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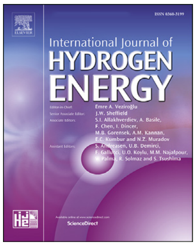

The potential of green ammonia production to reduce renewable power curtailment and encourage the energy transition in China

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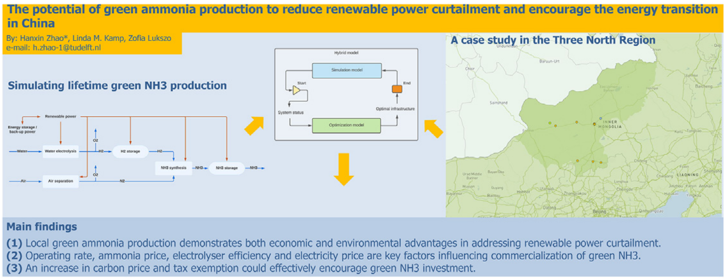
HIGHLIGHTS

- Local green ammonia production to reduce renewable power curtailment is explored.
- The impacts of institutional incentives on green ammonia production are evaluated.
- A hybrid model is applied to simulate the lifecycle green production.
- Green ammonia investment exhibits both economic and environmental advantages.
- The integration of oxygen manufacturing into green hydrogen production is proposed.

GRAPHICAL ABSTRACT



The potential of green ammonia production to reduce renewable power curtailment and encourage the energy transition in China

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Simulating lifetime green NH3 production

A case study in the Three North Region

Main findings

(1) Local green ammonia production demonstrates both economic and environmental advantages in addressing renewable power curtailment.
(2) Operating rate, ammonia price, electrolyser efficiency and electricity price are key factors influencing commercialization of green NH3.
(3) An increase in carbon price and tax exemption could effectively encourage green NH3 investment.

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ABSTRACT

The pursuing of inter-regional power transmission to address renewable power curtailment in China has resulted in disappointing gains. This paper evaluates the case of local green ammonia production to address this issue. An improved optimization-based simulation model is applied to simulate lifetime green manufacturing, and the impacts of main institutional incentives and oxygen synergy on investment are analysed. Levelized cost of ammonia is estimated at around 820 USD/t, which is about twice the present price. The operating rate, ammonia price, the electrical efficiency of electrolysers and the electricity price are found to be the key factors in green ammonia investment. Carbon pricing and value-added tax exemption exert obvious influences on the energy transition in China. A subsidy of approximately 450 USD/t will be required according to the present price; however, this can be reduced by 100 USD/t through oxygen synergy. Compared to inter-regional power transmission, green ammonia production shows both economic and environmental advantages. Therefore, we propose an appropriate combination of both options to address renewable power curtailment and the integration of oxygen manufacturing into hydrogen

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production. We consider the findings and policy implications will contribute to addressing renewable power curtailment and boosting the hydrogen economy in China.

Introduction

Renewable power curtailment in China

China is the world's largest renewable energy ‘fleet’, with wind and solar cumulative generation capacity reached 281.5 GW and 253.4 GW respectively by the end of 2020 [1]. Geographically, wind and solar energy resources are mostly distributed in the north, northwest and northeast of China (also known as the Three North region), while the economic clusters (i.e. electricity load centres) are generally located in the east and south of China [2]. Spatial imbalance between energy supply and demand and grid inflexibility have led to serious renewable power curtailment, which has resulted in a sharp decline of utilization and a growing divergence between installed capacity and actual power generation [3–6].

As a result, China has pursued the building of ultra-high voltage (UHV) lines to transmit renewable energy from the northern and western regions to eastern and southern China [7]. By 2020, 20 UHV lines had been built, stretching approximately 30,000 km and capable of supplying 4% of national demand [7,8]. However, progress has been less than expected. The overall operating rate of these dedicated lines was lower than 40% in 2019, and for some lines, the operating level has been even lower than 20% [9]. Moreover, most transmission has concerned coal and hydro power, with wind and solar energy only accounting for a small share, 13% of overall transmission in 2019 [9,10]. The main causes of this are the overcapacity of power generation and a lack of marketing mechanisms [11]. The growth rate of the national power demand fell to 4.5% in the last decade, from 11.7% in 2003, which led to 35% overcapacity in 2016 [7]. This has resulted in fewer buyers willing to accept power from other regions, since local power supply is still sufficient [7,9]. In addition, the fragmented and province-based electricity sector has been failing to prioritize the distribution of renewable sources [12].

Green ammonia production in China

These challenges call for a concerted effort. With the concept of ‘Power to Gas’ (P2G), hydrogen produced from renewables has become a potential enabler of the energy transition [13]. Today, around half of hydrogen is being consumed in ammonia plants, and hydrogen is mainly extracted from coal and natural gas, which generates over 420 million tons of CO2 annually [14,15]. In the future, ammonia would see it completely renewable by being made from using green hydrogen from water electrolysis, and nitrogen separated from the air, as shown in Fig. 1. Since hydrogen to ammonia is a well-established technology, and green ammonia increasingly draws attention as a stable and economical means to storing and transporting hydrogen, green ammonia production is regarded as an effective way to advance the hydrogen economy [16,17]. However, this has not gained much attention in China, the world's largest ammonia producer, whose interest remains in leading the global development of fuel cell vehicles (FCVs) [18]. As there is large-scale ammonia production in the Three North region, the evaluation of green ammonia commercialization is of great importance with respect to finding cost-effective and sustainable strategies to address renewable power curtailment in China, while decarbonizing the industrial sector and encouraging the energy transition.

Research on reducing renewable power curtailment in China

Recent studies have looked for solutions to the curtailment problem in China. Some researchers discuss institutional solutions. For example, Liu et al. suggested the enhancement of the use of renewable energy by resolving administrative barriers and introducing market-based mechanisms [19]. Luo et al. considered the operation and management coordination system to be key to enhancing wind power dispatch, and that market-based measures should also be applied [20]. In particular, some studies have investigated the low utilization of inter-regional power transmission and identified the potential barriers. For example, Luo et al. argued that electricity oversupply and a lack of marketing mechanisms are key causes and that electricity trade markets should be established [11]. Tan et al. found that the UHV grid makes a limited contribution to the mitigation of power curtailment and concluded that market-based reform is critical to improve the situation [21]. Qi et al. identified key institutional barriers, and recommended power sector reform that would lead to the establishment of a regional spot market to address the problem of wind curtailment [22]. Since there are still many obstacles standing in the way of institutional reform, researchers have also looked at technically-focused solutions. Pumped hydro-storage and electric boiler heating are the most well researched solutions in recent studies. For example, Zhang et al. evaluated the effectiveness of pumped hydro-storage and its combination with electric boiler heating to cope with wind curtailment [23]. Lei et al. proposed a multi-level operation mode for electric boiler heating systems to improve wind accommodation in north-eastern China [24]. In addition, other solutions such as: distributed power system and battery storage have been discussed (e.g. literature [25]).

In the above studies, P2G was not yet included as an option for addressing renewable power curtailment in China. With the growing awareness of the advantages of P2G, some related studies have been carried out. For example, Lin et al.

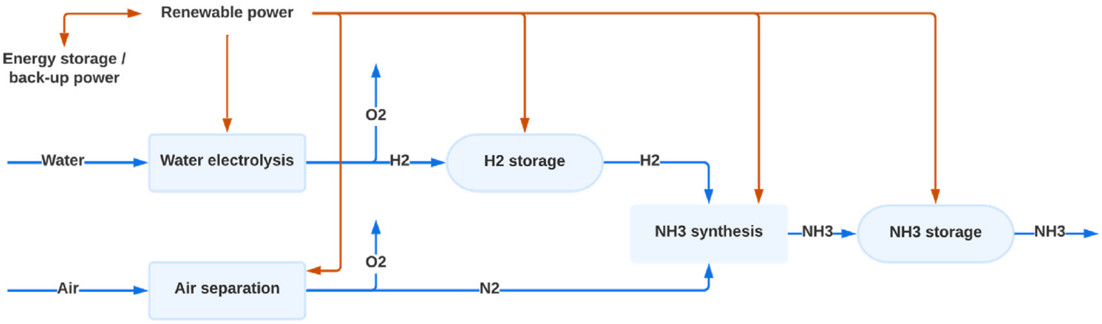

Fig. 1 – The process of green ammonia production.

examined the economic and technical feasibility of producing green hydrogen to reduce wind curtailment in China's Western Inner Mongolia [26]. Liu et al. evaluated the economic and environmental impacts of converting renewable energy to hydrogen and methane and injecting it into the existing natural gas system in China [27]. Yang et al. explored the optimal power and capacity allocation of grid-connected solar farms integrated with hydrogen production [28]. Although there is a large-scale coal-chemical industry including ammonia manufacturing located in the Three North region [29], none of these studies considered taking advantage of green ammonia production to reduce power curtailment in China.

Research on the techno-economic analysis of green ammonia production

Although the use of green ammonia to advance the hydrogen economy has not received much attention from either government or academia in China, it has attracted increasing interest on a global scale [16,30].

Regarding the techno-economic analysis of green ammonia production, some studies have focused on the operation and process levels, aiming to evaluate the detailed performance of ammonia production processes and operations (e.g. see Refs. [31–33]).

Another category of studies concentrate on a macro level, aiming to explore the potential incorporation of green ammonia production into a future ammonia industry. For example, Bicer et al. assessed the life-cycle environmental impacts of ammonia produced by hydropower, nuclear, biomass, etc. [34]. Pawar et al. evaluated the techno-economic potential of green ammonia production via solar and on-shore wind energy in India [35]. In a case study of Chile and Argentina, Armijo et al. found that the hybridization of wind and solar energy can reduce production costs of ammonia [36]. These studies were undertaken from a production perspective, that is, evaluating the production costs of ammonia and identifying influence factors.

There are also studies that have analysed the feasibility of green ammonia production from an investment perspective. For example, Jamie et al. evaluated the profitability of green ammonia production using PEM electrolysers, and found that the cost of electricity, the conversion rate and efficiency dominate the tonnage cost of ammonia [37]. Smith et al. studied the economic benefits of green ammonia production using hydro power in transforming economies in sub-Saharan Africa [38]. Guerra et al. investigated investment to green ammonia production in Chile using solar, wind and hydropower [39]. Zhang et al. examined the feasibility of investment in two types of green ammonia production including biomass to ammonia and power to ammonia [40]. Since investment costs for green hydrogen and ammonia will remain high, financial incentives are required [41–43]. Additionally, by-product oxygen in hydrogen production is one of the most consumed industrial gases widely used in steel-making, chemical industries, etc. [44]. However, in our literature search, we found that no research in the field has discussed the impacts of institutional incentives and by-product oxygen on investment in green ammonia.

