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Research paper

Cross-regional electricity and hydrogen deployment research based on coordinated optimization: Towards carbon neutrality in China

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ABSTRACT

In order to achieve carbon neutrality in a few decades, the clean energy proportion in power mix of China will significantly rise to over 90%. A consensus has been reached recently that it will be of great significance to promote hydrogen energy, that is produced by variable renewable energy power generation, as a mainstay energy form in view of its potential value on achieving carbon neutrality. This is because hydrogen energy is capable of complementing the power system and realizing further electrification, especially in the section that cannot be easily replaced by electric energy. Power system related planning model is commonly used for mid-term and long-term planning implemented through power installation and interconnection capacity expansion optimization. In consideration of the high importance of hydrogen and its close relationship with electricity, an inclusive perspective which contains both kinds of the foresaid energy is required to deal with planning problems. In this study, a joint model is established by coupling hydrogen energy model in the chronological operation power planning model to realize coordinated optimization on energy production, transportation and storage. By taking the carbon neutrality scenario of China as an example, the author applies this joint model to deploy a scheme research on power generation and hydrogen production, inter-regional energy transportation capacity, and hydrogen storage among various regions. Next, by taking the technology progress and cost decrease prediction uncertainty into account, the main technical–economic parameters are employed as variables to carry out sensitivity analysis research, with a hope that the quantitative calculation and results discussion could provide suggestion and reference to energy-related companies, policy-makers and institute researchers in formulating strategies on related energy development.

1. Introduction

1.1. Background and motivation

Hydrogen is the most abundant element in the universe. However, it normally exists in the form of water and organic compounds on Earth. At present, the majority of produced hydrogen comes from natural gas and coal, which will cause a certain amount of carbon dioxide emission (Anon, 2021a). Although using carbon capture and storage (CCS) equipment can reduce carbon emission in the hydrogen producing process, the resulting increase in costs has made produced hydrogen less competitive (The United Nations Environment Programme (UNEP), 2021). Water electrolysis is a fast developing, mature and promising method to produce hydrogen. It can be powered by clean electricity, and hydrogen produced in this way is almost carbon-neutral. There are other hydrogen production technologies such as biomass hydrogen production and water photolysis which also could achieve low or even zero carbon emissions, but due to the low production efficiency, it is still difficult to generalize and apply these technologies on a large scale.

The benefit of water electrolysis powered by clean electricity far outweighs that of decarbonization in the hydrogen producing area. Besides, water electrolysis is effective in decarbonizing in the whole energy sector. Energy activities have caused more than 80% of the total carbon dioxide emission in China (Anon, 2021b), thus decarbonization in energy-related activities is essential. Meanwhile, it is widely agreed that the key to solve the problem is to replace fossil fuels with clean energy and to advance

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electrification on energy consumption side. The significance of hydrogen is reflected in electricity sector and other energy activities sectors where electrification is difficult to achieve. On the one hand, in the future power system, clean energy power will account for more than 90% of the total installed capacity (GEIDCO, 2020). The large integration of Variable Renewable Energy (VRE) probably brings safety and stability problems to the operation of the power system. Therefore, a large amount of flexible energy storage, such as lithium battery and hydro pump storage, is required. However, this will lead to a tremendous inversion cost. Compared with electricity, hydrogen, as a kind of energy carrier that can be made from VRE electricity, can be stored more easily and efficiently on a large scale. In addition, the flexible load of water electrolysis may provide flexibility on the consumption side of the power system. Furthermore, the mutual conversion of renewable power electricity and hydrogen through fuel cells or hydrogen gas turbines can provide long-term flexible capabilities to ensure seasonally power supply for high VRE penetrated power system (Jiang et al., 2021a; Du et al., 2021). However, the high cost is probably the major hurdle to its widespread use in the future (Mahapatra and Singh, 2014; Coralli et al., 2019). On the other hand, the applications of hydrogen from VRE power in industries, such as chemistry, metallurgy, aviation, and industrial high-quality heating, have realized indirect electrification and reduction of Greenhouse Gas (GHG) emission in related fields. In chemical industry, hydrogen from VRE is mainly used to synthesize ammonia, methanol, methane and other fuels or raw materials to replace gray hydrogen in traditional processes. In metallurgy, hydrogen, as a reducing agent replacing coal and natural gas, can be an important solution to achieve decarbonization in the steel industry, etc. Consequently, with the foreseeable continuous increasing hydrogen demand driven by hydrogen utilization equipment technical development and political strategies on hydrogen enacted against global warming in the following decades, water electrolysis powered by VRE such as wind and solar photovoltaics will be widely applied. Thus, electricity and hydrogen are two forms of energy which are closely related, and VRE electricity and hydrogen are expected to become the two main energy sources supporting carbon neutrality in the future. However, how to coordinate electricity and hydrogen at energy system level is still an open question, which will provide insightful perspective for both VRE power and hydrogen development and deployment in the future.

