Energy 224 (2021) 120049

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Techno-economic and life cycle greenhouse gas emissions assessment of liquefied natural gas supply chain in China

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ARTICLE INFO

Article history:
Received 11 July 2020
Received in revised form
8 January 2021
Accepted 1 February 2021
Available online 9 February 2021

Keywords:
Liquefied natural gas
Techno-economic assessment
Life cycle greenhouse gas emission
Cold recovery
Blue hydrogen

ABSTRACT

This study assessed the techno-economic performance and life cycle greenhouse gas (GHG) emissions for various liquefied natural gas (LNG) supply chains in China in order to find the most efficient way to supply and use LNG. This study improves current literature by adding supply chain optimization options (cold energy recovery and hydrogen production) and by analyzing the entire supply chain of four different LNG end-users (power generation, industrial heating, residential heating, and truck usage). This resulted in 33 LNG pathways for which the energy efficiency, life cycle GHG emissions, and life cycle costs were determined by process-based material and energy flow analysis, life cycle assessment, and production cost calculation, respectively. The LNG and hydrogen supply chains were compared with a reference chain (coal or diesel) to determine avoided GHG emissions and GHG avoidance costs. Results show that NG with full cryogenic carbon dioxide capture (FCCC) is most beneficial pathway for both avoided GHG emissions and GHG avoidance costs (70.5–112.4 g CO_2-e/MJ_{LNG} and 66.0–95.9 \$/t CO_2-e). The best case was obtained when NG with FCCC replaces coal-fired power plants. Results also indicate that hydrogen pathways requires maturation of new technology options and significant capital cost reductions to become attractive.

1. Introduction

China consumes 22.3% of the total world primary energy consumption [1] resulting in 9.3 billion tonnes CO_2 emitted in 2017 [2,3]. NG is seen as the cleanest fossil fuel with 29%–44% less CO_2, 79%–80% less NO_x, 99.9%–99.996% less SO_2, and 92%–99.7% fewer particulates per unit of energy compared to oil and coal, respectively [4]. NG consumption in China reached 280.3 billion m^3 in 2018, while domestic NG production was only 157.5 billion m^3 [5]. As the domestic NG production cannot meet its consumption, China imports NG by two options: pipeline gas and liquefied natural gas (LNG). Chinese LNG imports have surged in recent years, surpassing pipeline gas imports in 2017 [6]. In 2018, LNG imports in China reached 73.0 billion m^3 [5], which is 26% of China's NG consumption and 2.8 times that in 2015 [7]. Moreover, the import infrastructure for LNG in China could double in 5 years from 2018 [8]. In 2018, 39.42 billion cubic meters of LNG (54%) were regasified directly and transported by pipeline to the end-users. The rest (33.58 billion m^3) of the LNG (46%) were transported in liquid form by truck, railway, or ship [9]. The imported LNG usage by sector in China by percentage was 18%, 45%, 22%, and 12% for power, industry, building, and transportation in 2016, respectively [10].

As the demand for LNG imports in China increases rapidly, it is essential to build new infrastructures in an economically and environmentally-friendly way. Life cycle assessment (LCA) is a robust methodology to evaluate technology, processes, projects, and supply chains for environmental impacts [11]. Previous studies focusing on life cycle GHG emissions of LNG can be divided into three general types. The first type of life cycle GHG emissions studies focus on parts of the LNG supply chain (mainly on the upstream). Barnett [12] assessed GHG emissions of liquefaction, shipping and regasification including 10 LNG plants in Australia and 5 shipping routes to Asia. He concluded that Australian LNG results in 38% less GHG emissions than other global suppliers. Safaei et al. [13] assessed well to tank GHG emissions of Nigerian LNG and they conclude that methane emissions could increase the life cycle (LC) GHG emissions by 59%. The second type of life cycle GHG emissions studies focus on comparing LNG with other energy sources, such as pipeline NG, synthetic natural gas (SNG), domestic NG, coal, diesel,

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https://doi.org/10.1016/j.energy.2021.120049

renewables etc. Jaramillo et al. [14] compared LC emissions of imported LNG, domestic NG, coal and SNG from coal gasification in United States for electricity generation. They found that imported LNG increased GHG emissions by 32% compared to domestic NG. Song et al. [15] compared LC emissions of diesel and LNG for heavy-duty vehicle for China using real time consumption data and actual vehicle population data. They found that replacing heavy duty diesel vehicles by LNG heavy vehicles could reduce emissions by 6.5−9.1 Mt CO_2 in 2020. The third type of life cycle GHG emissions studies focus on different usage options, such as power generation, hydrogen production, and vehicle fuel. Raj et al. [16] assessed well-to-wire GHG emissions of four Canadian shale gas reserves for power generation in China and found that the GHG emissions reduced by 38−43% compared to China's current coal-fired electricity. Zhang et al. [11] compared LC emission from regasification to various end-use for LNG including hydrogen production, electricity generation, and vehicle fuel. They found that the GHG emissions of using LNG to produce hydrogen was 45% and 53% of using LNG for electricity generation and vehicle fuel, respectively.

The abovementioned studies focus on a specific life cycle stage or a single usage option. However, few studies analyze the life cycle GHG emissions of various usage options, including hydrogen production, on the whole life cycle of LNG. There is also a lack of research focusing on the economic performance of the LNG supply chain, which could be as crucial as the life cycle GHG emissions performance of the supply chain. In addition, the opportunities for cold utilization of LNG in regasification processes are not included in previous studies, except for one study from Tamura et al. [17]. They assessed the reduction of GHG emissions by using LNG cold energy. Results shown 3% reduction in GHG emissions when suppling cold energy to air separation units and cold storage warehouses. Several studies assessed the technical performance of cold energy recovery of LNG regasification. Khor et al. [18] assessed the exergy efficiency and GHG emissions of LNG cold energy recovery for cryogenic applications, including air separation, dry ice production, deep freezing, and space cooling. They found that an LNG cold energy assisted power cycle reduced GHG emissions by 18.3%, while using LNG cold energy for space cooling could reduce GHG emissions by 38%. Gomez et al. [19] proposed an innovative LNG power plant, which capture CO_2 from flue gases using the cold energy of the LNG. Results indicated that the power plant could reach an efficiency of 65% with almost no GHG emissions. However, the life cycle GHG emissions and economic impact of these cold utilization systems for the entire LNG supply chain are not well investigated yet.

In anticipation of increased natural gas use in China in the near future, it is important to assess the GHG emissions and economic performance of different LNG supply chains to various end-users and to identify potential improvement in these supply chains resulting in improved environmental and economic performance. Therefore, this paper has the following objectives:

- To quantify the current LC energy efficiency, GHG emissions and costs of Australian LNG consumed in China for four end-users: power generation, industrial heating, residential heating, and truck usage;
- To estimate the impact on LC energy efficiency, GHG emissions and costs by applying cold energy recovery technologies and hydrogen production and usage in the current Australia-China LNG supply chain;
- To optimize Australia-China LNG supply chains to achieve the lowest GHG emission and costs.

The approach of this study is based on process-based material and energy flow analysis, LCA methodology, and production cost calculation to determine the energy efficiency, LC GHG emissions, and LC costs. This paper comprehensively assesses and compares the LC GHG emissions and LC costs of Australia-China LNG supply chains. The results aim to identify the potential improvement on LC GHG emissions and LC cost for various LNG end-users to accomplish energy-saving, cost-saving, and GHG emissions reduction for China.

2. Methodology

A process-based material and energy flow analysis method is used to calculate the energy consumption [20]. GHG emissions are determined based on LCA methodology following ISO 14040/44 [21,22]. The production cost of each LC stage is calculated based on annualized costs and yields [23]. The technical, economic, and environmental data for each stage can be found in Section 3 and Supporting Information. Three different functional units are selected in this study for LNG power generation, heat generation, and truck usage: 1 MJ electricity (MJ_e), 1 MJ heat (MJ_h), and 1 MJ work (MJ_w), respectively. The emissions and costs are normalized to a g $CO_{2\text{-}e}$/MJ and \$/MJ metric. This study excludes GHG emissions from the manufacturing and decommissioning of facilities. The economic analysis excludes land acquisition costs. The general parameters used in this study are shown in Table 1.

The energy efficiency η (%) per life cycle stage is calculated based Equation (1) [32]. Energy output E_{out} (MJ) is the delivered LNG for each life cycle stage. The energy input E_{in} (MJ) of each life cycle stage in the LNG supply chain is calculated as process fuel consumption PF_i (MJ) plus the delivered LNG or hydrogen (Equation (2)). Variable *i* is the type of process fuel used in this study, which includes LNG (NG) and electricity [33,34].

$$\eta = \frac{E_{in}}{E_{out}} \times 100\% \tag{1}$$

$$E_{in} = \sum PF_i + E_{out} \tag{2}$$

The life cycle GHG emissions of CO_2, CH_4, and N_2O from the operation of facilities are assessed for each supply chain. The GHG emissions (g $CO_{2\text{-}e}/MJ_{e,h,w}$) are aggregated as $CO_{2\text{-}e}$ emissions using IPCC AR5 GWP_{100} [26]. It includes upstream and combustion emissions of process fuel consumption, venting emissions, fugitive (methane leakage) emissions, and avoided CO_2 emissions, as shown in Equation (3). The upstream emission factor EF_u (g $CO_{2\text{-}e}$/MJ) refers to upstream GHG emissions related to the imported process fuel. The combustion emission factor EF_c (g $CO_{2\text{-}e}$/MJ) refers to GHG emissions due to the combustion of a certain type of fuel. Venting emission GHG_v (g $CO_{2\text{-}e}$/MJ) refers to the controlled release and burning of gases. Fugitive emission GHG_f (g $CO_{2\text{-}e}/MJ_{e,h,w}$) refers to leakage and unintended releases of gases. The cut-down CO_2 emission GHG_c (g $CO_{2\text{-}e}/MJ_{e,h,w}$) is due to the application of cold energy recovery of LNG to generate electricity, provide cooling duty and capture CO_2. The avoided GHG emissions GHG_a (g CO_2-e/MJ_{LNG}) are expressed in Equation (4), where GHG_{rc} (g $CO_{2\text{-}e}/MJ_{e,h,w}$) represents the life cycle GHG emissions of the reference chain. This study uses a process-based LCA approach to estimate the GHG emissions [35].

$$GHG = \sum PF_i \times (EF_u + EF_c)_i + \mathrm{GHG}_v + GHG_f - GHG_c \tag{3}$$

$$GHG_a = (GHG - GHG_{rc}) \times \eta \tag{4}$$

The production cost C_p (\$/MJ) is estimated for each LC stage. The upstream LNG life cycle cost is represented by the LNG importing price at the LNG terminal in China [36]. The downstream

Table 1
General technical, economic, and environmental parameters.