Research goal and contribution

In summary, as a large part of China's ammonia industry is located in the Three North region, local green ammonia production is a potential option to address renewable power curtailment and power overcapacity in China. Therefore, evaluating the possibility of green ammonia commercialization in China is of great importance. However, this has not attracted much attention in the research to date. Regarding the techno-economic assessment of green ammonia production, to the best of the authors' knowledge, no related studies have examined the impacts of institutional incentives and by-product oxygen synergy on the commercialization of green ammonia. Thus, this paper aims to explore the potential of green ammonia investment to reduce renewable power curtailment in China, while decarbonizing the industrial sector. The contributions of this paper are:

1) We evaluate the possibility of commercializing green ammonia with a typical case study in the Three North region, where renewable power is not successfully transmitted by the UHV transmission lines. The lesson learnt provides a solid reference and pathways to address renewable power curtailment and power oversupply in China, and may also give insights to other countries encountering renewable power curtailment.

2) The impacts of the main institutional incentives (including carbon pricing, subsidies and tax exemptions) and by-product oxygen synergy on clean energy investment are analysed. We consider this is of significance since green ammonia remains expensive at the moment, and also with respect to decarbonizing the industrial sector and encouraging the energy transition in China.
3) We propose a supply system for green hydrogen and ammonia production in which renewable power is imported via dedicated electricity lines for electrolysis close to the ammonia plant. Compared to hydrogen production distributed across multiple renewable power stations, centralized hydrogen production can avoid the construction of multiple hydrogen plants, and eliminate the need for hydrogen transportation from production sites to the consumption terminal.
4) A hybrid optimization-based simulation model is applied to simulate green ammonia production. This advances our previous work [45] by including new supply chain infrastructure and adding the effects of institutional incentives into the simulation.

Structure of the paper

The remainder of this paper is arranged as follows: the proposed supply system, modelling approach, details of the case study and assumptions are introduced in Section Methods. Section Results discusses the possibility of green ammonia investment to reduce renewable power curtailment, taking into account the impacts of institutional incentives and oxygen synergy. Section Discussions and policy implications discusses the key findings, policy implications and limitations of the work, while Section Conclusions presents our conclusions.

Methods

The green supply chain

As shown in Fig. 2, we propose a supply system for green ammonia production. Rather than distributed hydrogen production at multiple renewable power stations, it entails a centralized hydrogen production system.

Regarding the infrastructure required to integrate renewable power into existing power grids, electricity from renewable power stations is normally converged via 10/35 kV high voltage alternating current (HVAC) lines from renewable power stations to substations, where electricity is further boosted to 110/220 kV and transmitted to existing power grids by HVAC lines [46,47].

In the proposed supply chain, additional HVAC lines are built to import renewable power from the substations to a hydrogen plant at a distance that would normally be less than 100 km. The hydrogen plant is installed next to the ammonia plant, consisting of an electrical system, electrolysers and tanks for hydrogen and oxygen storage. Electricity is first transmitted to an electrical system and converted to direct current (DC) power with a lower voltage to feed electrolysers. The electrical system includes transformers, rectifiers, electrical control facility, etc. Alkaline electrolysers (AECs) are most applied, especially in China, due to low capital costs and high electrical efficiency [18]. Liquid storage of hydrogen can improve energy density; however, facilities and electricity

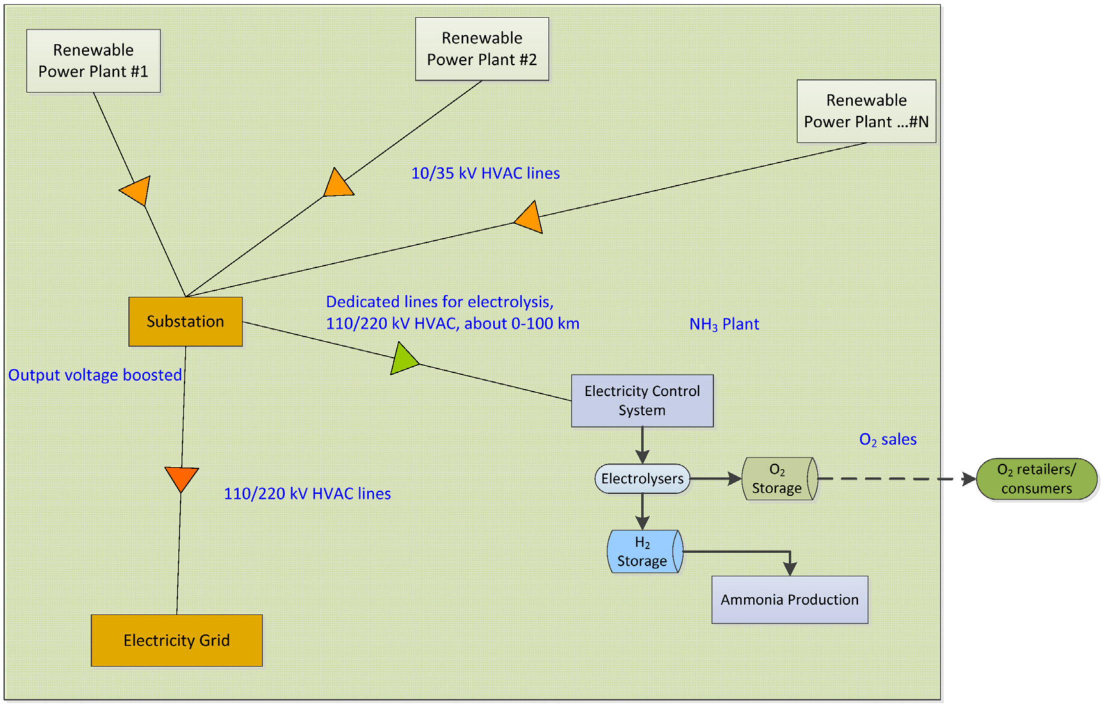

Fig. 2 – The supply system for green ammonia production.

required for liquefaction make this option costly [48,49]. This is also the case for oxygen storage. The combination of AECs and gaseous storage options was also examined as a cost-effective assemblage in our previous work [45]. Hence, this portfolio is selected in the supply chain design. Moreover, a gate price for oxygen is used to analyse the impacts on investing in green ammonia, and therefore additional transport or delivery charges are excluded from the price. In other words, transporting oxygen is not considered in the supply system. The related techno-economic parameters applied to the supply chain design are listed in Table 1. In short, data regarding electrolysis technology is collected from the recent IEA report and P2G projects [17,50], in which, capital costs of AECs applied are median values. Specifications of storage tanks used are average values summarized from related database and work [51–53]. Parameters with reference to electrical connection system and ammonia storage are also collected from latest literature and related projects [54–60].

Table 1 – Techno-economic parameters applied to the green supply chain.

Parameter	Value	Unit	Source
Electrical efficiency of AEC	70	%	[17]
Capital cost of AECs (1 MW)	1265	USD/kW	[50]
Capital cost of AECs (5 MW)	781	USD/kW	[50]
Capital cost of AECs (10 MW)	750	USD/kW	[50]
Capital cost of AECs (50 MW)	682	USD/kW	[50]
Annual capital cost decrease rate of AECs	3.2	%	[50]
Share of capital cost of stack in AECs	50	%	[17]
Lifetime of stack in AECs	10	Y	[17]
Lifetime of AECs (stack excluded)	20	Y	[17]
Single circuit of HVAC transmission lines	250	k USD/km	[55]
Lifetime of HVAC transmission lines	30	Y	[56,57]
Capital cost of electrical system	38.5	USD/kW AECs installed	[54]
Lifetime of electrical system	30	Y	[58]
Storage capacity of compressed tank	1000	cu m	[51,52]
Storage pressure of compressed tank	3	MPa	[51,52]
Capital cost of compressed tank	1000	USD/cu m	[51,52]
Lifetime of compressed tank	20	Y	[52,53]
Storage capacity of ammonia vessel	4500	T	[59]
Capital cost of ammonia vessel	3636	k USD/t ammonia	[59]
Lifetime of ammonia vessel	30	Y	[59,60]

The hybrid model

A hybrid optimization-based simulation model developed in our previous work [45] is applied and further improved in this study. The model is essentially a simulation model that runs recursively with optimization model embedded to solve the design of the supply system in each time slot of an expansion. The related optimization and simulation components are introduced as follows.

Optimization model

The mixed integer linear programming (MILP) optimization model is adjusted to model the supply system proposed in Section The green supply chain. It should be noted that the content below refers to the expanded supply system rather than the entire supply system of each year. The decision variables, optimization function and constraints are introduced as below.

Decision variables. Simplifying energy system modelling is necessary to achieve the best trade-off between the level of accuracy and complexity [61,62]. Since other facilities are supplementary and their sizes correlate to that of the main facilities, the size of the main facilities constitute the decision variables as shown in Table 2, where n ε [1, 2, …, N] standing for [Year 1, Year 2, …, Year N], and e ε [1–4] standing for [AEC (1 MW), AEC (5 MW), AEC (10 MW), AEC (50 MW)]. In addition, all the variables and parameters applied are also defined in the nomenclature.

Objective function. The objective function shown in Eq. (1) minimizes the overall cost of the green ammonia supply chain in each expansion year. The overall cost comes from the main components in the supply chain including: hydrogen production ($P^{cost}{}_n$) and storage ($S^{cost}{}_n$), oxygen storage ($O^{cost}{}_n$) and sales ($O^{rev}{}_n$), power transmission and control ($T^{cost}{}_n$), and ammonia synthesis and storage ($A^{cost}{}_n$). Costs of these components are elaborated from Eqs. 2–15. In details, hydrogen production cost given in Eq. (2) comprises electrolysis related expense and miscellaneous expenses, including construction and installation costs, etc. Electrolysis related expense derived from Eqs. (3) and (4) comprises capital investment and operating cost per year n. Hydrogen storage cost derived from Eqs. (5) and (6) includes storage cost and miscellaneous expenses, including construction and installation expenses, expenses of compressors, etc. Electrical connection cost given in Eq. (7) comprises electrical connection system expense, power loss expense derived from Eq. (8) and miscellaneous expenses, including expenses of transformers, transmission lines, etc. Ammonia related cost given in Eq. (9) comprises synthesis and storage expenses defined in Eq. (10) and Eq. (11) respectively. Oxygen storage cost given in Eq. (12) comprises storage cost and miscellaneous expenses, including construction and installation expenses, etc. Eq. (13) indicates oxygen storage capacity in year n. Eq.14 and 15 define revenue from oxygen sales. Besides, the capital recovery factor (CRF) applied to calculate depreciation expenses is based on Eq. (16).

$$min.\ P_n^{cost} + S_n^{cost} + T_n^{cost} + A_n^{cost} + O_n^{cost} - O_n^{rev} \tag{1}$$

Table 2 – Definition of the decision variables.

