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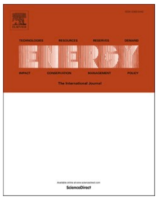

The role of green ammonia in meeting challenges towards a sustainable development in China

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A R T I C L E I N F O

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A B S T R A C T

The shift to a sustainable development has become an important issue in China. This paper discusses the role of green ammonia in promoting China's energy, environmental and economic sustainability which has not drawn enough attention. First, key challenges in China's energy transition, decarbonisation and regional sustainable development are explored. The coal-dominated energy consumption has placed great obstacles in achieving energy transition and led to massive CO2 emission since the large-scale industrialization. The high dependency on oil and gas import has threatened China's energy security. Imbalanced and unsustainable regional development is identified with data envelopment analysis. Second, the potential of green ammonia in meeting these challenges is analysed. Ammonia is examined to be a flexible and economic option for large-scale hydrogen transport and storage. Co-firing ammonia in coal power generation at 3 % rate is evaluated as an option for achieving low-carbon transition by 2030. Benefits of developing a green ammonia economy is discussed from energy, environmental and economic aspects. The practice can decline fossil energy consumption, enhance energy security, and facilitate renewable energy delivery and storage, industry decarbonisation, and regional development. We assume the findings and results contribute to addressing sustainability challenges and realizing a hydrogen economy in China.

1. Introduction

1.1. Green ammonia in the sustainable development

Sustainable development has emerged in the 21st century as a priority to address global challenges, such as climate change, resource depletion, etc. The transition to renewable energy resources has been recognized as the key to promoting sustainability by reducing greenhouse gas emissions, improving energy security and stimulating economic development. As the world's largest primary energy consumer, with carbon neutrality goals announced, China is well positioned to meet its climate commitments and transition to a sustainable development [1]. Investments in wind and solar energy grew significantly in China for the past two decades [2]. However, China is expected to remain the largest consumer of fossil energy by 2050, as the spatial renewable energy imbalance, grid inflexibility and insufficient transmission has led to a growing divergence between installed capacity and actual power generation from renewable energy [3,4]. The technology of 'Power to Gas' (P2G) enables a concerted effort from hydrogen for solving the challenges. China steps a move to green hydrogen with mid and long-term targets set in 2022 [5]. To date, the large-scale use of hydrogen faces challenges in shipping and storing hydrogen [6]. Green ammonia, a derivative of green hydrogen, is increasingly recognized as a clean fuel and a safe hydrogen carrier [7]. Green ammonia is expected to solve the problem of single hydrogen energy and play a key role in a hydrogen economy, and is therefore regarded as 'hydrogen 2.0' [7]. Despite the decarbonisation of traditional ammonia sector being highlighted in China's 2021–2035 Hydrogen Development Plan, the vital role of green ammonia in China's hydrogen economy has not been sufficiently recognized [5]. Until recently, green ammonia is gaining increasing attention from the government seeking for carbon neutrality [8]. As a result, an assessment of the development of green ammonia supply chains in meeting sustainability challenges in China is necessary.

1.2. Research on the hydrogen and ammonia economy

An increasing number of recent studies have discussed the hydrogen economy. Many studies discussed institutional conditions for the hydrogen economy. For instance, Harichandan et al. proposed to create hydrogen demand in key sectors in India and provide financial

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incentives for commercialization of green hydrogen production [9]. Chu et al. proposed to reinforce policies for hydrogen production to secure economic feasibility of a hydrogen economy in South Korea [10]. Some studies have evaluated policy impacts for developing the hydrogen economy. For instance, Li et al. found that subsidy policies for investment, production, electricity price and income tax are critical for developing the green hydrogen industry in China [11]. Some studies have contributed to the hydrogen market. For instance, Schlund et al. concluded that political intervention in the market ramp-up should focus on filling the economic gap between low-carbon hydrogen and fossil alternatives [12]. An increasing number of studies have contributed to discussing the feasibility of a hydrogen economy. For instance, Lee et al. explored technological and institutional vulnerabilities towards a hydrogen economy in South Korea [13]. Palacios et al. examined the feasibility of adopting a hydrogen economy in Mexico from economic, ecological and social perspectives [14]. Khan et al. concluded that the scale and growth of a hydrogen economy in the Mid-East would largely depend on the global hydrogen adoption [15]. Using a supply-demand-policy model, Huang et al. found that supply, demand and policy environment shape the hydrogen market and identified different hydrogen development patterns in cities in China [16]. However, limited studies have discussed the adoption of a hydrogen economy in a region or country from a comprehensive perspective. For instance, Hong et al. evaluated the sustainability of a hydrogen economy in South Korea from energy, economic and environmental aspects and proposed related policy implications [17]. Yet, a deep insight into the main challenges in national or regional wide energy transition and decarbonisation has been less considered in the current feasibility studies of the green hydrogen development.

Although a large proportion of studies up to date concern production process and operation of green ammonia, study on green ammonia economy have received increasing attention with the role of green ammonia valued in a hydrogen economy. A majority of studies have contributed to techno-economic assessment of the supply chain. Tu et al. explored different modes for transporting hydrogen in China, and found that the use of liquid ammonia pipelines proves to be the most effective modes [18]. Some studies focused on policy impacts for developing the supply chain. For instance, Zhao et al. evaluated impacts of economic incentives on investment in green ammonia production in China, and found operating rate, ammonia price, electrical efficiency and electricity price are key techno-economic factors in the investment [19]. A small number of studies have contributed to the clean ammonia market. For instance, market structures on green ammonia supply chains was explored in the work [20], where an integrated structures for the infancy of the supply chain development was proposed. Many studies on the green ammonia economy have concentrated on the feasibility of the economy. For instance, Sekhar et al. discussed the significance of green ammonia in the Sustainable Development Goals, technological obstacles and environmental impacts of green ammonia [21]. Morlanes et al. concluded that ammonia can play an important role in a hydrogen economy by securing energy while decarbonizing transportation, industrial and residential sectors [22]. Galimova et al. assessed the feasibility of importing green ammonia from the North Africa and South America to the Europe, and found that imports by sea from Chile is cost effective compared to pipeline imports from Morocco [23]. However, the role of green ammonia and feasibility of developing the industry subject to energy, economic and environmental concerns has not been well researched.

1.3. Research goal and contribution

In summary, green hydrogen has drawn attention for realizing a low-carbon and sustainable development worldwide and also in China. The adoption of hydrogen as an energy carrier faces challenges due to the low density and high flammability. Green ammonia, a derivative of green hydrogen, is increasingly drawn attention as a hydrogen carrier and clean fuel. However, its role in addressing China's challenges towards a sustainable development has not drawn sufficient attention by policymakers and recent studies in academia. This paper aims to study the development of green ammonia supply chains to meet sustainable development challenges in China. The main contributions are summarized as follows.

1. Distinct with recent studies on the adoption of a green ammonia economy, this study first takes a closer and comprehensive exploration on key challenges in China's energy transition, decarbonisation and regional sustainable development. The findings form a solid basis for evaluating the role of green ammonia in achieving sustainability in China and also provide insights regarding the main concerns in China's sustainable development.
2. The role of green ammonia as a hydrogen carrier and clean fuel, as well as the potential supply and demand from applicable sectors in China are analysed concerning the feasibility of developing the green ammonia industry in China. Based on the evaluations and the key challenges identified, the adoption of a green ammonia economy in China is comprehensively discussed from energy, environmental and economic aspects. The study provides references and pathways in addressing challenges towards a sustainable society and achieving a hydrogen economy in China.

The remainder of this paper is arranged as follows: the framework for analysing sustainability of energy systems is introduced in Section 2. Section 3 discusses challenges in China's energy transition, decarbonisation and regional sustainable development. Section 4 discusses the role of green ammonia in meeting the challenges. Section 5 presents the conclusions and limitations of the work.

2. Methods

2.1. Framework for analysing sustainable development

The definition of the term 'sustainability' varies with context. For instance, sustainability in a broad sense also contains social aspect. It should be noted that sustainability in this study is subject to the discourse on energy transition and climate change.

Since energy security, environmental conservation, and economic development are critical sustainable challenges, the energy-environment-economy (3E) concept, namely, the energy, environment and economic system, has been widely considered for achieving sustainable development and energy policy making and governance [24,25]. As the sustainable development requires a comprehensive coordination between energy development, economic growth and carbon emission reduction, the coordination degree between the three pillars is a typical way to evaluate the sustainable development [26]. The 3E framework and definition of each pillar tends to vary from case to case. For instance, the 3E was introduced as the 'three pillars' of Japan's energy policy in 2010, while safety was later considered as an addition since nuclear safety has been an integral part of the energy policy [25]. By referring to 3E frameworks from international discourse and Japan [25,27], the definition of 3E framework in this study for analysing main sustainability challenges and the development of the green ammonia industry is presented as follows.

As shown in Fig. 1, the dimension of energy denotes securing a stable energy supply, while the dimensions of environment and economy emphasizing environmental suitability and economic efficiency. Regarding the interactions between the three pillars, energy influences the environment, and the environment constrains the use of energy. This is because excessive energy consumption puts a burden to the environment. The environment forms the foundation of the economy as it can promote or hinder economic development. In turn, the economy

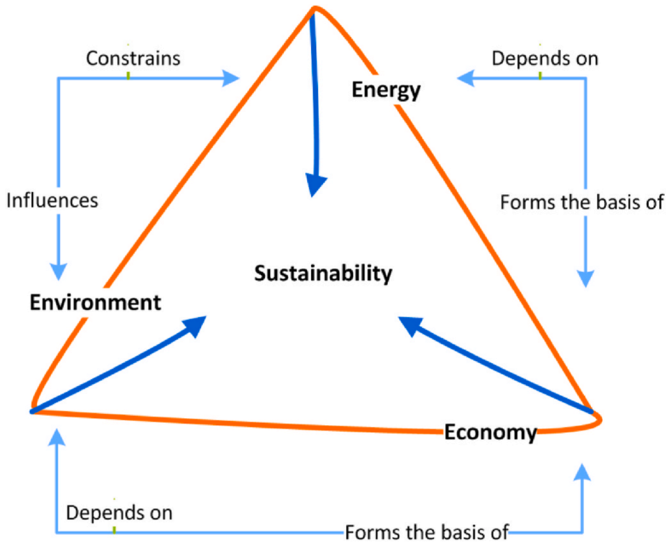

Fig. 1. The energy-environment-economy (3E) framework.

influences the environment as it exerts positive or negative impacts on the environment when the ecology and resources are protected or destructed, respectively. Further, economic development depends on energy, and energy forms the material base for economic development. Besides, trade-offs are required to achieve the sustainable development with priorities deciding the goals to focus on. Aligned with China's the 14th Renewable Energy Five Year Plan [28], in this study, securing a stable energy supply is regarded as the priority with the purpose of satisfying massive energy demand and enabling economic development in China. Meanwhile, energy security should be aligned with the goals of improving economic efficiency and carbon emission reduction.