Parameters	Unit	Value	Reference
Australia LNG composition	%	N_2:0.01, CH_4:87.82, C_2H_6:8.30, C_3H_8:2.98, i-C_4H_{10}:0.40, n-C_4H_{10}:0.48	[24]
LNG lower heating value	MJ_{LHV}/kg	49.1	[24]
H_2 lower heating value	MJ_{LHV}/kg	127.7	[25]
CO_2 GWP_{100}	–	1	[26]
CH_4 GWP_{100}	–	28	[26]
N_2O GWP_{100}	–	265	[26]
Emission factor for electricity in China	g CO_2-e/MJ	206.8	[27]
Discount rate	%	10	[28]
Total capital requirement[a]	%-equipment and installation cost	143	[28]
LNG import price[b]	$/$MJ_{HHV}$	0.0075	[29]
Electricity price for industry	$/$MJ_e$	0.0364	[30]

[a] Total capital requirement (TCR) includes the costs of equipment, installation, engineering fees, contingencies, owner cost, and interest during construction. The values here are within the ranges for industrial chemical process construction [23].
[b] The LNG import price is the Chinese LNG import price from Australia in 2018 [31].

production cost per LC stage is calculated based on Equation (5) [23,37]. The annualized capital cost C_{ac} ($/year) is calculated by considering the discount rate r and plant life n in Equation (6). The total capital requirement C_{TCR} ($) includes cost for equipment, installation, engineering fees, contingencies, owner cost and interest during construction [28]. C_{TCR} is calculated by multiplying equipment and installation costs with the typical percentage of other cost components. C_{PF} and $C_{O\&M}$ ($/year) are the annual costs of process fuel and operation and maintenance (O&M), respectively. P_{LNG} ($/MJ) is the average LNG import price in China. Y (MJ/year) is the annual yield of the supply chain. The GHG avoidance costs C_a ($/t CO_2-e) are calculated in Equation (7) to show the economic performance of each supply chain. $C_{p,rc}$ ($/MJ) is the production for the reference chain. All the cost data are indexed to $\$_{2018}$ using the Chemical Engineering Plant Cost Index (CEPCI).

$$C_p = \frac{C_{ac} + C_{PF} + C_{O\&M}}{Y} + P_{LNG} \tag{5}$$

$$C_{ac} = C_{TCR} * \left(\frac{r*(1+r)^n}{(1+r)^n - 1}\right) \tag{6}$$

$$C_a = \frac{C_p - C_{p,rc}}{GHG - GHG_{rc}} \times 1,000,000 \tag{7}$$

3. System boundary and description

3.1. Reference chain

The reference chains represent typical energy sources for power generation, industrial heating, residential heating, and truck usage in China, as shown in Fig. 1. LNG is considered as a potential substitute for typical energy sources to reduce GHG emissions. All data used in the calculation of the reference chain are shown in Supporting Information table S2.

The reference for power generation is a coal power plant. In 2020, 64% of power generation is from coal and only 3% is from natural gas; these values predicted to be 55% and 5% by 2025 according to the policies expressed in the 13th Five-Year Plan and 19th Party Congress [38]. The unit capacity of coal-fired power is from 50 MW to 1000 MW [39]. Therefore, a coal-fired power plant is chosen as reference chain for power generation with average GHG emissions of 263.9 g CO_2-e/MJ_e [40,41] and costs of 10.8 $/$GJ_e$ [41,42].

The reference for industrial heating is a coal-fired industrial boiler. Coal and oil represent 80% and 15% of total energy input for industrial boilers, respectively [43]. The national and local governments of China plan to eliminate coal-fired boilers with small capacity (steam less than 20 t/h) and retrofit large coal-fired boilers to increase their efficiency and decrease pollution [44]. Therefore, a coal-fired industrial boiler is chosen as the reference chain for industrial heating with average GHG emissions of 124.3 g CO_2-e/MJ_h [45] and costs of 5.4 $/$GJ_h$ [42,43,46].

The reference for residential heating is the central coal boiler heating system. The central heating supply policy is an important policy that affects people's life in China [47]. It covers approximately 70% and 5% of urban building areas in northern and southern China, respectively [48]. This central heating supply burns coal by up to 85% [49]. The heating of the rest of China is mainly provided by air conditioners using electricity [48]. The potential of replacing coal-fired electricity with NG will be shown in the power generation section. Therefore, a central coal boiler heating system is chosen as the reference chain for residential heating with average GHG emissions of 124.3 g CO_2-e/MJ_h [45] and costs of 9.0 $/$GJ_h$ [42,48,50,51].

The reference for truck usage is diesel trucks. Diesel represented 98% of truck fuel in China in 2018 [52]. Truck road freight accounts for approximately 80% of cargo transportation in China and will remain as such for a long time [53]. Diesel trucks are less than 10% of China's vehicle population but they are the primary contributor of nitrogen oxide emissions (70%) and particulate matter emissions (90%) of all on-road emissions [54]. The State Council issued the Air Pollution Prevention and Control Plan to control on-road emissions and promote cleaner fuel trucks, including CNG, LNG, or electric trucks [55]. Therefore, diesel trucks are chosen as the reference chain for truck usage with average GHG emissions of 1567 g CO_2-e/km [27,56–58] and costs of 0.07 million $ for a 23 tonnage truck [56,59,60].

3.2. LNG supply chain 1: current chain

The Australia-China LNG supply chain in Fig. 2 is the current LNG supply chain. LNG is imported from Western Australia and is received in the Shanghai LNG terminal. The imported LNG is distributed in the Near Harbor area (200 km) and Far from Harbor area (1000 km). The upstream GHG emissions of the LNG supply chain, including NG production and processing (and possible pipeline transport), liquefaction, and shipping, are 24.4 g CO_2-e/MJ_{LNG} based on average value of 7 previous studies [12,17,61–65]. Upstream production cost is 7.5 $/$GJ_{LNG}$ based on the LNG import price from Australia to China in 2018 [29].

Downstream life cycle stages include LNG regasification, transportation, and final use, as shown in Fig. 3. The energy consumption, GHG emissions, and cost of each LC stage are discussed in the

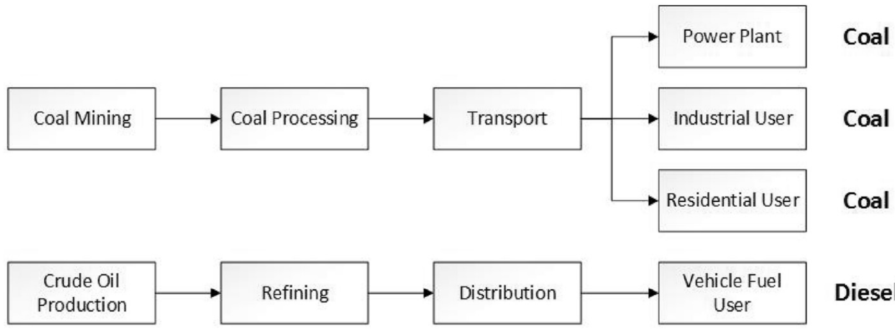

Fig. 1. Reference chains in China.

Fig. 2. Transport route of LNG or NG from Shanghai LNG terminal in China [5,66].

following paragraphs. All data used in calculation of downstream are shown in Supporting Information table S3, S5, S6, S7, S9, and S11. The locations of four end-users are assumed as follows:

- Near Harbor: The power plant and industrial heating users are located in the harbor and the residential heating users and truck users are located 200 km away from the harbor.
- Far from Harbor: All four end-users are located 1000 km away from the harbor.

Regasification process turns the LNG into NG for pipeline transportation, which includes LNG storage tanks and regasification systems [24,67]. Among several vaporizer types, three of them are used in China: open rack vaporizers (ORV) and submerged combustion vaporizers (SCV) are both applied in large-scale terminals for normal and secondary peak shaving operations [68]; Ambient air vaporizers (AAV) are used in small-scale terminals [69]. Seawater and air is used in ORV and AAV as the heat source, respectively. The heat source for SCV comes from the combustion of natural gas. The Shanghai Yangshan LNG terminal, which has 3 million tonne LNG per annual (MTPA) regasification capacity [70], is chosen to represent the large-scale regasification with electricity consumption of 0.89 MJ/GJ_{LNG} [64,67,69,71,72] and capital costs of 1472.5 million \$ [73]. The small-scale regasification capacity is assumed to be 0.45 MTPA with electricity consumption of 0.97 MJ/GJ_{LNG} [64,67,69,71,72] and capital costs of 258.7 million \$ [73], according to the IGU small-scale LNG report [68,74].