notation	Definition	Unit
$PN_{n,e}$	Number of electrolysers *e* required in the *n*th year.	ea.
SN_n	Number of hydrogen storage tanks required in the *n*th year.	ea.
ON_n	Number of oxygen storage tanks required in the *n*th year.	ea.
$HP_{n,e}$	Hydrogen production rate by electrolysers *e* in the *n*th year.	kg/d
$S_{n,}$	Hydrogen storage inventory in the *n*th year.	Kg
OS_n	Oxygen storage inventory in the *n*th year.	Kg
T_n	Size of electrical connection system in the *n*th year.	kW

$$P_n^{cost} = \sum_e P_{n,e}^{\cos t} + P_n^{mcost} \tag{2}$$

$$P_{n,e}^{cost} = \left(P_{n,e}^{invcost} * P_e^{crf} + P_{n,e}^{optcost}\right) * P_{n,e}^{cap} + E_n^{prc1} * WH * HP_{n,e} \Big/ CF^{hp} \tag{3}$$

$$P_{n,e}^{cap} = PN_{n,e} * P_e^{ucap} \tag{4}$$

$$S^{n\cos t} = \left(S_n^{inv\ \cos t} * S^{crf} + S_n^{opt\ \cos t} * S_n^{cap}\right) + S_n^{m\ \cos t} \tag{5}$$

$$S_n^{cap} = SN_n * S_s^{ucap} \tag{6}$$

$$T_n^{cost} = \left(T_n^{invcost} * T^{crf} + T_n^{optcost}\right) * T_n + T_n^{lscost} + T_n^{mcost} \tag{7}$$

$$T_n^{lscost} = E_n^{prc2} * T_n * DS * E^{ls} \Big/ \left(1 - DS * E^{ls}\right) \tag{8}$$

$$A_n^{cost} = A_n^{syncost} + A_n^{scost} \tag{9}$$

$$A_n^{syncost} = \left(E_n^{prc3} * E^{usyn} + C_n^{prc} * C^{usyn}\right) * WD * HP_{n,e} * CF^{ap} + AP_n^{mcost} \tag{10}$$

$$A_n^{scost} = E_n^{prc3} * A^{sp} * HP_{n,e} * CF^{ap} * E^{us} + AS_n^{mcost} \tag{11}$$

$$O_n^{cost} = \left(O_{n,r}^{invcost} * O^{crf} + O_n^{optcost}\right) * OS_n^{cap} + O_n^{mcost} \tag{12}$$

$$OS_n^{cap} = ON_n * O^{ucap} \tag{13}$$

$$O_n^{rev} = OP_n * O^{prc} \tag{14}$$

$$OP_n = HP_n * CF^{ho} \tag{15}$$

$$CRF = dr \Big/ \left(1 - (1 + dr)^{-m}\right) \tag{16}$$

Constraints. Hydrogen supply must meet incremental demand per year n, which is constrained in Eq. (17). In addition, Eq. (18) constrains the hydrogen production rate of electrolysers *e* which must not exceed its production capacity per year *n*. Hydrogen storage capacity constrained in Eq. (19) must satisfy its production volume in a given storage period per year *n*. Eq. (20) constrains the hydrogen storage inventory which must not exceed its storage capacity per year *n*.

Similarly, the oxygen storage capacity of each year is constrained in Eq. (21), and the constraint of storage inventory is given in Eq. (22). The size of the electrical system correlates with the production scale of hydrogen per year n, which is constrained in Eq. (23).

$$HP_n + \sum_e P_{n-1,e}^{cap} * CF^{hp} - HP_{n-1} \geq DM_n \Big/ CF^{ap}, \ \forall n, f, e, \ P_{0,e}^{cap} = 0, \ HP_0 = 0 \tag{17}$$

$$P_{n,e}^{cap} * CF^{hp} \geq HP_{n,e}, \ \forall n, f, e \tag{18}$$

$$S_n + S_{n-1}^{cap} - S_{n-1} \geq HP_n * S^{sp}, \ \forall n, a, f, s, S_{0,s}^{cap} = 0, \ S_{0,s} = 0 \tag{19}$$

$$S_n^{cap} \geq S_n, \ \forall n, s \tag{20}$$

$$OS_n + OS_{n-1}^{cap} - OS_{n-1} \geq OP_n * O^{sp}, \ \forall n, f, r, \ OS_{0,r}^{cap} = 0, OS_{0,r} = 0 \tag{21}$$

$$OS_n^{cap} \geq OS_n, \ \forall n, r \tag{22}$$

$$T_n \geq HP_n \Big/ CF^{hp} \tag{23}$$

Simulation model

The simulation model designed with the concept of System Dynamics (SD) runs iteratively simulating investment in production of green ammonia on a yearly basis over the project lifetime, as shown in Fig. 3.

Expansion of the green supply system is executed when a new expansion is required. The expansion is influenced by economies of scale dependent on the annual expansion rate, investment in and operating expenses of facilities, the renewable electricity price, learning effects due to specialization and efficiency improvement, and existing infrastructure of the green supply chain due to the last expansion. These factors vary over time and form parameters required for new infrastructure expansion which is achieved by the optimization model. The new system expansion is completed after new infrastructure is designed and added to the existing green supply system. Afterwards, green hydrogen and ammonia production are simulated and the related annual expenses are calculated based on technical parameters obtained for each year, such as: the size of main facilities for hydrogen and oxygen production; storage capacity and inventory of

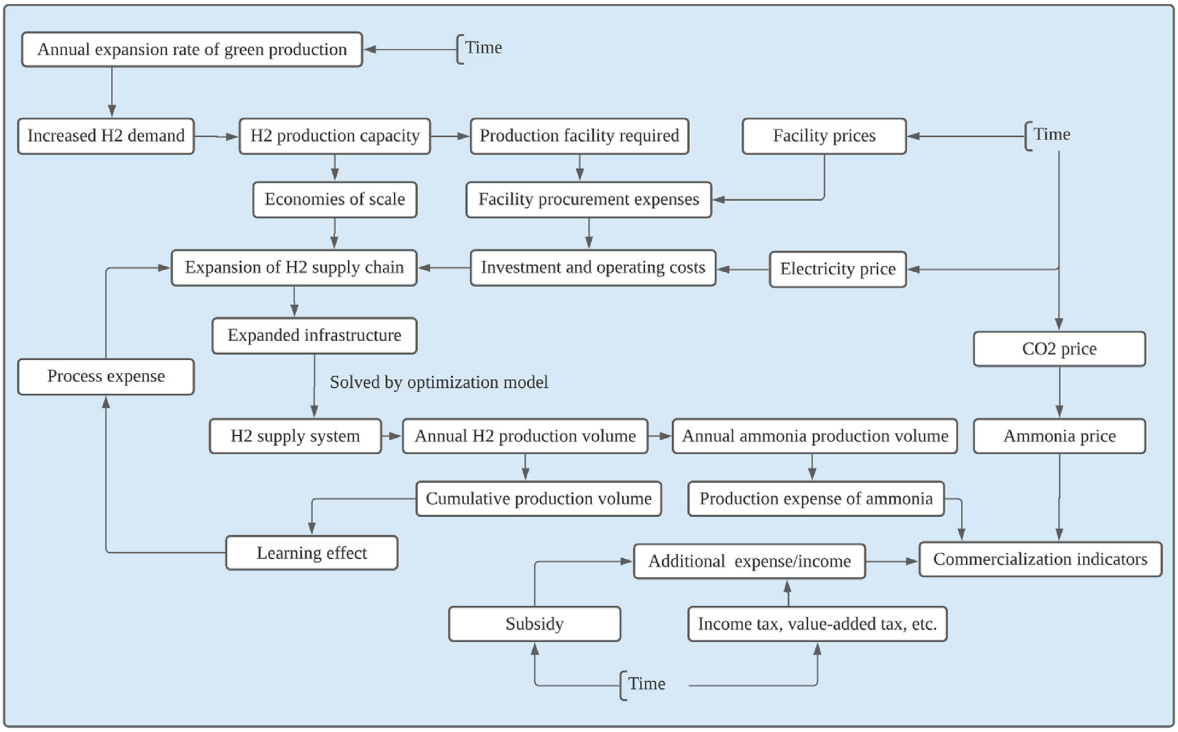

Fig. 3 – Causal loop of the simulation model.

hydrogen and oxygen; hydrogen and oxygen production rate and oxygen sales.

The model is improved to include the influence of main institutional incentives on the commercialization of green ammonia. The incentives considered include: carbon pricing, subsidies and tax exemptions. Enterprise income tax (EIT) and value-added tax (VAT), the primary corporate taxes in China, are taken into account [63,64]. In addition, we also consider minor taxes imposed in the chemical industry, including: stamp tax, education and urban construction tax [65]. Once the simulation reaches the end of the project lifetime, commercial feasibility is assessed according to annual production expenses, ammonia prices, and institutional incentives. Levelized costs of hydrogen and ammonia (LCOH and LCOA) as cost-effectiveness indicators over the project lifetime are evaluated based on Eq. (24) which is the fundamental calculation for levelized cost of energy (LCOE). Moreover, net present value (NPV), pay-back period of investment (PPI) and internal rate of return (IRR) as main economic indicators are used for assessing investment decisions, as elaborated from Eq.25–27.

$$\mathrm{LCOE}=\sum_n\left(\frac{NCF_n}{(1+dr)^n}-NCF_0\right)\bigg/\sum_n\frac{E_n}{(1+dr)^n} \tag{24}$$

$$NPV=\frac{NCF_n}{(1+dr)^n}-NCF_0 \tag{25}$$

$$\frac{NCF_n}{(1+IRR)^n}-NCF_0=0 \tag{26}$$

$$\sum\nolimits_n^{PPI}\frac{NCF_n}{(1+dr)^n}-NCF_0=0 \tag{27}$$

Background of the case study

Inner Mongolia is part of the Three North region and is well-known as a province rich in renewable energy resources [66]. This region has faced serious power curtailment after a rapid expansion of renewable electricity capacity in recent years [67]. The newly built UHV lines helping less than expected in carrying the power produced to load centres [9]. In addition, the region also enjoys rich coal resources, and there is a large-scale coal-chemical industry including the ammonia industry [68].