1.2. Literature review

The modeling and optimal configuration of hydrogen and clean energy has been widely studied, and previous work are mainly dealing with the potential coordinated operation with VRE power generation unit or station. Four different models of electrolyzer operation have been proposed in Sarrias-Mena et al. (2015) to investigate the operation coupling with wind turbine. The modeling of proton exchange membrane (PEM) electrolyzer dynamics has been investigated (Hernández-Gómez et al., 2020) so that the PEM operation could be well considered in the control and dynamic analysis of the power system. The energy operation of a hybrid wind turbine, water electrolyzer and Pumped-hydro-compressed air system has been formulated in Guo and Sepanta (2021). As for energy demand, a new energy system of a building integrating hydrogen production and distribution system to the combined cooling, heating and power (CCHP) system has been investigated in Li et al. (2021). Above mentioned works provided multiple perspectives analyzing hydrogen producing and its potential cooperation modeling with VRE power. However, the technical connection modeling and operation optimization between the renewable power generators and electrolyzers is incapable of revealing the potential value of hydrogen energy on power and energy sector due to the lack of the global perspective on energy system operation simulation involving diverse elements, such as energy generations, transportation, storage, etc.

Many research works have also investigated the optimal planning and operation of power system considering the hydrogen. For example, power grid has been incorporated in the hydrogen supply chain to jointly optimize the configuration of electrolyzer and hydrogen storage (Li et al., 2019). But, it has ignored the VRE power source deployment optimization and its impact on the future power grid as well as the hydrogen supply chain formation. Multi-objective optimization operation models have been proposed in Khanmohammadi et al. (2017) and Ruiming (2019), revealing the value of multi-objective optimization algorithm. However, the energy system is simplified that only wind and solar PV are involved as generators and the energy transportation modeling is absent. Multiple hydrogen production, such as biomass and natural gas with carbon capture devices, have been taken as alternatives to produce hydrogen in the integrated energy system in Gabrielli et al. (2020), optimizing the selection, size and location of the hydrogen production technologies with multi-objectives. Unfortunately, only grid electricity is involved ignoring the variable power source impact on the future power grid. A network optimization tool Hydrogen Production and Transmission (HyPAT) model is used to identify the lowest cost centralized production and pipeline transmission infrastructure within real geographic regions in Johnson et al. (2012), but only coal-based hydrogen production is considered. Further, as indicated in Hanley et al. (2018), the uncertainty and complexity surrounding hydrogen may be as a result of the difficulty of representing hydrogen technologies and systems in energy system models, especially in the highly VRE power penetrated energy system, leading to uncertainty and complexity of hydrogen development prediction. Considering the deep electrification in energy sector and VRE power domination in the future power system, researchers develop the hydrogen model based on the matured and available power or energy system models (Xu et al., 2022) to expand the variables scope of optimization. The basic power system model should be ready for the high VRE penetrated power system simulation, such as GOPT (Du et al., 2018; Zhuo et al., 2022), PLEXOS (Drayton et al., 2004; Deane et al., 2014), MESSAGE (McPherson et al., 2018), and even other customized ones (Jin et al., 2021). The implications of future storage and hydrogen technology costs for low-carbon energy transitions is explored in McPherson et al. (2018) by using MESSAGE. In that case, the hourly time-scale energy balance has been ignored which is regarded important in the high VRE penetrated energy system. The energy system capacity expansion simulation coordinating the electricity and hydrogen is realized in Jin et al. (2021), it proved electrolysis could become an important consumer-side regulation resource in power system and effectively promote the penetration and utilization of VRE, but the energy network topology is as simple as only two nodes are included due to its model limitation. The power generation and transmission expansion model of GOPT has been employed to deal with the hydrogen supply chain optimization (Jiang et al., 2022), but only trail hydrogen transportation for local distribution is considered.