3. Challenges in the sustainable development

This section discusses the main challenges in China's sustainable development, incl. challenges in energy transition, carbon emission reduction and regional sustainable development from the energy, environmental and economic aspects, respectively.

3.1. Energy development

3.1.1. Energy consumption and supply

China is by far the largest primary energy consumer in the world. The primary energy consumption in China experienced a constant increase in the past decade [29]. As shown in Fig. 2, the energy consumption in 2020 reached 4.56 Btce which is 25 % higher than that of in 2010. In addition, fossil fuels still dominate in the energy consumption, and there was no remarkable improvement in the past decade, e.g. 92 % of primary energy from fossil fuels compared to the share of 95 % in 2010. China's energy consumption still relies heavily on coal, although the share of coal in total energy consumed has been decreased to 62 % in 2020 from 73 % in 2010. In contrast, the share of crude oil remained at around 20 % in the past decade. Natural gas consumption increased dramatically with the amount being twice that of in 2010. However, the overall share is still limited, standing at 9.2 % in 2020.

Regarding energy supply, China's energy sources heavily depend on imports. Fig. 3 shows the imports of main fossil fuels to China from 2010 to 2020. Despite accounting for 13 % of world's coal reserves, China has been a coal exporter prior to 2009 and overtaken Japan as the world's top coal exporter since 2011 [30]. The net import of coal peaked in 2016, reaching 224.4 Mtoe which is 1.6 times that of in 2010 [30]. Afterwards, it decreased to 32.5 Mtoe in 2010. The external dependence of coal ranged from 1.7 % to 11.7 % in the past decade. In contrast, China's economy heavily depends on crude oil and natural gas imports, due to the massive demand growth and limited domestic supply. Net oil import almost doubled in the past decade, reaching 506.8 Mtoe in 2020. The external dependence raised from 56.6 % in 2010 and ended up at 72.2 % in 2020. Natural gas import grew 10 times in the past decade from 10.5 Mtoe in 2010 to 117.6 Mtoe in 2020. As a result, its external dependence raised to 41.3 % in 2020.

The fossil energy-dominant energy consumption pattern and high external dependence of fossil energy has threaten the security of long-term and sustainable energy supply. For example, despite the large crude oil import each year, China's strategic crude oil reserves is less than 60 days which is far below the threshold of a 180-day security reserve [31]. Therefore, it is difficult to maintain a sustainable energy supply, especially under an emergency. In addition, despite the diversity of oil and gas imports, the main importers are from the Middle East, North Africa, Asia Pacific and Russia [30]. Furthermore, the transportation corridors are relatively limited. For example, more than 70 % of oil transportation passes through the Strait of Hormuz and the Strait of Malacca, which is highly subject to geopolitical risks [32].

3.1.2. Renewable energy and hydrogen development

As a result of the coal-dominant primary energy supply and steady growth in energy consumption, China has been the world's largest CO2 emitter [30,33]. The government targeted to phase out fossil fuel use by increasing the share of renewable energy in total energy consumption. The aggregate wind and solar generation capacity reached over 500 GW by 2020 accounting for 23 % of total generation capacity in China [34]. Geographically, the installed capacity is mostly distributed in the north, northwest and northeast of China (also known as the Three North

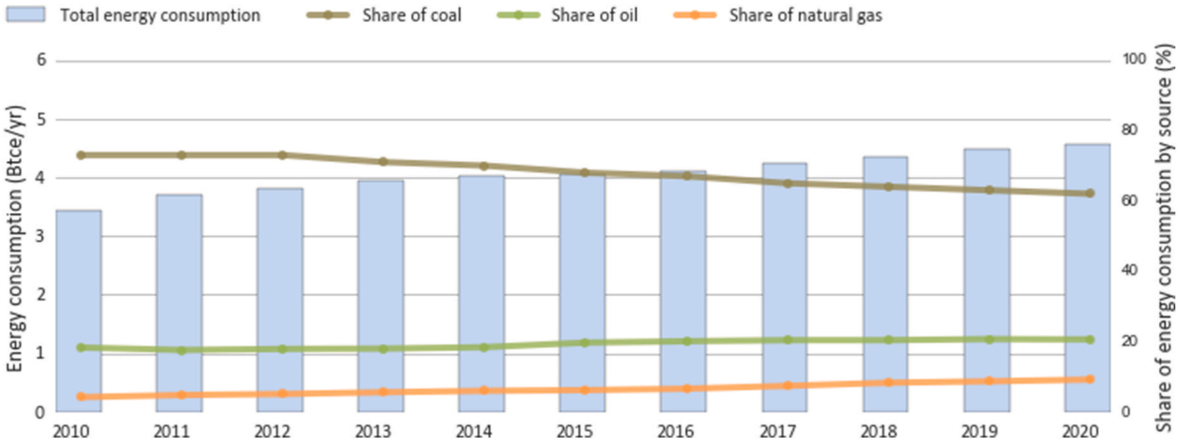

Fig. 2. China's energy consumption from 2010 to 2020.

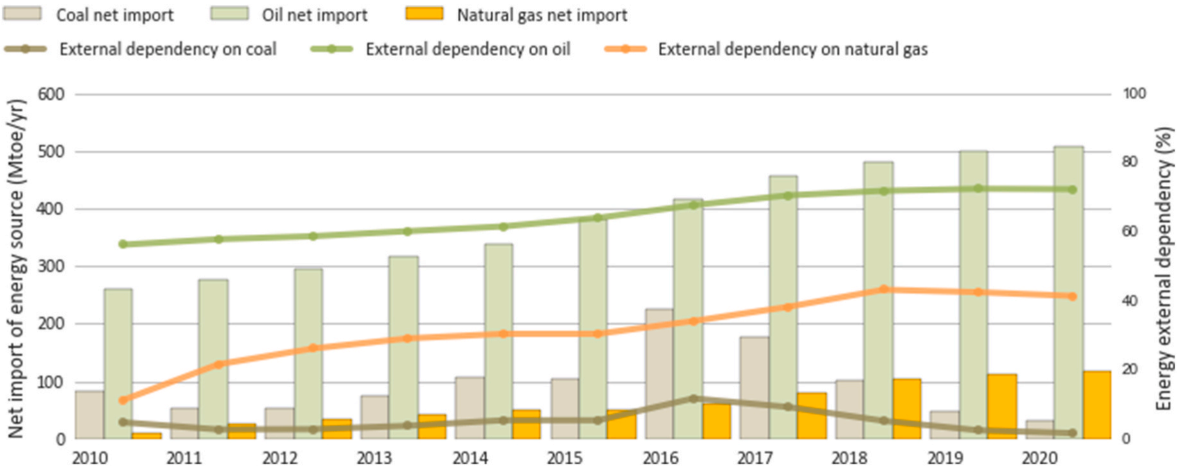

Fig. 3. China's fossil fuels imports from 2010 to 2020.

regions) with the share being 60 % by 2020, as shown in Fig. 4, thanks to the abundant renewable resources in these regions [34]. In contrast, economic clusters are generally located in the east and south of China, as indicated in Fig. 5 which shows China's gross domestic product (GDP) by region in 2020. Therefore, the energy condition in China presents an obvious spatial mismatch between renewable energy supply and potential demand. This has resulted in a sharp decline of utilization and a growing divergence between installed capacity and actual power generation [35]. For example, renewable energy excluding hydro-power only supplied 5.3 % of overall energy demand in 2020 [30]. Therefore, large-scale and long-distance renewable energy distribution is fundamental to facilitating the energy transition in China.

Power system extension is by far the centric solution to address energy distribution. By 2020, 20 ultra-high voltage lines were built to support power transmission to load centers, which is far from sufficient considering the fast expansion of renewable power bases in recent years [36]. Meanwhile, the intermittent power aroused challenges for grid integration that the overall operating rate of these lines was lower than 40 % in 2019 [37].

As the world's largest hydrogen producer, only 1.2 % of hydrogen is produced from electrolysis, in which, less than 0.1 % is powered by renewable energy in 2021 [38]. The rest is produced from fossil fuels and industrial by-production [38]. The abundant renewable energy is well placed to produce green hydrogen. With the 2021–2035 Hydrogen Development Plan delivered, China has increasingly recognized the position of green hydrogen for the large-scale use of renewable energy to meet decarbonisation and industrial transformation goals [39]. A 6000 km pipeline network is planned to build by 2050 linking regions with hydrogen supplied and demanded [40]. However, investment in hydrogen pipeline construction is around 2.5 times that of natural gas and is very time consuming [41]. In addition, the expansion of green hydrogen in China is currently constrained by the cost, market demand, and a lack of infrastructure and industry standards, as hydrogen development is in its early stage without clear hydrogen development pathway in place [38].

3.2. Carbon emission

China is now the world's top CO2 emitter, accounting for around 30 % of the global CO2 emission [42]. The CO2 emission in China raised

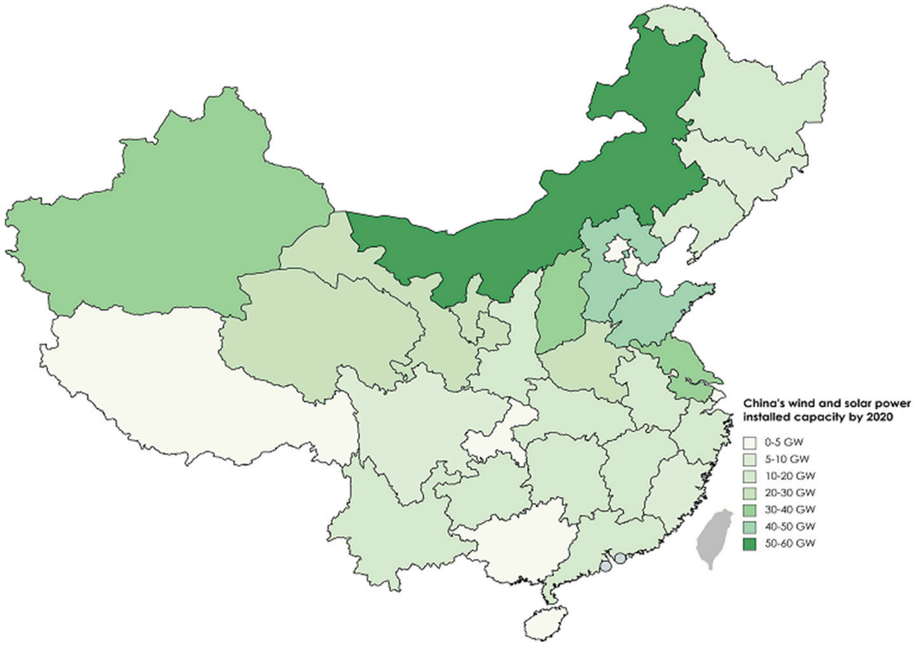

Fig. 4. China's aggregate wind and solar installed capacity by region in 2020.