A wind park and an ammonia producer in close proximity in Xilin Gol in eastern Inner Mongolia are selected for the case study, as shown in Fig. 4. The wind park comprises 36 wind farms, with total installed capacity of 7 GW [69]. Fig. 5 presents the details of the electricity infrastructure in this area. Wind energy generated in the northern section converges at substations A, B and C and is boosted to 220 kV. Subsequently, renewable electricity is sent to the main substation F by 220 kV transmission lines, where the electricity is further boosted to 500 kV. After converting the alternating current to direct current and raising the voltage to 800 kV at the converter station H, renewable power is sent to Jiangsu province by the UHV DC line from Xilin Gol to Taizhou. Similarly, wind farms

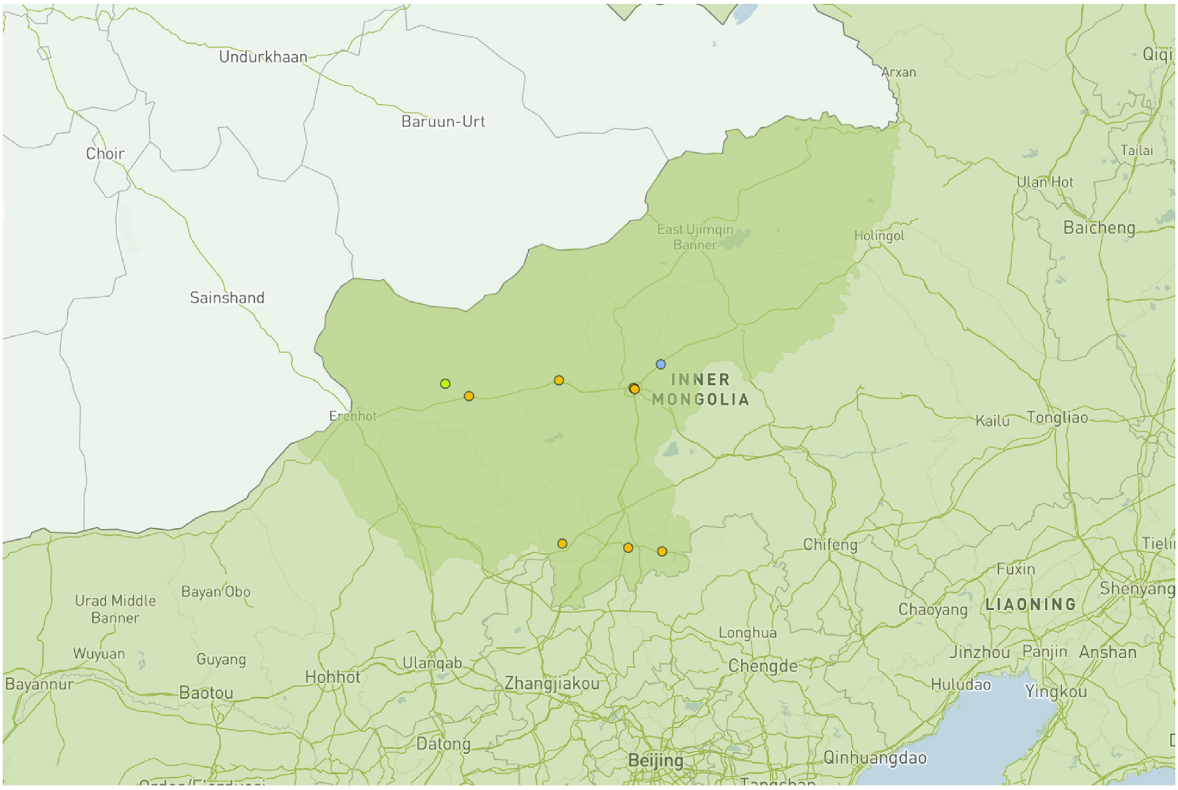

Fig. 4 – Location of the case study (in dark green) in the Three North region of China (in light green). The points refer to the electricity infrastructure and ammonia plant.

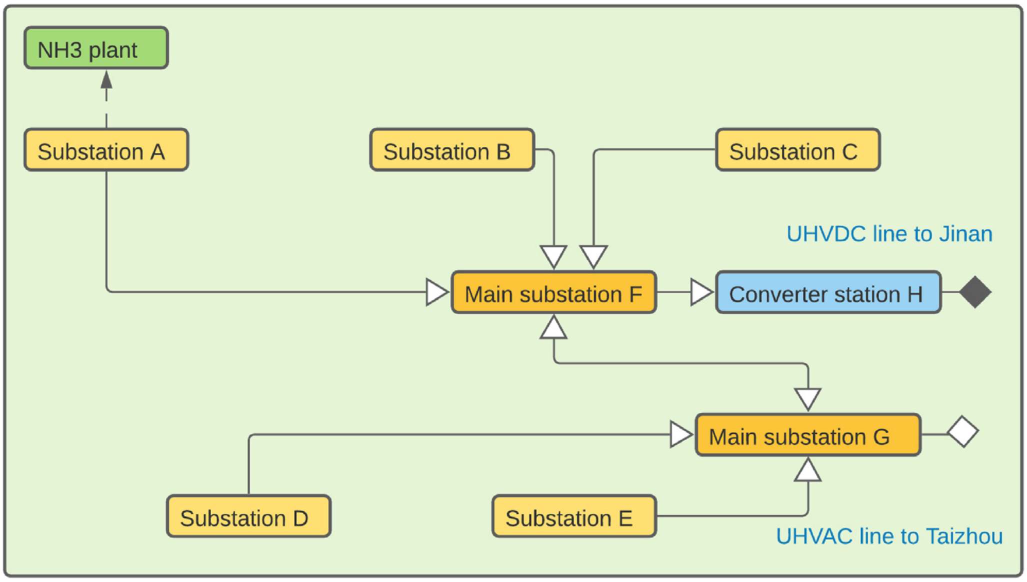

Fig. 5 – Topology of the electricity infrastructure in the case study.

in the southern section transmit power to substations D and E, from which power is then pooled to the main substation G. Wind energy in this area is mainly transmitted to Shandong province along the UHV AC line from Xilin Gol to Jinan after power is boosted to 1000 kV. The main substation F in the north and G in the south are also inter-connected by 500 kV transmission lines to enhance the reliability of power transmission to eastern China. In addition, about 8.6 GW of thermal power is available to support intermittent renewable power delivery to Jinan and 9 GW for power delivery to Taizhou, which are not presented in Fig. 3 [70].

Despite the available transmission infrastructure, renewable power is still being curtailed, as the operating rates of these two lines are currently below 20% [9]. This provides an opportune case to study the potential of local green ammonia production to address power curtailment in these regions. An existing ammonia producer is already located close to substation A. Additional 220 kV transmission lines (i.e. the dotted lines in Fig. 3) are assumed to transmit wind energy from substation A to the ammonia plant. Subsequently, infrastructure designed for green production is deployed at the ammonia plant, as discussed in Section The green supply chain.

Assumptions and data collection

To study the potential of green ammonia to reduce the power curtailment taking place in China, we set the period of 2021–2040 as the time frame for the entire lifetime of the project, with all the initial investment completed one year in advance, so ammonia production is fully renewable-based since 2021. In addition, we consider the current context in China that coal gasification (CG) and steam methane reforming (SMR) are both prevalent in the conventional fossil fuel-based production of ammonia by consuming coal and natural gas respectively (about 76% by CG, and 20% by SMR) [71]. Therefore, although the selected ammonia producer in the case study is initially CG-based, we measure the results of transiting to green production from both manufacturing processes, especially in the assessment of potential impacts from carbon pricing. Since oxygen synergy is taken into account in the model, we also compare the results between two scenarios where oxygen is not valued or is valued. The valued oxygen entails electrolysis process, since the amount of oxygen from air separation is limited and can be used internally for heating and other purposes. In addition, the following assumptions apply. 1) Stacks in AECs are replaced after 10 years of operation, given that the lifetime of a stack is basically 10 years [17]. 2) A power purchase agreement (PPA) is made between power suppliers and the ammonia producer. The lifetime of the PPA is assumed to be 10 years with a constant electricity price, and a further extension is made for the following 10 years as buyers are often reluctant to lock in power prices for more than 10 years [72]. Since wind energy in this area has basically achieved grid parity due to rich renewable resources and the power price is below 50 USD/MWh, we assume the renewable power price in the first 10 years is 50 USD/MWh. The price in the second 10 years is reduced by 15% assuming that strong completions around 2030 will force the price down [73]. 3) To avoid large-scale storage and satisfy demand fluctuations, we assume that the hydrogen and oxygen storage periods at the ammonia plant are 2 and 5 days, respectively. This is also because: first, back-up power is applied in electrolysis to ensure a stable gas supply; second, we assume large-scale ammonia storage capacity is equivalent to 8.5 inventory days to reduce hydrogen storage, given that storage in the form of ammonia is more cost-effective [59]; Finally, there is sufficient oxygen demand, since there is a large-scale coal-chemical industry in this area, as mentioned above. 4) Since surtaxes in China (including urban construction, education surcharges, etc.) can differ slightly per district, we assume that the total surtax is the same as that of wind power producers in the Three North region, which is 10% of VAT in total [74]. Moreover, there is no discount on surtax if VAT is reduced, which is the current practice in the wind power industry [75]. Finally, the related techno-economic parameters are summarized in Table 3.

Table 3 – Techno-economic parameters of the case study.

Parameter	Value	Unit	Source
Installed capacity of wind farms pooled at substation A	1.4	GW	[69]
Distance to the ammonia plant from substation A	31	km	[69,76]
Price of on-grid electricity (back-up power)	42.8	USD/MW h	[77]
Ammonia production capacity	180	kt/y	[76]
Annual operating hours	8160	h/y	[45]
Weighted average cost of capital (WACC)	8%	Dimensionless	[45]
Learning rate	2%	Dimensionless	[45]
Utilization hours of wind power	3000	h/y	[78]
Capital cost of HVAC line	209	USD/m	[79]
Loss rate of power transmission	1.2%	/10 km	[79]
Average price of oxygen	110	USD/t	[80]
Extra energy for heating and pressurization for ammonia production	0.6	MWh/t	[81]
Costs of catalyst, chemicals for ammonia production	2.9	USD/t	[82]
Average price of ammonia	430	USD/t	[83]
EIT rate	25%	Dimensionless	[84]
VAT rate	9%	Dimensionless	[85]
Stamp tax rate	0.03%	Dimensionless	[86]

Results

An assessment of the commercialization of green ammonia is discussed below based on the data obtained including: 1) number of main facilities for green hydrogen production and storage for each year; 2) hydrogen production rate, storage inventory for each year; 3) expenses of hydrogen production and storage for each year; 4) capacity and expense of electrical infrastructure for each year; 5) number of oxygen storage tanks, oxygen production and storage inventory for each year; 6) expenses of oxygen production and storage and oxygen sales income for each year. 7) expenses of ammonia synthesis and storage for each year; 8) investment, operating costs and tax imposed for each year.