Although various optimization models of power system considering hydrogen have been proposed, it is still ambiguous to determine the coupling relationship between electricity and hydrogen and their optimal configuration, especially for energy planning on system level crossing large geographic area scale. Simultaneously adding hydrogen into power system planning models is still a challenge as hydrogen features larger supply and demand balance time-scale than electric power and relates diverse aspects such as hydrogen demand, production and transportation, etc.

1.3. Contribution and article organization

In this work, a multi-node electricity and hydrogen coupled energy coordinated optimization model, named GTSEP-EH, is established. This model enables different balance timescale chronological operation for electricity and hydrogen respectively. Through using this model, we focus on the coordinated optimization on both electricity and hydrogen at energy system level in terms of energy production, storage and transportation among multiple nodes. The main conducted works by using this model are twofold.

(1) An empirical analysis for China with carbon neutrality scenario is performed. The power generation and hydrogen production, cross-regional energy transportation capacity, and hydrogen storage among various regions are identified.

(2) The main technical–economic parameters are employed as variables to carry out sensitivity analysis research considering the technology progress and cost decease prediction uncertainty.

The reminder of the paper is organized as follows. The research flow framework is constructed and the electricity-hydrogen coordinated planning model is formulated in Section 2. A case study is performed in Section 3. Section 4 is results and discussion. Finally, Section 5 concludes this article.

2. Methodology

2.1. electricity–hydrogen coordination patterns

Generally, there are two main patterns to realize electricity and hydrogen coordination. One is that the energy sending regions generate more electricity delivered to the energy receiving regions, not only to fulfill the power demand, but also to produce hydrogen for the local demand. The other one is that the energy sending regions produce more hydrogen than local demand and transport the excess part to the energy receiving regions. These two patterns are schematically presented in Fig. 1.

The former pattern requires more centralized VRE power generation bases in the areas where the VRE power resources are abundant, such as the northern and western regions of China. Under the condition that the local power for both electricity and hydrogen production usage demand is fulfilled, the excess power could be delivered outbound to the load centers, such as the central and eastern regions through power transmission channels. By consuming the received electricity, hydrogen is produced near the load center and used locally.

The latter pattern requires large-scale deployment of hydrogen production units, hydrogen storage, and other equipment in the energy sending regions. Hydrogen production exceeds local demand, and the excess part is transported outbound to the energy load centers by hydrogen pipelines. Hydrogen producing equipment, i.e., water electrolysis, can track the fluctuating output of VRE sources, and the produced hydrogen can be used locally or stored for later use and delivery.

These two patterns both require the configuration of the VRE power installation, energy transportation and storage infrastructure, and the corresponding system flexibility resources such as energy storage. However, they are different in energy transportation mode and equipment location deployment which are related to process efficiency, power delivery and hydrogen pipeline cost, etc. Actually, these two patterns are not mutually exclusive. Through cost competition between the two patterns, an ideal combined scheme of capacity deployment relating on-site and off-site hydrogen producing, power delivery and hydrogen transportation, as well as the hydrogen storage in various regions can be approached to maximize the advantages of the both. In order to achieve this ideal combined scheme, the joint optimization model GTSEP-EH is established.

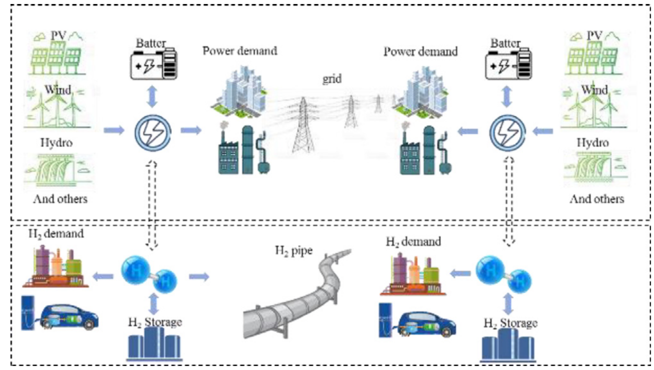

Fig. 1. Electricity–hydrogen coordination patterns schematic diagram.