Natural gas pipeline mainly includes transmission pipelines and compression stations. The capacity of the natural gas pipeline is assumed according to a pipeline project of the Shanghai Gas Limited Company [75] that is 1.75 billion m^3 NG. The lengths of natural gas pipelines considered in this study are 1000 km and 200 km. The energy consumption of natural gas compression station is assumed as the average natural gas consumption of an entire year (MJ/MJ_{NG}) [76]. The natural gas consumption is 0.19 kJ/($GJ_{NG}\cdot$km) [76] and the capital costs are 27.1 k\$/km [75,77,78].

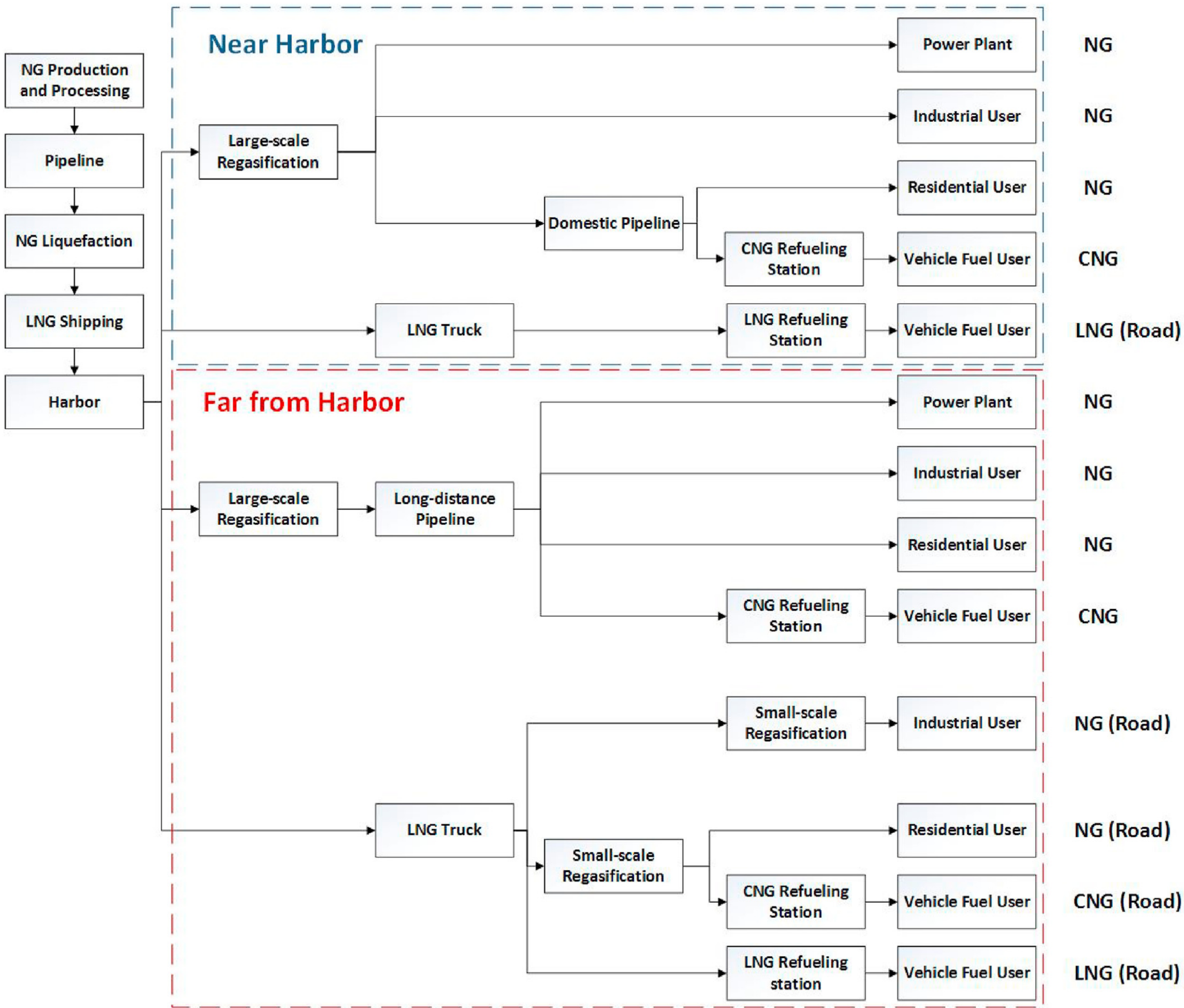

Fig. 3. LNG Supply Chain 1: Current chain.

LNG trucks are an alternative transport method to deliver LNG in liquid form. Some remote areas with dispersed populations, isolated factories, and complex terrain are not economically viable for pipelines constructions [79]. For these potential end-users, LNG road transport could have an advantage over pipelines. In China, the LNG road transport network, which is referred to as a “virtual pipeline”, covers approximately 1000 km from the Eastern Coast to Western China [80]. The LNG truck capacity, which is 23 tonnes, is collected from Chart LNG transport trailers [81]. However, transporting LNG through trucks is expensive and limited to low volume [82]. The natural gas consumption is 0.20 kJ/(GJ_{NG}·km) [27] and average costs per truck are 0.25 million $ [73].

The specific refueling systems for LNG and CNG are investigated separately in this study. The capacities of LNG and CNG refueling stations are assumed to be the same based on several studies [73,83], in terms of total stored 520 tonnes per annual (TPA) product. LNG refueling stations are technologically mature and settled with more than 3200 stations in China in 2016 [83,84]. An LNG refueling station is mainly comprised of storage tanks, cryogenic pumps, heaters, and dispensers [84]. The energy consumed by the LNG refueling stations is mainly electricity to run pumps and heaters, which is 2.10 MJ/GJ_{LNG} [83]. The capital costs for 520 TPA LNG refueling station are 0.16 million $ [77,83,85]. CNG refueling stations are connected to the local NG grid and mainly consist of inlet gas treatment, a compressor, storage tanks, and dispensers. China has the largest natural gas vehicle population around the world with more than 8400 CNG refueling stations in 2018 [86]. Vehicles are filled with CNG at 200 bar [87]. The energy consumption of CNG refueling station is mainly electricity for compressors and is approximately ten times higher than the respective value for LNG refueling stations, which is 19.40 MJ/GJ_{LNG} [88,89]. The capital costs of 520 TPA CNG refueling station are approximately 1.5 times higher than that of LNG refueling station, which are 0.25 million $ [77,83,85].

The life cycle stage of end-users is the last life cycle stage considered in this study. For LNG or NG, five end-users are included: power plants, industrial steam systems, residential central heating systems, CNG trucks, and LNG trucks.

A natural gas combined cycle (NGCC) power plant is considered for power generation in this study. NGCC power plants have high efficiency ranging from 55% to 60% [90] because the waste heat is recovered to run steam turbines [16]. The natural gas consumption is 1.74 MJ/MJ_e [16,45,62,90,91]. The capacity of NGCC power plants, which represent large-scale power plants, are assumed as 300 MW electricity (MW_e) [92]. The capital costs are 229.26 million $ [46,50,91].

An industrial steam system with a natural gas boiler is considered for industrial heating in this study. The efficiency of the industrial NG boiler is assumed as 90% to produce saturated steam at 1 MPa [45,46,93]. The capacity of the industrial steam system is 29.98 MW heat (MW_h) according to several studies [43,94]. The natural gas consumption is 1.11 MJ/MJ_h [43,45,49,93] and the capital costs are 3.91 million $ [43,46,50]. The residential central heating system is considered for residential heating is based on a natural gas boiler. The efficiency of the NG boiler for the central heating system is assumed as 90%, according to previous studies [45,49]. The capacity of the central heating system is 7.59 $MW_{h,}$ according to the area size of 0.5 million m^2 [48]. The capital costs of residential central heating system is much higher than industrial steam system due to additional costs of heating stations, external networks, and indoor radiators [48]. The natural gas consumption is 1.11 MJ/MJ_h [43,45,49,93] and the capital costs are 0.89 million $ [46,48,50].

Two types of heavy-duty trucks are considered in this study: CNG and LNG heavy-duty trucks. CNG and LNG trucks have similar energy efficiency and costs due to their similar engine systems [27]. The average natural gas consumption for CNG and LNG truck (23 tonnages) are 17.07 MJ/km and 16.81 MJ/km [27,86,88,95], respectively. The primary difference between them is the fuel storage tank; CNG trucks need high pressure tanks and LNG trucks need insulated cryogenic tanks. The storage tanks of LNG trucks are cheaper than those of CNG trucks, which makes the price of LNG trucks 10% lower than that of CNG trucks [96]. The average costs for CNG and LNG truck (23 tonnages) are 0.11 million $ and 0.10 million $ [59,60,97], respectively.

3.3. LNG supply chain 2: cold energy utilization chain

To improve the current LNG supply chain (Supply Chain 1), LNG cold energy utilization technology is applied in the cold energy utilization chain (Supply Chain 2 in Fig. 4). LNG releases a large amount of cold energy in the regasification process, which could be recovered by cold recovery application to improve its efficiency. Cold recovery application is considered an add-on modification in existing regasification plants in this study. After modification, the energy consumption in the original regasification process is saved, and part of cold energy in LNG is recovered, however, the cost of the regasification plant also increases. It is assumed that venting and fugitive emissions after adding cold recovery remain the same as in the original regasification plant. Four types of cold recovery options are used in this study: cold power generation (CP), direct cold usage (DC), partial cryogenic carbon dioxide capture (PCCC), and full cryogenic carbon dioxide capture (FCCC). All data used in calculation of cold energy recvoery are shown in Supporting Information table S8.

