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How sustainable is liquefied natural gas supply chain? An integrated life cycle sustainability assessment model

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ABSTRACT

Integrating sustainability into the distribution network process is a significant problem for any industry hoping to prosper or survive in today's fast-paced environment. Since gas is one of the world's most important fuel sources, sustainability is more important for the gas industry. While such environmental and economic effects have been extensively researched in the literature, there is little emphasis on the full social sustainability of natural gas production and supply chains in terms of the triple bottom line. This research aims to perform the first hybrid life cycle sustainability assessment (LCSA) of liquefied natural gas and evaluate its performance from the natural gas extraction stage to LNG regasification after delivery through maritime transport carriers. LCSA is used for estimating the social, economic, and environmental impacts of processes, and our life cycle model included the multi-region input–output analysis, Aspen HYSYS, and LNG maritime transport operations sustainability assessment tools. The results spot the light on the most contributors of CO_2-eq emission. It is found that LNG loading (export terminal) is the source that generated the highest carbon footprint, followed by the MDEA sweetening unit with the contribution of 40% and 24%, respectively. Socially, around 73% of human health impact comes from SRU and TGTU units which are the most contributors to the particulate matter emission. Based on the interpretation of life cycle results, the environmental indicators show better performance in the pre-separation unit and LNG receiving terminal representing a sustainability factor equal to 1. In terms of social and economic impacts, the natural gas extraction stage presents the best performance among all other stages, with a sustainability factor equal to 1. Based on this study's findings, an integrated framework model is proposed. Various suggestions for sustainability strategies and policies that consider business sustainability and geopolitics risk are presented.

Introduction

Natural gas (NG) has undergone tremendous transformations all around the world. Due to industry changes, heavy investment in supply chains is required to efficiently reach the global supply of liquefied natural gas (LNG). LNG trading is undergoing a rapid transformation from regional, bilateral trade flows to local and eventually to the global economy. Many countries that rely on coal for electricity generation have increased their demand for NG to lessen the causes of environmental challenges. NG customers assessed that LNG is a viable and promising alternative to coal in terms of restoring coal and meeting energy requirements, including power generation [1].

The global LNG sector has seen fast expansion, with commerce reaching a new high of 355 million tons in 2019 (up 13% from 2018) [2]. LNG exports are expected to continue to expand, with predicted worldwide demand estimates ranging from 450 to 700 million tons per annum by 2040. At the same time, considerable reductions in greenhouse gas (GHG) emissions must be reduced to accomplish the Paris Agreement's goal of maintaining the greenhouse effect far below 2 degrees Celsius.

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Environmental, social and economic impacts

The whole supply of NG is reliant on the distribution and pipeline networks that connect the demand and supply fields. Manufacturers of LNG are currently focusing on more advanced liquefaction and regasification processes in order to comply with a more ecologically acceptable working environment [3]. The conversion of NG through the various stages of the LNG production chain involves the usage of a significant amount of fuel, which is mostly derived from the NG feed. The combustion of the fuel produces a considerable amount of carbon dioxide (CO_2) and other pollutants such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x). As long as LNG production continues, the expectation of industrial air pollutants being ventilated into the atmosphere still exists. To verify the economics of LNG management and supply networks and evaluate the LNG product's sustainability, comprehensive accounting and tracking of the midpoint air pollution footprint is required [4]. Furthermore, the LNG sector's waste consumption and land usage area are critical resources for assessing the environmental impact of any similar industry.

It is hard to deny that the industrial activity-to-trade revolution is assisting countries in growing and meeting numerous social status requirements, such as job creation, alleviating poverty, labor standards, gender equality, and exceptional access to health care and education. On the other hand, industrial methods may have disastrous impacts on the environment, resulting in numerous serious and international challenges such as global warming, natural resource loss, water and air pollution, and biological degradation. The increase in air pollution is one of the most serious impacts of LNG industrial expansion. Humans, plants, and the ecosystem are all harmed in different ways by air pollution and resource usage. Exposure to a specific subject matter raises the risk of lung cancer and cardiovascular disease in people. Ground-level ozone, eutrophication, and acidification are all effects of air pollution on ecosystems [5]. More societal ramifications are associated with employment, salary and benefits, total taxation and other expenses, and total man-hours completed for a certain activity or process chain.

Since the Fukushima nuclear disaster in 2011, the need for LNG, which is a preferred mode of transport for offshore NG shipments, has risen rapidly [6]. Bjørndal et al. (2010) estimated that the LNG production line represents 30–40% of the cost in the LNG value chain [7]. It has been recommended that pressurized LNG (PLNG) be used as a solution to the issue of high LNG manufacturing costs. According to the Oxford Center for Energy Studies research, the cost analysis per LNG plant area (LNG liquefaction facility) can be separated into various cost variables [8]. Pre-operational economic factors include the project's magnitude and sophistication and maritime facilities such as jetties [9].

Capital expenditure (CAPEX) for regasification plants generally includes costs for vessel drydock, storage vessels, regasification systems, send-out pipelines, and metering of new facilities [10]. As a result, this valuation chain-link exposes the cost considerations associated with the contact between LNG ships and onshore facilities. Although CAPEX makes up a significant amount of a project's budget, it's also critical to assess overall operational expenditure (OPEX) across the entire distribution network to identify possible investment risks. Based on PwC data and a report published in the journal of Industrial & Engineering Chemistry Research (I&EC) [11], the operational costs for a general value chain are as follows. Upstream development accounts for 10–11% of costs, refrigeration, and liquefaction for 40–42% of costs, shipping and transportation for 20–30% of costs, and regasification and distribution for 20–27% of costs.

The structure of this research article is as follows; Section 1 provides an overview of LNG, the LNG process chain, and the LCSA. Section 2 represents a general review of literature on LCSA, followed by a description of the LNG LCSA concept, including all incorporated processes. The proposed LCSA is presented with correlations to other investigations on the same topic in Section 3. Section 4 presents the findings used to create an integrated framework that connects all three sustainability components, which will benefit academics and policymakers alike. The findings are used to develop suggestions that industries might use to enhance operational sustainability. Section 5 includes the conclusion and highlights opportunities for future research work.

Literature review

In this section, a literature review focused on the LNG process chain with details on the process description and parameters, the sustainability pillars and their integration, and the motivation, novelty, and objectives of this research. The authors decided to design the process and select the LNG maritime transport carrier close to the Qatar case. The case of Qatar was chosen according to global statistics showing that Qatar is one of the world's most significant producers of LNG [12].

LNG process chain

Fig. 1 depicts a flow block schematic of the LNG process chain used in this study. The crude NG is extracted in the offshore platforms and transferred using pipelines to onshore facilities. The onshore facilities have two main sections concerned with LNG production: cold and hot [13]. The hot section is divided into the NG receiving unit from the well, NG pre-separation, acid gas removal (AGR), Sulfur recovery unit (SRU), and drying units. Whereas, the cold section comprises Natural Gas Liquids (NGL) recovery and fractionation, Helium Extraction (HeX), gas liquefaction, and Nitrogen Removal (NR) units. Both sections require associated infrastructure and electrical power. LNG is transported to an importing terminal through maritime shipping following the liquefaction process, where it is regasified and distributed for use [13].

The LNG technique consists of a set of units, each of which is described briefly in this section. Hydrocarbons are the first element found in NG, along with some impurities. The liquids from the NG extracted at the well must be transferred to a downstream processing plant for recovery. The sour water and condensate are removed from the input sour NG in the pre-separation unit. The sweetening unit then takes the separated sour NG and removes undesired components such as H_2S and CO_2, also known as acid gases, benzene, methylene, xylene (BTX), and Mercaptans. Streams from the sweetening unit are directed towards the SRUs, which produce elemental Sulfur allotropes from H_2S. Likewise, the burning of acid gas results in the formation of SO_x.

Integrated sustainability assessment

Environmental life cycle assessment

The life cycle assessment (LCA) method aims to assess the product's impact from environmental perspectives, such as pollution, resource consumption, and waste. For instance, Aberilla et al. (2020) established an integrated environmental and economic assessment model in order to provide water and energy applications with the most sustainability options that satisfy the community's current and future needs [14]. Barnett [15] studied the environmental implications of LNG liquefaction, regasification, and shipping operations. Tamura et al. [16] focused on carbon footprints as well as other atmospheric pollutants during LNG production, where the study considered these pollutants during the delivery of LNG. In Western Australia, Biswas et al. (2013) examined carbon emissions throughout LNG production and supply chain, considering Australia's LNG exports to customers, such as China [17].

Compared to the other processes, such as separation and exploration, the proportion of carbon footprint emitted during the LNG delivery process is significantly lower. For example, Jaramillo et al. [18] estimated emissions from LNG-based electricity generation, linking Sulfur, nitrogen oxides, and greenhouse emissions to the life cycle of the gas, especially those originating from sources of energy. The study conducted a life cycle based comparison of air pollutants for electricity generation from various energy sources such as coal, domestic NG, LNG,

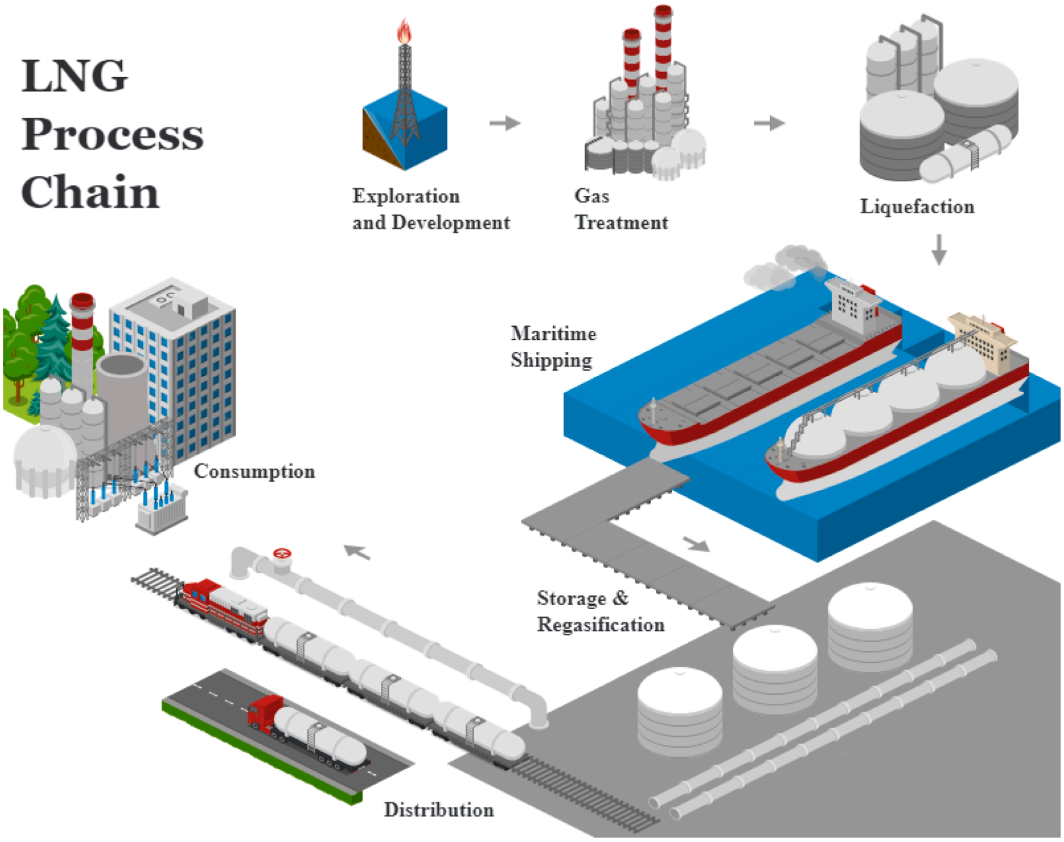

Fig. 1. LNG process chain.

and synthetic NG.

Social life cycle assessment

Social life cycle assessment (SLCA) is a method followed to adequately assess and evaluate manufactured products' beneficial and adverse impacts on society. Social concerns have been shown to substantially impact the successful deployment of various technologies and systems. For instance, when analyzing emerging technologies, Lehmann et al. (2013) recognized the importance of addressing the social determinants in the early stages of technological innovation as well as in the decision-making phase of businesses. The authors investigated how the UNEP/SETAC recommended SLCA approach can be used to study the social aspects of new technologies [19].