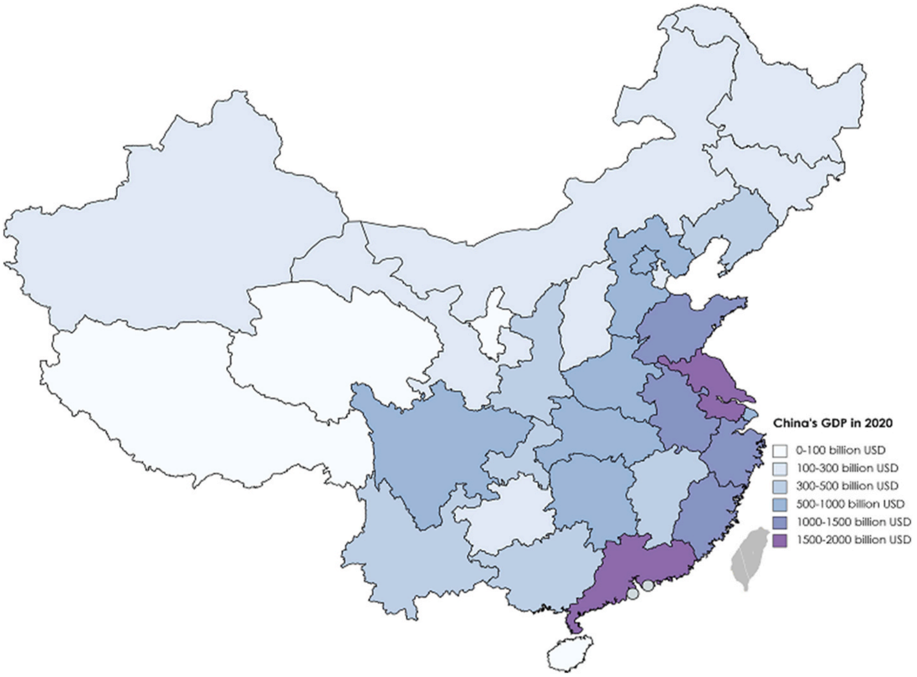

Fig. 5. China's gross domestic product (GDP) by region in 2020.

significantly since 2020 (∼3 Gt) and reached 10.38 Gt by 2020, mainly due to the dramatic expansion in manufacturing after joining the World Trade Organization (WTO) [42]. Fig. 6 shows the breakdown of CO2 emission, power and heat consumption in China by sector [43–45].

The overall emission amount in 2019 reached 10.9 Gt, in which, power and heat supply toped other sectors, accounting for 51.7 % of the overall China's CO2 emission. Other industries (excl. power and heat sectors) contributed 33.9 % of overall emission, which is around 3.7 Gt CO2 emission in 2019. Besides, other sectors in total accounts for around 14.4 % of CO2 emission. Although China has ranked the first in the world in terms of the number of vehicles (∼253.8 M units in 2019), the share of CO2 emission from the transportation sector only accounted for 6.7 % in 2019 [46]. The breakdown of power and heat consumption by sector is also analysed to further investigate the causes for the enormous CO2 emission from power and heat supply. Energy consumed in heating accounts for around 13 % of the overall energy consumption in both power and heat supply [29]. Therefore, most of CO2 is emitted from power generation process. As also shown in Fig. 6, around 68.2 % of power in China in 2019 is consumed by the secondary sector (i.e. the industry sector) [47]. Similarly, around 70 % of heat is consumed by the

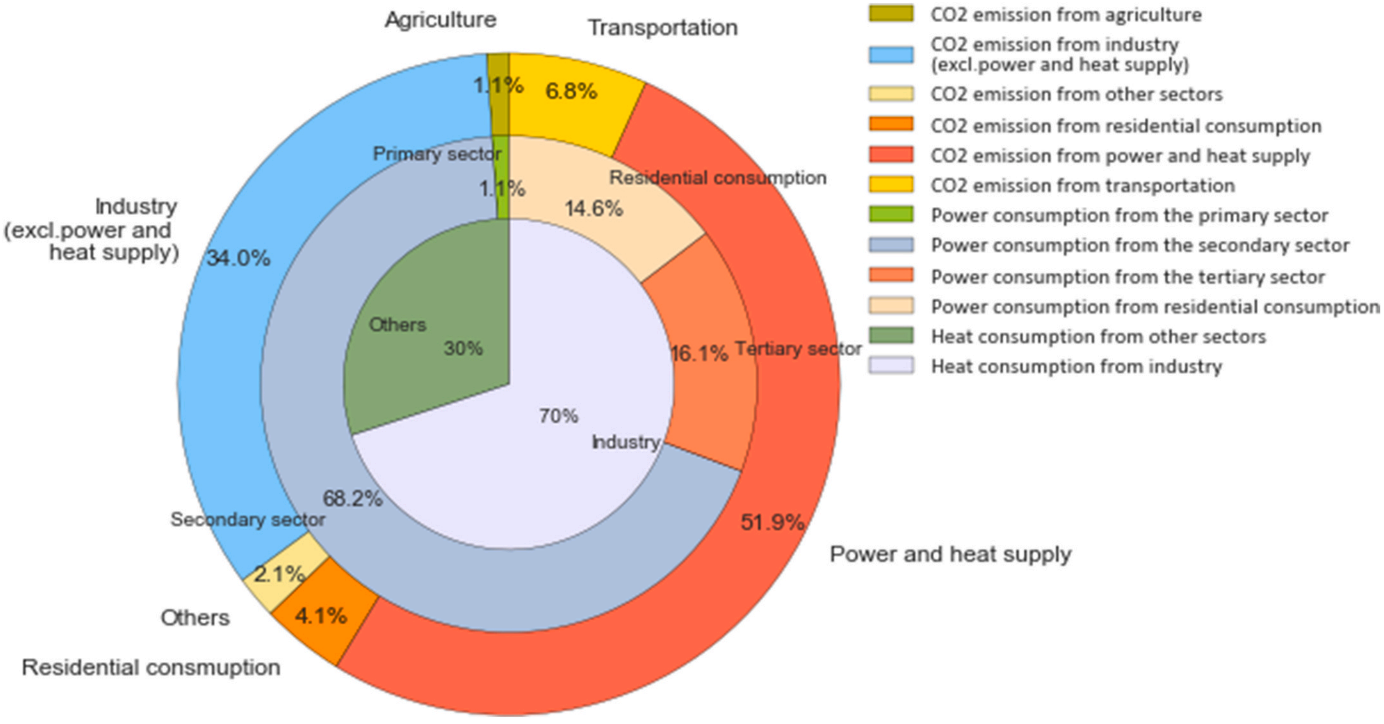

Fig. 6. China's CO2 emission, power and heat consumption by sector in 2019.

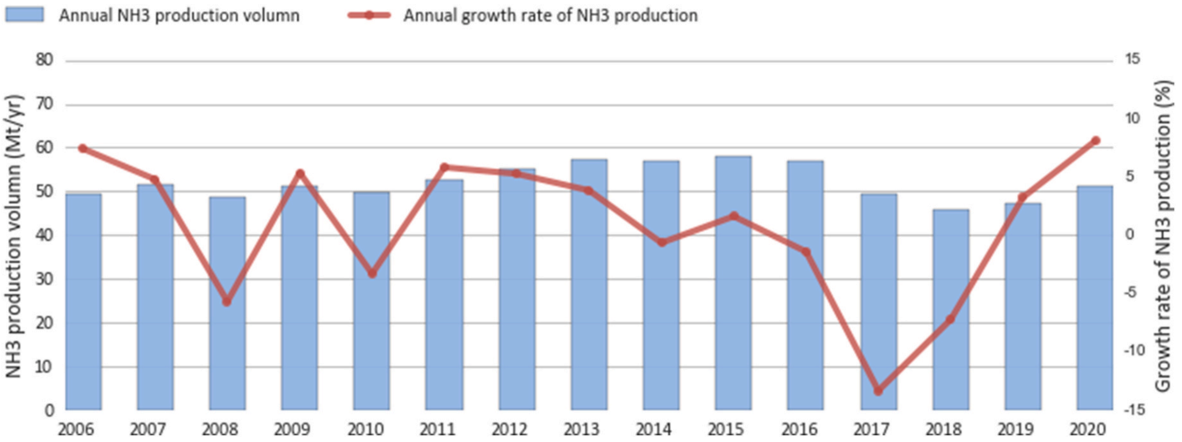

Fig. 7. China's ammonia production from 2006 to 2020.

industry sector [48]. Combined with the direct emission from the industry, this indicates that around 70 % of CO2 emission in China is caused by the industrial production. As a result, the industry decarbonisation, incl: decarbonisation in production processes and energy conservation, is essential in achieving carbon reduction goals in China.

China's CO2 emission mainly comes from the use of coal. The chemical industry, accounting for around 20 % of CO2 emission in the industrial sector, is one of the heavy industries difficult to realize decarbonisation, as it relies heavily on coal as the main energy source [49]. The segments of ammonia, methanol, oil refining, ethylene, and modern coal chemicals (e.g. coal-to-gas, coal-to-liquids, etc.) are the five biggest emitters in the chemical industry [49]. China is the world's largest ammonia producer consuming 45 % of hydrogen produced domestically [50]. The annual production amount ranged from 48.8 to 58 Mt from 2006–2020, as shown in Fig. 7 [29]. Ammonia production process is very energy intensive. Around 75.7 % of ammonia is produced by coal, compared to 20.6 % of ammonia produced by natural gas [51]. The production capacity is widely distributed in each region of China, as shown in Fig. 8, especially in the north, southwest, mid-south and east of China, such as: in Shandong, Henan, Shanxi, Hebei, Hubei and Jiangsu province [29]. Natural gas-based ammonia production in China is mainly distributed in Sichuan and Xinjiang province due to more gas reserves in these regions [52]. As a result, ammonia industry top other chemical industries in terms of CO2 emission (1.93 Mt CO2 emitted in 2019), and also emits other pollutants such as sulphur dioxide (SO2) and nitrogen oxides (NOx) [52,53]. These have significantly contributed to environmental problems in China.