Production costs of hydrogen and ammonia

Since cost matters greatly to the transition to a hydrogen economy and the competitiveness of green ammonia in the future, it is important to understand the production costs of both hydrogen and ammonia [16]. Fig. 6 shows LCOHs and

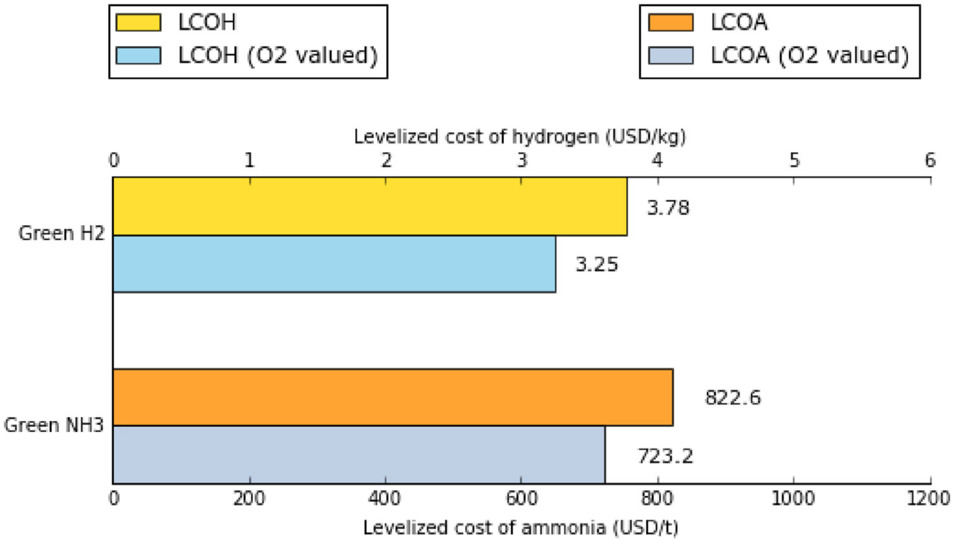

Fig. 6 – Levelized costs of hydrogen and ammonia.

LCOAs over the lifetime of the project. It should be noted that the estimated production costs are calculated before taxes. In addition, as oxygen synergy is taken into account in the simulation, we also compare the cases where oxygen is unvalued and valued. LCOH for the next two decades is estimated at 3.78 USD/kg in this case study, which is relatively low, since the cost covers the entire supply chain. Moreover, as power is transmitted to the ammonia plant directly rather than relying on hydrogen transportation, savings can be made on the expenses of hydrogen transportation and temporary storage. LCOH can be further reduced by about 0.5 USD/kg if there is oxygen synergy. Nevertheless, ammonia produced using this green hydrogen is still costly. LCOA is estimated at 822.6 USD/t which is about twice the price of grey ammonia. Meanwhile, the cost can be reduced by more than 100 USD/t when oxygen is valued indicating that the integration of hydrogen and oxygen production from the business side is the key to bringing the cost down prior to any institutional incentives offered.

Institutional impacts on the commercialization of green ammonia

Impacts of carbon pricing

Carbon pricing has been introduced in recent years as an institutional incentive to encourage carbon emission reduction and the use of low-carbon energy [87]. China launched a carbon trading market in 2021, while considering the rollout of a carbon tax to help achieve carbon neutrality by 2060 [88,89]. Therefore, it is necessary to examine the potential of carbon price growth in stimulating the transition to green ammonia production.

Fig. 7 shows the impacts of carbon price on the NPV of green ammonia investment over the project lifetime, when transiting from SMR-based ammonia production. Fig. 8 shows the case with oxygen synergy. In the case without oxygen synergy, lifecycle NPV undergoes a gradual increase when the carbon price is above 200 USD/t. Otherwise, there is a constant decline in NPV throughout the project lifetime because

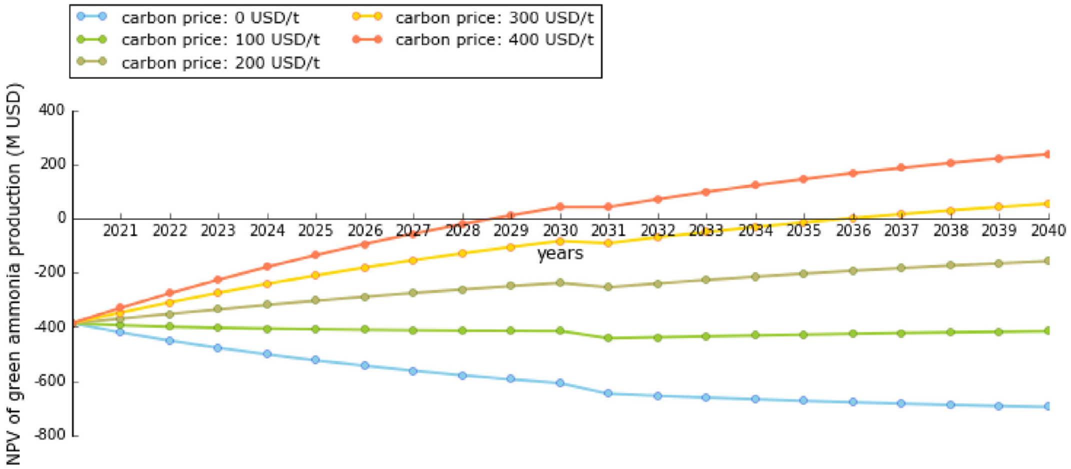

Fig. 7 – Project lifetime NPVs varied with level of carbon price (transition from SMR-based production, oxygen synergy unvalued).

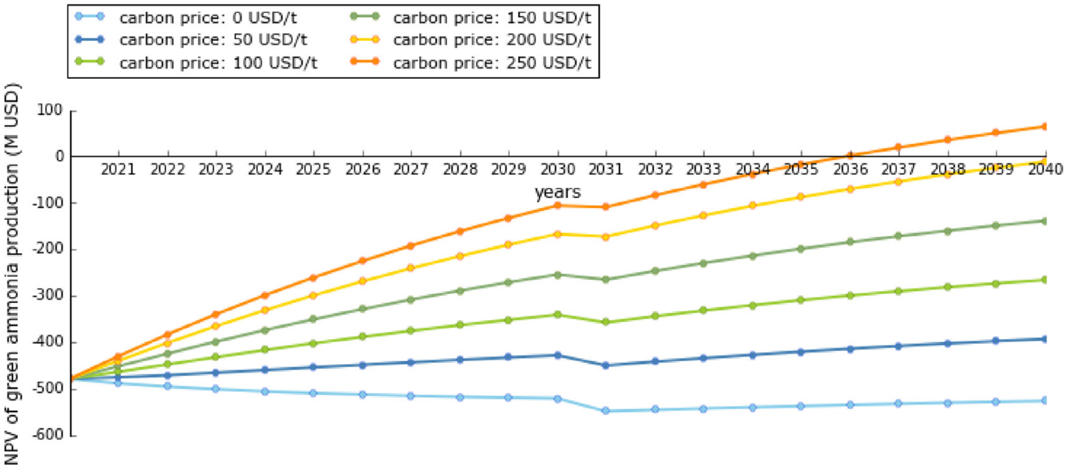

Fig. 8 – Project lifetime NPVs varied with level of carbon price (transition from SMR-based production, oxygen synergy valued).

income does not even cover the operating costs for each year. In addition, a sharp decline in NPV occurs in 2030–2031 in all cases, due to additional investment in replacing electrolyser stacks after reaching their lifetime of 10 years. Subsequently, NPV continues to grow when the carbon price is at least 200 USD/t. This also indicates that it is not feasible to commercialize green ammonia until the carbon price rises to around 300 USD/t. In contrast, an increase in NPV starts at 50 USD/t if oxygen production is coupled to the process. In the case of 50 USD/t, the curve is nearly flat, such that a mere 7.7% increase is achieved across the entire project lifetime. However, the figure is much lower than in the former case. Similarly, a sudden decline in NPV also occurs in 2031 for the same reason as above. The results also indicate that the commercialization of green ammonia is feasible when the carbon price is above 200 USD/t. NPV is close to zero by the end of the project lifetime, when CO2 is at 200 USD/t, but in the case of 250 USD/t, green ammonia investment becomes profitable from 2036.

Fig. 9 shows the clean investment decision from an initially CG-based ammonia production influenced by the carbon price. Fig. 10 shows the case with oxygen synergy. In contrast to the SMR-based case, carbon pricing exerts a relevant influence on the transition to low-carbon production. Without oxygen synergy, there is a growth in NPV and investment is feasible when the CO2 price is above 110 USD/t, a level much lower than for SMR plants due to a larger amount of CO2 emitted. Instead of experiencing a sudden decline, the growth in NPV slows down in 2030–2031, indicating that additional investments exert a smaller influence on the cash flow. With oxygen synergy, the investment turns a profit from 2037 when CO2 is at 100 USD/t.

Impacts of tax exemption

Tax incentives have been one of the main policy drivers for the growth of renewable energy in China, for example, a 50% reduction in VAT has been in place for wind power generation since 2008 [90]. An assessment of the impacts of such potential tax incentives on the commercialization of green ammonia is thus of relevance here. As mentioned above, we consider taxation on green ammonia production, in which EIT

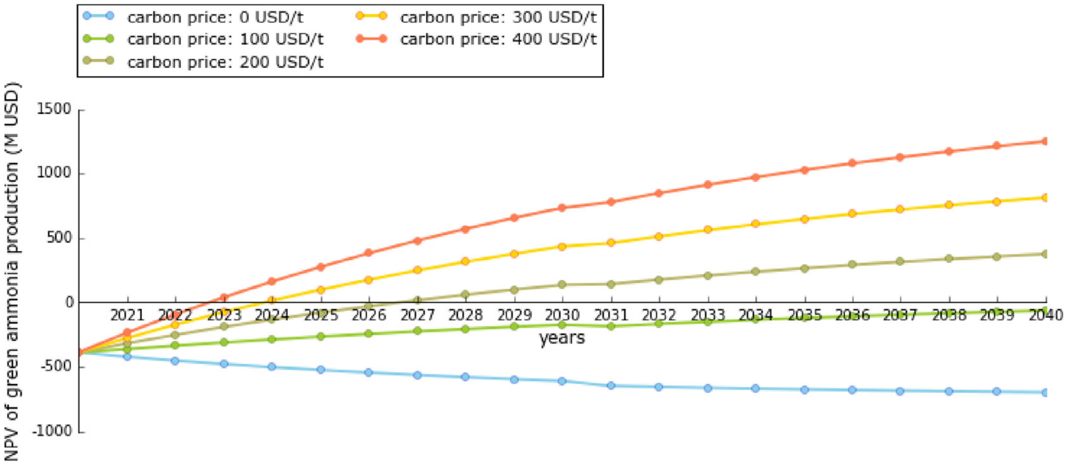

Fig. 9 – Project lifetime NPVs varied with level of carbon price (transition from CG-based production, oxygen synergy unvalued).