The current external context and circumstance, such as policy initiatives, affect the integration of social aspects in the technology development cycle, such as the implications on employees, community, and society, as well as the overall productivity of an organization and their intrinsic behavior in selecting a technology [20,21]. By legislating the eradication of specific environmental impacts and supporting the development and deployment of improved technology, policymakers can contribute to creating a sustainable regulatory environment [22]. International, regional, and state climate regulations, for example, have attempted to regulate GHG emissions, compelling firms to change their activities in order to reduce pollution [23]. Additionally, by offering incentives or fines, environmental regulations can encourage the growth and acceptance of innovative technology. For instance, given the carbon tax imposed by the State of Alberta on large emitters through the Climate Crisis and Emissions Monitoring Fund, the Emissions Reduction Alberta funding supports the momentum and increased capacity of technological developments that contribute to a lower carbon industry [24]. In addition, policymakers can support the development of ecologically superior technologies that reduce environmental repercussions by promoting appropriate social conditions that facilitate the deployment of these innovations.

Life cycle costing

The abundance of fossil fuels is currently one of the key drivers for being the most utilized energy source. Fossil fuels satisfy around 85% of the world's commercial energy demand. As a result, it has the potential to be a catalyst for a country's long-term development. There are few extensive studies on the LNG distribution network Life Cycle Costing (LCC) and economics due to the system's sophistication and insufficient information. For example, Jokinen et al. suggested a computational formula to aid in creating LNG supply chains. However, their central emphasis was on cutting gasoline procurement prices, with only the regasification-to-end-users segment of the chain receiving attention [25]. Raj et al. (2016) research focused on the comprehensive GHG emissions and delivery costs of Canadian LNG to China from well to wire; nevertheless, the study did not account for the chain's strong properties [26].

Sapkota et al. (2018) investigated the NG supply chain's techno-economic and life cycle GHG emissions from Canadian manufacturing locations to European receivers. Nonetheless, their study relied on estimations and ranges rather than detailed equipment modeling and emission measurement [27]. Kim et al. proposed a novel LNG distribution network that relied on liquid nitrogen (LN_2) for liquefaction, and they looked at the supply chain's LCC and profit. Despite this, they did not include NG preprocessing or any other important processing components in their study [28]. The cost of a pressurized LNG distribution chain, which comprised maritime development, transportation, and consumption, was studied by Lee et al. [29]. They also looked at the chain's LCC to see the economic feasibility. The focus of the investigation was on the hydrolysis reaction, which is the most significant step in non-baseload LNG networks.

Life cycle sustainability assessment

The scope of traditional LCA has been expanded from considering environmental consequences alone to the integration of the three dimensions of sustainability (environmental, economic, and social). Furthermore, a more comprehensive and long-term answer for life cycle analysis can be acquired by combining the three aspects of sustainability, namely environmental, economic feasibility, and social for any product. The product life cycle assessment (PLCA) is a tool for determining the influence of a manufacturing distribution network on sustainability (of varying lengths). The PLCA model was used to investigate environmental damage and remediation costs. PLCA later created the concept of SLCA to explore the consequences of the production process on social organization [30]. The LCA's definition has been expanded to include the three elements of sustainability (planet, profit, and people). People refer to the societal dimension, Planet to the ecological extent, and Profit to the economic aspect [31]. At the UN Sustainable Development Summit in South Africa, the 3Ps were renamed People, Planet, and Prosperity. The contrast between profitability and prosperity highlights how economic evaluation incorporates more than business aims. More LCA variables help determine whether commodities, operations, and services progress toward sustainable development and allow proactive decisions [32].

From the start, it was evident that a comprehensive assessment of sustainable development would include two additional factors: monetary and social [33]. Environmental LCA for ecological implications, economic performance for measuring the LCC, and SLCA for analyzing social effects are the methods used to examine the three principles of sustainability. LCSA is the outcome of merging the three strategies mentioned above. LCSA provides a holistic view of supply network sustainability to policymakers and decision-makers, increasing their support [34]. Today, the bulk of LCSA publications consist of literature reviews, operational improvements, and comments, suggesting that LCSA's conceptual base is still being formed [35]. Despite the fact that the LCSA approach is still in its inception, many scholars have contributed to it [36–38]. Their research has used it to investigate the potential of self-sufficiency in all three components: environmental, economic, and social.

Elhuni and Ahmad [36] presented key performance indicators (KPIs) for evaluating sustainable manufacturing in Libya's oil and gas industry. The performance indicators for all three dimensions of sustainability were assessed, although there was no framework in place to evaluate sustainable output. Hannouf and Assefa [37] provided a systematic method for performing an LCSA of polyethylene in Canada, outlining difficulties in defining the interrelationships between the three pillars of sustainable development (LCA, LCC, and SLCA). Several of the authors discussed above stated that the absence of a relationship between the three dimensions of sustainability was a significant study gap [38,39]. There was also a lack of evidence of the interaction of three sustainability characteristics in the gas industry. According to Costa et al. [35], the bulk of the LCSA research articles were from countries like the United States and Germany. Case studies are required for all industries and sectors to raise awareness of developing challenges and develop techniques for adopting LCSA.

Evidently, the full breadth of sustainability has not been considered in previous LNG studies, as concluded from the literature review assessment on LCSA. As such, this study is novel as it is the first to incorporate all aspects of sustainability within the LNG industry. The emphasis of this research is on implementing the LCSA in the LNG processing chain. Using data from manufacturing, use, input materials requirements, and emissions during a given time period, an LCA, LCC, and SLCA are undertaken. An effort has been made to combine the aspects of sustainable development through a theoretical foundation. Sustainability improvement initiatives and strategic framework proposals are also provided in order to attain sustainability objectives. The study has some assumptions, such as a lack of environmental LCA data, numerous overhead charges, and a few cultural subcategories. Secondary data are acquired from databases, resource integration assessments and annual reports, and research articles when primary information is not available.

Motivation, novelty, and objectives

The conception of sustainable development is executed at the policy level. Still, it must be extended in the business context and encourage evidence informed decision-making connecting the two levels. Given this, the oil and gas industries have integrated sustainability into their growth maps due to more conscious purchasers' boosted need for sustainably manufactured goods. Moreover, corresponding to the Global Reporting Initiative (GRI) guidelines [40], the gas industry must identify and disclose the substantial consequences of its many processes on the environment and various stakeholders from a sustainable development standpoint. The progress in the direction of sustainability necessitates improving the approaches for evaluating the life cycle and aiming for sustainable products [41]. Aside from environmental preservation, the approach also includes economic and social safeguards. Accordingly, this research framework of LCSA was established as it combines environmental protection, economic outlook, and social equity. The LCSA model is the brightest and offers the highest level of assessment among the sustainable assessment methods [42].

The primary aim of this study is to examine and identify the LNG product's sustainability in relation to the LNG value chain, which includes natural gas extraction, treatment, liquefaction, maritime transport, and regasification at receiving ports. The approximate air pollution footprint is used to obtain the endpoint effect on human health based on ReCiPe 2016 characterization factors. The objectives of this research are achieved using numerous quantification technologies such as the EXIOBASE multi-regional input–output (MRIO) database, Aspen HYSYS [43], and LNG Maritime Transport Operations Sustainability Assessment tools [44]. Furthermore, data from the Aspen HYSYS are used for LCC assessment. This hybrid model is then used to build the principal LCSA for LNG businesses.

This study is motivated by the need to assess LNG within sustainability pillars encompassing each stage of the LNG value chain, considering the global energy that strives towards sustainability by supporting gas as an energy transition fuel followed by integrating renewable energy sources. In this regard, a functional and new model for the LNG value chain has been developed in this study to assess LNG's long-term viability. The proposed model considers environmental, social, and economic assessments. The followings present the main objectives:

- Introducing a novel system for calculating the hybrid LCSA of LNG processing and distribution.
- Developing and implementing a hybrid LCSA model that incorporates MRIO models, Aspen HYSYS simulation tool, LNG Maritime Transport Operations Sustainability Assessment tool, and data from a variety of sources and domains.
- Developing a sustainable impact assessment tool that can be used by a variety of gas and oil process-related professions.
- Developing the basis for evaluating the holistic sustainability of the LNG value chain considering both processing and shipping stages.

Materials & method

Research flow chart

According to UNEP/SETAC standards, the approach for analyzing the LNG LCSA involves four steps: LCSA purpose and range, evaluation methods, impact analysis, and LCSA interpretation (see Fig. 2). LCSA is the result of combining three life cycle characteristics: LCA, LCC, and SLCA. LCA is the only one of these that is ISO-14040–44 certified. Further research and clarity on the technique of the LCC and SLCA tools

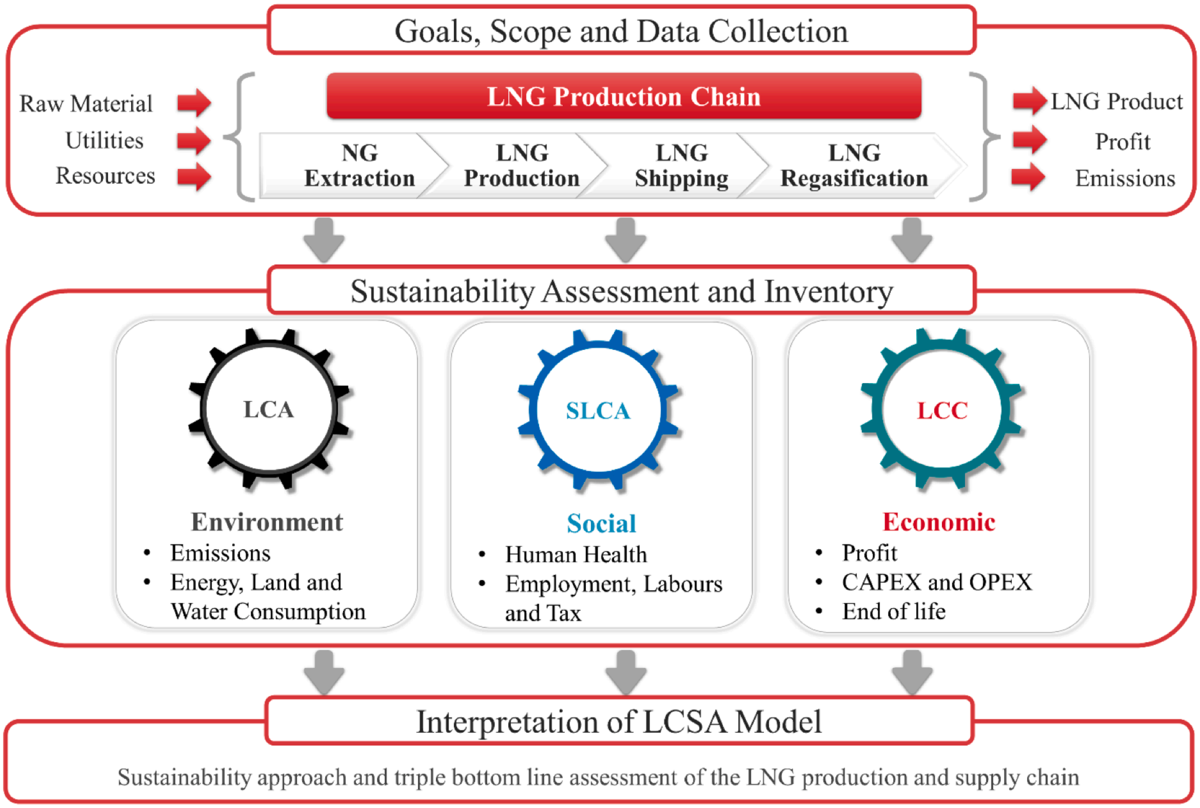

Fig. 2. Research method.

are required [38]. The following are the steps involved in LCSA:

LCSA goal and scope

The research's purpose is to conduct an LNG LCSA and evaluate its performance from start to end or from the extraction of raw materials to final LNG dispatch from holding and regasification. One metric ton (MT) of LNG generated was utilized as the functional unit for the LCA and LCC assessments. Because empirical information is recorded for SLCA and subsequently translated into quantitative data for evaluation, there is no need for a fundamental structure; nonetheless, UNEP/SETAC advice states that a primary structure should be chosen for conducting SLCA. The factor chosen was one MT of LNG. According to the UNEP/SETAC report, "establishing a base structure for SLCA is as important as establishing a fundamental structure for LCA because it is the offset for establishing a product line" [45].