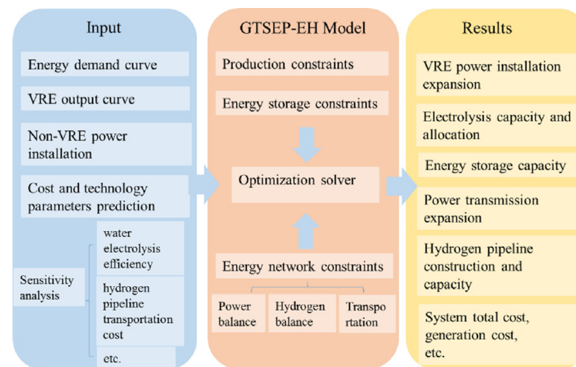

Fig. 2. General framework diagram of the research flow.

The general framework for conducting the research work is schematically demonstrated in Fig. 2. The calculation model employs the LP (linear programming) method, employing the lowest system total cost as the optimization target. By applying the electricity and hydrogen joint optimization model, the optimal electricity–hydrogen coordination patterns are quantitatively approached.

2.2. Calculation model

In order to couple the hydrogen and electricity models, different time-scales for energy balance should be considered. Unlike power grid system, which requires instant power balance, the substance balance of hydrogen supply and demand could be fulfilled in a longer period of time, such as a day, a week, or even a month. In this study, hydrogen load in 1-day (24 h) resolution is adopted. We establish a joint model combing the GTSEP (Generation Transmission Storage Expansion Planning) model that we proposed in Jiang et al. (2021b) and hydrogen production, transportation and storage models featuring daily balance together, and we name it GTSEP-EH joint model. This GTSEP-EH model realizes multiple timescale chronological operation simulation to adapt to the future high VRE penetrated power system and long-cycle supply and demand characteristics of hydrogen. By defining the technology features and demand characteristics, other kinds of substance derived from the power, such as methane and heat, can also be included.

GTSEP-EH model enables multiple nodes network. Each node enables various technical equipment, such as VRE power installation, electrolysis capacity, electricity and hydrogen storage. Each node defines its own electricity and hydrogen demand. All nodes could be connected by power transmission lines and hydrogen transportation pipes. Both electricity and hydrogen are regarded as energy carriers which can be produced and stored in their most favorable nodes, and can be transported from one node to another, to approach the lowest total system cost.

Based on a one-year long simulation calculation, the GTSEP-EH model determines the expandable capacity of energy production, storage and transmission with the lowest cost optimization objective. We use simplified classic power system unit combination model (Du et al., 2018) to form linear constraints for fast operation simulation. The model's mathematical expression is described in the following section in terms of production, storage and transportation respectively. Considering that the cost of fuel cell is probably still too high to realize widespread application in the future (Mahapatra and Singh, 2014; Coralli et al., 2019), electricity generation from hydrogen is excluded in this study.

2.2.1. Production constraints

Power generation

The VRE power modeling introduces the theoretical output ration $\omega^{\mathrm{W}}_{w,t}$ for VRE power w generation at t, and the curtailment is permitted when VRE electricity exceeds and the surplus power is neither used for electrolysis nor stored in the battery.

$$P^{\mathrm{W}}_{w,t} + P^{\mathrm{W,Cur}}_{w,t} = \omega^{\mathrm{W}}_{w,t} Cap^{\mathrm{W}}_{w}, \forall w, t \tag{1}$$

$$P^{\mathrm{W}}_{w,t}, P^{\mathrm{W,Cur}}_{w,t} \geq 0, \forall w, t \tag{2}$$

In the above equation, the w indicates the VRE power, $P^{\mathrm{W}}_{w,t}$, $P^{\mathrm{W,Cur}}_{w,t}$ indicates the power output and curtailment, Cap^{W}_{w} is the installed capacity.

Hydrogen electrolysis

The electrolysis modeling has been studied by various researchers as introduced in the literature review. Although the actual producing process of hydrogen from electric power is complicated, considering that the main objective of this work is the long-term energy planning scheme study, it is simplified in the model as an energy conversion process that produces hydrogen by consuming wind and solar PV power. The amount of electricity consumed to produce hydrogen in one day as well as the hydrogen volume are shown in the Eq. (3). The Eq. (4) indicates that for the electrolyzer h, the output does not exceed its capacity at any time.

$$H^{\mathrm{Ele}}_{h} = \left(\eta^{\mathrm{Ele}}_{e} \sum_{t=1}^{24} P^{\mathrm{H,Ele}}_{h,t} \right) / \mathrm{LHV_H} \tag{3}$$

$$0 \leq P^{\mathrm{Ele}}_{e,t} \leq Cap^{\mathrm{Ele}}_{e}, \forall e, t \tag{4}$$

$\mathrm{LHV_H}$ is the low heating value of hydrogen [MJ/kg], η^{H}_{h} is the energy conversion efficiency of electrolyzer h.$P^{\mathrm{H,Ele}}_{h,t}$ is the electrolyzer power load at t hour, thus H^{Ele}_{h} is the amount of produced hydrogen in [kg] in one day (24 h).