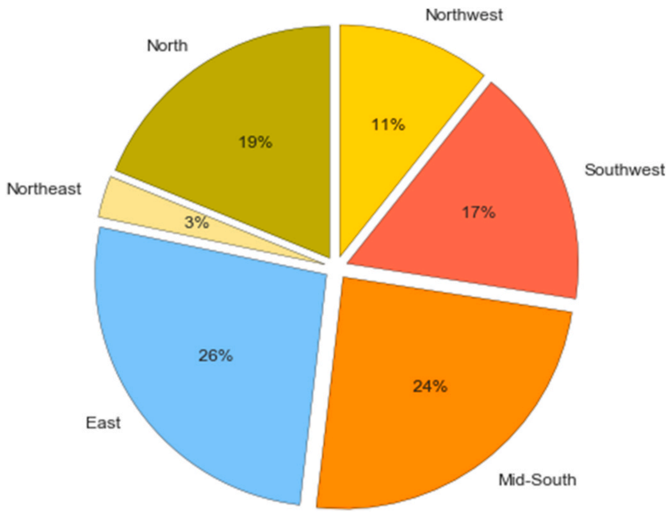

Fig. 8. China's ammonia production by region in 2018.

3.3. Regional sustainable development

Compared to the traditional approaches for evaluating economic development, the green productivity, or known as green total-factor productivity (GTFP), is increasingly paid attention as a measurement of synergistic performance between economic growth and environmental costs [54]. Therefore, it is applied as an index for observing regional sustainable development in this study. The approach of data envelopment analysis (DEA) has been widely applied in assessing total-factor productivity, as it can compare the technical efficiency between decision-making units (DMUs) with multiple and similar types of inputs and outputs [55]. A constant returns to scale (CRS) DEA model is applied in this study to assess the regional GTFPs in China. The objective function and associated constraints of the ith DMU are formulated in Eqs. (1)–(4), where θ_i denotes the efficiency of the DMU i ranging from 0 to 1; X_i and Y_i are the inputs and outputs of the DMU i, respectively; X_j and Y_j are the inputs and outputs of the DMU j, respectively; λ_j is the weight of the DMU j.

Fig. 9 shows the input-output framework of the DEA model. Labor force and capital stock are considered as socio-economic input factors. In addition, energy consumption and carbon emission are also considered as energy and environmental costs in measuring the green productivity. Gross domestic product (GDP) is considered as the output of the DEA model. Regional GTFPs in 2019 are measured to eliminate impacts of epidemic from 2020 to 2022 in China. Table 1 shows parameters applied in the assessment, in which, data is collected from 31 administrative areas in China and integrated into six regions, including: north, northeast, east, mid-south, southwest and northwest of China. Regional

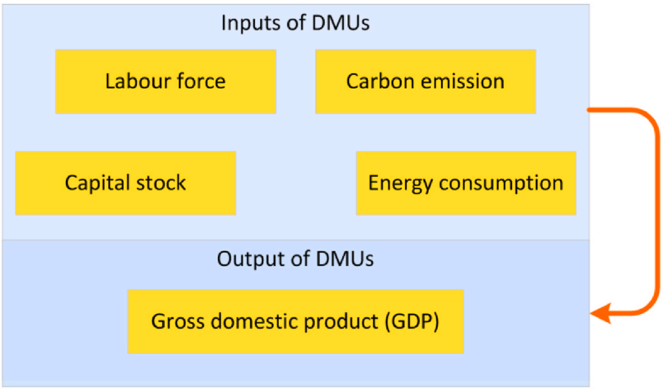

Fig. 9. Framework of the DEA model.

Table 1
Parameters for evaluating regional GTFP of China in 2019.

Parameter (2019)	Region	Value	Unit	Source
Energy consumption	North	943.50	M tce/yr	[29,60]
	Northeast	408.49		
	East	1452.58		
	Mid-South	1032.93		
	Southwest	515.58		
	Northwest	521.88		
Labour force	North	87.28	M p/yr	[29]
	Northeast	50.75		
	East	244.29		
	Mid-South	220.64		
	Southwest	114.33		
	Northwest	54.62		
Capital stock	North	2290.21	B USD	[29]
	Northeast	795.42		
	East	4428.91		
	Mid-South	3433.75		
	Southwest	1707.82		
	Northwest	1009.98		
CO2 emission	North	2521.59	Mt CO2/yr	[43,58,59]
	Northeast	1015.26		
	East	3244.51		
	Mid-South	2001.62		
	Southwest	924.63		
	Northwest	1180.19		
GDP	North	1697.42	B USD	[29]
	Northeast	717.84		
	East	5363.89		
	Mid-South	3919.61		
	Southwest	1257.92		
	Northwest	783.19		

capital stock is estimated on the basis of the level in 2000 estimated by Zhang et al. and the perpetual inventory method [56]. As shown in Eq. (5), the perpetual inventory method is applied to calculated the capital stock of a following year, where $K_{i,n}$ and $K_{i,n+1}$ denote the capital stock of year n and $n+1$ in region i, respectively; $I_{i,n+1}$ denotes fixed capital stock of year $n+1$ in region i; δ is the depreciation rate which is set as 9.6 % as Zhang proposed [57]. Since CO2 emission of Tibet in 2019 is excluded from China's Carbon Emission Accounts and Datasets, it is estimated based on the emission level in 2014 and annual average growth rate of China from 2014 to 2019 [43,58,59]. Besides, energy intensity and carbon intensity are also calculated based on Eq. (6) and Eq. (7), respectively, where $E_{i,n}$ and $EI_{i,n}$ denote energy consumption and intensity of region i in year n, respectively; $C_{i,n}$ and $CI_{i,n}$ denote CO2 emission and carbon intensity of region i in year n, respectively; $G_{i,n}$ is the GDP of region i in year n.

$$\min \theta_i, s.t. \tag{1}$$

$$\sum_j X_j\lambda_j \le \theta X_i, \forall j \in \{1, 2, \dots, \mathrm{M}\} \tag{2}$$

$$\sum_j Y_j\lambda_j \ge Y_i, \forall j \in \{1, 2, \dots, \mathrm{M}\} \tag{3}$$

$$\lambda_j \ge 0, \forall j \in \{1, 2, \dots, \mathrm{M}\} \tag{4}$$

$$K_{i,n+1} = I_{i,n+1} + (1-\delta)K_{i,n} \tag{5}$$

$$EI_{i,n} = E_{i,n} / G_{i,n} \tag{6}$$

$$CI_{i,n} = C_{i,n} / G_{i,n} \tag{7}$$

Fig. 10 shows the results of regional GTFPs, energy intensities and carbon intensities of China in 2019. Both east and mid-south of China reach the optimal productivity with GTFPs being 1. In addition, energy and carbon intensity in mid-south of China are the lowest in all the six regions, being 7.32 Btu/USD and 0.51 kg CO2/USD, respectively. East of China is slightly higher than the Mid-South in term of energy and carbon intensity, but much lower than that of in other regions. This indicates that east of China is more efficient in converting labour and capital factors into economic outputs compared to the Mid-South, which can attribute to the technological, organizational factors, etc. In general, both two regions have less energy-intensive and pollutant industry and higher overall productivity. In contrast, GTFPs in the three North regions are low, and energy and carbon intensity are higher than the rest of regions. Northwest of China obtains the lowest productivity in China, with its GTFP being 0.65. Further, its energy and carbon intensity are also the highest, being 18.50 thousand Btu/USD and 1.51 kg CO2/USD, respectively. It is also the case for the north and northeast of China, where energy and carbon intensity are also high, but GTFPs are relatively higher than that of the Northwest, being 0.89 and 0.75, respectively. It indicates that there is a large-scale energy-intensive and pollutant industry in the Three North regions, and the Northwest especially needs to improve technology, management and industrial structure, due to the lowest GTFP. The GTFP of southwest of China is slightly higher than that of in the Northwest, however, its energy and carbon intensity are much lower, being 11.38 thousand Btu/USD and 0.74 kg

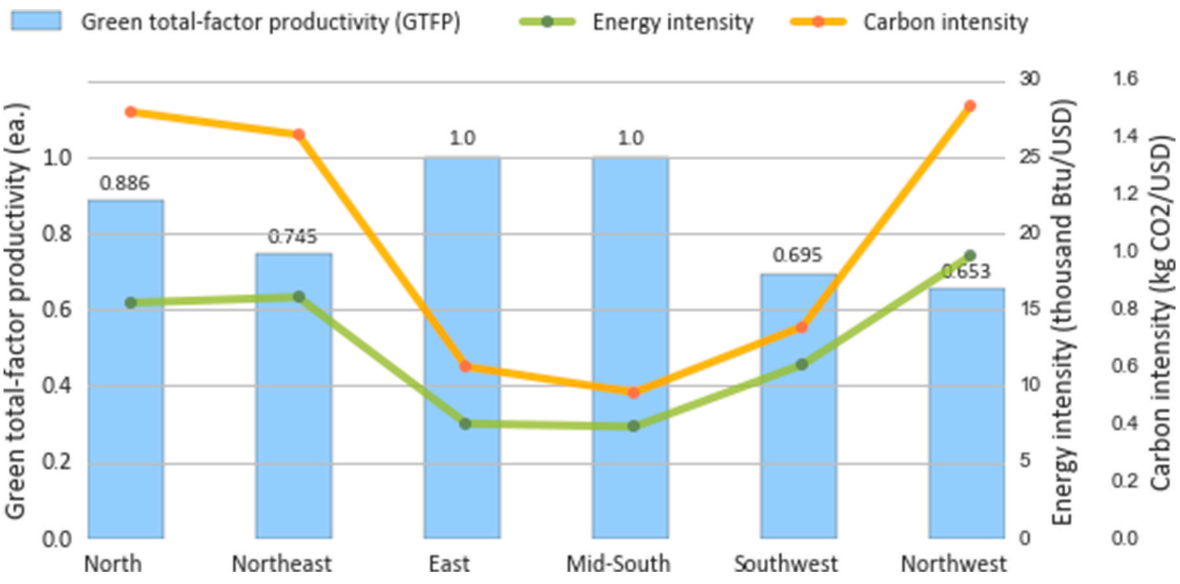

Fig. 10. GTFP and energy and carbon intensity in the six administrative regions of China in 2019.

CO2/USD, respectively. This indicates that there is less heavy industry in this region, but its economy lacks of technology and capital inputs.

4. Potential of green ammonia in meeting sustainability challenges

Confronting challenges towards a sustainable development in China, the further development of renewable energy is a necessity. The settlement of administrative barriers and introduction of market-based solutions are crucial to increase the share of renewable energy [61]. Meanwhile, a concerted effort from hydrogen has been increasingly recognized for addressing these challenges. The development of the green ammonia industry towards a sustainable development in China is comprehensively discussed in this section.