Table 1 presents some assumptions and constraints in the LNG process that were considered in this simulation to comply with the environmental protection requirements, minimize environmental pollution and apply the best operational practices:

Inventory analysis

For the assessment, a life cycle inventory (LCI) is generated for every phase of the LNG processing chain. Qatar is used as a case study, and Qatar-United Kingdom trade is the case selected for LNG trade and shipping. To achieve this goal, consider the LNG process chain domain, which is previously established as the estimation's functional and boundary unit system. NG extraction from offshore to onshore, gas processing, liquefaction and LNG storage in acquiring stations, maritime product transport, and regasification are all part of the process chain. Second, the sustainability indicators that must be recognized, showing environmental, social, and economic factors, are briefly outlined in Table 2. The MRIO sector used for the upstream unit is namely natural gas and services related to natural gas extraction, excluding surveying.

Finally, for each life cycle stage, the environmental assessment life cycle data connected with each unit's processes are collected. The data are extracted from a variety of places, including the LNG Marine Transport Operations Sustainability Assessment tool, Aspen HYSYS, oil and gas yearly sustainability reports, and the MRIO database. The human health impact endpoint is derived from [43]. Finally, the functional unit will be defined as one MT of LNG output.

Impact assessment tools

MRIO database and analysis

The Economic Input-Output (EIO) criterion is an essential factor in the LCA research's industrial ecology toolkit. Jeswani et al. (2010) stress the necessity of combining input–output analysis with LCA to create a hybrid model that can portray the impacts of LCA inter- and intra-sectoral events [47]. When working with complex systems like LNG supply chains, IO-developed LCA models can be quite valuable in assisting the process-based assessment. The database, including the obligations of trade-based economic exchanges between different sectors [48], provides a comprehensive impact assessment, which is a critical contributor.

In this context, IO-based LCA models provide a top-down analysis using a dealing financial matrix between sectors of the economy, taking into account sophisticated interactions across sectors within a single country. Given the advancement of the MRIO models for examining the triple bottom line (TBL) consequences of consumption and production on a global scale [49,50]. Previous research studies [51] have extensively employed single-region IO models. Many studies on the carbon impact of consumption [52], manufacturing [53], commerce [54], and countries [55] employed MRIO datasets. In comparison to the traditional EIO-LCA model, EXIOBASE 3.41 is the favored option due to improvements made by Carnegie Mellon University's EIO-LCA in the 2015 model compared to the 2007 model. The EXIOBASE 3.41 is a high-

Table 1
Various assumptions, limitations, and constraints were considered in the research.

Process stage	Assumptions/Limitations/Constrains
All stages	– Minimum flaring is anticipated. – Utility allocation is achieved based on availability and cost. – Water withdrawal is assumed for the seawater intake with a once-through concept. – Water consumption is assumed to be associated with fresh cooling water. Taxes are assumed to be 10% of total revenue. – LNG price is assumed to be 35 $/MMBTU [46] – Point sources stack emissions shall not exceed the limits set by the authorities. – Zero liquid discharges of treated industrial water to the sea.
LNG manufacturing, LNG loading, LNG unloading, and regasification	– BOG flaring while holding and loading modes is reliquefied and reused to the maximum extent. – The capital cost is approximated using Aspen HYSYS based on the purchase and installation costs of equipment, civil, instrumentation and electrical, and administration costs. – Operating cost is approximated using Aspen HYSYS based on the consideration of operational and labor charges, maintenance, plant overhead, and administration costs. – Seawater cooling water intake and outfall differential temperature are assumed to be within three degrees Celsius for heating/ cooling purposes.
LNG loading	– LNG product holding mode is assumed in this research. However, another assumption is that all LNG products are loaded and distributed to customers throughout the year by LNG carriers.

resolution global MRIO resource covering 90% of the world's marketplace. It summarizes all that EIO-LCA provides for the 2015 database [56], including the most up-to-date data, including material satellite and socioeconomic data. The development of a multinational life cycle framework sustainability assessment using the most extensive EXIOBASE 3.41 database is regarded as revolutionary and unique in the LNG industry. However, for a global life cycle sustainability analysis of power production sectors and energy management in many regions throughout the world, the MRIO database indicated above is insufficiently integrated. According to a review of MRIO studies, the energy sector's sustainability impacts must be assessed using the TBL measure, which includes the entire world and reveals as many countries and sectors as feasible [57].

The parameter factors relevant to this work are CO_2, CH_4, N_2O, NH_3, $PM_{2.5}$, SO_x, NO_x (SO_x and NO_x are considered as SO_2 and NO_2, respectively), energy inputs, operating surplus, employment, compensation of employment, total tax, and employment hours, according to the MRIO table for NG extraction and processing. The elements are weighed in different units per million Euros as an annual expenditure. The annual investment in NG extraction and processing per million Euros must be estimated to calculate the yearly values. The cost of NG extraction has been estimated to be USD 4 per MMBTU NG [58]. Designers employed the unit conversion method [59] to convert the NG to LNG factors. The following Equations (1) and (2) were used to compute the price of each ton of LNG in Euros:

$$Unit\ cost_{Naturalgasextraction} = CostperMMBTUnaturalgas \times Conversionfactor \tag{1}$$

$$\begin{aligned} Unitcost_{Natural\ gas\ extraction} &= \frac{4.0USD}{MMBTU\ natural\ gas} \times \frac{EURO}{1.21USD} \\ &\times \frac{1 \times 10^6\ MMBTU}{TriBTU\ natural\ gas} \\ &\times \frac{0.021\ TriBTU\ natural\ gas}{1,000\ ton\ LNG} \\ &= 0.0694\frac{USD}{Ton\ LNG\ Produced} \end{aligned}$$

$$Annual\ cost_{Natural\ gas\ extraction} = Annual\ LNG\ production \times Unit\ cost \tag{2}$$

$$\begin{aligned} Annual\ cost_{Natural\ gas\ extraction} &= 126 \times 10^6\ Ton\ LNG \\ &\times 0.0694\frac{EURO}{Ton\ LNG\ produced} \\ &= 8.75M\ EURO \end{aligned}$$

To calculate the annual parameters, each MRIO factor is multiplied by the annual cost of NG extraction, as per Equation (3).

$$\begin{aligned} Annual\ Impact_{Natural\ gas\ extraction} &= Annual\ Cost_{Natural\ gas\ extraction} \\ &\times MRIO\ Factor \end{aligned} \tag{3}$$

Aspen HYSYS modeling

This software is frequently used for modeling systems in the power industry. The optimization process, which includes downstream, upstream, and midstream operations, is the major goal of this program. Hydrocarbon processes, gas flue enumeration for emissions reporting, sewage treatment (among other activities), process performance debugging, and tracking are all part of the flow process for many industrial applications. The simulation method used in this study appears promising, and it has been in use for more than 35 years [60].

Except for the transportation stage, the phases from the pre-separation unit to the regasification unit in the receiving stations are simulated in this study's Aspen HYSYS chemical reaction simulator. There are two sections within the LNG conversion system: hot and cold. The hot and cold sections require cooling, heating, electricity, and shaft work supplies. The majority are created and provided through the utility part of the facility, which is powered by hot and cold waste hydrocarbons. After liquefaction, the LNG is delivered to exporting stations, where it is shipped to end-users. The end-receiving user's terminal is responsible for re-gasifying the LNG by heating it for future customer distribution. During tank holding mode, approximately 126 MMTPA of LNG is delivered to end-users, with an 18,146 MMSCFD NG feed based on the modeling of the whole LNG chain. The NG feed terms and product specifications are listed in Table 3.

The LNG train's rough feed acid NG first passes through the condensate and water pre-separation stage. The Reid Vapour Pressure (RVP) condensate output is the method's main constraint. The reboiler workload of methane is increased in the model, resulting in 9.4 psi of RVP condensate. According to the model, the provided NG feed produces roughly 336,000 standard units of stable condensate (kS-bbl/day), which is equivalent to approximately 90.8% of feed pentane plus recovery.

After the pre-separation section, the separated sour NG is sent to the sweetening unit to extract harmful acidic emissions (CO_2 and H_2S), mercaptans, and BTX and send them to the SRU and Tail Gas Treatment (TGT) sections. Following the simulation technique, the flowsheets of the sweetening and SRU/TGT units are shown in Fig. 3. On the basis of a reaction separation model, methyl diethanolamine (MDEA) based solvent is used to eliminate NG acid vapors in this investigation. Aside from the kinetically limited CO_2, all reactions are assumed to be in equilibrium. SRUs produce Sulfur allotropes as a by-product of the sweetening unit's acid gases. The steam production and reaction chamber's heat recovery system make up the first phase. Part of the H_2S input is oxidized in this stage, resulting in Sulfur allotropes and SO_2. A downstream TGT

Table 2
LCI of the study.

Impact area	Impact/Indicator	Unit	Description	Source of data
Environmental	Global Warming Potential (GWP)	kg CO_2-eq.	Total GHG emissions based on IPCC's factors for GWP100 according to Assessment Report 5 (AR5)	Upstream: MRIO Midstream: Aspen HYSYS Shipping: LNG Maritime Transport Operations LCSA Tool Downstream: Aspen HYSYS
	Particulate Matter Formation Potential (PMFP)	kg $PM_{2.5}$-eq.	Total criteria air pollutant emissions	Upstream: MRIO Midstream: Aspen HYSYS Shipping: LNG Maritime Transport Operations LCSA Tool Downstream: Aspen HYSYS
	Photochemical Oxidant Formation Potential (POFP)	kg NO_x-eq.	Amount of airborne substances able to form atmospheric oxidants	Upstream: MRIO Midstream: Aspen HYSYS Shipping: LNG Maritime Transport Operations LCSA Tool Downstream: Aspen HYSYS
	Energy Consumption	TJ	The entire amount of energy is derived from natural resources.	Upstream: MRIO Midstream: Aspen HYSYS Shipping: LNG Maritime Transport Operations LCSA Tool Downstream: Aspen HYSYS
	The Use of Water	m^3	The volume of water permanently withdrawn from its source for use.	Upstream: MRIO Midstream: Aspen HYSYS Shipping: LNG Maritime Transport Operations LCSA Tool Downstream: Aspen HYSYS
	Land Used	Km^2	The set of activities done by humans on land to get benefits from the use of land resources.	Upstream: MRIO Midstream: Aspen HYSYS and google earth Shipping: LNG Maritime Transport Operations LCSA Tool Downstream: Aspen HYSYS and google earth
	Removal of Water	m^3	The amount of water that has been taken from a source of water for private use and subsequently returned to the source.	Upstream: MRIO Midstream: Aspen HYSYS Shipping: LNG Maritime Transport Operations LCSA Tool Downstream: Aspen HYSYS
Social	Employment	person	The number of employees in each industry in Qatar and worldwide,	Upstream: MRIO Midstream: Aspen HYSYS Shipping: LNG Maritime Transport Operations LCSA Tool Downstream: Aspen HYSYS
	Compensation of Employment	USD	The monetary value assigned to a service, loss, accident, debt, or other events.	Upstream: MRIO Midstream: Aspen HYSYS Shipping: LNG Maritime Transport Operations LCSA Tool Downstream: Aspen HYSYS
	Total Tax	USD	The entire tax income is generated by each industry, both within and outside Qatar.	Upstream: MRIO Midstream: Aspen HYSYS Shipping: LNG Maritime Transport Operations LCSA Tool Downstream: Aspen HYSYS
	Man Hours	hours	Total number of working hours throughout the year.	Upstream: MRIO Midstream: Aspen HYSYS Shipping: LNG Maritime Transport Operations LCSA Tool Downstream: Aspen HYSYS
	Human Health	DALY (Disability-Adjusted Life Year)	The number of years of life lost as a result of infirmity, illness, or death at a young age.	Upstream: MRIO Midstream: Aspen HYSYS Shipping: LNG Maritime Transport Operations LCSA Tool Downstream: Aspen HYSYS

(*continued on next page*)

Table 2 (*continued*)

Impact area	Impact/Indicator	Unit	Description	Source of data
Economic	Net profit value (Revenue – Total Annualized Cost) / Gross Operating Surplus	USD	Corporations' available capital allows them to pay taxes, reimburse creditors, and support their investments.	Upstream: MRIO Midstream: Aspen HYSYS Shipping: LNG Maritime Transport Operations LCSA Tool Downstream: Aspen HYSYS
	Operational Cost (utilities, maintenance, operating cost)	USD	The expenses a business incurs in their normal day-to-day operations.	Upstream: MRIO Midstream: Aspen HYSYS Shipping: LNG Maritime Transport Operations LCSA Tool Downstream: Aspen HYSYS
	Equipment Cost	USD	The purchase price therefore paid by the Owner to install the equipment	Upstream: MRIO Midstream: Aspen HYSYS Shipping: LNG Maritime Transport Operations LCSA Tool Downstream: Aspen HYSYS
	Salvage value (End of life)	USD	The book value of an asset after all depreciation has been fully expensed	Upstream: MRIO Midstream: Aspen HYSYS Shipping: LNG Maritime Transport Operations LCSA Tool Downstream: Aspen HYSYS

Table 3
Chain feed conditions and product specifications.

