourage the usage of natural gas in the future include:

1. The expedition of the production, storing capability, and pipeline carriage volume. This is a way through which the domestic production of LNG can be improved. Furthermore, there should be an

enhanced focus on growing the production of unconventional gas. An excellent example of unconventional gas is marine shale gas. This strategy should take into consideration factors such as storage and environmental circumstances to provide a guarantee for the LNG demand [213].
2. The analysis of the traits of gas and oil consumption should be undertaken to set up a timely warming system for the safety of gas and oil consumption based on historical data and predictions due to any changes in the claim for both natural gas and oil in the future. The stability of both demand and supply is important to the degree of extending that the maintenance of business accomplishments in the country is apprehensive [214].
3. There is a need for breakthroughs in industrial technologies for cleaning coal to be advanced, especially in countries with large supplies of coal and scarcity of natural gas. As far as the historical law of energy development is concerned, natural gas can be considered the "bridge" for changing from the use of fossil fuels to using renewable energy sources. The LCA of the various sources of energy should be part of any perspective that is used for strategic development [214].
4. Set the strategy towards the reduction of GHG emissions, CO2 capture and storage, minimum flaring, process optimization, waste heat recovery, restriction on fugitive methane emissions, and the treated industrial water reuse and recovery [215].

4.7. Policymakers' opportunities

Policies are vital in the promotion of the development of the LNG economy and services. Herein are some areas that are worth focusing on:

1. Organizations are encouraged to come up with systems and procedures for slowly improving their energy efficiency by following the ISO 50001 energy management system standards [216].
2. Studies can look into more details on the research gaps, especially energy efficiency [217]. Technology and innovation processes are among the hottest research topics concerning energy efficiency [218, 219].
3. The provision of financial incentives for those of buy LNG-powered vehicles is an alternative that has been discussed. This is an approach necessitated by the greater fee of LNG-powered automobiles than those powered by diesel [220]. Most commercial users of HDVs have been sensitive to the acquisition cost of vehicles because they are considered assets whose value depreciates. Therefore, financial incentives can be a way of promoting the purchase of LNG-powered vehicles [103].
4. The production of LNG transit buses should be prioritized in regions where natural gas is available in abundance. Notably, the preference of governments would have a considerable impact on the development of LNG transit buses. LNG buses offer lower costs and higher technological advancements than green options such as fuel cell buses, electric buses, and hybrid electric buses [103].
5. There should be an application of the emission prices control approach. In this approach, there are various strategies used, including [221]:
   - Charges "en route". This is a cost-effective program that has been implemented in many sectors to influence the route option for energy optimization and lower emissions.
   - Environmental taxes and fees. This program is enforced by environmental authorities to apply penalties for excess pollution, natural resource misusing, and any environmental damage which can degrade the baseline environment
   - Environmentally enhanced fairway or port dues. This concept is cost-related to the environmental impact, such as air emissions caused by idle ships (e.g., waiting, parking, etc.).
6. The emission quantity control approach involves using limits, and the rights to emit, which can be traded, can also be applied. This approach includes [221,222]:
   - Credit programs. This program will provide an allowable limit for each company on the total amount of GHG emissions that must not be exceeded.
   - Cap-and-trade programs. In case the company has consumed its credit, it can purchase other company's credit under a secured trading system.
   - Benchmarking programs. In this case, the company is benchmarking its system and performance with other similar sectors. This evaluation focuses on energy efficiency, energy optimization, pollution reduction, and continual improvement.
7. Subsidies can also motivate entities that have invested in decarbonization research towards implementation [221].
8. Providing enough refueling stations that can be easily accessed is important for increasing the use of LNG for transportation. New regulations for controlling and mitigating risks such as fugitive emission and BOGs are strongly encouraged. Most importantly, overall vehicle efficiency needs to be improved for the benefits that are linked to the use of LNG to be fully realized. Suppose the efficiency is not improved by the year 2024; in that case, policymakers should opt for fixing the fuel duty gap and raising the duty on natural gas as a way of reflecting the expenses related to technology [223].
9. Research needs to be undertaken to reduce the quantity of methane released into the air because of the expected lifecycle of the LNG industry. Most methane is released during the transportation of LNG through pipeline systems. Other impacts that LNG-powered vehicles have, such as the release of NOx and PM require further investigation. More focus should be on the impact and probable solution of the impacts in densely populated areas [223].