2.2.2. Energy network constraints

The long distance and large scale of hydrogen transportation is the main focus of this study. Given that the geographical scope in this study is mainland China, pipeline should be the most appropriate choice for the transportation. Similarly, only overland power transmission is considered in this study. Regarding the time lag, the hydrogen injection and exportation time lag exceeding the balance time scale is neglected, because unlike the trailer transportation, pipeline transportation is normally continuous under stabilized pressure and flow rate in normal operation. Besides, daily balance time scale for hydrogen actually allows the hourly hydrogen supply and consumption deviation. Thus, both electricity and hydrogen are real-time balanced in their corresponding time scale.

Similar to the power transmission, hydrogen transportation network model determines the maximum pipeline transportation capacity as the variable to be optimized. The daily transportation schedule during the whole year can be optimized under the maximum daily transportation capacity constraint.

Ruled by both constraints equations of energy balance at each node and energy flow at each potential energy transportation channels, The energy network model is established with energy loss being taken into account. For a certain node, the mathematical expression is shown in (5)–(8):

$$\begin{aligned} &\sum P^{\mathrm{G}}_{g,t} + \sum P^{\mathrm{W}}_{w,t} + (S^{\mathrm{B,Dis}}_{b,t} - S^{\mathrm{B,Cha}}_{b,t}) + (\sum Tr^{L,in}_{l,t} - \sum Tr^{L,out}_{l,t}) \\ &= De^{E}_{t} + P^{\mathrm{H,Ele}}_{h,t} - De^{E,curt}_{t}, \forall g, w, b, h, t \end{aligned} \tag{5}$$

$$H^{Ele}_{e,t'} + (S^{\mathrm{H,Dis}}_{h,t'} - S^{\mathrm{H,Cha}}_{h,t'}) + (Tr^{P,in}_{p,t'} - Tr^{P,out}_{p,t'}) = De^{H}_{t'}, \forall h, p, t' \tag{6}$$

$$0 \leq Tr^{E,H}_{l,p,t,t'} \leq Tr^{\mathrm{E,H,Max}}_{l,p,t,t'}, \forall l, p, t, t' \tag{7}$$

$$Tr^{\mathrm{Loss}}_{l,p,t,t'} = \lambda^{E,H}_{l,p,t,t'} \left| Tr^{E,H}_{l,p,t,t'} \right|, \forall l, p, t, t' \tag{8}$$

Eqs. (5) and (6) describes respectively the electricity and hydrogen balance for its corresponding time period t (hour) and t'(day). $\mathrm{De}^{\mathrm{E}}_{t}$ is the original power demand while $\mathrm{De}^{\mathrm{E,curt}}_{t}$ is the power demand curtailment at time t. The electrolyzer is modeled as electricity load $P^{\mathrm{H,Ele}}_{h,t}$. The $S^{\mathrm{B,Dis}}_{b,t} - S^{\mathrm{B,Cha}}_{b,t}$ is the power net generation from battery, while the $Tr^{L,in}_{l,t}$ and $Tr^{L,out}_{l,t}$ are the inbound and outbound electricity respectively at one time t. Similarly, The $S^{\mathrm{H,Dis}}_{h,t'} - S^{\mathrm{H,Cha}}_{h,t'}$ is the net hydrogen discharge from storage, while the $Tr^{P,in}_{p,t'}$ and $Tr^{P,out}_{p,t'}$ are the inbound and outbound hydrogen respectively at one time t'. Eq. (7) indicates that the energy delivery at line l or pipeline p at each time interval should not be superior to its transportation capacity. Eq. (8) describes the energy loss in transportation.