Parameters	NG Feed	LNG Product
Temperature (°C)	27	−161
Pressure (bar)	84.5	3
Higher heating value (BTU/SCF)	1,129	1,040
Flowrate (MMSCFD)	18,146	17,028
Flowrate (MMTA)	166	126
Composition (mol%)		
N_2	3.78	0.70
H_2S	0.80	≤4 (ppm)
CO_2	2.43	≤59.2 (ppm)
C1	81.3	93.4
C2	4.84	5.90
C3	1.84	0.03
C4	1.03	
C5+	2.93	
BTX	0.24	
Mercaptans	0.04	
H_2O	0.74	
He	0.04	

unit is employed to reduce excess SO_x production from SRUs. The acid gas removal unit is followed by a two-stage Claus process and a TGT unit in the SRU system [61]. The acid gas from the first regenerator rich in CO_2 goes straight to the TGT unit, whereas the acid gas-rich in H_2S goes to the SRU unit to be converted into elemental Sulfur.

Water must be removed from NG, leaving the sweetening unit to prevent downstream erosion and hydrate development, which can clog pipelines and heat exchanger channels (dehydration). The Process Flow Diagram (PFD) of the simulated dehydration unit with three molecular sieve adsorbers is shown in Fig. 3. If an adsorber becomes saturated with water, the NG feed must be renewed into a new adsorber with two active beds and one in a regeneration state. The sweet NG has been completely dehydrated according to the characteristics given in Table 4.

After pre-treatment, dehydrated NG is fed into the NGL recovery unit. This part aids in the recovery of leftover condensate and the ethane/propane cooling makeup and the manufacture of LNG requirements for the liquefaction system. A scrub section for feed pre-cooling and reflux generation is placed in the NGL treatment facility for the chain under evaluation, as shown in Fig. 4. Over two vapor compression cycles, compress, condense, subcool, and throb refrigerant confinement, allowing coolers to be delivered primarily through evaporation. In the primary cryogenic heat exchanger (MCHE), low-pressure mixed refrigerations (MRs) are used for cooling and liquefaction, as shown in Fig. 4. The NG is discharged from the NGL recovery unit at 36 degrees Celsius and 67 bar, as shown in Table 5, and then liquefied to −148.4 degrees Celsius and 43 bar.

The LNG is delivered to the combined HeX and NR plants for helium and nitrogen recovery after the liquefaction process. As shown in Fig. 4, helium is separated using a self-refrigeration discharge mechanism from the chain. Nitrogen is expelled through a section with a stripper generated by a cold built-in reboiler. Some light hydrocarbons found in the expelled nitrogen are used as fuel. Tables 4 and 5 show the unit conditions and requirements for the hot and cold sections of the LNG project.

Three traditional distillation columns make up the majority of the fractionating unit. As shown in Fig. 4, one is the de-ethanizing column (C-21), another is the de-propanizer (C-22), and the third is the de-butanizer (C-23). Table 5 depicts the characteristics and specifications of this unit. Liquefied petroleum gas (LPG) is returned to the liquefaction process to be blended with LNG.

After entering the tank, the LNG pressure is reduced and the storage temperature is regulated to roughly −161 °C, as shown in Fig. 4. BOG is found as a result of excessive LNG pressure in the storage tank, heat leakage, pipe cooling via part of the LNG, and steam displacement filling the vapor space. LNG storage, regasification, and support utilities are mostly found at LNG receiving terminals. Table 6 shows the precise characteristics of the simulated regasification plant. The conditions specific to hot, cold, and regasification sections are illustrated in Tables 4–6. For the simulation technique and the PFDs, see Figs. 3–5.

According to studies on energy sustainability valuation, there has been a scarcity of research on suitable energy up to this point, and many researchers have focused on building sustainability evaluation models

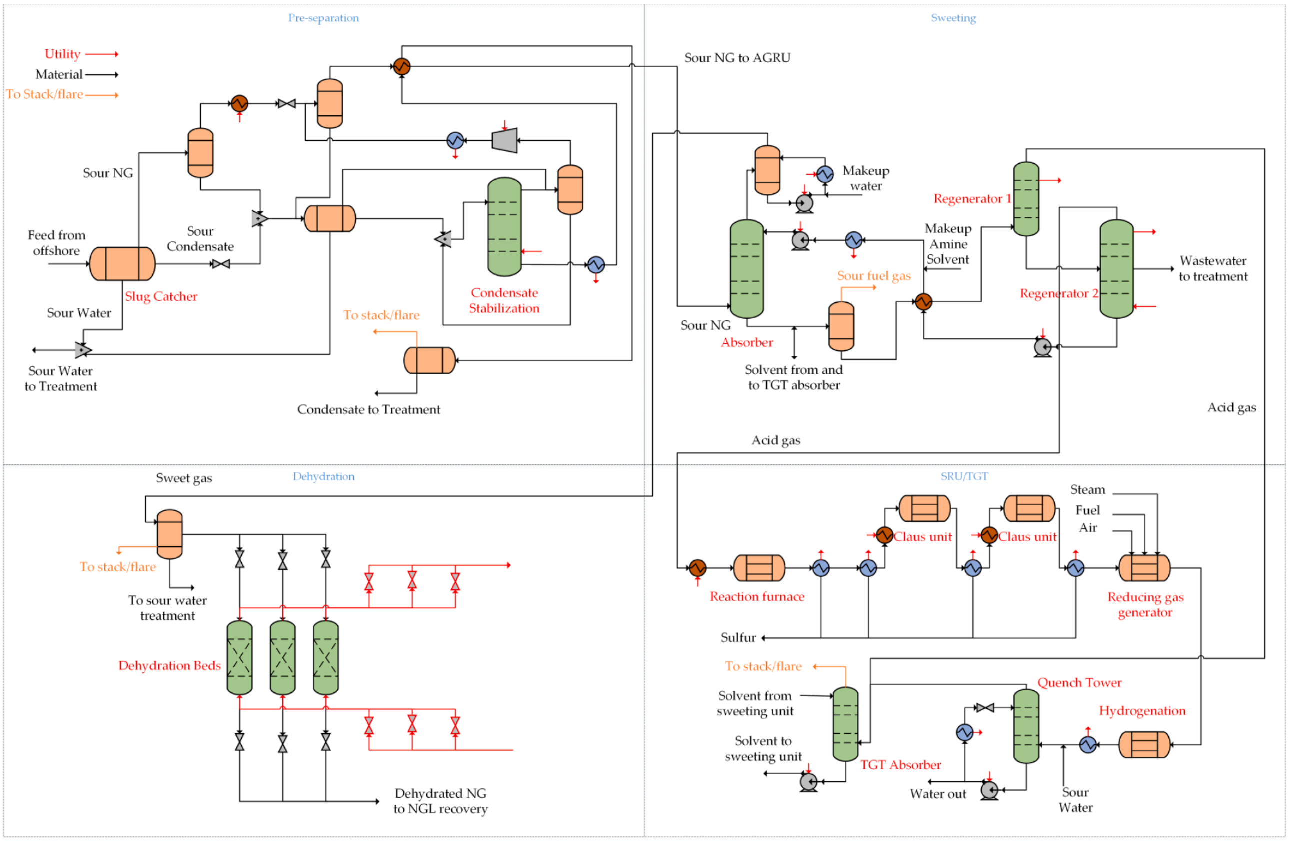

Fig. 3. PFD of the simulated LNG hot section.

Table 4
LNG hot section conditions and specifications.

Specification \Stream	Feed from Off-Shore	Condensate	Sour Water (Pre-separation)	Wastewater	Sour Water (SRU/ TGT)	Water Out	Absorber Top	Sulfur	Sour Water (Dehydration)	Dehydrated NG
Temperature (°C)	27.00	40.24	28.64	127.60	25.00	100.01	35.00	135.00	24.96	24.08
Pressure (bar)	84.50	74.66	28.00	2.30	1.01	1.01	1.06	1.43	67.54	66.81
Flowrate (MMSCFD)	18,145.67	368.79	135.21	1.16	0.58	437.34	577.56	118.43	1.00	16,817.03
Composition (mol%)										
N_2	3.78						77.64			4.04
H_2S	0.80	0.01	0.05	27.56			0.02			
CO_2	2.43		0.06	4.51			10.28			0.01
C1	81.30			0.02						86.80
C2	4.84	0.02		0.01						5.12
C3	1.84	0.50		0.01						1.90
C4	1.03	9.13		0.01						0.92
C5+	2.93	82.46		0.01						1.14
BTX	0.24	7.80		0.05						0.03
Mercaptans	0.04	0.08		0.03						
H_2O	0.74			67.79	100.00	100.00	5.28		100.00	
H_2							6.78			
S								100.00		
He	0.04		99.89							0.04

with little regard for environmental implications and the introduced examination. Furthermore, there is no clear LCSA of directed LNG process chains and overseas transport literature. Aside from the bottom lines of sustainable development, the LNG sector still requires integration of the life cycle environmental, social, and economic spectrum.

The integrated LNG production with hot and cold sections that have been simulated using the Aspen HYSYS program employed certain assumptions while conducting the steady-state simulation and the economic and environmental analysis that are listed here in addition to Table 1:

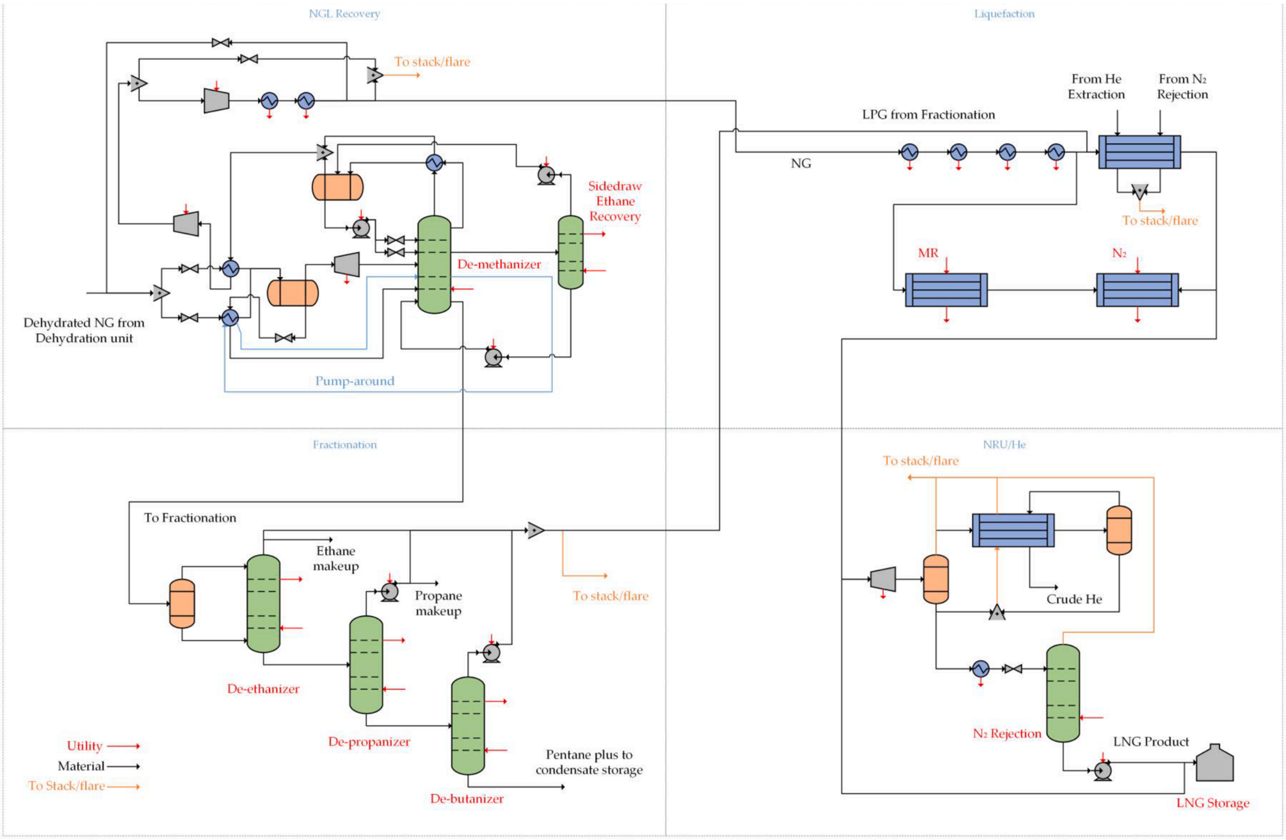

Fig. 4. PFD of the simulated LNG cold section.