4.1. Potential of green ammonia as a hydrogen carrier, clean fuel and fertilizer

4.1.1. Green ammonia as a hydrogen carrier

The economic feasibility of transporting energy as ammonia is examined by comparing the delivery and storage costs with the major options of liquid hydrogen and pipeline. The related levelized costs are calculated based on Eqs. (8) and (9), where *LCOE* denotes levelized cost of energy. Exp_n denotes the total expense in year *n*, which consists of investment cost ($Capex_n$) and operating cost ($Opex_n$) and fuel cost (F_n). E_n is the energy delivered or stored per year *n*, and *dr* is the discount rate. The applied parameters are listed in Table 2, in which, a median conversion rate of ammonia reform is applied based on the literature [62, 63].

Fig. 11 shows breakdown of hydrogen delivery costs for these options by volume with a 500 km distance. The options of ammonia and liquid hydrogen are less influenced by volume. Delivery cost of ammonia remains at around 1.4–1.5 USD/kg H2 in all cases, and is dominated by ammonia production cost and decomposition cost. The sheer transportation cost only accounts for around 5 % of the overall cost. In contrast, although pipeline appears to be the ultimate solution, hydrogen delivery is influenced dramatically by volume due to the high capital and operating expenses required. The effect of delivery distance is also examined for transporting hydrogen from 500 to 3000 km, as shown in Fig. 12. Similarly, hydrogen delivery by pipeline is influenced dramatically by volume with the cost ranging from 0.6 to 3.3 and 0.8–5.1 USD/kg H2 for delivering 100 and 50 kt hydrogen per year, respectively. Liquid hydrogen and ammonia are more flexible options which have similar costs and limited influences by distance. The transportation will be more efficient if ammonia can be directly used. In this case, ammonia reform is excluded, and the overall cost can reach around 0.8–1.2 USD/kg H2, as the light blue line shows.

Table 2
Parameters for evaluating hydrogen transport and storage costs.

Parameter	Value	Unit	Source
Weighted average cost of capital	8	%	[50]
Capital cost of ammonia plant	714	USD/t NH3	[65]
Capital cost of ammonia reformer (10 kt/yr)	354	USD/t NH3	[62]
Capital cost of ammonia reformer (30 kt/yr)	267	USD/t NH3	[62]
Capital cost of ammonia reformer (50 kt/yr)	234	USD/t NH3	[62]
Capital cost of ammonia reformer (100 kt/yr)	196	USD/t NH3	[62]
Capital cost of ammonia tanker	30,000	USD	[66]
Capital cost of ammonia vessel	808	USD/t	[63]
Capital cost of liquefier (10–30 kt/yr)	8219	M USD/t H2	[67]
Capital cost of hydrogen liquefier (50 kt/yr)	7397	M USD/t H2	[67]
Capital cost of hydrogen liquefier (100 kt/yr)	6301	M USD/t H2	[67]
Capital cost of hydrogen vaporizer (10 kt/yr)	20	K USD	[66]
Capital cost of cyro-tank	1000	USD/cu m	[66]
Capital cost of hydrogen pipeline (10 kt/yr)	531	K USD/km	[68]
Capital cost of hydrogen pipeline (30 kt/yr)	599	K USD/km	[68]
Capital cost of hydrogen pipeline (50 kt/yr)	665	K USD/km	[68]
Capital cost of hydrogen pipeline (100 kt/yr)	833	K USD/km	[68]
Conversion rate of ammonia synthesis	95	%	[69]
Conversion rate of ammonia reform	95	%	[62, 63]
Energy for heating and pressurization in ammonia production	0.6	MWh/t	[70]
Energy for decomposing ammonia	1.4	MWh/t	[63]
Energy for ammonia cooling	0.19	MWh/t	[63]
Energy for ammonia storage	5.6	kWh/t/d	[63]
Energy for hydrogen liquefaction	10	MWh/t	[67]
Energy for hydrogen regasification	0.06	kWh/t	[71]
Energy for hydrogen pipeline transport	0.26	MWh/t/100 km	[63]
Evaporation in ammonia transport	0.024	%/d	[72]
Evaporation in liquid hydrogen transport	0.2	%/d	[73]
Leakage in hydrogen pipeline transport	0.05	%/1000 km	[74]

Fig. 13 shows costs of hydrogen storage by time in the form of ammonia and liquid hydrogen. Underground storage which is normally used for pipeline transportation is not presented due to a lack of data. The case of transporting 100 kt hydrogen per year is examined assuming 20 % of the total volume is stored for short-term and seasonal supply (i.e. 30 and 150 days, respectively) considering the proportion for natural gas is at least 15 % [64]. Storage costs for longer periods are also assessed to examine the potential for future long-term energy reserve, as strategic petroleum and gas reserves of today. In general, hydrogen storage as ammonia is little impacted by storage length. Storage costs range from 0.6 to 0.7 USD/kg H2 which is three to four times less than that of liquid hydrogen, due to mild storage conditions. Liquid hydrogen storage experience a stable increase in cost over time due to the incremental energy for extreme cryogenic condition required. In addition, ammonia defeats liquid hydrogen in terms of safe transportation and long-term storage due to much lower flammability [6]. Therefore, these advantages enable transporting hydrogen as ammonia a flexible, economical and safe option. Since infrastructure for ammonia is already in place due to a century of use in agriculture, the development of green ammonia supply chains and direct use of ammonia are proposed to avoid large uncertainties and significant initial investment in the early stage.

$$LCOE = \sum_n \left(\frac{Exp_n}{(1+dr)^n} \right) \Bigg/ \sum_n \frac{E_n}{(1+dr)^n} \tag{8}$$

$$Exp_n = Capex_n + Opex_n + F_n \tag{9}$$

4.1.2. Green ammonia as a fertilizer and fuel

Currently, ammonia produced from fossil fuels (i.e. grey ammonia) is primarily used as a fertilizer in agriculture. The price of grey ammonia in China fluctuates between 285 and 500 USD/t with an average price at around 430 USD/t in the past decade [50,75]. In contrast, green ammonia price ranges from 700 to 1400 USD/t worldwide, with the level of 700–800 USD/t primarily reported and estimated [76–78]. Levelized cost of green ammonia is estimated at 720–820 USD/t in eastern Inner Mongolia in the north of China, where enormous availability of renewable resources are located [19]. In the light of this, green ammonia price is currently at least around twice that of grey ammonia in China. Therefore, a moderate increase of the share of green ammonia as a fertilizer provides a potential pathway to gradually phase out the use of grey ammonia in agriculture.

Besides, green ammonia is emerging as a clean fuel with co-firing ammonia with coal in power generation as an important application to decarbonize the power sector and provide sufficient demand. The mixed fuel cost and related power generation cost are evaluated based on average thermal coal trading price from 2012 to 2021 and green ammonia price, in which, green ammonia price is estimated with production cost and gross margin in the works [19,50]. Scenarios with different co-firing rate ranging from 0 to 20 % are defined in Table 3. Levelized cost of electricity for the co-fired power generation is evaluated based on Eqs. (8) and (9). Specifically, unit fuel cost is evaluated based on Eq.(10) and (11), where FC^m denotes consumption of the mixed fuel for power generation per unit of power generated; FE^m denotes

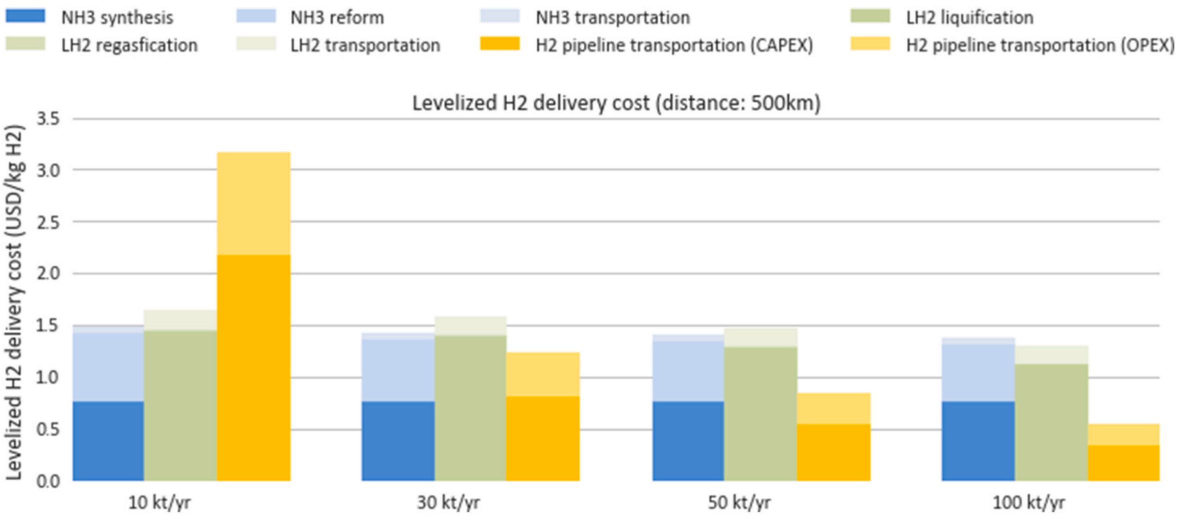

Fig. 11. Impacts of transport volume on hydrogen delivery cost.

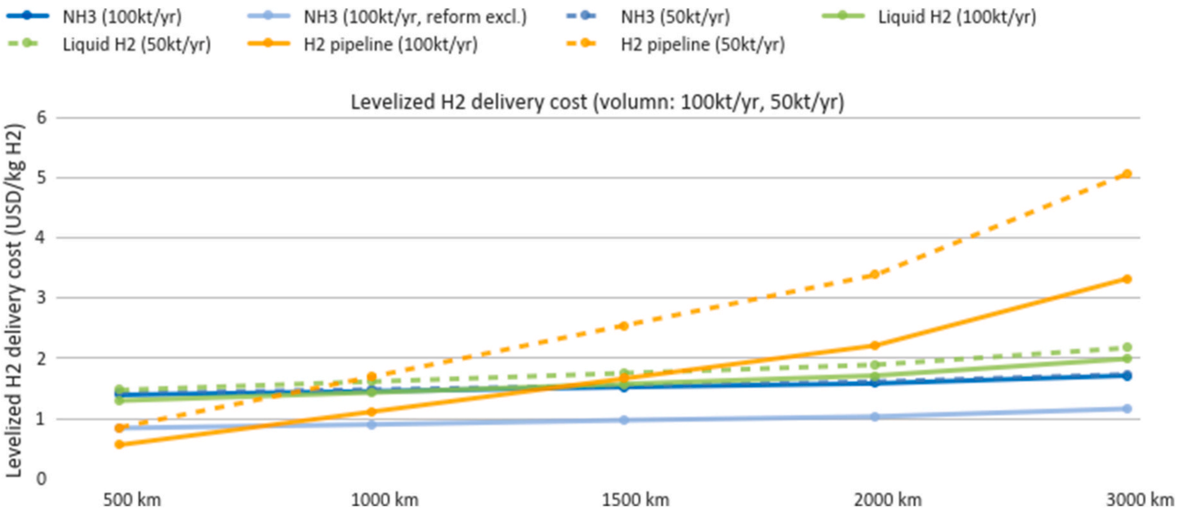

Fig. 12. Impacts of transport distance on hydrogen delivery cost.