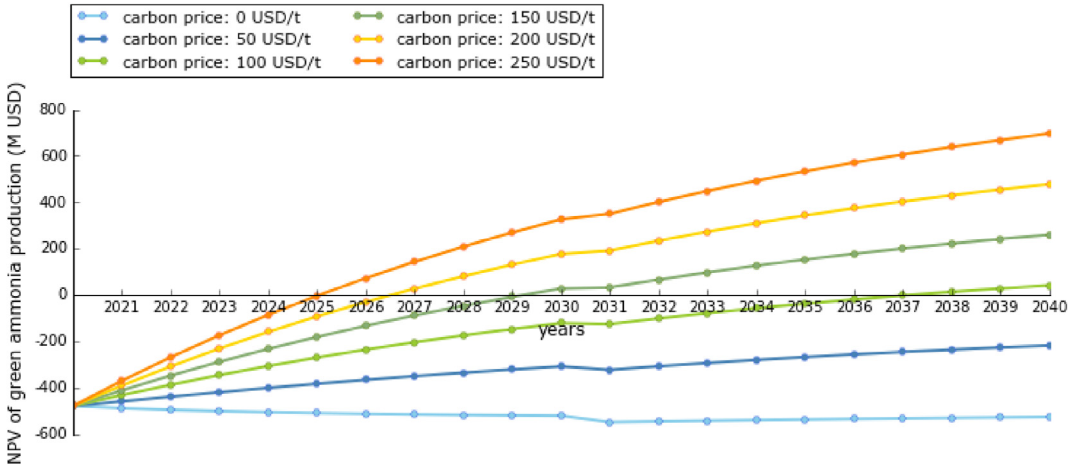

Fig. 10 – Project lifetime NPVs varied with level of carbon price (transition from CG-based production, oxygen synergy valued).

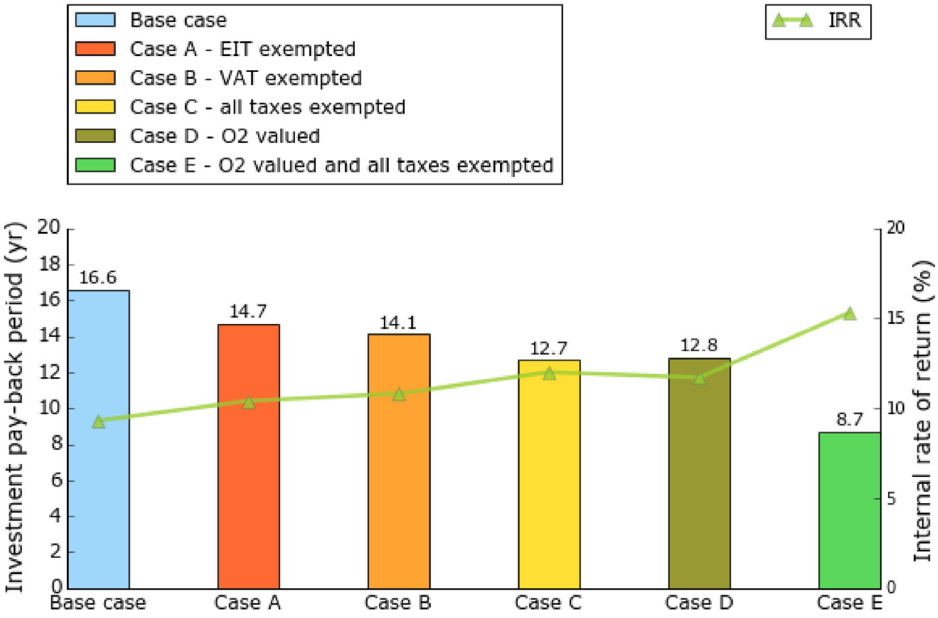

Fig. 11 – PPIs and IRRs impacted by tax exemption.

and VAT are the primary taxes imposed on the industrial sector. Fig. 11 shows how tax exemption influences investment decisions in contrast to benefits from oxygen synergy - at a price of 900 USD/t for green ammonia. The PPI is the largest in the base case where taxes are imposed and oxygen is not valued. The IRR ends at 9.3%, slightly higher than the weighted average cost of capital (WACC), indicating that a sales price of around 850–900 USD/t is required if there is no premium to drive investment. The PPI is reduced by 1.9 and 2.5 years when EIT and VAT are exempted respectively. It shows that the VAT imposed is potentially more than EIT. Therefore, exemption from VAT is slightly more effective than exemption from EIT in facilitating green ammonia production. The PPI further decreases to 12.7 years and the IRR rises to 12.0% if there is no taxation, which demonstrates that a tax-free policy is an effective incentive to encourage the energy transition. However, even when tax incentives are not in place, economic benefits from oxygen synergy can drive the PPI down to 12.8 years. This indicates that the integration of oxygen production into hydrogen production is an effective way to cover the high costs of green ammonia production. The PPI is further reduced to 8.7 years and the IRR rises to a highly profitable level of 15.3% when oxygen production is integrated and there are tax exemptions. This implies that a synergy of sector integration and economic incentives can dramatically facilitate clean energy investment in the future.

Impacts of subsidies provided

For years, China has been subsidizing renewable energy development, and has successfully stimulated the world's biggest renewable industry in terms of both installation and equipment manufacturing [12]. Therefore, the effectiveness of subsidizing a potential future green ammonia industry is also examined. Fig. 12 shows economic investment influenced by

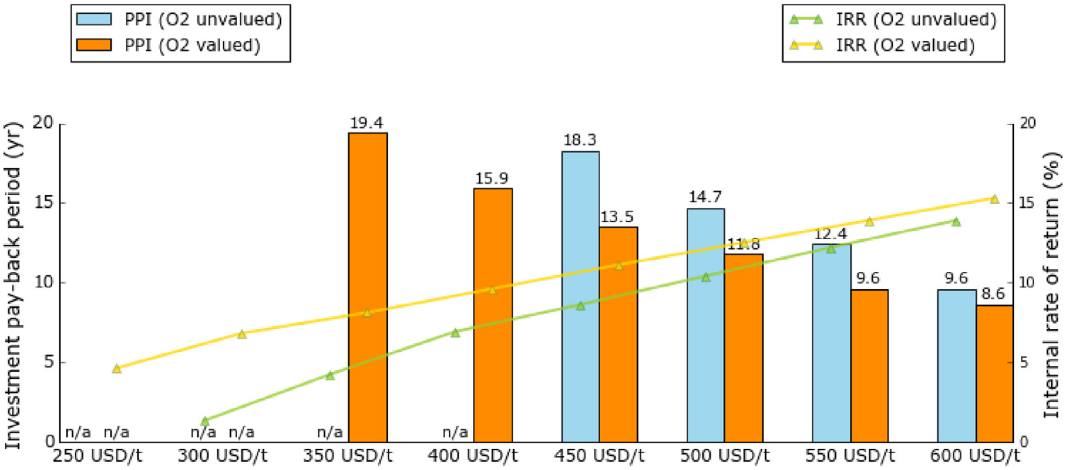

Fig. 12 – PPIs and IRRs varied with level of subsidy offered.

the level of subsidies provided when green ammonia is priced the same as conventional grey ammonia. PPI beyond the lifetime of the project is not presented, since it makes no sense. Likewise, IRR is not displayed until it is above zero. Without the synergy of oxygen, PPI falls in the project lifetime since the subsidy is raised to 450 USD/t, while the IRR rises to 8.6%, slightly higher than the WACC. This indicates that investment in green ammonia is not feasible until the subsidy rises to around 450 USD/t. The PPI decreases and the IRR increases when the level of the subsidy is lifted. The shortest period stands at 9.6 years when a 600 USD/t premium is offered. The period is around half of the project lifetime, indicating that the investment is profitable in this case. In contrast, with the benefits from oxygen production and sales, the investment becomes profitable during the project lifetime when a subsidy is offered at a level of around 350 USD/t. IRR rises to 15.3% and PPI is reduced to 8.6 years when a 600 USD/t of subsidy is offered, turning it into a higher quality investment compared to the case where oxygen synergy is not considered.

Table 4 – Additional parameters for evaluating eco-environmental benefits of green ammonia production.

Parameter	Value	Unit	Source
Installed capacity of coal power to that of wind power	1.5	Dimensionless	[94]
Utilization hours of coal power plants	4500	h/y	[95]
Share of fuel costs in total costs of coal power plants	70%	Dimensionless	[73]
LCOE of thermal (coal) power	41.2	USD/MWh	[91,92]
LCOE of wind power	42.5	USD/MWh	[91,93]
CO2 emission of coal power generation by ultra-super critical technology	0.8	t/MWh	[96]
Average CO2 emission of power generation	0.7	t/MWh	[97]
CO2 emission of CG-based ammonia production	3.8	t/t ammonia	[98]
CO2 emission of SMR-based ammonia production	1.6	t/t ammonia	[98]

Local green ammonia production to reduce renewable power curtailment

As there is a large-scale ammonia industry in the Three North region, the shift to green ammonia production is a potential way to consume renewable power generated in the local area. We compare this with inter-regional power transmission with respect to both the economic and environmental aspects. The related parameters required are summarized in Table 4, in which, LCOEs for coal and wind power are estimated based on the work [91,91–93] respectively.

Economic aspect

Given that thermal power has an assistant function in power transmission, its generation capacity is at least 1.5–2 times that of wind power [7,94]. Therefore, the corresponding deficit due to inactive thermal power generation is taken into account in addition to the economic loss of wind power generation. Fig. 13 shows the minimum premium required for investment in green ammonia in this case study, in contrast to the economic cost of inter-regional transmission when the equivalent amount of power for ammonia production is curtailed due to the low operating rates of the transmission lines. It should be noted that the costs of UHV lines caused by low-level operation are not included due to a lack of relevant data. Nevertheless, and although green production is expensive, the premium for green ammonia investment is still less than half of the costs incurred when the equivalent amount of power is not successfully transmitted by the dedicated electricity lines. The figure is even smaller than both the deficit in additional thermal power generation and the economic loss due to wind power itself being curtailed.

Environmental aspect

The environmental benefits of green production are evaluated. Fig. 14 shows CO2 emission avoidance by the green production per annum in contrast to the cases where the equivalent amount of wind power is transmitted and the ammonia production remains fossil fuel-based. Therefore, the emissions arise from the thermal power generation supporting inter-regional transmission and grey ammonia

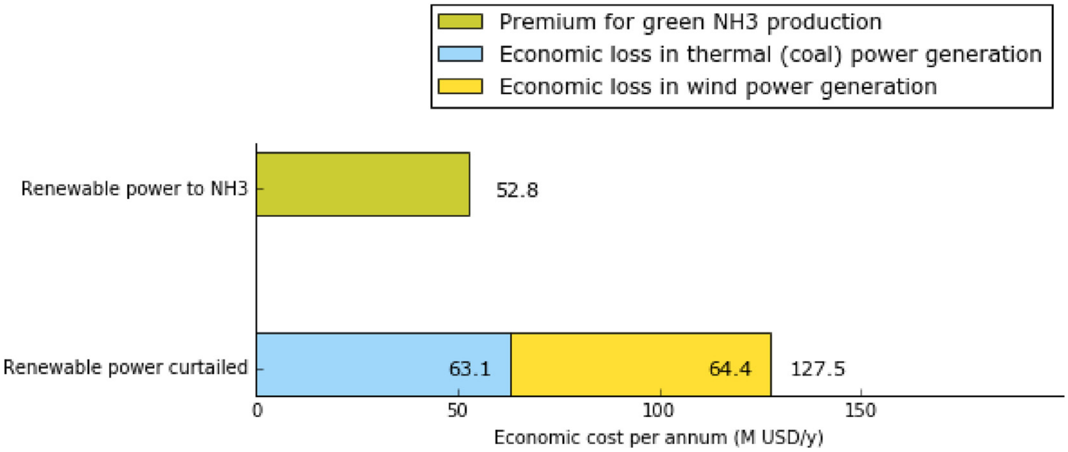

Fig. 13 – Premium for green ammonia production in contrast to economic costs incurred when the amount of power is not transmitted.