CP is the most studied application of LNG cold energy recovery and is based on a direct expansion cycle, Rankine cycle, Brayton cycle, or a combination of these [98]. The power generated from CP application is assumed as the mean value of 13 studies and 2 operation data [98] and is assumed to replace electricity from the grid. The electricity replaced from CP is 2.62 MJ/GJ_{LNG} [98] and the capital cost is 54.5 million $ [99]. The DC considered in this study includes four applications: air separation units, dry ice production, freezing, and district cooling [18]. The cold energy recovered from DC is assumed to replace electricity from the grid, which is used to generate cold. The cold energy recovered from DC is also assumed as the mean value of the four applications [18]. The electricity replaced from DC is 2.62 MJ/GJ_{LNG} [18] and the capital cost is 42.1 million $ [99]. The CP and DC applications are only applied in large-scale regasification, where the potential industrial users are nearby.

PCCC and FCCC are established according to four studies [19,99–101]. PCCC recovers LNG cold energy to partially capture and liquefy CO_2 from flue gas from the power plant or industrial end-users, and FCCC needs additional electricity input to fully capture and liquefy CO_2. The electricity input for FCCC in power plants is from its generation, and the electricity input for FCCC in industrial end-users is from the national electricity grid. The electricity consumption for FCCC is 20.43 MJ/GJ_{LNG} [19,99–101]. The capital costs of PCCC for large-scale and small-scale liquefaction are 69.0 and 9.2 million $ [99], respectively. The capital costs of FCCC for large-scale and small-scale liquefaction are 83.5 and 12.5 million $ [99], respectively. After the CO_2 is captured from flue gas, it is transported to its storage site or industrial CO_2 utilization facilities [102]. As CO_2 transport, storage, and utilization fall outside the system boundary, their impacts on energy efficiency, GHG emissions, and costs are not considered in this study.

3.4. LNG supply chain 3: hydrogen chain

As an alternative to the current LNG supply chain, this study includes H_2 production and transport after LNG arrived in the harbor as shown in Fig. 5 (Supply Chain 3). Hydrogen is seen as an interesting energy carrier as it can be used to decarbonize the hard-to-abate sectors [1]. The energy consumption, GHG emissions, and costs of each LC stage of hydrogen supply chain are based on existing pioneer projects and are discussed in following. For the NH area, the imported LNG is directly sent to a hydrogen production factory, which is located near the harbor. Then, the hydrogen is distributed by pipeline to nearby users. For the FH area, the LNG is transported by truck to a hydrogen production factory. Then, the hydrogen is distributed to end-users. All data used in calculation of hydrogen chain are shown in Supporting Information table S4 and S10.

Hydrogen production is based on the steam methane reforming (SMR) method to produce hydrogen using natural gas as feedstock. SMR is the most common production method for hydrogen, and therefore, it is selected in this study to produce hydrogen [103]. It involves a catalytic conversion of methane and steam to hydrogen [25]. The capacity of hydrogen production is assumed to be 0.15 MTPA, which is based on the capacity of small-scale regasification. This hydrogen production capacity belongs to large-scale plants, which are more energy-efficient (85%) than the small-scale plants [103]. The natural gas and electricity consumption are 1.17 MJ_{NG}/MJ_{H2} and 4.67 × 10^-3 MJ/MJ_{H2} [25,103]. The capital costs for a 0.15 MTPA hydrogen plant are 231.9 million $ [25,77,104].

The capacity of the hydrogen pipeline is assumed according to a DOE report [78], which is 1.01 billion cubic meters H_2 annually. Hydrogen needs a dedicated pipeline because it can only be blended in the natural gas pipeline up to 15% due to leakage issues [77]. The length and design pressure are 200 km and 60 bar, respectively. It is assumed that the energy consumption for hydrogen compression stations is equivalent to natural gas compression stations with a difference in electricity use. The venting and fugitive emissions for hydrogen pipelines are zero. The electricity consumption is 0.31 $kJ/(GJ_{H2}\cdot km)$ [76] and the capital costs are 18.4 k$/km [75,77,78].

The capacity of hydrogen refueling stations is assumed as 240 TPA based on previous research [103]. Hydrogen refueling stations mainly consist of storage tanks, a compressor, and dispensers [103]. China is planning to increase its number of hydrogen refueling stations to more than 100 in 2020 [105]. The hydrogen of the fuel cell vehicles is at 600–700 bar [77,103]. The energy consumption of hydrogen refueling stations, which is mainly electricity for compressors, is highest among the three types of refueling stations in this study. It is four times higher than CNG refueling stations with equivalent amounts of fuel filled [88,103]. For a 240 TPA hydrogen refueling station, the electricity consumption is 76.10 MJ/GJ_{H2} [103] and the capital costs are 0.49 million $ [77,83,85].

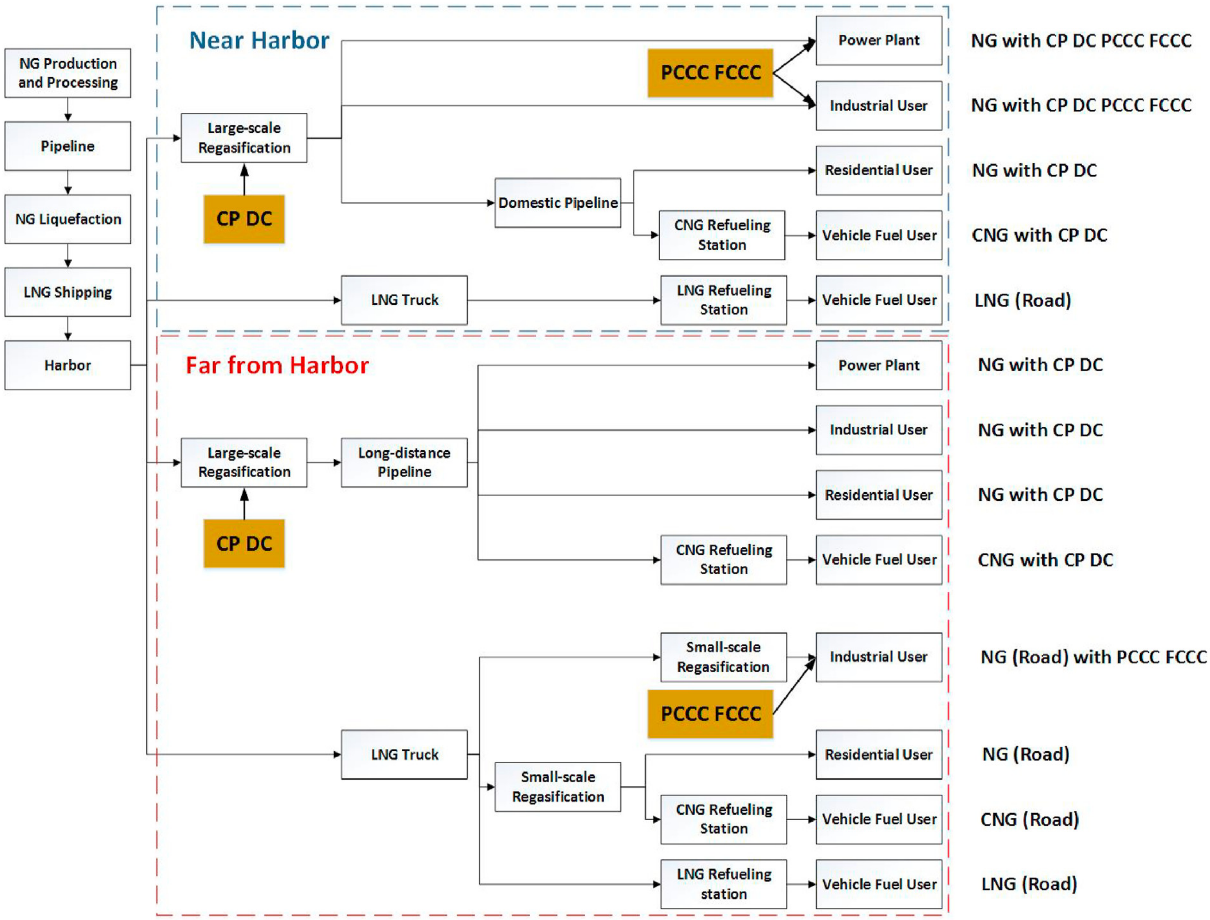

Fig. 4. LNG Supply Chain 2: cold energy utilization chain.