Table 5
LNG cold section conditions and specifications.

Specification\Stream	From He	From N_2	LNG	Ethane	Propane	Pentane Plus	Crude He	LNG Product
Temperature (°C)	−155.30	−161.90	−148.40	35	45	130.63	−155.30	−161.60
Pressure (bar)	3.18	1.20	43.35	27.5	30.09	8.30	3.18	1.20
Flowrate (MMSCFD)	13.51	1,547.55	16,487.81	7.09	4.61	170.27	13.51	14,931.41
Composition (mol%)								
N_2	49.94	37.61	4.20				49.94	0.70
H_2S (ppm)								≤4
CO_2 (ppm)			0.01					≤59.2
C1	2.00	62.35	90.39				2.00	93.38
C2		0.01	5.33	98.02	1.61			5.88
C3			0.03	1.98	96.44			0.03
C4					1.95	0.34		
C5+						97.49		
BTX						2.17		
He	48.06	0.03	0.04				48.06	

- Investment and operating costs of the exporting terminal are approximated at \$26.7 billion and annually \$504.0 million, while for the import regasification terminal are approximated at \$1.3 billion and annually \$28.8 million based on literature studies [62,63]
- Total annualized cost is approximated using the following Equation (4):
- Net profit is approximated using the following Equation (5):

$$Net\ profit = \frac{Revenue\ (Gross\ operating\ surplus) - Total\ annualized\ cost}{Annual\ LNG\ production} \tag{5}$$

- The land use for the different sections of the LNG process is approximated using the built-in sizing tool in Aspen HYSYS of the

$$Total\ annualized\ cost = Capital\ cost\frac{i(1+i)^n}{(1+i)^n - 1} + Operating\ cost + Raw\ material\ cost + Emissions\ tax \tag{4}$$

equipment and following the heuristic of process synthesis and plant layout configuration [62,63]

- Energy consumption is approximated based on the electricity usage of each plant section.
- Employment is approximated considering three shifts per day and the requirement of shift operators, shift supervisors, maintenance technicians, discipline engineers, human resource coordinators, health, safety, and environment specials, managers, and a chief operating officer.
- Man-hours are approximated considering 8 h per shift and 22 days per month in addition to the required period for engineering, procurement, and commissioning stages specific for each plant section.
- The compensation of employees is approximated to be on the average of $11,000 per employee monthly.

LNG maritime transport operations sustainability assessment tool

The transportation of LNG products is an integral part of the LNG trading supply chain and plays a role in the LNG industry's whole life cycle. Aseel et al. (2021) created the LNG maritime transport emission quantification and human health effect calculation method. The data gathering process, assumptions, tools to estimate the energy utilized, emissions calculations as a midway impact, and human health impact as an endpoint estimation were all included in the tool. This study utilizes the proposed mechanism to quantify the midway and endpoint implications of Qatar's LNG supply to the United Kingdom as a case study. The tool's method is to compute GHG, other emissions, and human health based on an estimate of the fuel burned, as well as to calculate principal pollutants using emission factors [64].

Calculating emissions begins with gathering the necessary data and laying out the assumptions that are used to compute the emission value for each vessel. Many data points were collected during the data gathering stage, including but not limited to marine route distance between exporter and importer, days of operation duration, types of carriers, carrier maximum loading capacity in accordance with IMO requirements, fuel types per carrier, carrier's engine, and BOG operations during the Laden and Ballast operations. The next phase employs the required emissions parameters to convert the total energy combusted into midway emissions after estimating fuel consumption per carrier and selecting the fuel category. Cooper and Gustafsson [65] reported the emission factors that are employed in the suggested tool. Equation (6) shows the methods of calculation that have been considered:

$$LNG\ transport\ emission_{midpoint} = \sum Fuel\ consumption \times Emission\ factor \tag{6}$$

The energy consumption in the LNG maritime transport operations is mainly from the fuel consumption due to transport purposes or usage of BOG. The land used for the LNG carrier is assumed to be the length multiplied by the width of each carrier and then multiplied by the annual number of roundtrips of Qatar-United Kingdom trade. The size of the carriers is found in [66]. The utility water used in the LNG carrier for domestic use, boiler feed water, fire incident response, etc is assumed as 5% of the voyage capacity, and the removal of ocean seawater and return back for the ballast trip balancing is assumed as 15% of voyage capacity multiplied by the annual number of roundtrips for each parameter.

For the social part, the approximate consequence of a substance on human health is calculated by multiplying the ReCiPe 2016 characterization factor with the amount of substance emitted to the atmosphere following Equation (7):

$$Endpoint\ HH_{Hierarchic} = Midpoint_{Hierarchic} \times CF_{Hierarchic} \tag{7}$$

where Endpoint $HH_{Hierarchic}$ is the human health impact and $CF_{Hierarchic}$ is the characterization factor. The approximate number of full-time employments, compensation for employees, and total man-hours information are provided by subject matter experts in LNG maritime transport. The total taxes are assumed as 15% of the total revenue of LNG trade between Qatar and the United Kingdom based on the annual LNG supply agreement contract.

For the economic part, the capital cost is the cost associated with the equipment construction, installation, and commissioning of the LNG

Table 6
LNG loading, unloading, and regasification conditions and specifications.

Specification\Stream	LNG Loading	LNG Unloading	LNG Distribution
Temperature (°C)	−156.6	−160.6	25
Pressure (bar)	81	3	81
Flowrate (MMSCFD)	751.3	751.4	751.3
Composition (mol%)			
N_2	4.51	4.51	4.51
H_2S (ppm)	≤4	≤4	≤4
CO_2 (ppm)	≤59.2	≤59.2	≤59.2
C1	95.3	95.3	95.3
C2	0.19	0.19	0.19

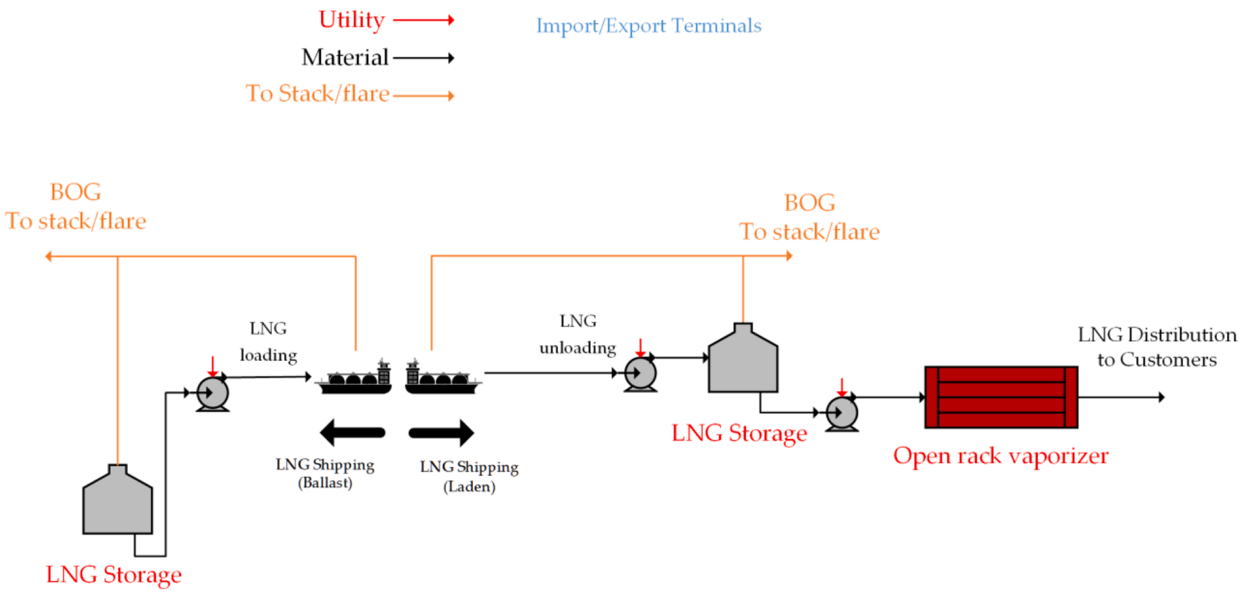

Fig. 5. PFD of the simulated loading and regasification units.

carrier used. In this research, LNG conventional carrier type 2 is assumed. Moreover, the fuel cost associated with the roundtrip along the calendar year based on United Kingdom demand is considered and counted. The LNG BOG is assumed to be 0.15% of the total loaded quantity, and the boil-off cost is calculated. Below Equation (8) has been followed to quantify the operational, revenue, and salvage value (end of life) [67]:

$$\begin{aligned} \mathit{LNG\ boil\ off\ cost} &= \mathit{LNG\ loaded\ quantity}(\mathit{MMBTU}) \\ &\quad \times \mathit{LNG\ cost}(\$/\mathit{MMBTU}) \times 0.15\% \end{aligned} \tag{8}$$

The charter rates for Qatar-United Kingdom trade are assumed for ST and SSD (in $/day) equal to 47,125 and 79,342, respectively. The charter cost calculation as per Equation (9):

$$\mathit{Charter\ cost} = \mathit{Roundtrip\ voyage\ days}\ (\mathit{days}) \times \mathit{Charter\ rate}\ (\$/\mathit{days}) \tag{9}$$

Port cost is counted following the below Equation (10):

$$\mathit{Port\ cost} = \mathit{Port\ days} \times \$100,000/\mathit{day} \tag{10}$$

The Suez Canal is the only canal considered in this research, and the fee is assumed to be $400,000/LNG ship. Agents, broker fees, and insurance can be assumed as per the following Equation (11):

$$\mathit{Agent, broker, amd\ insurance\ cost} = 2\%\ \mathit{of\ Charter\ cost} + \$2,600/\mathit{day\ for\ inusratnce} \tag{11}$$

The total operational cost is calculated following the below Equation (12):

$$\mathit{Total\ cost} = \mathit{Charter\ cost} + \mathit{Fuel\ cost} + \mathit{Canal\ cost} + \mathit{Port\ cost} + \mathit{Agent, broker, amd\ insurance\ cost} \tag{12}$$

Salvage Value (end of life) is calculated using the formula given in Equation (13) below:

$$\begin{aligned} \mathit{Salvagevalue} &= \mathit{Purchasepriceoftheengineeringmachinery} - (\mathit{Depreciation} \\ &\quad \times \mathit{Usefullife}) \end{aligned} \tag{13}$$

The annual revenue (gross operating surplus) is counted following Equation (14):

$$\mathit{Revenue}\ (\mathit{Gross\ operating\ surplus}) = \mathit{Annual\ supply\ of\ LNG} \times \mathit{LNG\ price} \tag{14}$$

Interpretation of hybrid LCSA model

At this stage, the data gathered from the impact analysis results must be recognized, quantified, validated, and assessed. The evaluation is based on our research findings, which were collected using the methods described earlier. The findings are also discussed, highlighting the most serious concerns for LNG's long-term viability. The areas that need to be improved are also included.