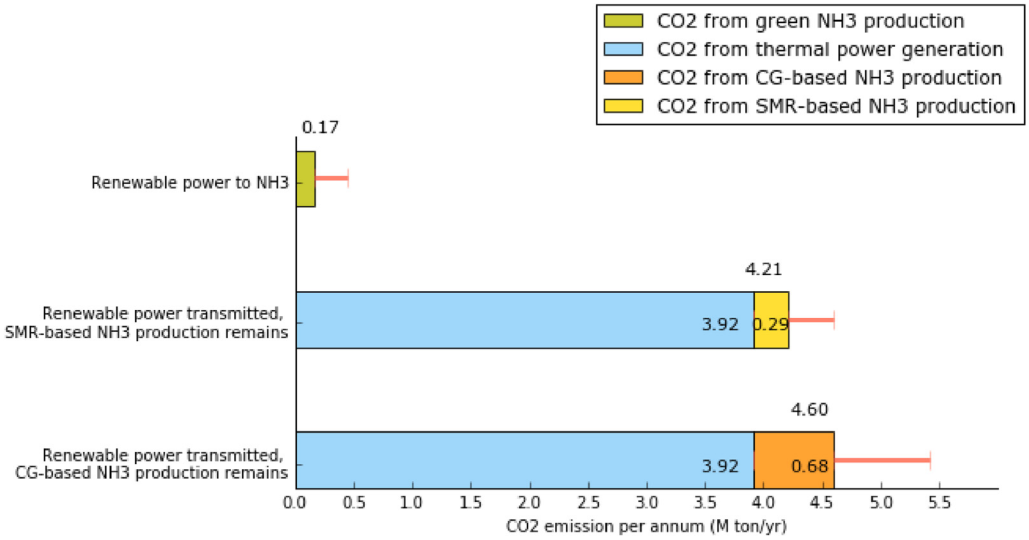

Fig. 14 – CO2 emission of green ammonia production in contrast to the case in which the amount of power is transmitted and local ammonia production remains fossil fuel-based. The whiskers indicate additional emission from using on-grid electricity.

production. CO2 emissions from SMR-based and CG-based ammonia production are both evaluated. The green column shows the maximum CO2 emission for green ammonia production when fossil fuels are used for heating and compression. In addition, since electricity is the alternative energy for these processes, and certain amounts of on-grid power are both used in green and grey ammonia production, additional CO2 emission from using on-grid power is also evaluated and added, as the whiskers indicate. As shown in Fig. 12, emission from thermal power generation is the largest at 3.92 million tons per annum indicating that inter-regional transmission does not help with CO2 reduction if the corresponding thermal power generation in coastal China is not phased out. At least 4.04 and 4.43 million tons of CO2 are avoided per annum by power to ammonia shifted from an SMR-based and CG-based ammonia plant respectively. If emission from on-grid power is included, CO2 can also be reduced by 4.15 million tons from an SMR process initially, and 4.97 million tons from a CG process.

Model evaluation

To examine the appropriateness of the model and the impacts of uncertainties on the results, it was validated following the behaviour tests recommended in the work [99]. First, an extreme condition test was carried out. In this scenario, when green ammonia demand is lowered to zero, no supply system is deployed and hydrogen and oxygen production are inactive. There is no sharp decline in NPV in 2030–2031, when the life span of each component in the supply chain is set to the time frame of the project, namely, no additional investments are required in 2030–2031. These results match well with those of actual conditions.

Table 5 – Results of the sensitivity tests.

Test case	LCOH (USD/kg)	LCOA (USD/t)	Final NPV (M USD)	PPI (y)	IRR (%)
Base case	3.25	723.2	87.1	14.8	10.2
Operating rate reduced by 10%	3.42	764.2	30.4	17.7	8.8
Price of green ammonia rises by 10%	3.25	723.2	184.7	11.7	12.7
Ammonia storage period rises by 50%	3.25	726.5	82.1	15.1	10.1
Distance to the substation rises to 100 km	3.42	755.4	48.4	16.8	9.2
Electrical efficiency of electrolysers rises by 10%	2.93	664.5	156.6	12.2	12.1
Electricity prices drop by 20%	2.74	627.8	213.4	9.9	13.4
Hydrogen storage period rises 50%	3.41	752.0	52.8	16.6	9.3
Price of hydrogen tanks drops by 20%	3.19	711.7	90.2	14.7	10.3
Oxygen storage period rises by 50%	3.42	755.2	44.5	17.2	9.0
Price of oxygen tanks drops by 20%	3.18	710.4	90.9	14.7	10.3
Oxygen price drops by 10%	3.16	706.8	105.9	14.1	10.7

Second, a sensitivity test was conducted to examine the influence of uncertainties on outputs. Table 5 shows the results of the sensitivity analyses, with a set of items tested on the basis of green ammonia being priced at 800 USD/t and oxygen synergy being valued. In addition, carbon pricing and subsidy factors are not applied, and LCOH and LCOA are pretax costs. In this scenario, LCOA rises by 5.6% and NPV decreases by 47.4 MUSD/y when the operating rate of green ammonia production is reduced by 10%. Furthermore, IRR rises by 24.5% and PPI is reduced by 3.1 years when the sales price rises by 10% indicating investment in green ammonia is highly sensitive to the operating rate of the production and price of green ammonia. Electrolyser efficiency and electricity price also have a key impact on commercialization. A 10% increase in electrical efficiency leads to a 9.2% increase in IRR, and investment is paid back 4.9 years in advance when electricity prices decrease by 20%. Distance to power sources is less sensitive, with IRR decreasing by 9.8% when distance is extended to 100 km. However, this factor still exerts an impact on investment decisions, since distance can vary widely with circumstance. Similarly, LCOA rises by 2.3% and PPI decreases by 0.7 years when the oxygen price is reduced by 10% (~99 USD/t). Given that the oxygen price has fluctuated between 57 and 171 USD/t in the past years, the oxygen price still has an influence on green ammonia production. Investment in hydrogen and oxygen tanks contributes less to green ammonia investment. For example, PPI is only reduced by 0.1 years when the price of hydrogen tanks is reduced by 20%, due to the small proportion in the overall cost. In contrast, green production is more sensitive to the length of storage periods for hydrogen and oxygen. For example, LCOA increases by 28.8 USD/t when the hydrogen storage period is extended by 50%. However, a mere 3.3 USD/t increase in LCOA occurs in the case of ammonia storage being extended by 50%, indicating that ammonia storage is more cost-effective than that of hydrogen.

Discussions and policy implications

Currently in China, the Three North region has the largest share of renewable electricity capacity (70% in wind generation and 60% in solar generation) due to the enormous availability of renewable resources in this area [100]. In addition, since this area is also rich in coal, there is also a large-scale ammonia industry [29]. These circumstances offer an opportunity to evaluate investment in green ammonia production as an option to address renewable power curtailment. Based on the results of this study, the main findings are summarized below:

(1) LCOH in the next two decades is estimated at around 3.8 USD/kg, and could be further reduced by around 15% if by-product oxygen is valued at 110 USD/t. LCOA is around 820 USD/t which is roughly twice the price of grey ammonia, due to the higher expense of hydrogen production. However, oxygen synergy can help to reduce the total cost by around 100 USD/t. In addition, the commercialization of green ammonia is highly sensitive to operating rate, ammonia price, electrical efficiency of electrolysers and electricity price. In contrast, distance to power sources and oxygen sale price are relatively less sensitive; however, they still exert an effective influence on investment due to the wide range in variation.

(2) The influence of carbon pricing to encourage green ammonia investment differs depending on the current production process being used. Carbon pricing exerts a strong influence on a transition from CG-based ammonia plants. Clean investment is feasible since the carbon price is above 110 USD/t, and the carbon price could decrease to around 90 USD/t if there is oxygen synergy. In contrast, the impact on a transition from SMR-based ammonia plants is lower. In this case, investment in green ammonia is not feasible until the CO2 price is almost 300 USD/t. The condition improves that the CO2 price is reduced to above 200 USD/t when oxygen synergy is valued.

(3) Tax exemption can play a role in the commercialization of green ammonia. PPI is reduced by 3.9 years from 16.6 years when green ammonia is priced at 900 USD/t. Specifically, the impacts of EIT and VAT, the main taxes in China, are examined. The PPI is reduced by 2.5 years when VAT is not imposed and 1.9 years when EIT is not taxed, indicating that VAT exemption is more effective than EIT. In contrast, oxygen synergy advances PPI by 3.8 years, which is as effective as the tax exemption. Additionally, a combination of both reduces PPI to 8.7 years.

(4) Without other incentives, a subsidy of around 450 USD/t is required to commercialize green ammonia if the sales price remains at the present level. However, with the integration of oxygen production into hydrogen production, the subsidy required can be reduced to 350 USD/t. In addition, oxygen synergy can also help improve the quality of investment which becomes profitable 4.8 years in advance of the initial period of 18.3 years.

(5) Although there is still an obvious price gap between green ammonia and conventional grey ammonia, the premium required to cover the gap per annum is still half of the cost incurred when the equivalent amount of power is not successfully transmitted to other regions. The cost includes expenses from renewable power curtailment and the low operation rate of thermal power generation assisting renewable power transmission. From the environmental perspective, the green ammonia plant in the case study could help avoid above 2 million tons of CO2 emission per annum compared to the case in which renewable power is transmitted by inter-regional transmission lines. The reduced CO2 includes avoidance due to clean energy production, and inter-regional power transmission since it contains a certain proportion of thermal power.