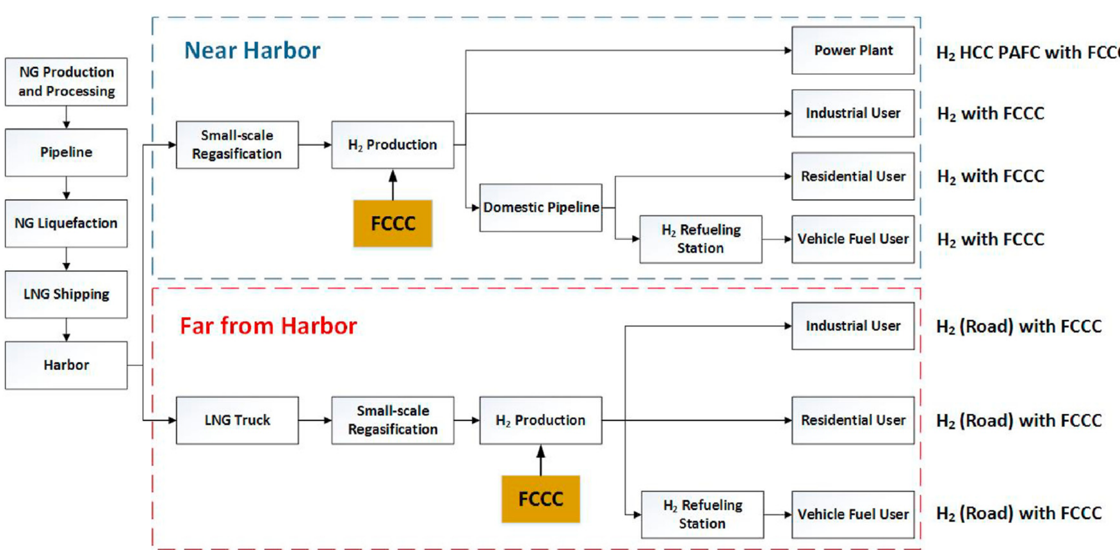

Fig. 5. LNG Supply Chain 3: Hydrogen chain.

The life cycle stage of four end-users, which include power generation, industrial heating, residential heating, and truck usage, is the last life cycle stage for hydrogen.

There are two types of large-scale hydrogen power plants considered in this study: a hydrogen-fueled combined cycle (HCC) plant and phosphoric acid fuel cell (PAFC) hydrogen power plant. The first hydrogen power plant in the world is the Fusina (Venice) hydrogen power plant, which is an HCC power plant built in 2010 with a 16-MW capacity [106]. The cost and capacity of the Fusina hydrogen power plant are used in this study to represent HCC power plants. The efficiency of HCC power plants is assumed to be the same as that of NGCC power plant based on the work of

Pambudi et al. (2017) [107]. The hydrogen consumption is 1.74 MJ/MJ_e [107] and the capital costs are 64.85 million $ [106]. Large-scale PAFC hydrogen power plants are considered in this study. The Daesan hydrogen fuel cell power plant in Korea is the world's first large-scale hydrogen fuel cell power plant with a 50-MW capacity. The cost, capacity, and efficiency of the Daesan hydrogen power plant are used in this study to represent PAFC hydrogen power plants. The hydrogen consumption is 1.82 MJ/MJ_e [108–110] and the capital costs are 216.01 million $ [111,112].

The industrial and residential heating system for hydrogen in this study is the hydrogen boil system. Hydrogen has a similar Wobbe Index as natural gas, which enables the existing natural gas boilers to run on hydrogen mixtures up to 28% [113]. It also implies that the hydrogen boiler has comparable efficiency to a natural gas boiler. Based on the Frazer-Nash Consultancy report [114], newly built hydrogen boiler systems are as efficient as natural gas boiler systems. As NG boilers can run on high concentration of hydrogen with the small modification of replacing the burner tips [115], it is assumed that hydrogen boiler systems cost 5% more than the natural gas boiler systems [114]. The hydrogen consumption for hydrogen heating system is 1.11 MJ/MJ_e [114]. The capital costs for the hydrogen industrial and residential heating system are 4.11 million $ and 0.93 million $ [43,46,114], respectively.

Hydrogen fuel cell (HFC) heavy-duty trucks are considered in this study as vehicular end-users for hydrogen. The energy efficiency of HFC trucks is two times higher than CNG/LNG trucks [86,88] but the cost for HFC trucks is also much higher than CNG/LNG trucks. The cost estimation of HFC heavy-duty trucks is mainly based on a report of Fuel Cell and Hydrogen Joint Undertaking [59], which focuses on the technical and economic performances of these trucks. The hydrogen consumption for Hydrogen fuel cell truck is 8.24 MJ/km [27,86,88,95] and the costs are 0.35 million $ [59,60,97].

4. Results

The results in Fig. 6, Fig. 7, Fig. 8, and Fig. 9 show that CP and DC slightly reduce GHG emissions by 0.9–1.2% and production costs by 0.2–0.8% compared to the NG pathway in all four end-users. The PCCC reduced GHG emissions by 9.5–10.4% and production costs by 0.2–0.7% compared to the NG pathway in power generation and industrial heating. FCCC and hydrogen production pathways have significantly changed the GHG emissions and production costs of the LNG supply chain. The detailed results are shown in section 4.1–4.4.

4.1. Power generation

The life cycle GHG emissions, production cost, and energy efficiency of each pathway for power generation are shown in Fig. 6. The avoided GHG emissions and GHG avoidance cost compared to a coal-fired power plant are shown in Table 2. In the NH area, the GHG emissions of NG with FCCC are approximately 15% lower than those of H_2 HCC with FCCC and H_2 PAFC with FCCC. The production costs are 76.4% and 70.8% lower than those of H_2 HCC with FCCC and H_2 PAFC with FCCC, respectively. NG with FCCC has the largest avoided GHG emissions of 112.4 g CO_2-e/MJ_{LNG} and NG with PCCC has the lowest GHG avoidance cost of 57.4 $/t CO_2-e in the NH area. In the FH area, NG, NG with CP, and NG with DC have similar performances. NG with CP has the largest avoided GHG emissions of 73.1 g CO_2-e/MJ_{LNG} and the lowest GHG avoidance cost of 70.1 $/t CO_2-e in the FH area.

4.2. Industrial heating

Fig. 7 presents the results of the life cycle GHG emissions, production cost, and energy efficiency of each pathway for industrial heating. Table 3 shows the avoided GHG emissions and GHG avoidance cost compared to a coal-fired industrial boiler. In the NH area, the GHG emissions and production costs of NG with FCCC are 27.8% and 66.7% lower than that of H_2 with FCCC, respectively. In the FH area, the GHG emissions and production cost of NG (road) with FCCC are 29.3% and 66.8% lower than that of H_2 (road) with FCCC, respectively. For industrial heating NG with FCCC in the NH area and NG (road) with FCCC in the FH area have the largest avoided GHG emissions of 70.5 and 66.3 g CO_2-e/MJ_{LNG} and lowest GHG avoidance costs of 95.9 and 124.1 $/t CO_2-e, respectively.

4.3. Residential heating

As shown in Fig. 8, the life cycle GHG emissions, production cost, and energy efficiency of residential heating are compared between pathways. The avoided GHG emissions and GHG avoidance costs compared to a central coal boiler heating system are shown in Table 4. Due to the same NG boiler efficiency in industrial and residential heating systems, the GHG emissions performance of each pathway for residential heating is similar to that of industrial heating. Due to the additional costs of heating stations, external networks, and indoor radiators compared to industrial heating, the production costs of residential heating is higher than industrial heating. It is clear for residential heating that H_2 with FCCC has the largest avoided GHG emissions of 51.8 and 49.5 g CO_2-e/MJ_{LNG} in the NH and FH areas, respectively. NG, NG with CP, and NG with CD have similar GHG avoidance costs in the NH and FH areas for residential heating.

4.4. Truck usage

Fig. 9 shows the life cycle GHG emissions, production costs, and energy efficiency of each pathway for truck usage. Table 5 presents the avoided GHG emissions and GHG avoidance costs compared to diesel trucks. In both the NH and FH areas, the GHG emissions and production costs of LNG (road) are 7.2–8.4% and 16.9–18.5% lower than that of CNG (CNG (road)) pathways, respectively. H_2 with FCCC has the highest GHG emissions but also the highest production costs in the NH and FH areas. It is also clear that H_2 with FCCC has the largest avoided GHG emissions of 104.9 and 102.2 g CO_2-e/$MJ_{LNG,}$ and the LNG (road) has the lowest GHG avoidance costs of 79.4 and 114.3 $/t CO_2-e in the NH and FH area, respectively.

4.5. Overall results of four end-users for avoided GHG emissions and GHG avoidance costs

The comparison of pathways on avoided GHG emissions and GHG avoidance costs is shown in Fig. 10. CP and DC slightly reduced GHG emissions and production costs compared to NG pathway in all four end-users. The reason for a minor reduction in GHG emissions is that energy-saving and energy generated (electricity and cold) in the regasification process is only a small portion (around 1%) of the LNG supply chain. The reason is that the cost-saving caused by energy-saving exceeds the increase in capital costs. PCCC pathways have higher avoided GHG emissions and lower GHG avoidance costs than CP and DC pathways in power generation and industrial heating, indicating that using LNG cold energy to capture CO_2 has better performance on reducing GHG emissions compared to cold power generation and direct cold usage.