Without specific weighting, LCSA is a blend of LCA, LCC, and SLCA. LCSA necessitates a multi-criteria review to handle the markers' balance as well as their grading. The metrics chosen for this research have varying percentages of contributors to the overall sustainability of the systems analyzed to tie various indicators and their influence on the system component and keep the number of social indicators presented to a tolerable and comparative number. Based on their contribution to sustainable development in connection to the properties of the systems studied, beneficial and adverse indicators have been established. Bad indicators have high values and have a negative impact on sustainability, whilst positive indicators have a positive impact on sustainability.

In order to perform the sustainability assessment, the variables used in LCA, LCC, and SLCA have been combined into three sustainability factors (SF) in this study: $SF_{environmental}$, $SF_{economic}$, and SF_{social}. The following are the phases of SF calculation:

1. Following the acquisition of the LCA, LCC, and SLCA outcomes, the data for all indicators are transformed into contribution proportions. These proportions are analyzed by comparing the values collected by each collecting system for the same marker, with the greatest marker value providing 100% and the rest systems receiving a comparable amount.
2. Based on the percentage of contribution attributed to each indication, a score of 1 to 5 is assigned. Bad signals (higher percentages of involvement indicate a lower contribution to sustainability) and good indicators (higher percentages of contribution suggest a higher contribution to sustainable development) have been distinguished (greater percentage of contribution means a greater contribution to sustainability). For negative signs, the scoring scale is as follows: 1 point for the participation of 100–81%, 2 points for 80–61%, 3 points for 60–41%, 4 points for 40–21%, and 5 points for 20–1%. On the other side, positive metrics are graded as follows: 1 point for a percentage contribution between 1 and 20%, 2 points for a percentage contribution between 21 and 40%, 3 points for relative proportions between 41 and 60%, 4 points for a percentage contribution between 61 and 80%, and 5 points for a percentage contribution between 81 and 100%. To be more random across economic variables, the overall cost in the LCC scoring system has been obtained instead of examining individual indicators independently.
3. After assessing all indicators, a total score is obtained for each evaluation (LCA, LCA, and SLCA). To compare the three collection systems and the three dimensions studied: environmental, economic, and social, total scores were recalculated into indicator proportions to get the same magnitude (between 0 and 1) and to compare the three collection systems and the three dimensions studied: environmental, economic, and social. The relative values found were given the acronym SF, which stands for three sustainability factors: $SF_{environmental}$, $SF_{economic}$, and SF_{social}. Because SF values range from 0 to 1, those around 1 contribute significantly to sustainability assessments, while those near 0 contribute less.

Results and discussion

Sources and LCI clustering in the LNG supply chain

The life cycle sustainability indicators for each operation stage are

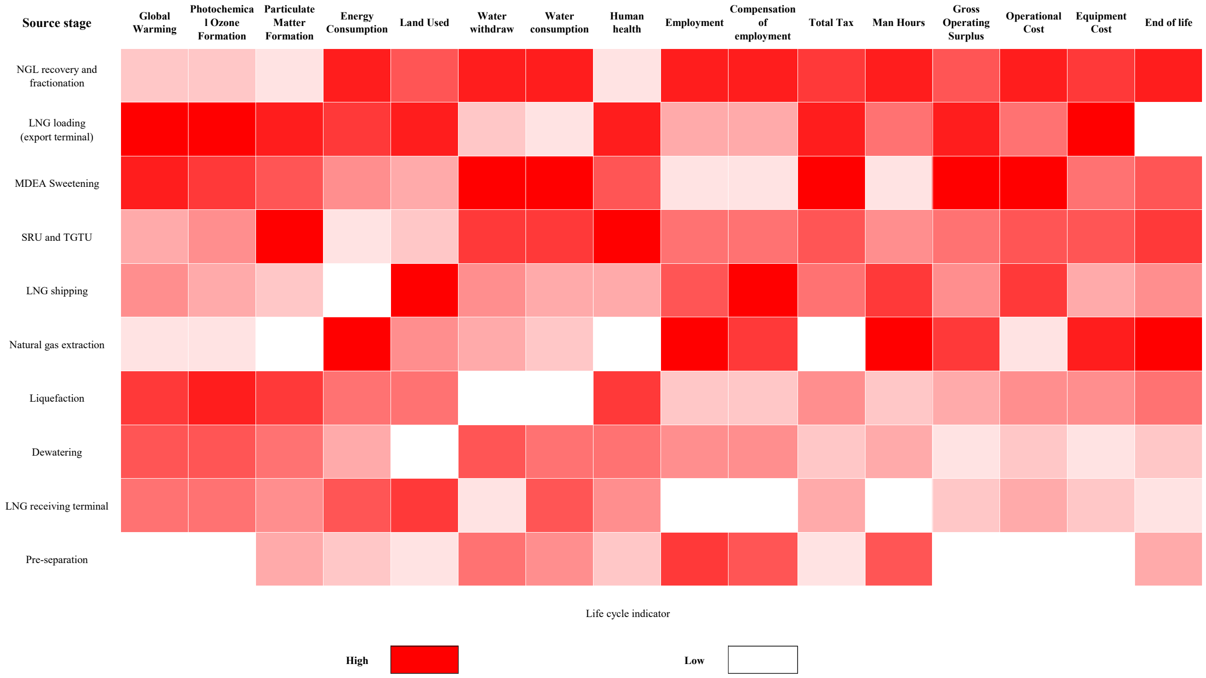

Fig. 6. Heat map diagram for LCIs of LNG process chain.

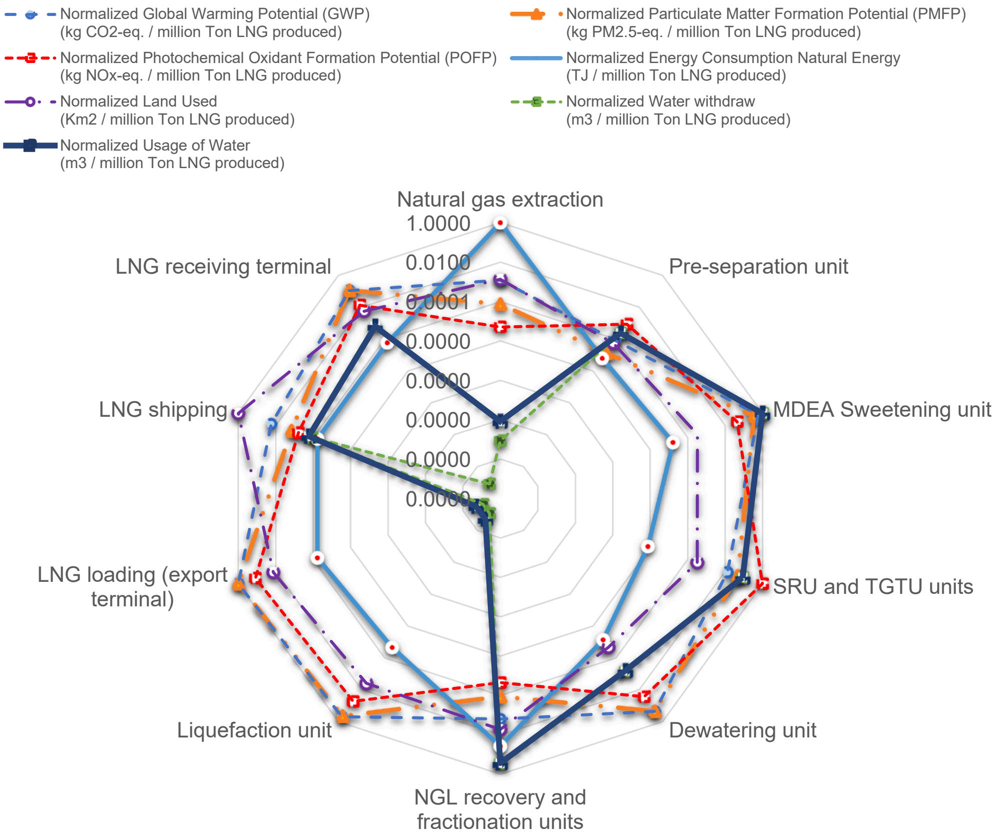

Fig. 7. Normalized LCA results of the LNG supply chain.

identified and analyzed using a heat map diagram for LNG production and supply chain, as shown in Fig. 6. As a result, the highest environmental, social and economic impact was from the NGL recovery and fractionation unit, without differentiating between the adverse and beneficial effects followed by LNG loading and MDEA sweetening unit. However, the lowest in terms of the sustainability pillars is the pre-separation unit. The above shows a clear correlation between employment, the compensation of the employment, and the total man-hour results. Moreover, most processing units' social and economic impacts are slightly the same. It is recommended to further research and enhance technology to reduce or capture the particulate matters with higher efficiency to minimize the environmental and human health impacts associated with the LNG midstream process.

LCA, LCC, and SLCA analysis

LNG process chain provides various quantities and quality of sustainability indicators. The sustainability results from various tools were normalized in ratios for each stage throughout the process chain to make the analysis easier and more beneficial for decision-makers. After, the highest value was considered for all the stages. The results of every single stage were divided by the highest value considered in the previous stage to perform the deemed normalization. Post normalizing, results shall be unitless and dimensionless, and within a range from zero to one. The LCI results are provided for each value chain stage in supplementary information file 1.

LCA results

Fig. 7 indicates the normalized environmental indicators comparison of the LNG supply chain. As for the normalized CO_2-eq emission, LNG loading (export terminal) found the highest source of contribution throughout the process chain with 40.3%, followed by the MDEA sweetening unit, which represents 24.3%, and the liquefaction unit with 20.1%. The highest contribution is found again for the normalized NO_x-eq emission from LNG loading (export terminal), Liquefaction unit, and MDEA Sweetening unit with 45.7%, 20.6%, and 16.1%, respectively. The lowest normalized CO_2-eq and NO_x-eq emission were found from the pre-separation unit. The highest contribution is found for the normalized $PM_{2.5}$-eq emission from SRU and TGTU units, LNG loading (export terminal), and Liquefaction unit with 79.3%, 9.5%, and 4.3%, respectively. The lowest normalized $PM_{2.5}$-eq emission was found from the natural gas extraction. It is essential to treat the LNG loading unit as a hot spot where further process improvement and emission caption are required. The emissions are generated mainly from product storage, utility consumption, loading to carriers, and BOG flaring. A reliquification unit shall exist to maximize the gas recovery, avoid losses and abate ecological degradation. The depreciation of the environmental releases to the atmosphere is definitely helping to save human lives.

From the normalized energy consumption perspective, the most contribution is from the natural gas extraction stage with 96.3%. The raw data was taken from MRIO, which is expected to cover the direct and indirect emissions associated with natural gas extraction and processing. It is recommended to furtherly have deep research to validate the current MRIO factors. On the other hand, normalized land used found the highest with 97% for LNG shipping as LNG carriers and taking massive space in the loading and unloading ports throughout the year. The MDEA Sweetening unit found the highest with 73.6% and 73.5%, respectively, regarding the normalized water withdrawal and water consumption. The environmental impact quantitative results related to the LNG process chain are provided for each value chain stage in Table 7.

LCC results

Fig. 8 shows the normalized economic impacts directly related to the LNG process chain. MDEA Sweetening unit presents the maximum gross operating surplus, followed by LNG loading (export terminal) and the natural gas extraction stage with 26%, 19.7%, and 17.7%, respectively. The minimum gross operating surplus is found in the Pre-separation unit. Moreover, the MDEA Sweetening unit found the highest operational cost with 44% contribution, followed by NGL recovery and fractionation units with 22%, and the lowest in the Pre-separation unit. Furthermore, LNG loading (export terminal) followed by Natural gas extraction stages presented most of the total equipment cost, and the Natural gas extraction stage introduced more than half of the end of life throughout the process chain. The economic impact quantitative results related to the LNG process chain are provided for each value chain stage in Table 8.

SLCA results

Fig. 9 shows the social impacts directly related to the LNG process chain. It was found that more than 73% of human health impact comes from SRU and TGTU units which are the most contributors to $PM_{2.5}$-eq, as illustrated earlier. The second highest contributor to human health impact is the LNG loading (export terminal) stage with approximately 12%. On the other hand, Natural gas extraction and NGL recovery and fractionation units found the highest full-time employment with 57.7% and 13%, respectively. Also, the same stages have the highest man-hours estimated in this research.