Since the case selected is typical in the Three North region of China, the findings obtained are universally applicable with respect to the potential of local green ammonia production to address renewable power curtailment in these regions. Therefore, we present the following policy implications:

(1) Local green ammonia production is an effective complement to inter-regional power transmission in addressing renewable power curtailment in China. The key to addressing renewable power curtailment is to increase power demand. Solutions such as pumped hydro-storage and electric boiler heating are subsidiary since they are supply-side approaches and are less likely to grow significantly due to the cost limits of renewable power generation. Therefore, as mentioned, the primary practice in China is to create demand from electricity load centres in eastern and southern China. Thus, a number of UHV lines have been built or are planned to support inter-regional power transmission. However, this solution has not been successful due to a mismatch between energy supply and demand, which is caused by electricity oversupply and a lack of marketing mechanisms in China [11]. Therefore, on the one hand, the barriers call for power sector reforms that include establishing power trade markets to increase access to renewable energy. On the other hand, although producing green ammonia is still expensive, it exhibits obvious economic and environmental advantages over inter-regional power transmission. Since there is already a large-scale ammonia industry in these renewable resource areas, green ammonia production can play a complementary role in addressing power curtailment. An appropriate combination of both options makes sense - especially when planning new transmission infrastructure - to avoid unnecessary governmental investment, as the related electricity infrastructure and matched thermal power plants are highly costly and environmentally unfriendly.

(2) The integration of oxygen manufacturing and green hydrogen production should be encouraged and not limited to the future ammonia industry, but also adopted in other industries using renewable electrolysis. In this study, we found oxygen synergy in hydrogen production offers an effective way to reduce costs and risks in green ammonia investment. The potential integration, on the one hand, reduces the need for economic incentives from the government, and thus relieves costs to society. On the other hand, it can assist the transition from conventional oxygen manufacturing to renewable-based industry, thus offering additional economic and environmental benefits.

(3) Institutional incentives should be appropriately provided to stimulate green ammonia investments, for example, improve carbon tax mechanisms, exemption from taxes, and tariffs or price premiums for the purchase of green ammonia. In addition, the carbon price should be further increased in the coming decades. The carbon price in China is likely to rise to about 10 USD/t by 2025 and 13 USD/t by 2030 [101]. However, the price is expected to rise dramatically in some countries over the next decades. For example, it has been proposed that in Canada, the carbon price will rise to 133 USD/t by 2030, in the EU to about 100 USD/t by 2030, and in Singapore to about 75–120 USD/t by 2040 [102–104]. China has announced it will hit peak carbon emission before 2030 and reach carbon neutrality by 2060 [105]. To achieve these ambitious goals, the carbon price in China should be further increased to encourage clean production. Given that 76% of ammonia is produced using coal in China, the carbon price required to phase out grey ammonia production is much lower, thus playing a more active role in stimulating clean energy investment.

Our study has some limitations. First, in this case study, renewable power for electrolysis is operated close to its base load to ensure a relatively steady power input. This can be adjusted in the light of actual conditions and costs could increase due to more fluctuations in power supply. Second, since there has been no obvious upward or downward trend in ammonia and oxygen sale prices over the past few years, constant average prices are applied in the study. However, the prices vary with time which could also be modelled in the light of actual conditions. Third, the results obtained from the case study represent the general conditions in the Three North region of China, but cannot reflect all conditions. Studies regarding specific facts and circumstances can be further carried out. Finally, this study concerns green ammonia as a potentially important application in the future hydrogen economy that can address power curtailment in China; however, this is not the only pathway to deal with the issue. Other alternatives, such as green methanol, could also be studied to further inform policy.

Conclusions

The pursuing of inter-regional power transmission to address renewable power curtailment mainly occurring in the Three North region of China has resulted in disappointing gains. This paper evaluated the possibility of local green ammonia investment to address this issue with a case study in this area. The potential of main economic incentives to stimulate green energy investment were analysed. A hybrid optimization-based simulation model was applied to simulate lifetime green manufacturing. We found that production cost of green ammonia is around twice the price of grey ammonia, with LCOH estimated at 3.8 USD/kg and LCOA at 820 USD/t. The operating rate, ammonia price, and electricity price are the key factors with respect to commercialization. An increase in the carbon price could effectively encourage the energy transition from CG-based ammonia production, which predominates in China. Tax exemptions also stimulate clean energy investment, with respect to which, exemption from VAT is more effective than that of other taxes. Without other incentives, the subsidy required for clean production is high, at around 450 USD/t according to the present ammonia price. However, this can be further reduced by 100 USD/t by oxygen synergy at a price of 110 USD/t. Compared to inter-regional power transmission, local green ammonia production demonstrates both economic and environmental advantages. In addition to the mitigation of large amounts of CO2 emission, the annual premium required for clean production is less than half of the costs incurred when the equivalent amount of renewable power is not transmitted. Since the selected case study represents the general conditions in this area, we believe that local green ammonia production is a solid complement to inter-regional power transmission in addressing power curtailment. An appropriate combination of both approaches can avoid high levels of government investment in dedicated power lines and significantly reduce CO2 emission. The integration of oxygen manufacturing into hydrogen production is also proposed, as it provides an effective way to reduce the high costs and risks of green ammonia investment, while the transition to renewable-based oxygen production offers additional economic and environmental benefits. In addition, incentive policies should be enacted to further encourage the energy transition. Finally, we consider our findings and the policy implications provide an informative base for policymaking on renewable power curtailment and the development of a hydrogen economy in China, and may also shed light on relevant solutions for other countries.

Declaration of competing interest

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

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Nomenclature

AEC	Alkaline electrolysers
CG	Coal gasification
CRF	Capital recovery factor
DC	Direct current
EIT	Enterprise income tax
HVAC	High voltage alternating current
IRR	Internal rate of return
MILP	Mixed integer linear programming
NPV	Net present value
P2G	Power to gas
PPA	Power purchase agreement
PPI	Pay-back period of investment
LCOA	Levelized cost of ammonia
LCOE	Levelized cost of energy
LCOH	Levelized cost of hydrogen
SD	System dynamics
SMR	Steam methane reforming
UHV	Ultra-high voltage
VAT	Valued-added tax
WACC	Weighted average cost of capital
Index	
e	Type of electrolysers
n	Year
Variable	
Acostn	Ammonia production cost in the *n*th year. USD/yr
Ascostn	Ammonia storage cost in the *n*th year. USD/yr
Asyncostn	Ammonia synthesis cost in the *n*th year. USD/yr
En	Amount of energy produced in the *n*th year. kg
HPn,e	Hydrogen production rate by electrolysers e in the *n*th year. kg/d
NCF0	Initial investment cost. USD
NCFn	Net cash flow in the *n*th year. USD/yr
Ocostn	Oxygen storage cost in the *n*th year. USD/yr
Orevn	Income of oxygen sales in the *n*th year. USD/yr
ONn	Number of oxygen storage tanks required in the *n*th year. ea
OPn	Oxygen production rate in the *n*th year. kg/d
OSn	Oxygen storage inventory in the *n*th year. kg
OScapn	Oxygen storage capacity in the *n*th year. kg
Pcapn,e	Installed capacity of all the electrolysers e in the *n*th year. kW
Pcostn	Hydrogen production cost in the *n*th year. USD/yr
Pcostn,e	Cost relating to all the electrolysers e in the *n*th year. USD/yr
PNn,e	Number of electrolysers e required in the *n*th year. ea
Sn	Hydrogen storage inventory in the *n*th year. kg
Scapn	Hydrogen storage capacity in the *n*th year. kg
Scostn	Hydrogen storage cost in the *n*th year. USD/yr

SNn	Number of hydrogen storage tanks required in the *n*th year. ea
Tn	Size of electrical connection system in the *n*th year. kW
Tcostn	Electrical connection cost in the *n*th year. USD/yr
Tlscostn	Costs of power loss in the transmission in the *n*th year. USD/yr

Parameter

Asp	The given time period of ammonia storage. d
APmcostn	Miscellaneous expenses of ammonia production in the *n*th year, including land expense, capital and maintenance expenses of the reaction system, etc. USD/yr
ASmcostn	Miscellaneous expenses of ammonia storage in the *n*th year, including land expense, capital and maintenance expenses of the storage vessel, etc. USD/yr
Cusyn	Catalyst consumption in ammonia synthesis kg/kg NH_3
CFap	Coefficient for calculation of ammonia production rate with hydrogen production rate. dimensionless
CFho	Coefficient for calculation of oxygen production rate with hydrogen production rate. dimensionless
CFhp	Coefficient for calculation of hydrogen production rate with the capacity of the electrolyses. kg/kW/d
DMn	Demand of green ammonia in the *n*th year. kg/yr
Dr	Discount rate. %
DS	Distance from the ammonia plant to the power source. km
Els	Loss rate of power transmission. %/km
Eprc1n	The price of electricity for hydrogen production in the *n*th year. USD/kWh
Eprc2n	The price of renewable electricity in the *n*th year. USD/kWh
Eprc3n	The price of on-grid electricity in the *n*th year. USD/kWh
Eusyn	Electricity consumption in ammonia synthesis. kWh/kg NH_3
M	Lifetime of a project or facility. yr
Ocrf	Capital recovery factor of oxygen storage. dimensionless
Oinvcostn	Unit investment cost of the oxygen storage tanks in the *n*th year. USD/kg
Omcostn	Miscellaneous expenses for oxygen storage in the *n*th year, including land expense, installation expense, and expenses of other facility, etc. USD/yr
Ooptcostn	Annual unit operating cost of the oxygen storage tanks in the *n*th year. USD/kg/yr
Oprc	Oxygen price. USD/kg
Osp	The given time period of oxygen storage. d
Oucap	Capacity of an oxygen storage tank. kg
Pcrfe	Capital recovery factor of electrolysers e. dimensionless
Pinvcostn,e	Unit investment cost of electrolysers e in the *n*th year. USD/kW
Pmcostn	Miscellaneous expenses of the eth type of hydrogen production in the *n*th year, including expenses of construction and installation, etc. USD/yr
Poptcostn,e	Annual unit operating cost of electrolysers e in the *n*th year. USD/kW/yr
Pucape	Capacity of the electrolyser e. kW
Scrfs	Capital recovery factor of the storage tank s. dimensionless
Sinvcostn	Unit investment cost of the hydrogen storage tanks in the *n*th year. USD/kg
Smcostn	Miscellaneous expenses of hydrogen storage in the *n*th year, including land expense, expenses of construction and other facility, etc. USD/yr
Soptcostn	Unit operating cost of the hydrogen storage tanks in the *n*th year. USD/kW/yr
Ssp	The given time period of hydrogen storage. d
Sucap	Capacity of a hydrogen storage tank. kg
Tcrf	Capital recovery factor of electrical baseline. dimensionless
Tinvcostn,t	Unit investment cost of the electrical baseline in the *n*th year. USD/kg
Tmcostn	Miscellaneous expenses of electrical connection in the *n*th year, including land expense, expenses of transformers, transmission lines, etc. USD/yr
Toptcostn	Unit operating cost of the electrical baseline in the *n*th year. USD/kg/yr
WD	Annual work days. d/yr
WH	Annual operating hours. h/yr

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