NG with FCCC pathways have the highest avoided GHG emissions with relatively low GHG avoidance costs in power generation

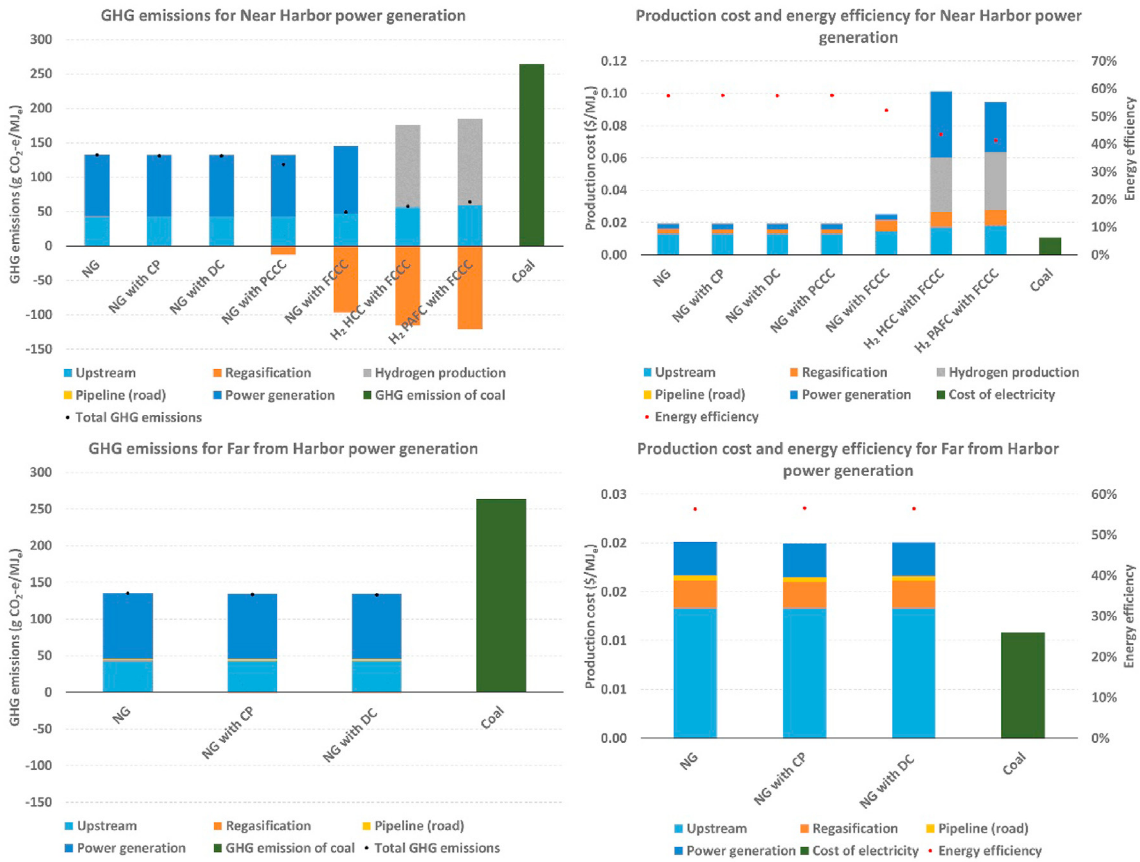

Fig. 6. GHG emissions, production cost and energy efficiency for power generation.

and industrial heating in NH compared to H_2 pathways. This is because H_2 pathways have the same or slightly higher power generation and industrial heating efficiency compared to NG with FCCC pathways. Moreover, H_2 pathways need one more conversion step from NG to H_2. Notably, H_2 pathways are relatively novel, the cost is significantly high in all four end-users on short term. Therefore, H_2 pathways have lower energy efficiency and higher GHG emissions compared to NG with FCCC pathways, indicating that the H_2 pathways do not have advantages compared to NG with FCCC in both GHG emissions and production costs for power generation and industrial heating in short term.

For residential heating, H_2 pathways have the highest avoided GHG emission but also the highest GHG avoidance costs. CP and DC pathways are only slightly better than NG pathways. Therefore, the current NG pathways for residential heating are the most attractive pathways for residential heating in the short term. In the long term, H_2 pathways could be applicable when cost is reduced due to technological development and economies of scale. For truck usage, NG pathways include CNG pathways and LNG pathways. LNG pathways have higher avoided GHG emission and much lower GHG avoidance costs than CNG pathways. This is because LNG pathways do not need regasification process and LNG pathways have lower energy consumption, GHG emissions, and costs on LNG refueling station compared to CNG refueling stations. The high energy consumption, GHG emissions, and costs of CNG refueling stations are caused by the need for NG to be compressed to CNG. This indicates that LNG trucks are more environmentally-friendly and economical compared to CNG trucks. H_2 fuel cell truck have much higher avoided GHG emissions with similar GHG avoidance costs than CNG pathways. The low GHG emissions are mainly due to the high energy efficiency of H_2 fuel cell truck, which is two times higher than CNG and LNG trucks. Therefore, LNG pathways and H_2 pathways are the best pathways for truck usage in terms of GHG avoidance costs and avoided GHG emissions, respectively.

The comparison of four end-users shows that NG with FCCC pathways for power generation are the best pathways with high avoided GHG emissions and low GHG avoidance costs. Besides power generation, FCCC for industrial heating is also attractive compared to other pathways for industrial heating due to high GHG emissions and low GHG avoidance costs. In conclusion, applying FCCC to the LNG supply chain for power generation is the best pathway among all four end-users that can avoid a large amount of GHG emissions at relatively low costs. FCCC, CP and DC, and LNG pathways are the most attractive pathways in industrial heating, residential heating, and truck usage, respectively.

5. Discussion

5.1. Sensitivity analysis

As the energy consumption and costs of NG pipeline, H_2 pipeline, and LNG truck transport per unit distance and unit energy are relatively insignificant compared to other life cycle stages, the GHG emissions and production costs are not sensitive to transport options [27]. The major factors affecting GHG emissions and production costs include LNG import price and upstream GHG emissions, energy efficiency for hydrogen production, energy efficiency for cold recovery, and energy efficiency and costs for end-users.

China's average LNG import prices varied from 0.0036 $/MJ to

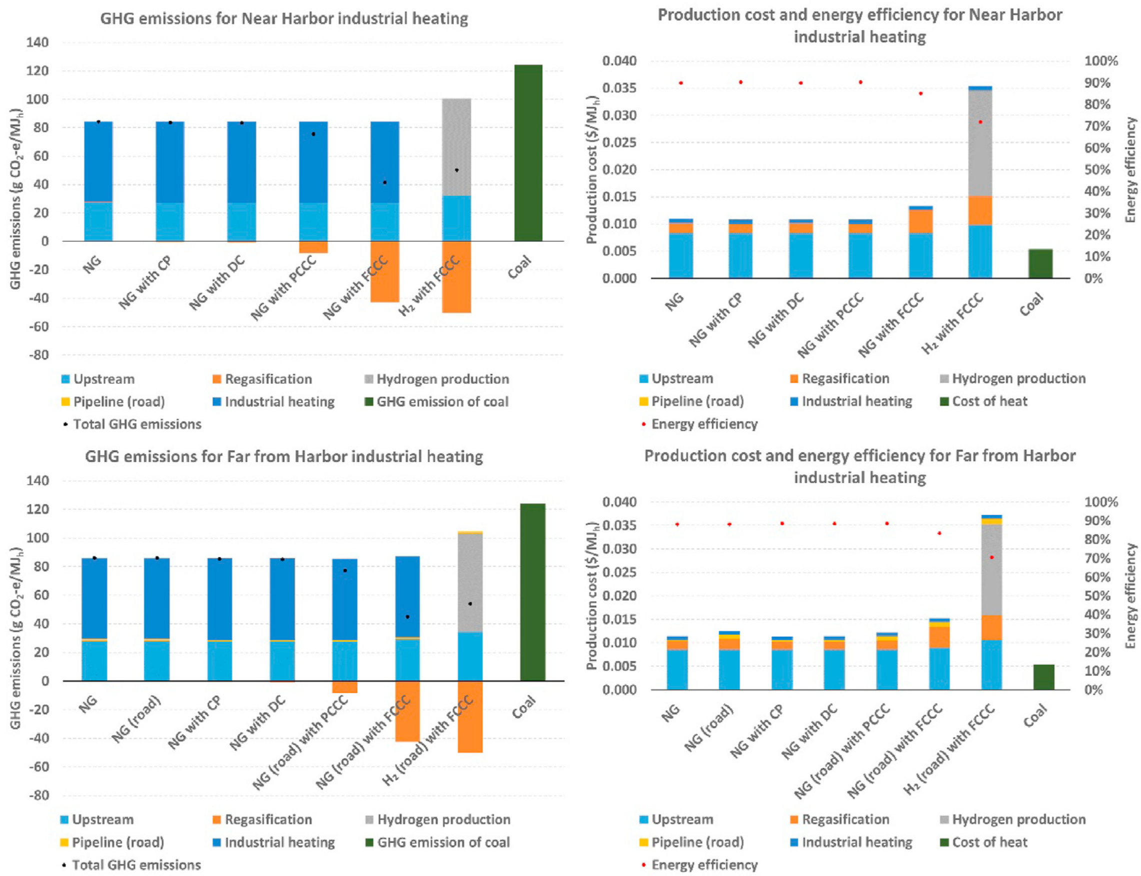

Fig. 7. GHG emissions, production cost and energy efficiency for industrial heating.

0.0133 $/MJ from 2008 to 2018 [29]. The upstream GHG emissions for LNG from Australia to China varied from 14.45 g CO_2-e/MJ_{LNG} to 43.64 g CO_2-e/MJ_{LNG} (according to section 4.1). The impact of LNG import price and the upstream GHG emissions is illustrated by the pathway of NG with FCCC for power generation in the NH area. If the LNG import price is assumed to be 0.0036 $/MJ, the GHG avoidance costs will be 45.7 $/t CO_2-e, which is reduced by 48%. If the LNG import price is assumed to be 0.0133 $/MJ, the GHG avoidance costs will be 149.3 $/t CO_2-e, which is increased by 70%. If the upstream GHG emissions are assumed to be 14.45 g CO_2-e/MJ_{LNG}, the avoided GHG emission and the GHG avoidance costs will be 103.3 g CO_2-e/MJ_{LNG} and 79.1 $/t CO_2-e, respectively. The avoided GHG emissions increase by 11% and the GHG avoidance costs are reduced by 10%. If the upstream GHG emissions are assumed to be 43.64 g CO_2-e/MJ_{LNG}, the avoided GHG emission and the GHG avoidance costs will be 74.1 g CO_2-e/MJ_{LNG} and 110.3 $/t CO_2-e, respectively. The avoided GHG emissions decrease by 21% and GHG avoidance costs increase by 26%. The LNG import price and upstream GHG emission significantly affect the GHG emissions and production costs for NG with FCCC; a similar impact can be found for other pathways.