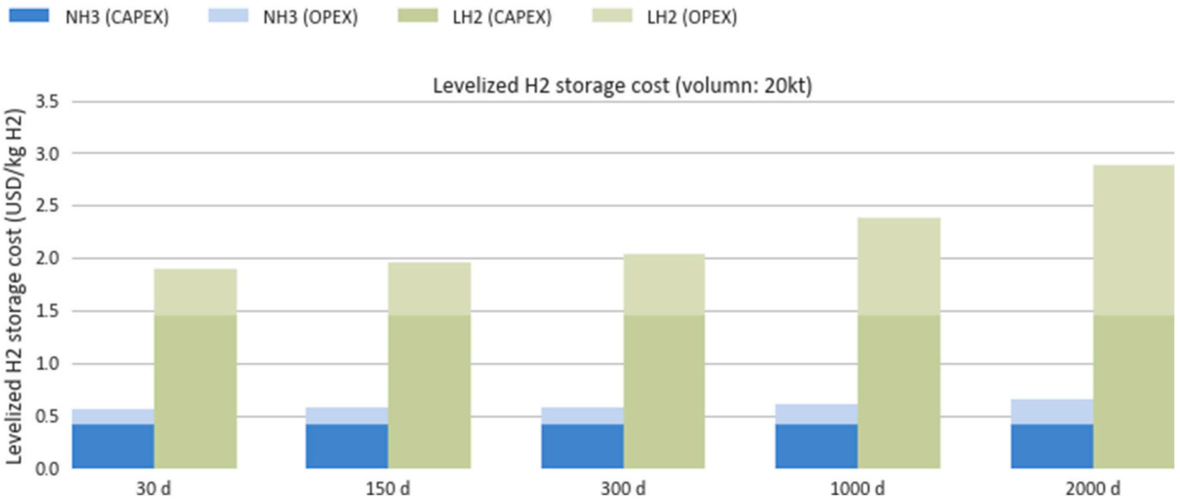

Fig. 13. Impacts of storage time on hydrogen storage costs.

Table 3
Scenarios of co-firing ammonia in coal power generation.

Co-firing scenario	Co-firing rate
Base case	0 %
Case A	3 %
Case B	5 %
Case C	10 %
Case D	15 %
Case E	20 %

mixed fuel cost; FC^c denotes coal consumption per unit of power generated; EL^m denotes energy utilization efficiency loss in ammonia co-firing; FE^{am} denotes cost of fuel ammonia; FE^c denotes cost of thermal coal; CR^m denotes ammonia co-firing rate. Parameters applied for evaluating costs of fuel ammonia are shown in Table 4. Currently, reports on performance and costs of the co-fired power generation are still limited, since ammonia co-firing is not yet commercialized. Some studies reported that retrofits in coal power plants may be required when co-firing rate is higher than 20 %, and a relatively low level of energy utilization efficiency loss in co-firing process [79,80]. For largely considering these possible impacts, additional costs in retrofits, operation and fuel for the 3–15 % co-firing scenarios are estimated based on the work which includes additional costs and higher energy efficiency loss for the 20 % co-firing case in Japan [81]. Besides, the ammonia price applied is based on production costs of green ammonia in the work [19].

Fig. 14 shows fuel and electricity costs as well as carbon emission intensity for ammonia co-firing. Both electricity and fuel costs undergo a stable increase with ammonia co-firing scaled up. Levelized cost of electricity for the base case is estimated based on average thermal coal costs from 2012 to 2021 [82]. Since currently green ammonia remains expensive, in the 3 % co-firing scenario, the mixed fuel cost grows by 22.8 %, which leads to a 19.2 % increase in levelized cost of electricity. However, the fuel cost is still lower than the maximum coal price in this period (2012–2021) which is 195.4 USD/tce, and much lower than the average natural gas price which is 393.5 USD/tce. Around 25.1 kg CO2 emission is reduced per MWh of power generated. A 5 % ammonia co-firing resulted in a 32.4 % increase in fuel cost and a 38.1 % cost increase in power generation. The fuel cost reaches 211.9 USD/tce which is slightly higher than the maximum coal price, but still much lower than the average natural gas price. Carbon emission intensity is reduced by 41.9 kg CO2/MWh. Mixed fuel cost rises by 2.6 times and power generation cost reaches 150.3 USD/MWh when co-firing rate is 20 %, compared to the base scenario without co-firing considered. However, the mixed fuel cost in this case just reaches the level of the average gas price.

Table 4
Parameters for evaluating costs of ammonia co-firing.

Parameter	Value	Unit	Source
Thermal coal trading price (2012–2021)	142.4–195.4	USD/tce	[82]
Industry natural gas price (2012–2021)	385.7–349.5	USD/tce	[84]
Lower heating value of thermal coal	5500	kcal/kg	[82]
Lower heating value of ammonia	18.6	MJ/kg	[85]
Green ammonia price	800	USD/t	[19]
Gross Margin of ammonia sales	5	%	[50]
Coal consumption in power generation	0.31	tce/MWh	[86]
CO2 emission of coal power generation	838	kg/MWh	[80]
Investment cost increase in co-fired power generation (3–20 % co-firing rate)	1.65–11	%	[81]
Operating cost increase in co-fired power generation (3–20 % co-firing rate)	1.5–10	%	[81]
Energy utilization efficiency loss in co-fired power generation (3–20 % co-firing rate)	1.8–12	%	[81]
Average share of investment cost in coal power generation	7	%	[87]
Average share of operating cost in coal power generation	18	%	[87]
Average share of fuel cost in coal power generation cost	75	%	[87]

Besides, the comparison of mixed fuel cost and that of natural gas does not consider efficiency of thermal power units. In practice, despite of the higher power generation efficiency of natural gas-fired units (~52 %) than that of coal-fired units (~38 %), the integrated efficiency (incl. coal and heat generation) is lower than that of coal-fired units (~57.6 % vs. ~75.7 %) in China [83]. Considering the high proportion of cogeneration (~62 %) in China's coal power plants [83], the mixed fuel cost is further economic. Further, the cost calculation is based on the average thermal coal price from 2012 to 2021. In practice, the fuel cost can be guaranteed and further reduced with long-term contracts with fuel suppliers. Therefore, ammonia co-firing at 3–5% rates (esp. 3 % rate in the near future) can be options for China for low-carbon transition, compared to increasing the share of natural gas in power generation.

$$FC^m = FC^c / (1 - EL^m) \tag{10}$$

$$FE^m = FE^{am} * CR^m + FE^c * (1 - CR^m) \tag{11}$$

4.1.3. Supply and demand

As analysed in above sections, it is economic to increase green ammonia demand in its early development stage from sectors where ammonia can be consumed directly. The current ammonia sector where ammonia is produced for traditional usage (fertilizer and chemical product) is a potential large consumer of green ammonia. In addition, ammonia to be used as a clean fuel for thermal power generation and shipping are also potential options, which has been considered in some countries [69]. Besides, the demand from the transportation sector is also taken into account, since the development of fuel cell vehicles (FCVs) is considered a high priority in China, and hydrogen is expected to achieve price parity with gasoline by 2025 [88,89].

The potential green ammonia supply capacity and demand in 2030 are evaluated with parameters shown in Table 5, in which, demands of conventional ammonia and heating oil for shipping, annual use hours of coal power, and its share in thermal power generation in 2030 are estimated based on sources [29,90]. Scenarios for supply capacity and demand are defined in Tables 6 and 7, respectively. Three supply levels are categorized by the available wind and solar power capacity for green ammonia production. Level A concerns a possible case and Level C is an ideal condition. Potential demand is divided into five levels (Level A-E) with penetration of green ammonia in the ammonia, power, shipping and automotive sectors.

Fig. 15 shows the potential supply capacity and demand levels of green ammonia in 2030. The lowest level of demand can be met if 15 % of wind and solar power generated is used for green ammonia production. However, the ideal supply capacity can only meet around 58 % of the highest level of demand. This is because power sector consumes significant amount of energy in China, thus a slight increase in ammonia co-firing rate results in a dramatic rise in ammonia demand. In contrast to Japan's plan to achieve 20 % ammonia co-firing rate in coal power plants by 2030 [91], a 5 % co-firing rate requires around a half of overall wind and solar power capacity in China by 2030. As a result, a maximum of 3 % co-firing rate is more reasonable for China, as it requires about 32 % of wind and solar power generated by 2030. The ammonia sector can also provide sufficient demand for green ammonia, although its demand is lower than that of the power sector. A 50 % transition to green ammonia production consumes about 10 % renewable power generation by 2030. In contrast, despite of China's ambitious goals to have one million FCVs on the road by 2030 [92], the share of demand from FCVs is relatively insignificant, as only 1.8 Mt of ammonia is required annually for the ideal case. The demand of ammonia as shipping fuel is 6.7 Mt

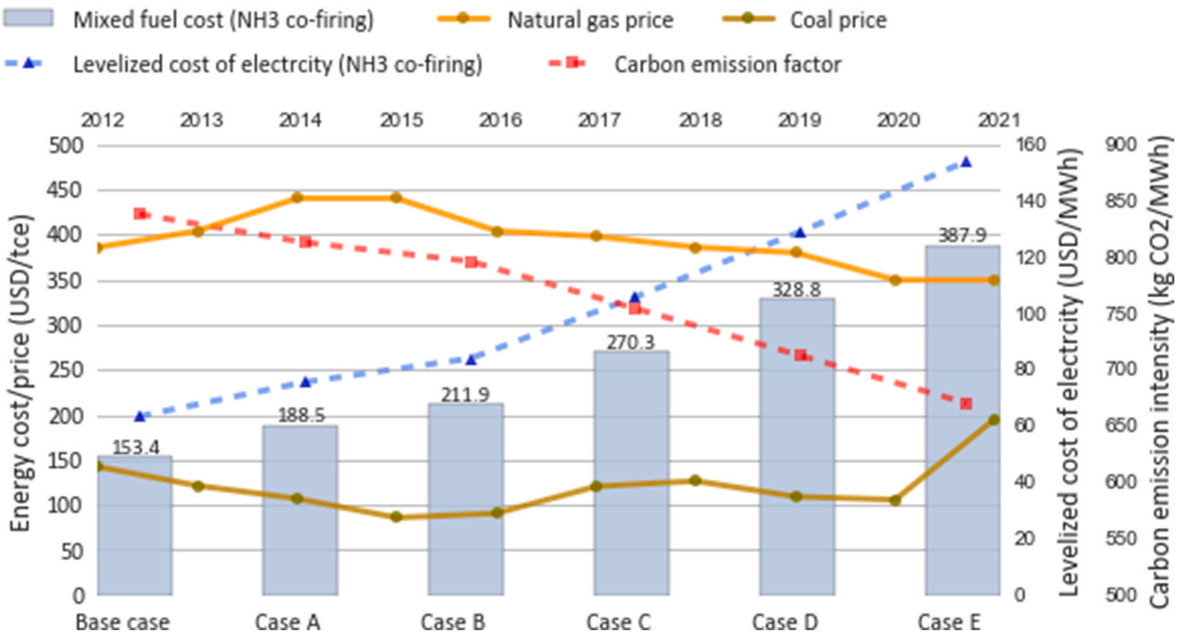

Fig. 14. Fuel and electricity costs and carbon emission intensity in ammonia co-firing.