2.2.3. Energy storage constraints

The hydrogen storage tank is the buffer link in the hydrogen supply chain, and its function is similar to the electric storage device in the power system. When the produced hydrogen exceeds its demand due to the surplus of VRE power, the extra part of hydrogen can be stored and then retrieved in the moment once the power for electrolysis, i.e. the hydrogen supply, is not sufficient. Thus the hydrogen storage is modeled in the same way as battery but longer balance time scale. The operating constraints are as shown in the following Eqs. (9)–(11).

$$0 \leq S^{\mathrm{B,H,cha}}_{b,h,t,t'}, S^{\mathrm{B,H,dis}}_{b,h,t,t'} \leq Cap^{\mathrm{B,H}}_{b,h} \tag{9}$$

$$E^{\mathrm{B,H}}_{h,b,t,t'} - E^{\mathrm{B,H}}_{h,b,t-1,t'-1} = \eta^{\mathrm{B,H}}_{h,b} P^{\mathrm{B,H,cha}}_{h,b,t,t'} - P^{\mathrm{B,H,dis}}_{h,b,t,t'} / \eta^{\mathrm{B,H}}_{h,b} \forall h, b, t, t' \tag{10}$$

$$0 \leq E^{\mathrm{B,H}}_{b,h,t,d} \leq T^{\mathrm{B,H}}_{b,h} Cap^{\mathrm{B,H}}_{b,h} \tag{11}$$

Eq. (9) constrains energy storage and retrieval from exceeding its maximum capacity at time t or t'. Eq. (10) describes the energy balance between adjacent moment, $E^{\mathrm{B,H}}_{h,b,t,t'}$ is the state of charge (SOC) of battery or hydrogen storage state, $P^{\mathrm{B,H,cha}}_{h,b,t,t'}$ and $P^{\mathrm{B,H,dis}}_{h,b,t,t'}$ are the stored and retrieved energy and their corresponding efficiency is $\eta^{\mathrm{B,H}}_{h,b}$. Finally, Eq. (11) limits the maximum energy state of storage from exceeding its maximum capacity, $T^{\mathrm{B,H}}_{b,h}$ is the working time duration at the maximum discharging capacity.

2.2.4. Joint GTSEP-EH capacity expansion model

As is introduced previously, the optimization objective of the joint model is the lowest total cost of the energy system after the capacity expansion of both electricity and hydrogen related technologies. Together with the batch of chronological operation simulation constraints presented in Sections 2.2.1–2.2.3.

The objective function to minimize the total cost of the system is expressed in Eq. (12).

$$\arg\min f(Cap_w^{\mathrm{W}}, Cap_e^{\mathrm{Ele}}, Tr_{l,p}^{\mathrm{E,H,Max}}, Cap_{b,h}^{\mathrm{B,H}}) = \sum_{w=1}^{N_{\mathrm{W}}} IC_w^{\mathrm{W}} Cap_w^{\mathrm{W}} + \sum_{e=1}^{N_{\mathrm{E}}} IC_e^{\mathrm{Ele}} Cap_e^{\mathrm{Ele}} + \sum_{l=1}^{N_{\mathrm{L}}} IC_{l,p}^{\mathrm{E,H}} Tr_{l,p}^{\mathrm{E,H,Max}} + \sum_{b=1}^{N_{\mathrm{B}}} IC_{b,h}^{\mathrm{B,H}} Cap_{b,h}^{\mathrm{B,H}} + C_{\mathrm{Sys}}^{\mathrm{Oper}} \tag{12}$$

$s.t.$ operation constraints (1)–(11)

In the equation, IC_w^{W} indicates the investment cost of VRE power, while IC_e^{Ele} presents the investment cost of water electrolyzer. $IC_{l,p}^{\mathrm{E,H}}$ is the investment cost of energy transportation and $IC_{b,h}^{\mathrm{B,H}}$ is the energy storage investment cost, regarding electricity and hydrogen respectively.

The GTSEP-EH model adopts the mixed integer linear programming method (Du et al., 2018) regarding the conventional power source such as thermal power and hydropower to simulate the unit start-up and down. The GTSEP-EH model is solved by the commercial optimization solver *Cplex*.