The energy efficiency for H_2 production using SMR varies from 74% to 85% [25]. The energy efficiency of 85% is used in this study for the newly built H_2 production plant. The impact of the energy efficiency of H_2 production is illustrated by the pathway of H_2 PAFC with FCCC in the NH area. If the energy efficiency is 74%, the avoided GHG emissions and the GHG avoidance costs will be 88.7 g CO_2-e/MJ_{LNG} and 441.1 $/t CO_2-e, respectively. The avoided GHG emissions decrease by 5% and GHG avoidance costs increase by 17%. As SMR is the most common method for H_2 production and its technology is mature [25], the energy efficiency cannot be significantly improved in the short term. Therefore, the energy efficiency used in this study can indicate SMR H_2 production in the short term.

Cryogenic power generation from LNG regasification varies from 0.00108 MJ/MJ_{LNG} to 0.00595 MJ/MJ_{LNG} [98,116]. The impact of electricity generated from CP is illustrated by the pathway of NG with CP for power generation in the NH area. If the 0.00108 MJ/MJ_{LNG} electricity is generated from CP, the GHG emissions and economic benefits would almost vanish compared to NG pathways. If the 0.00595 MJ/MJ_{LNG} is generated from CP, the avoided GHG emissions and GHG avoidance costs will be 58.2 g CO_2-e/MJ_{LNG} and 94.6 $/t CO_2-e, respectively. The avoided GHG emissions increase by 2% and GHG avoidance costs reduce by 3%. The GHG emissions and economic benefits could make CP options applicable in the short term.

The power generation efficiency for H_2 PAFC with FCCC is assumed as 55% [108,109] in this study. If an alkaline fuel cell is used in the H_2 power plant, the electric efficiency can reach 70% [108,117]. Then the avoided GHG emissions in the NH area will be 116.2 g CO_2-e/MJ_{LNG} and 320.4 $/t CO_2-e, respectively. The avoided GHG emissions increase by 40% and the GHG avoidance costs reduces by 23%. The high efficiency of alkaline fuel cell makes the avoided GHG emissions of H_2 fuel cell power plant exceed those of NG with FCCC by 3% in the NH area. The costs for the H_2 fuel cell truck is assumed as 0.35 million $ in this study. According to a Fuel Cell and Hydrogen Joint Undertaking report [59], the costs for the H_2 fuel cell truck will be 0.12 million $ in 2030. If the costs for the H_2 fuel cell truck is assumed as 0.12 million $ for the H_2 with FCCC in

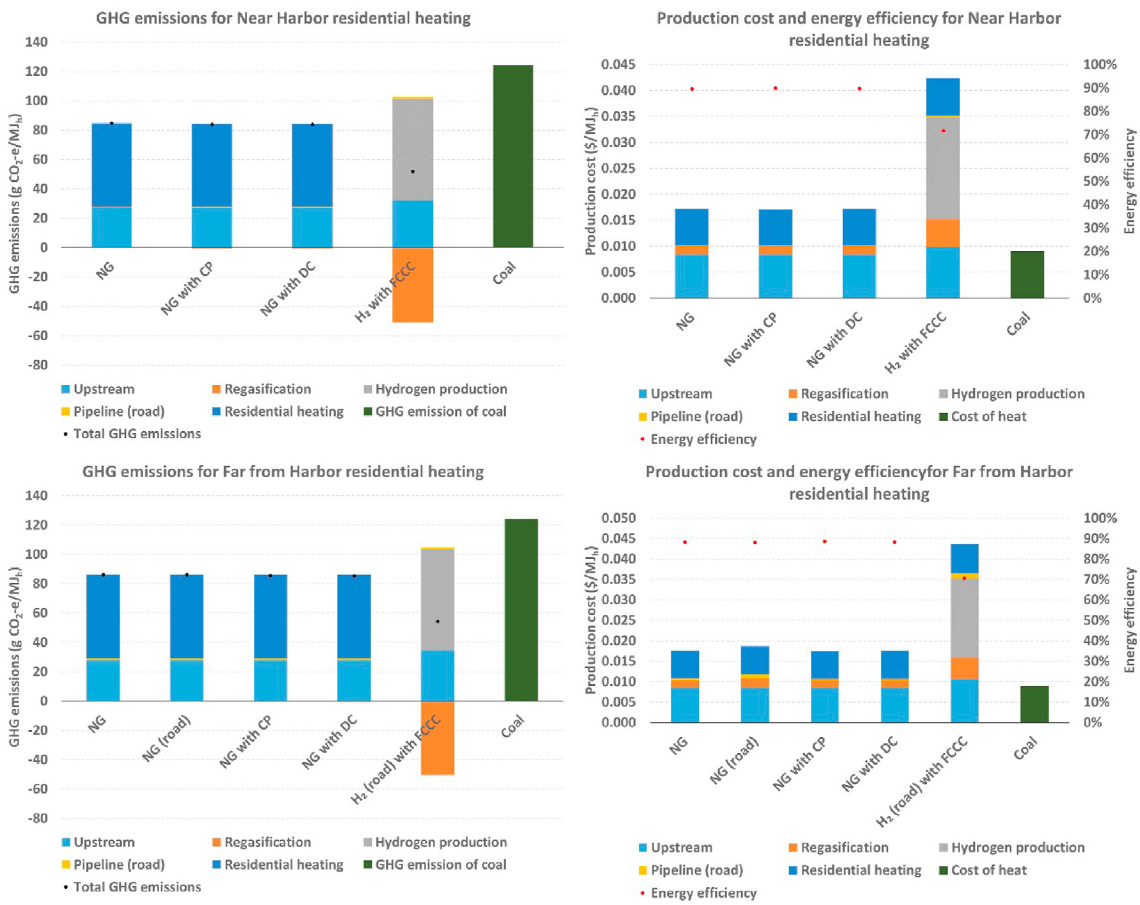

Fig. 8. GHG emissions, production costs, and energy efficiency for residential heating.

the NH area, the GHG avoidance costs will be 192.5 \$/t CO_2-e, which is a 60% reduction. This indicates that the hydrogen pathway could only have better GHG emission and cost performances by technological development and cost reduction.

5.2. *Study limitations and future work*

The results of this study have some limitations. One limitation of this study is data quality of capital cost for each life cycle stage, especially for the cost estimation of cold recovery at the regasification process and hydrogen pathways, due to limited information for capital cost and the difficulty of capital cost estimation. Much literature lack cost estimation and optimization.

Combined heat and power generation for the hydrogen fuel cell is a promising end-use and its overall efficiency can reach 85% [108,110]. It is not included in this study to avoid high complexity in allocation of GHG emissions and comparison between four end-users. Further efforts should be made in investigating the performance of combined heat and power generation and cover various end-users.

The GHG emissions are not the only environmental benefit of LNG use considered in this study. Other environmental benefits achieved by substituting coal and diesel by LNG, can lead to reduction of about 80% NO_x, over 99% SO_2, and between 92% and 99% particulates per unit of energy compared to oil and coal [4]. To get a comprehensive environmental performance of LNG, the life cycle air pollutant emissions should be further addressed in future studies. The benefits of air pollutant reduction makes the transition from coal and diesel to LNG more attractive.

6. Conclusion

This study aims to find the best way to supply and use LNG in China from a GHG mitigation and economic perspective. To quantify and optimize GHG emission and economic performance for LNG supplied for the four end-users, we proposed three LNG supply chains and defined the life cycle stages involved in each one. The energy efficiency, life cycle GHG emissions, and production costs for each LNG supply chain were determined in this study. Lastly, pathways for each end-user are compared with a reference chain in China to show the avoided GHG emissions and GHG avoidance costs. From the results, the following can be concluded:

- The CP and DC options slightly reduce GHG emissions by 0.9–1.2% and production costs by 0.2–0.8% compared to the NG pathway in all four end-users, indicating that using the cold energy of LNG to produce electricity or provide cooling does not significantly affect GHG emissions and costs in a life cycle perspective. The PCCC option reduced GHG emissions by 9.5–10.4% and production costs by 0.2–0.7% compared to the NG pathway in all four end-users, indicating that using the cold energy of LNG to capture CO_2 has more benefits on GHG emissions compared to CP and DC.
- NG with FCCC reduces GHG emissions by 55.5% with an 11.1–17.3% production costs increase in power generation and industrial heating compared to NG pathway. H_2 with FCCC reduces GHG emission by 38.5–48.6% with a 194.1–425.3% production costs increase compared to NG pathway in power generation and industrial heating. This demonstrates that the