The employment compensation is investigated and found that the highest compensation comes from LNG shipping, followed by NGL recovery and fractionation units. Regarding the tax impact on the social, the MDEA Sweetening unit and NGL recovery and fractionation units present the highest impact with 43% and 27%, respectively. The social impact quantitative results related to the LNG process chain are provided for each value chain stage in Table 9.

Cumulative triangle chart and sustainability assessment results

Table 10 and Fig. 10 show the results of the LCSA and the different values obtained for the SF defined. According to the results obtained, the Pre-separation unit and LNG receiving terminal have the best environmental performance by having the lowest environmental impact, with SF equal to 1. The environmental impact still exists, although the

Table 7
Quantitative results of environmental impacts related to LNG process chain.

Process Stage	Global Warming (kg CO_2-eq)	Photochemical Ozone Formation (kg NO_x-eq)	Fine Particulate Matter Formation (kg $PM_{2.5}$-eq)	Energy Consumption (TJ)	Land Used (Km2)	Water withdraw (m3)	Water consumption (m3)
Natural gas extraction	53,648,395	78,932	7,740	2,838	1.93	0.10	0.42
Pre-separation unit	3,630,834	14,129	1,308,947	0.02	0.08	2,933,491	1,257,210
MDEA Sweetening unit	25,414,306,084	367,511,207	67,015,269	0.05	0.47	11,842,116,930	5,075,192,970
SRU and TGTU units	569,820,482	50,239,730	1,483,250,846	0.00	0.46	1,046,177,060	448,361,597
Dewatering unit	9,591,964,940	226,246,569	40,551,701	0.02	0.03	7,489,438	3,209,759
NGL recovery and fractionation units	65,316,380	118,701	33,094	107	7.37	3,195,927,235	1,369,683,100
Liquefaction unit	21,012,275,442	469,812,499	79,849,788	0.06	5.38	0.00	0.00
LNG loading (export terminal)	42,201,635,518	1,043,728,533	177,395,647	0.17	18.50	0.00	0.00
LNG shipping	742,164,478	1,522,491	925,655	0.17	1,390	1,306,193	870,795
LNG receiving terminal	4,933,090,400	122,400,674	20,803,647	0.17	8.20	0.00	3,354,545

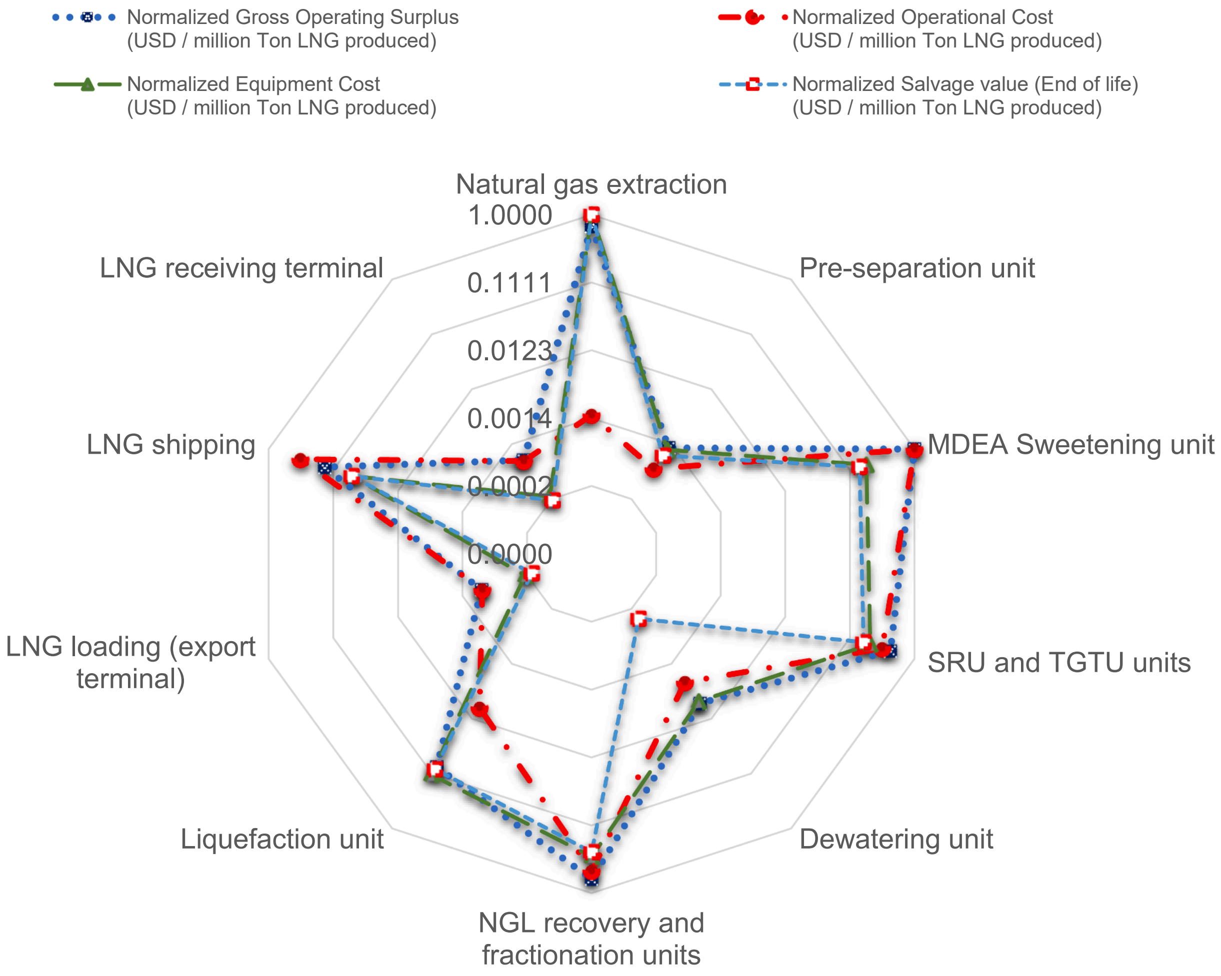

Fig. 8. Normalized LCC results of the LNG supply chain.

Table 8
Quantitative results of economic impacts related to LNG process chain.

Process Stage	Gross Operating Surplus (USD/y)	Operational Cost (USD/y)	Equipment Cost (USD)	Salvage value (End of life) (USD)
Natural gas extraction	53,450,199,668	10,584,000	26,224,254,197	6,556,063,549
Pre-separation unit	93,163,622	3,546,411	28,529,135	5,705,827
MDEA Sweetening unit	79,068,030,658	6,937,933,632	5,084,543,088	1,016,908,617
SRU and TGTU units	34,873,299,933	2,325,693,306	5,818,353,647	1,163,670,729
Dewatering unit	530,124,670	20,020,317	163,115,540	1,483,983
NGL recovery and fractionation units	50,009,767,755	3,394,922,207	8,052,653,996	1,734,728,535
Liquefaction unit	6,760,701,129	55,597,005	3,052,785,600	610,557,120
LNG loading (export terminal)	56,680,321	4,846,930	4,261,190	852,238
LNG shipping	11,780,425,564	2,355,957,653	1,547,870,305	386,967,576
LNG receiving terminal	57,065,750	4,847,280	4,448,960	949,242

performance is the best among other units. On the other hand, the MDEA Sweetening unit has the worst environmental performance and the lowest SF, equal to 0.66. Note that MDEA Sweetening unit is removing the undesired components such as H_2S, CO_2, and BTX, which are then released into the environment. The MDEA unit is expected to be the worse from an environmental perspective among the other units.

In terms of social and economic impacts, the Natural gas extraction stage system presents the best performance among all other stages, with SF equal to 1. However, SRU and TGTU units illustrate the lowest performance in the social perspective, with SF equal to 0.41. Moreover, LNG loading (export terminal) and LNG shipping are both showing the minimum performance in terms of economic impact, with SF equal to 0.73 for each stage. Overall, the natural gas extraction stage shows the best performance among other stages in the LNG value chain from the sustainability perspective.

Note that transportation is only considering the United Kingdom demand of 6.6 MMTA, and accordingly, all sustainability impacts are considered per the current demand. The sustainability assessment results, contribution percentage, and scoring results are provided for each LNG value chain stage in supplementary information file 1, Tables 1–3.

Policy implications

The establishment and implementation of sustainability policy in the energy sector, including the LNG supply chain, is crucial and promotes business development, social acceptance, and a green environment.

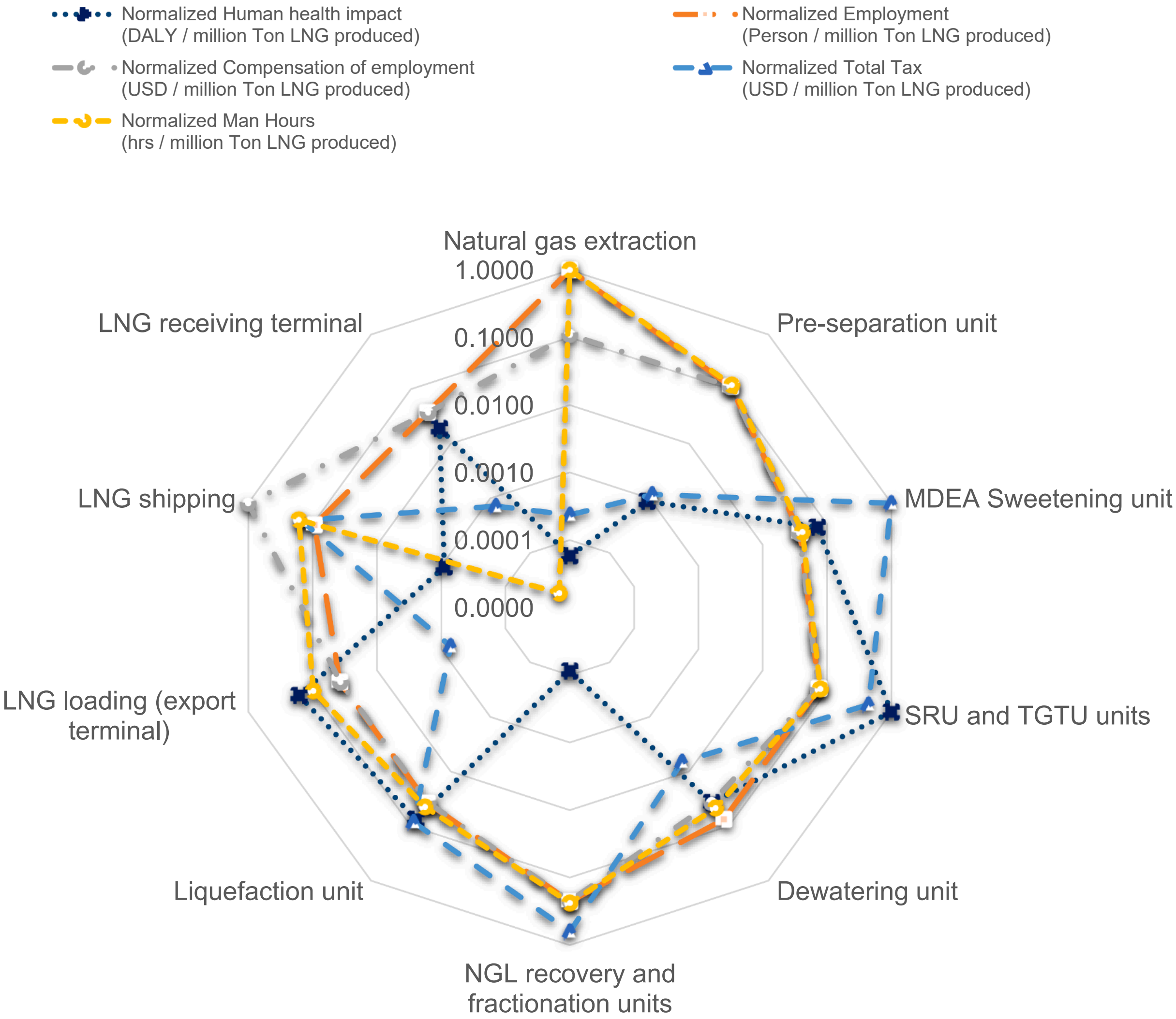

Fig. 9. Normalized SLCA results of the LNG supply chain.

Table 9
Quantitative results of social impacts related to LNG process chain.