3. Case study

From the available reports for carbon neutrality scenario of China (GEIDCO, 2020), we extracted the required data for the case study such as the electricity and hydrogen demand prediction, non-VRE power capacity installation, etc. We focus on the study of hydrogen related energy production, transportation and storage deployment among seven regions of China, namely, North (N), East (E), Central (C), Northeast (NE), Northwest (NW), Southwest (SW), and South (S). It should be noted that the scenario data used in this work for calculation is to explore the usability of the model and the viability of the study method, and analyze the influence of the main technical parameters on the results. Thus the optimization results comparison among distinct carbon neutrality scenarios is out of the framework and is not discussed. Furthermore, from the perspective of long-term capacity planning for energy transmission corridors among each region, both power transmission and hydrogen transportation are optimized neglecting energy transportation loss in this study case.

3.1. Scenario description

The energy demand prediction comes first. According to the neutrality scenario of China (GEIDCO, 2020), the electricity consumption of the whole society was estimated to reach 17.2 TWh in 2060, among which hydrogen demand was predicted to be around 7000 × 10^4 tons which is equivalent to nearly 2.9 TWh if 90% efficiency of electrolysis is considered, which accounts for about 17% of the electricity–hydrogen total energy demand (GEIDCO, 2020), as shown in Fig. 3.

Required by the adopted hourly chronological operation simulation method, the historical load characteristics of the seven regions and the predicted maximum load in 2060, i.e., the 8760-h load curve of the seven regions in 2060 is collected. Regarding the hydrogen load, by referencing historical natural gas consumption, we define a 365-day hydrogen demand data featuring similar monthly evolution as natural gas. It shows high consumption in winters and low in summers mainly due to the weather and temperature, as shown in Fig. 4.

In terms of the power installations mix, the predicted installed capacities of non-VRE power in each region are employed (GEIDCO, 2020). The detailed data and figure can be found in Appendix A. Regarding the wind and solar PV, the fluctuating generation characteristics are derived from the database of the global

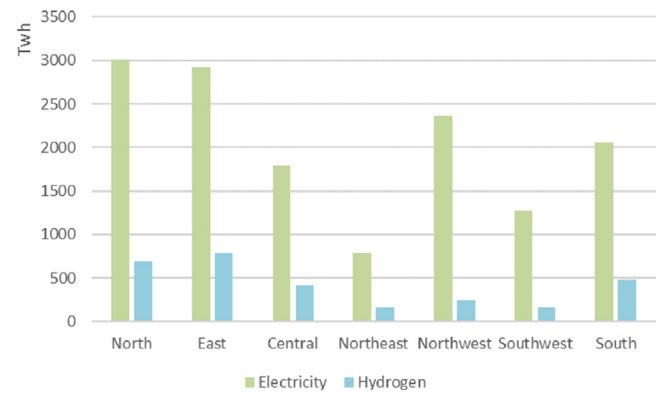

Fig. 3. Electricity consumption and hydrogen load prediction in the seven regions.

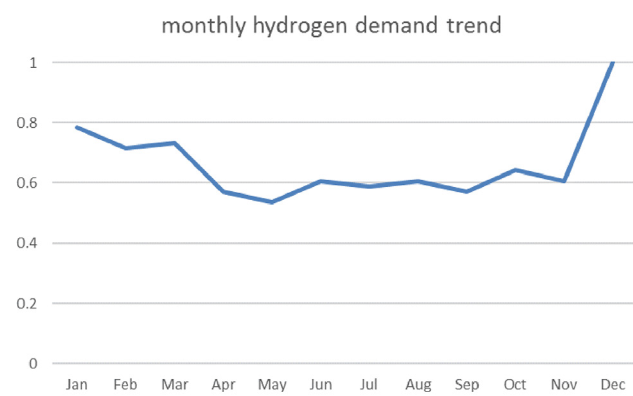

Fig. 4. Monthly demand trend of hydrogen.

clean energy development evaluation platform (GREAN platform) developed by us. For each region, multiple representative locations for generation characteristics constitution have been selected and 8760-h output characteristic curves are obtained by averaging them. For example, for North region, three different locations have been selected, which are Mengxi (west Inner Mongolia), the north of Hebei province, and Shandong province, to reflect the regional characteristics of VRE power generation in the entire North region.

In general, the characteristics of wind resources in the Northwest, North and Northeast China are better. The full-load hours of wind power generation are to be 2700–2830 h (annual generation divided by rated installed capacity). North and Northwest has good solar resource, and the full-load hours are about 1660–1910 h, as shown in Fig. 5.