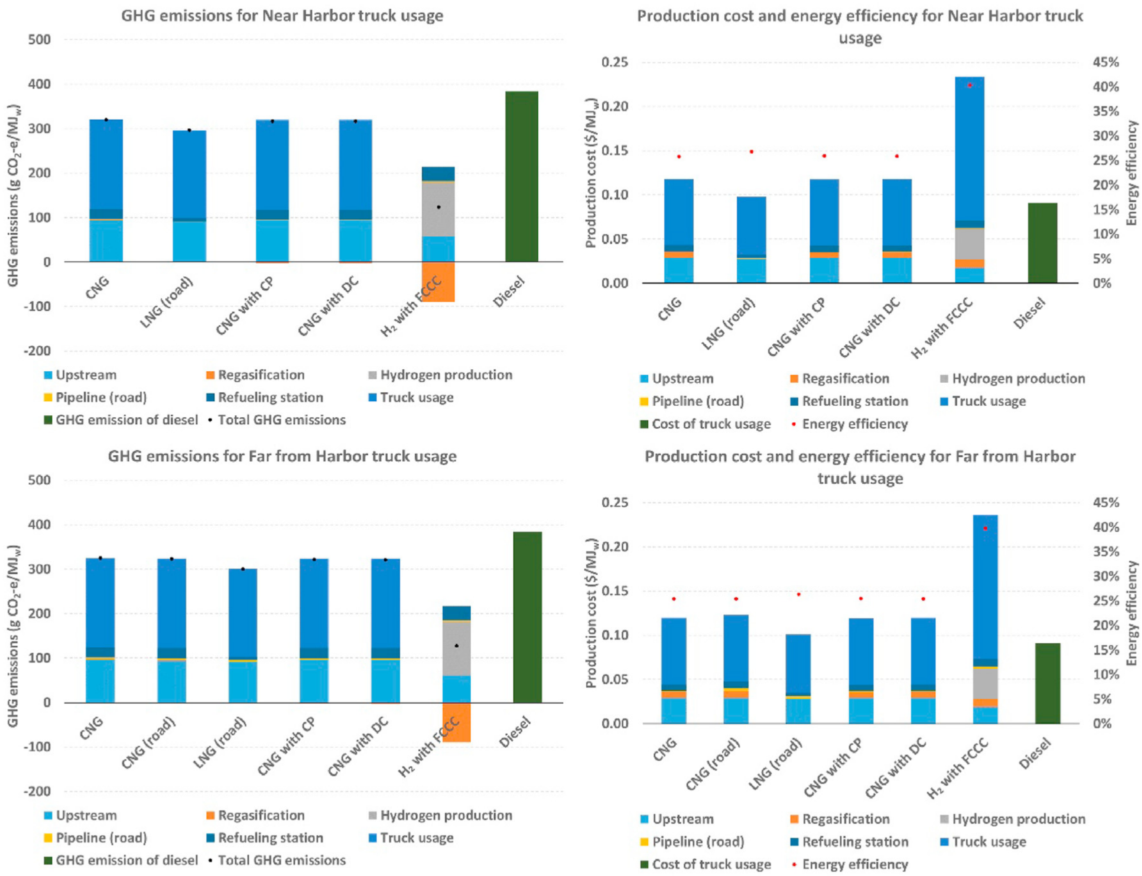

Fig. 9. GHG emissions, production costs, and energy efficiency for truck usage.

Table 2
Avoided GHG emissions and GHG avoidance costs for power generation.

location	Supply chain	GHG_a (g CO_2-e/MJ_{LNG})	C_a (\$/t CO_2-e)
Near Harbor	NG	75.6	64.3
	NG with CP	76.7	62.6
	NG with DC	76.6	63.1
	NG with PCCC	83.8	57.4
	NG with FCCC	112.4	66.0
	H_2 HCC with FCCC	89.8	438.6
	H_2 PAFC with FCCC	83.0	417.9
Far from harbor	NG	72.7	72.0
	NG with CP	73.7	70.1
	NG with DC	73.7	70.7

Table 3
Avoided GHG emissions and GHG avoidance costs for industrial heating.

location	Supply chain	GHG_a (g CO_2-e/MJ_{LNG})	C_a (\$/t CO_2-e)
Near Harbor	NG	35.9	138.9
	NG with CP	36.8	133.8
	NG with DC	36.9	134.5
	NG with PCCC	43.9	112.3
	NG with FCCC	70.5	95.9
	H_2 with FCCC	53.3	405.4
Far from harbor	NG	33.7	158.8
	NG (road)	32.0	198.1
	NG with CP	34.6	152.9
	NG with DC	34.7	153.6
	NG (road) with PCCC	41.6	145.1
	NG (road) with FCCC	66.3	124.1
	H_2 (road) with FCCC	49.5	454.6

Table 4
Avoided GHG emissions and GHG avoidance costs for residential heating.

location	Supply chain	GHG_a (g CO_2-e/MJ_{LNG})	C_a (\$/t CO_2-e)
Near Harbor	NG	35.4	205.8
	NG with CP	36.3	199.1
	NG with DC	36.4	199.5
	H_2 with FCCC	51.8	460.8
Far from harbor	NG	33.7	213.1
	NG (road)	32.0	265.6
	NG with CP	34.6	216.7
	NG with DC	34.7	217.0
	H_2 (road) with FCCC	49.5	494.5

Table 5
Avoided GHG emissions and GHG avoidance costs for truck usage.

location	Supply chain	GHG_a (g CO_2-e/MJ_{LNG})	C_a (\$/t CO_2-e)
Near Harbor	CNG	16.5	421.1
	LNG (road)	23.4	79.4
	CNG with CP	17.4	397.4
	CNG with DC	17.5	396.4
	H_2 with FCCC	104.9	547.2
Far from harbor	CNG	15.1	479.3
	CNG (road)	14.0	527.4
	LNG (road)	22.1	114.3
	CNG with CP	15.9	450.6
	CNG with DC	16.0	448.9
	H_2 with FCCC	102.2	563.5

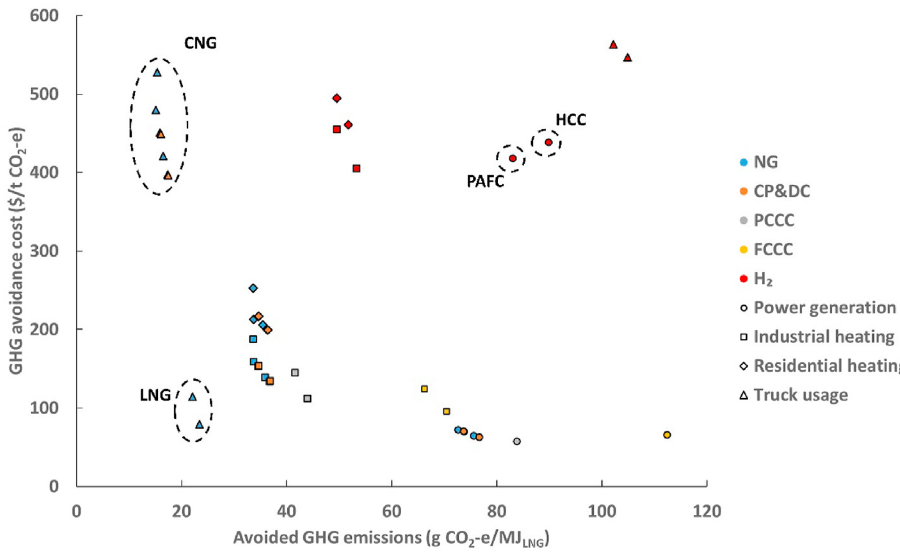

Fig. 10. Comparison of four end-users on avoided GHG emissions and GHG avoidance costs.

NG with the FCCC pathway has better GHG emission and cost performances than H_2 with FCCC in the current situation.

- When the power generation efficiency of fuel cell hydrogen power plant with FCCC is 70%, it has a better GHG emission performance compared to NG with FCCC. According to a Fuel Cell and Hydrogen Joint Undertaking report [59], the costs for an H_2 fuel cell truck will be only one-third in 2030 compared to the costs used in this study. This indicates that the hydrogen pathway could have better performance on GHG emissions and production costs with technological development and long-term cost reductions.
- LNG trucks have lower GHG emissions by 7.2−8.4% and lower production costs by 16.9−18.5% compared to CNG trucks. This indicates that the LNG truck is more environmentally-friendly and economical than the CNG truck.
- The comparison of the four end-users shows that the NG with FCCC for power generation is the best pathway, as it can avoid a large amount of GHG emissions at relatively low GHG avoidance costs.

In conclusion, the pathway of NG with FCCC is the most beneficial pathway for both avoided GHG emissions and GHG avoidance costs. The LNG supply chain of hydrogen production is only applicable when new technology options are mature and costs are significantly reduced in the future. A comparison of four end-users shows that it is better to first promote NG with FCCC to substitute coal-fired power plants in the power generation section.

This study aims to find the most adequate way, in terms of life cycle GHG emissions and costs, to supply and use LNG in China in the short term. Other important environmental benefits besides GHG emissions, which are not addressed in this study, include significant reductions in NOx, SO_2, and particulates emissions [4] by applying LNG to substitute coal and diesel. The benefits of air pollutant emissions could be another important driver of the transition from coal and diesel to LNG. The infrastructures in the three proposed supply chains could further reduce GHG emissions in the long term. The potential of using LNG infrastructures to supply and use biogas, bio-SNG (synthetic natural gas), and H_2 from renewable energy should be investigated in the future to evaluate how the current LNG infrastructures can be used as a bridge toward renewable sources and achieve further GHG emission reductions in the future.

Author contribution

Jinrui Zhang: Data curation; Formal analysis; Investigation; Methodology; Visualization; Writing − original draft; Hans Meerman: contribute equally to this paper: Supervision; Writing − review & editing; René; Benders: contribute equally to this paper: Supervision; Writing − review & editing; André Faaij: contribute equally to this paper: Supervision; Writing − review & editing

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.

Acknowledgment

This work is supported by the China Scholarship Council and University of Groningen (awarded to Jinrui Zhang for four years of study at the University of Groningen).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2021.120049.

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