Process Stage	Human health impact (DALY)	Employment (Person)	Compensation of employment (USD)	Total Tax (USD)	Man Hours (hrs)
Natural gas extraction	54	2,329	2,875,972	1,859,175	4,774,176
Pre-separation unit	826	262	2,871,232	9,316,362	568,632
MDEA Sweetening unit	66,071	88	964,383	7,906,803,065	198,120
SRU and TGTU units	933,539	175	1,917,808	3,487,329,993	377,496
Dewatering unit	34,614	175	964,383	53,012,467	222,144
NGL recovery and fractionation units	81	524	5,742,465	5,000,976,775	1,130,040
Liquefaction unit	70,152	88	964,383	676,070,112	212,568
LNG loading (export terminal)	151,694	88	964,383	5,668,032	464,400
LNG shipping	835	216	26,004,221	1,178,042,556	780,126
LNG receiving terminal	17,774	88	964,383	5,706,575	88

Rare studies are focusing on the LNG supply chain strategies and policymaking. Recent research by Al-Yafei et al. (2021) highlighted critical areas of potential improvement from an energy policy perspective toward sustainability [68]. Generally, representative sustainability performance data shall exist to adopt any new policy. However, it was challenging to get accurate data from the specialized sector during this research, especially natural gas extraction and processing. Towards valid policymaking, precise data is needed. Further policy focus can be provided on the below subjects:

1. LNG loading and MDEA sweetening units need more focus to minimize the adverse environmental impacts. The process of LNG loading requires more optimization and improvement by process engineers and designers to reduce the pollution and human health impacts. For the MDEA sweetening and SRU units, applying recent engineering control (such as scrubbers and absorbers) is recommended from the early stage of future projects. Authorities could set compliance action plans on non-compliance or excess emission sources for the existing projects to achieve the minimum impact and meet the local and international standards.

Table 10
LCSA results summary.

Total Scores	Natural gas extraction	Pre-separation unit	MDEA Sweetening unit	SRU and TGTU units	Dewatering unit	NGL recovery and fractionation units	Liquefaction unit	LNG loading (export terminal)	LNG shipping	LNG receiving terminal
LCA	31	35	23	31	33	33	31	27	31	35
SLCA	17	9	13	7	9	15	9	12	13	9
LCC	15	12	12	12	12	13	12	11	11	12

Sustainability Factors (Relative values)	**Natural gas extraction**	**Pre-separation unit**	**MDEA Sweetening unit**	**SRU and TGTU units**	**Dewatering unit**	**NGL recovery and fractionation units**	**Liquefaction unit**	**LNG loading (export terminal)**	**LNG shipping**	**LNG receiving terminal**
$SF_{environmental}$	0.89	1.00	0.66	0.89	0.94	0.94	0.89	0.77	0.89	1.00
Sf_{social}	1.00	0.53	0.76	0.41	0.53	0.88	0.53	0.71	0.76	0.53
$Sf_{economic}$	1.00	0.80	0.80	0.80	0.80	0.87	0.80	0.73	0.73	0.80

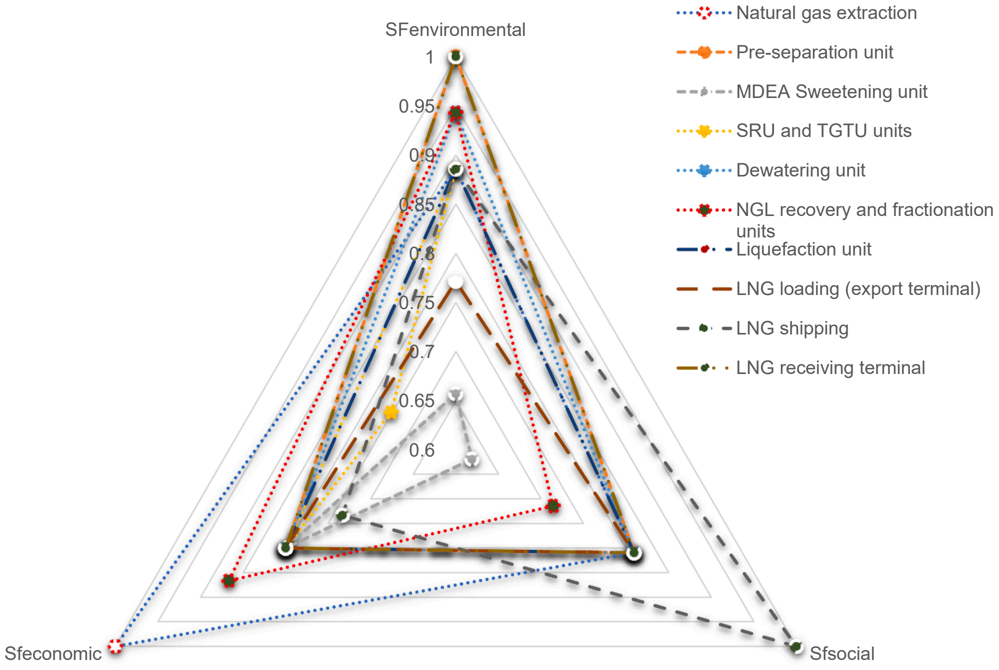

Fig. 10. Interpretation of LCSA results.

2. As CO_2 emissions are produced throughout the LNG process, maximization of CO_2 use as a by-product for syngas production or enhancement gas for oil recovery is recommended to policymakers and industry owners with specifications that meet the requirement.
3. The construction material is expensive for the process equipment that handles sour gases. Further study and research can focus on other alternatives supported by LNG industries for further investigation. Moreover, LNG maritime carrier design, process, and traveling routes require further optimization. Energy shipping security is an essential factor in the shipping part, reducing pollution, satisfying customers, and promoting more business globally. As the LNG demand forecast increases, the governments shall focus more on energy security policy.
4. From a worldwide geopolitics risk perspective, any rise in the risk due to countries' relationship shocks, political issues, wars, attacks, etc., has a high potential to increase the spot charter cost rates of the LNG. Geopolitics plays a significant role and could have negatively affected the exporting and importing countries due to the lack of energy security [69]. Accordingly, the price of LNG and its delivery are expected to be affected by a noticeable increase. International unions must consider the geopolitical risk of energy trading to ensure the minimum sudden adverse impact on economic development, social satisfaction, and environmental releases.
5. Governments and unions to set objectives, targets, and action plans towards utilizing renewable energy. The achievement and success stories can get benefits such as tax exemption, governmental support, and free marketing. Parallelly, help can be provided to the LNG manufacturers who are producing carbon–neutral LNG.
6. The integrity of old wellhead platforms, pipelines, process units, maritime carriers, etc., should meet the minimum requirements of potential concerns for process safety, personal safety, and environmental impacts.
7. Most LNG exporting companies focus on environmental, social, and economic studies before establishing any plant for the compliance requirement. After the industry production starts, the focus is on economic development and business growth worldwide. However, policymakers have the authority to insist on revalidating their supply chain sustainability impact study on the surroundings, such as the air quality, wastewater discharges, waste management, human health impact, etc., in such a frequency. The frequency of the reoccurring

studies can be decided by the authority to verify the sustainability consistency.

8. Implement the best available technology for any new process unit considering its high reliability and integrity. The new units shall be designed to be environmentally friendly, not cause the community complaint, and be cost-effective.
9. Include the carbon footprint reporting as one of the Tender Criteria of LNG trade to insist on the importance of customer and supplier awareness and derive the sellers ensuring the best sustainability performance. Not to limit the monitoring and reporting to the production unit only, but to cover the maritime transport as well.

Conclusion and recommendations

The integration of sustainability pillars in the LNG sector is crucial and has not been discussed earlier in the literature; however, the demand for the product increases and requires further research on LNG product sustainability. Several data have been considered in this research from different domains. An LNG plant with up to 126 MMTA was designed and simulated as part of this novel research. After gathering the data, sustainability interpretation is adopted to verify each stage's sustainability impact and factor throughout the LNG value chain, considering the negative and positive impacts.

According to the environmental life cycle results obtained, the CO_2-eq and NO_x-eq emission were found to be the highest in the LNG loading (export terminal) stage, with around 42.2 million tons of CO_2-eq and 1.04 million tons of NO_x-eq annually (around 40% contribution of the LNG value chain). SRU and TGTU units have the highest contribution of $PM_{2.5}$-eq emission, 79.3%, among other stages, with around 1.48 million tons of $PM_{2.5}$-eq annually. Midpoint air emission impacts are highly dependent on the nature of the process equipment and the design purpose of the unit. Also, it depends on the fuel used and the characteristics of the fired stream. From the energy consumption and the land used perspectives, the majority contributors are the natural gas extraction stage with around 2,800 TJ and LNG shipping with 1,390 Km^2 annually, respectively. The MDEA Sweetening unit found the highest with approximately 73% in normalized water withdrawal and water consumption, representing 11.8 and 5.08 billion m^3, respectively. The gross operating surplus and salvage value indicators for the economic impact are considered positive, and operational and equipment costs are negative. The results concluded that the MDEA Sweetening unit presents the maximum annual gross operating surplus and operational cost with around 79.1 and 6.9 billion USD, respectively (about 26% and 44% contribution of each). Furthermore, the natural gas extraction stage showed most of the annual equipment cost and salvage value throughout the process chain with 26.2 and 6.56 billion USD, respectively. From the social perspective, all indicators are considered positive except for the human health impact. The natural gas extraction stage found the highest full-time employment and man-hours with around 2,300 Full-Time Employees and 4.78 million hours. On the other hand, human health impact is mainly affected by SRU and TGTU units. The employment compensation is investigated, and it found that the highest compensation comes from LNG shipping and the maximum total tax from MDEA Sweetening unit.

The sustainability assessment is then converted to sustainability factors following this research method. According to the results obtained, the Pre-separation unit and LNG receiving terminal have the best environmental performance by having the lowest environmental impact, with SF equal to 1. The MDEA Sweetening unit is considered the worst environmental performance, with the most inferior SF equal to 0.66. In terms of social and economic impacts, the natural gas extraction stage system presents the best performance among all other stages, with SF equal to 1. However, SRU and TGTU units illustrate the lowest performance from a social perspective, with SF equal to 0.41. On the economic side, LNG loading (export terminal) and LNG shipping are both showing the minimum performance in terms of economic impact, with SF equal to 0.73 for each stage. This research discussed several policy-making recommendations, and the importance of geopolitics risk factors and concerns is highlighted. Moreover, provide some essential suggestions that are expected to improve the sustainability of LNG as the current cleanest fossil fuel option worldwide.

Limitations of the current research

There is a lack in the literature getting information on drilling and extraction of natural gas to validate the accuracy. The MRIO sector is called natural gas extraction and processing, but there are no further details about the type of process. It would appear much more informative if further MRIO data splitting between natural gas extraction and natural gas processing. Uncertainty could also be presented in the Aspen HYSYS due to the design of the equipment and estimation of equipment cost social and environmental impacts. It is expected that the Aspen HYSYS is not deciding the maximum equipment capacity by the equipment's manufacturer or adding standby units that are available by design in real applications. It requires a manual entry for each additional tank, vessel, pump, valve, etc.

Moreover, LNG maritime transport operation is assumed as one type of carrier from Qatar to the United Kingdom throughout the calendar year. However, several types of carriers are currently in use for this trade. Finally, there was a limited number of social indicators in this research; however, more social indicators provide a comprehensive overview of the impact on people, communities, forests, oceans, and the whole world. SLCA and LCSA studies are of late, and more research is required to provide enough evidence on the sector's sustainability performance.

The LCSA method proposed and followed in this research is helpful and clear for each step. It is recommended to apply the tool to other industrial systems and identify any gap that can improve the method. As much as indicators provided and accurate data, the results are expected to be more representative. Furthermore, an uncertainty-embedded hybrid LCSA framework is needed to assess the uncertainty of LNG supply chains.

CRediT authorship contribution statement

Hussein Al-Yafei: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Ahmed AlNouss:** Methodology, Software, Formal analysis, Writing – original draft, Visualization. **Saleh Aseel:** Validation. **Murat Kucukvar:** Methodology, Writing – original draft, Conceptualization, Supervision, Project administration. **Nuri C. Onat:** Investigation, Validation, Resources, Supervision. **Tareq Al-Ansari:** Validation, Resources, Supervision.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecmx.2022.100246.

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