Table 5
Parameters for evaluating green ammonia supply and demand in 2030.

Parameter	Value	Unit	Source
Wind power capacity in 2030	780	GW	[93]
Solar power capacity in 2030	840	GW	[93]
Thermal power capacity in 2030	1570	GW	[94]
Share of coal power generation in thermal power generation in 2030	85	%	[95]
Demand of conventional ammonia in 2030	52	Mt/yr	[29]
Demand of heating fuel for shipping in 2030	20	Mt/yr	[29]
Annual use hours of wind power	2246	h/yr	[29]
Annual use hours of solar power	1163	h/yr	[29]
Annual use hours of coal power	4000	h/yr	[90]
Proportion of coal power in thermal power	87	%	[90]
Electrolyser efficiency	70	%	[6]
Number of HRSs in 2030	1000	ea.	[92]
Average capacity of HRSs	1000	kg H2/d	[92]

Table 6
Scenarios for green ammonia supply capacity in 2030.

Supply capacity scenario	Share of wind and solar power capacity required
Level A	15 %
Level B	35 %
Level C	65 %

Table 7
Scenarios for green ammonia demand in 2030.

Demand scenario	PR in ammonia sector	PR in power sector	PR in shipping sector	PR in mobility sector
Level A	10 %	1 %	3 %	10 %
Level B	20 %	3 %	5 %	20 %
Level C	30 %	5 %	7 %	30 %
Level D	40 %	7 %	10 %	50 %
Level E	50 %	10 %	15 %	80 %

per year if 15 % of heating oil is replaced, which is higher than that of the automotive sector in the Level E.

4.2. Sustainability of developing a green ammonia industry

The sustainability of developing the future green ammonia industry in China is analysed from energy, environmental and economic aspects, by discussing the main barriers for China's sustainable development and the expected advantages of developing a green ammonia industry to mitigate and address these problems.

4.2.1. Energy aspect

From the energy aspect, the key challenges in China's energy transition are summarized as below.

(1) Coal-dominated energy structure. China planned to slow down the growth of energy consumption and phase out fossil fuel use, however, the primary energy consumption experienced a constant increase in the past decade, and China's economy remains closely tied to fossil energy.
(2) High vulnerability in energy security. Beside coal consumption, demand of crude oil and natural gas gradually increases. Due to the limited domestic supply capacity, more than 70 % of oil and 40 % natural gas supply depend on imports, which threatens capability of long-term and sustainable energy supply. In addition, the limited energy importers and energy transportation corridors have further worsened China's energy security.
(3) Low level of renewable energy utilization. China's renewable energy sector grows fast and accounts for 23 % of total power generation capacity. However, the divergence between installed capacity and actual power generation grows dramatically due to the spatial mismatch between energy supply and demand. China pursues inter-regional power transmission to facilitate the power transmission to load centers, however, failed to meet its expectation. The intermittent power generation has resulted in low-level transmission and creation of extra thermal power capacity. In addition, the transmission capacity is far from sufficient.

The expected advantages of developing the green ammonia industry from the energy perspective are summarized as follow.

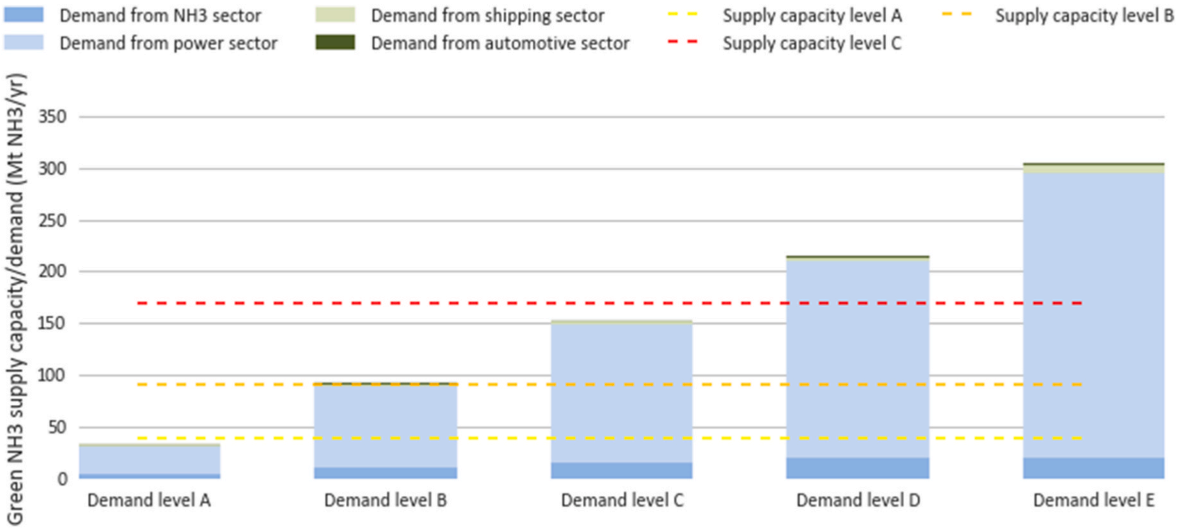

Fig. 15. Potential green ammonia supply capacity and demand in 2030.

(1) Declining the share of fossil fuels in overall energy consumption. As a potential hydrogen carrier and clean fuel, massive renewable energy can be converted and stored in the form of ammonia which can be further consumed for power generation, heat supply and other purposes. In particular, this can improve the coal-dominated energy structure by lowering the share of coal in the overall primary energy consumption.
(2) Enhancing energy security. Oil and natural gas supply is by far heavily dependent on imports which are subject to high geopolitical risks. The use of green ammonia as a fuel can reduce the reliance on the imports of oil and natural gas, therefore enhancing the China's energy security.
(3) Enabling large-scale and long-distance hydrogen distribution and long-term hydrogen storage. As ammonia is considered to be a safe and economic medium for hydrogen transportation and storage, and a mature infrastructure already exists, green ammonia can play a key role for large-scale energy distribution and long-term energy storage. As a result, green ammonia can contribute to addressing the challenges of intermittent renewable power generation and facilitating inter-regional power transmission and energy distribution. In addition, since ammonia industry has a wide distribution in China, green ammonia is crucial to reduce and tackle the renewable power curtailment especially in the north of China.

4.2.2. *Environmental aspect*

From the environmental aspect, the key challenges in China's decarbonisation are summarized as below.

(1) Massive CO2 emission due to the industrialization. The coal-dominated energy structure has posed a big challenge to China's goals towards the low-carbon energy transition. Power and heat supply emit around half of the overall CO2 in China, and around 70 % of which is consumed by the industry sector. In addition, the direct emission from industry accounts for more than 30 % of the overall CO2 emission. These indicate that approximately 70 % of CO2 emission is caused by China's industrialization, especially after joining the WTO in 2001. Therefore, the industry decarbonisation is essential in achieving China's carbon reduction goals.
(2) The traditional ammonia industry as a representative of one of the most energy-intensive and pollutant industries difficult to achieve decarbonisation. The conventional ammonia sector accounts for 40 % of global production capacity due to the significant demand mainly from the agricultural and industrial sectors [96]. Ammonia industry is widely distributed in each region, especially in north, east, and mid-south of China. Ammonia is primarily produced from coal and natural gas, especially coal-based ammonia plants is dominant accounting for 76 % of production capacity in China. As a result, the ammonia industry is one of the largest energy consumers and most pollutant sectors in China, which has significantly contribute to energy and environmental issues.

The expected advantages of developing the green ammonia industry from the environmental perspective are summarized as follow.

(1) Facilitating carbon emission reduction by using green ammonia as a clean fuel. Around 70 % of CO2 emission is caused by industrial production directly and indirectly, and coal is still the dominated energy source in China. Therefore, the use of green ammonia in energy-consuming and pollutant power generation and industrial processes as a clean fuel instead of coal can facilitate industry decarbonisation and energy transition.
(2) Decarbonising the traditional ammonia industry. Since conventional ammonia is exclusively produced from fossil energy and the industry is highly energy-intensive and pollutant, the shift to green ammonia production can reduce the reliance on fossil fuels (especially on coal) and decarbonize the industry.

4.2.3. *Economic aspect*

From the economic aspect, the main issues of China's regional sustainable development are summarized as follow.

(1) Imbalanced and unsustainable regional development. China's economy has grown as the second largest in the world, but the economic growth is imbalanced, and some regions experience unsustainable development. East and mid-south of China are the most developed regions with high GTFPs and low energy and carbon intensities. In contrast, northwest, southwest, and northeast of China are unsustainable regions with low productivity and high energy consumption and pollution as per economic size.

The expected advantages of developing the green ammonia industry from the economic perspective are summarized as follow.

(1) Advancing the development of a hydrogen economy. Ammonia is a flexible and economic hydrogen carrier and clean fuel, in

addition to being a widely used chemical product. Transporting and storing hydrogen as ammonia can further reduce the cost. Without cracking back to hydrogen, the direct use of ammonia can further reduce the cost and decarbonize the industry sector, and is easy to gain economies of scale effect. Further, the re-use of current ammonia supply chains existing for 10 decades for hydrogen transportation and storage can significantly save the cost in new hydrogen infrastructure investment. Therefore, these are essential to advance the hydrogen economy, especially in the early stage.