4.8. Natural gas liquefaction design and optimization of future research directions

The process that requires the most volume of energy in the life cycle of natural gas is the liquefaction process. This is the reason why there has been an increase in the interest in the scheme and optimization of liquefaction industries. The minimization of costs and energy used for liquefaction has been of interest to researchers. The growth of the LNG market and technological advancement has led to an increase in the extent to which designers are focused on small-scale markets. The anticipated trend is likely to come with an increase in the optimization of the liquefaction process. Optimization goals can be met by Ref. [224]:

- Consideration of the process optimization, design of natural gas liquefaction, and integration before starting any project.
- Natural Gas Liquid (NGL) and LNG plants should be integrated to avoid duplication and provide a synergy of equipment. This is an implication that trends relating to optimization are likely to include revenue streams associated with processing plants.
- The design and optimization of natural gas should consider the environmental impact and other factors such as operational and capital costs.
- Optimization should be carried out with the intent of responding to ambient and feed fluctuations.

5. Conclusions and future work

There are two sides to using LNG. One side is that it leads to a substantial reduction in the total of GHGs that are released into the air. This is among the primary goals of sustainable development. Additionally, the availability of LNG and the increase in the interest in its production are factors that can be considered.

However, before LNG can reach its developmental potentials, some concerns have to be addressed. Among the concerns that need to be addressed is the excessive release of methane into the atmosphere. Methane is considered to be of more harm to the environment than CO_2 and NO_x. Therefore, it is appropriate to put measures in place to ensure that the risks of environmental pollution are mitigated.

There is also a question of the cost of using LNG equipment compared to the costs of equipment that run on diesel. Notably, economic sustainability is another dimension of sustainable development. Governments need to level the groups for LNG if in any case, it is to be used as the lowest environmental impact among non-renewable energy sources in the course of seeking sustainable development. In the absence of government intervention, there is likely to be a failure in the use of LNG because the diesel equipment and vehicles are more affordable as compared to the LNG ones. LNG vehicles and equipment need to be financially viable for the people using them on a large scale.

To better understand the above, this research accompanied a comprehensive universal literature overview concentrating on the sustainability development study of the LNG industry. It emphasized the key gaps in the literature. The review focused on 168 studies that have been studied, and the bibliometric analyses outcomes are the number of publications per year, country, scope margin, and analysis theory of each study. Upon further analysis, the triple bottom line impacts world LNG commerce and associated services require close attention to understand the triple bottom line sustainability impacts considering all the stages of the LNG sector. The authors also propose to conduct a global multiregional life cycle sustainability assessment which can be also ensure safe, healthy, secured energy use and marketing around the world.

Governments should also act on the issue of the low number of LNG fueling stations by subsiding their development. Notably, various factors make putting up LNG filling stations problematic. First is the issue of transportation that has been considered among the major concerns about the use of LNG. Second, the issue of having the right storage facility because of the nature of LNG to ensure the process of safety as far as energy production is concerned. Therefore, the relevant stakeholders need to work with the government to sort out the barriers and make favorable provisions for future implementation. Businesses in the marine sector should also work closely with the government to make sure that the use of LNG is practically achieved. It is projected that there will be an increase in the number of ships using alternative energy sources such as LNG because of the 0.5% sulfur cap targeted for marine fuels starting in 2020. The usage of LNG as an option to achieve sustainable development is only possible if there are changes to address all the challenges associated with its use.

Future work aims to study the triple bottom line for world LNG production sustainability assessment, including import and export. The authors moreover recommend covering the following areas of the gap which were not fully covered in LNG production and supply chain literature:

- LCA of the carbon footprint for major LNG importers and exporters. As LNG's future demand increases, importers must keep evaluating the LNG option, monitor the improvement of CO_2 reduction, and optimize energy usage. On the other hand, the exporters shall ensure the utilization of the best available control technologies during the LNG production operations and shipping to target the lowest emissions throughout LNG manufacturing.
- LCA of air emissions and human health impact of LNG production and distribution networks. This is to ensure the human health impact elimination by controlling the emissions either before or after the process and transportation units. Human health is one of the main core values of any business.
- A global multiregional life cycle sustainability assessment of LNG production, including its supply chains. The supply chain is indirectly affecting the triple bottom line sustainability performance based on several requirements of multiregional policies.
- Uncertainty-based life cycle sustainability assessment model of LNG supply chains in which the major contributors to the economic, environmental, and social impacts can be addressed. This step is valuable for sorting out and focusing deeply on the bad actors and evaluating the impact reduction opportunities and their sustainability.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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