(2) Facilitating synergetic regional development. The concept and technology of power-to-x (P2X) is expected to transform and reshape the industrial system, especially phasing out the current coal and oil-chemical industries in China. Currently, around a half of the ammonia production capacity is distributed in the most developed regions, incl. east and mid-south of China. A geographical restructuring of the ammonia industry is inevitable with more production capacity moving close to renewable power bases mainly in north, northwest, northeast and southwest of China. The restructuring would bring a massive transfer of production factors, incl. capital, labour force, and technology, to these regions which can facilitate the local economic development. In addition, these regions would also see a further rise in regional development with the promotion as the supply centre of green ammonia (as well as other green products) in China.

4.2.4. *Barriers to achieving a green ammonia industry*

With the 2021–2035 Hydrogen Development Plan delivered, China seeks for decarbonizing the traditional ammonia sector with renewable energy [5]. As a result, China is scaling up green ammonia production with demonstration projects announced. A total of 13 projects are under construction (capacity being 790,000 t/yr) and 77 projects (capacity being 12.3 Mt/yr) planned by the end of 2023 [97]. For instance, the world's largest ammonia plant is under construction in Jilin province with production capacity being 180,000 t/yr [98]. Besides, with the potential of green ammonia for decarbonisation increasingly seen, China announced to use biomass, green ammonia and carbon capture technologies to tackle emissions from coal-based power plants [99]. However, there are many barriers to achieving a green ammonia economy. From the technical aspect, due to the intermittent renewable power generation, green ammonia production faces challenges of flexible operation of electrolysers, which requires further optimization for scale-up [100]. In addition, though green ammonia production does not involve direct CO2 emission, the combustion process emits nitrogen oxides (i.e. NOx and N2O), in which, N2O has a much higher greenhouse effect than that of CO2. Research and technologies to avoid the emissions is currently in progress. For instance, selective catalytic reduction (SCR) technology is tested and applied in Japan to reduce NOx emissions by 90 % [101]. From the economic aspect, though ammonia price is expected to decrease dramatically by 2030 and 2050, the current green ammonia price remains high (ranging from USD 720–1400 in 2020) mainly due to electricity price, investment in electrolysers and operating costs [102]. Therefore, the current price compared to that of grey ammonia questions about the demand [102]. From the institutional aspect, the speed of construction of green ammonia plants is outstripping the establishment of institutions. As the position of green ammonia in China's energy transition is still vague, there is a lack of overall planning and policy for the development of the green ammonia industry [103]. In addition, related regulations and standards for implementing affordable, effective development routes and safe operation of the production, transportation and storage are not yet in place [104].

5. Conclusions and policy implications

This study evaluated the sustainability challenges in China and potential role of green ammonia in meeting these challenges. The analysis was carried out from a 3E perspective with discussion on energy, environmental and economic aspects. The main findings and results are summarized as follows.

First, the main challenges in China's energy transition, decarbonisation, and regional sustainable development were explored.

(1) Despite of calling for reducing fossil energy use, the fossil fuel especially coal-dominated energy consumption poses great challenges to achieving energy transition. In addition, the high dependency on oil and gas import with limited importers and energy transportation corridors has threatened the energy security. Despite the leading renewable energy investment, the utilization of renewable energy remains low due to the spatial energy mismatch and the lack of power market mechanisms.

(2) The coal-dominated energy consumption and large-scale industrialization after joining WTO have led to massive CO2 emission. The traditional ammonia industry is one of the largest energy consumers and pollutant industrial sectors, significantly contributing to energy and environmental issues.

(3) Imbalanced and unsustainable regional development were observed by applying indexes of GTFP, carbon and energy intensities in the six administrative regions of China. GTFPs were calculated by applying a DEA optimization model with labour force, capital stock, energy consumption and carbon emission as inputs and GDP as the output. Northwest, northeast and southwest China were evaluated as unsustainable regions with low GTFPs and high energy and carbon intensities, in contrast to East and mid-south China.

Next, the role of green ammonia in meeting these challenges was analysed.

(1) The potential of green ammonia as a hydrogen carrier, fertilizer and fuel was evaluated. Ammonia was examined to be a flexible and economic option for long-distance and large-volume hydrogen transport and long-term energy storage. Ammonia delivery cost is little influenced by volume and distance (~1.2–1.6 USD/kg H2 for 500–3000 km) and can be further reduced by 45–54 % if ammonia can be consumed directly. Storing hydrogen as ammonia is less influenced by storage length (~0.6–0.7 USD/kg H2 for 30–2000 days). For the use of green ammonia as a fertilizer, green ammonia price is at least twice that of grey ammonia in China. For fuel ammonia, ammonia co-firing in coal power plants at 3–5% rates can be options for China to implement carbon reduction, compared to investing into gas power generation. Especially, a 3 % co-firing resulting in a 19.2 % increase in levelized cost of electricity is a potential option for the near future. Regarding potential supply capacity and demand by 2030, the ammonia and power sectors can provide sufficient demand for green ammonia. Especially for power generation, a 3 % co-firing ammonia in coal power plants can provide significant green ammonia demand (~82 Mt NH3/yr), requiring 32 % wind and solar power generated in 2030, due to the large-scale coal power generation.

(2) The sustainability of a green ammonia economy was analysed from energy, economic and environmental perspectives. From the energy aspect, the use of green ammonia especially as a clean fuel can reduce fossil energy consumption and enhance energy security by lessening the imports of oil and gas. In addition, the use of green ammonia as a hydrogen carrier can facilitate energy transition by enabling large-scale energy distribution and storage. From the environmental aspect, the use of green ammonia as a fertilizer and clean fuel can facilitate industry decarbonisation by phasing out energy-intensive and pollutant production processes and the use of fossil fuels. From the economic aspect, the

potential of green ammonia being a fertilizer, fuel and energy carrier can advance the development of a hydrogen economy. In addition, the green ammonia economy can facilitate synergic regional development by driving the industry restructuring with forming new P2X industries and bringing production factors close to renewable resource-rich areas which are mainly located in unsustainably developed regions in China.

In addition, policy implications resulted from this study are presented as follows.

(1) Based on the findings and results, the development of a green ammonia industry to meet China's energy, economic and environmental challenges and facilitate the hydrogen economy is proposed. First, a green ammonia policy from a national level should be enacted to formulate clear objectives and overall strategies for the industry development, such as the fields of green ammonia utilization, market creation, investment in the industry, etc. Second, regulatory reform is necessary to allow using green ammonia as a hydrogen carrier and a clean fuel. Third, mid and long-term development plans should be developed for developing the industry in different stages. The plan should be in line with the overall policy. Fourth, detailed policies, rules, and regulations for market and infrastructure development should be developed. Specifically, for the large-scale use of green ammonia, a proper and rigorous framework should be developed to prevent safety and environmental hazards, given the corrosive and toxic nature of green ammonia and potential nitrogen oxides (esp. N2O) emissions during its combustion process.

(2) The use of fuel ammonia in power generation and transportation should be paid attention as important applications to facilitate the industry development in the early stage. Based on the analysis in this study, the power sector particularly can provide significant demand for green ammonia. China considers increasing the share of natural gas in thermal power generation instead of coal to achieve carbon reduction, since natural gas is a cleaner fossil energy with 68 % carbon emission that of coal [105]. In contrast, co-firing ammonia can reuse the existing coal power plants to avoid massive investments in natural gas power plants, meanwhile reducing carbon emission. Further, since natural gas consumption heavily relies on import, co-firing ammonia can secure energy safety by producing ammonia with renewable power, meanwhile addressing renewable power curtailment in China. In the long run, the direct use of ammonia in fuel cells should be paid attention. The practice can reduce complexity of processing ammonia without cracking ammonia to hydrogen separately, increase the efficiency and further broaden the use of green ammonia.

Besides, this study has some limitations. First, it mainly discussed the importance of developing a green ammonia industry towards a sustainable development in China. However, the safety and emission concerns and associated impacts on developing the green ammonia industry require further evaluations. Second, the levelized hydrogen delivery and storage costs were estimated based on a constant cost and energy delivered or stored per year. The mixed fuel cost and levelized cost of electricity for ammonia co-firing are evaluated based on a set of parameters with average numbers. Therefore, these can vary in the light of actual operating and regional conditions. Third, ammonia co-firing was analysed in terms of supply and demand and cost increase in power generation, however, the impact on demand side, such as the industry and residential sectors has not been considered. In addition, impact of co-firing on fuel and electricity costs does not consider carbon tax. These can be studied to further inform policy.

CRediT authorship contribution statement

Hanxin Zhao: Writing – original draft, Validation, Software, Methodology, Formal analysis, Conceptualization.

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.

Data availability

Data has been shared in the article.

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Nomenclature

Abbreviation	Full name	
3E	Energy-environment-economy	
Btce	Billon ton of standard coal equivalent	
CRS	Constant return to scale	
DEA	Data Envelope Analysis	
DMU	Decision-making unit	
GDP	Gross domestic product	
GTFP	Green total factor productivity	
P2G	Power to gas	
Mtoe	Million ton of standard oil equivalent	
WTO	World trade organization	
Index	Definition	
n	Year	
i	DMU	
j	DMU	
Variable/Parameter	Definition	Unit
δ	Depreciation rate	%
θ_i	Efficiency of the DMU i ranging from 0 to 1	ea.
λ_i	Weight of the DMU j	ea.

(*continued on next page*)

(*continued*)

Abbreviation	Full name	
$Capex_n$	Investment cost in year n.	USD/yr
$C_{i,n}$	CO2 emission of region i in year n	B kg/yr
$CI_{i,n}$	Carbon intensity of region i in year n	kg/USD
CR^m	Ammonia co-firing rate in power generation	%
dr	Discount rate	%
E_n	Quantity of energy delivered or stored in year n.	kg/yr
$E_{i,n}$	Energy consumption of region i in year n	B Btu/yr
$EI_{i,n}$	Energy intensity of region i in year n	Btu/USD
EL^m	Energy utilization efficiency loss in ammonia co-firing	%
Exp_n	Total expense in year n	USD/yr
F^n	Fuel cost in year n.	USD/yr
FC^c	Fuel consumption for coal power generation per unit power generated	tce/MWh
FC^m	Consumption of the mixed fuel for power generation per unit power generated	tce/MWh
FE^{am}	Fuel cost for green ammonia	USD/tce
FE^c	Fuel cost for thermal coal	USD/tce
FE^m	Mixed fuel cost	USD/tce
$G_{i,n}$	GDP of region i in year n	B USD/yr
$I_{i,n}$	Fixed capital stock of year n in region i	B USD
$K_{i,n}$	Capital stock of year n in region i	B USD
$Opex_n$	Operating cost in year n.	USD/yr
X_j	the inputs of the DMU j	n.a
Y_j	the outputs of the DMU j	n.a

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