The adjustable range of power output represents the adjustment capabilities of the power plants, e.g., the natural gas power is considered flexible because the output ranges from 10% to 100% full output capacity. The adjustment capabilities of each kind of energy resource and energy storage are shown in Appendix B, Table B.1. Especially, the electrolysis power load is characterized by minimal operation period of 8 h, the ramp-up and ramp-down rate of 0.8, and the load adjustability ranges from 0.3 to 1 to imitate the actual operation.

The energy conversion and storage efficiency are summarized in Appendix B, Table B.4. The battery is given by a rate of 90% for the entire store and retrieve process. Considering the chosen scenario, hydrogen technology probably achieves a breakthrough to increase its comprehensive producing efficiency to 90%, although the current one is only about 60%. Therefore, this parameter is to

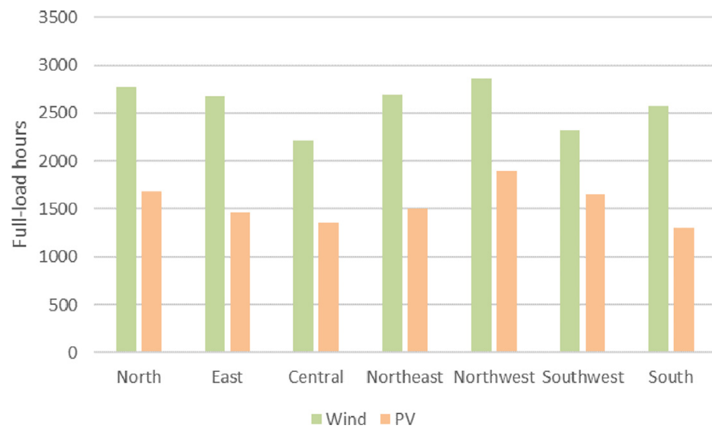

Fig. 5. Full-load hours of power generation in the seven regions.

be altered in the sensitivity study section. An overall storage loss of 10% for hydrogen is assumed.

3.2. Cost prediction

For each kind of technology, the cost parameters consist of the initial investment cost, fixed operation cost, and maintenance cost. The cost factors are summarized in Table B.2 of Appendix B. The investment cost parameters of the generation units of wind, solar PV cells, CSP, and battery storage are extracted from Global Energy Interconnection Development and Cooperation Organization (2020a). The power transmission technologies considered in this work include the high-voltage direct current (HVDC) technologies at distinct voltage levels for long-distance power delivery. And the predicted cost for 2060 is referenced from a published report (Global Energy Interconnection Development and Cooperation Organization, 2020b).

Regarding hydrogen, the equipment investment of hydrogen production, mainly water electrolyzer, is estimated to be 1800 yuan/kW, which is approximately 25% of the current water electrolysis cost 7000 yuan/kW. At the current level of electricity prices, the cost of hydrogen production from electrolysis of water is higher than that from fossil energy, such as steam reforming and gasification on coal. In addition, with high product purity, hydrogen from VRE powered water electrolysis is clean and zero-carbon, with high product purity, which is of great significance to the realization of carbon neutrality in the whole society. Thus it is predictable that with the cost decline of VRE power generation, as well as the technological advancement, efficiency improvement and cost reduction of electrolyzers, it will gradually become economically competitive and the mainstream hydrogen production method.

As for hydrogen transportation, since there is no large-scale, long-distance prototype project available for reference, we adopt a rate 30% lower than that of natural gas pipelines, approximately 13.5 million yuan/km with annual transportation capacity 12 billion m^3 (Zhang et al., 2020). Besides, a sensibility study is carried out in which a series of cost parameter ranging from 70% to 130% of the benchmark is adopted. The production, transmission, and storage costs of hydrogen are summarized in Table B.2 in Appendix B.

4. Results and discussion

Firstly, a basic scheme that only comprises electricity demand is calculated by the GTSEP-EH model for giving a reference of initial VRE power installed capacity and cross-regional power transmission capacity. Detailed results of the reference scheme are presented in Appendix C.

After adding the hydrogen demand, the production–storage–transport of both electricity and hydrogen are coordinately expanded. In total there are 56 variables to be optimized, namely, the wind and PV solar power installation increase in seven regions, the storage capacity of electricity and hydrogen respectively in seven regions, and the power transmission expansion and hydrogen transportation deployment among 14 potential channels.

The hourly power balance is revealed in Fig. 6(a), while the hydrogen balance in the same time period is demonstrated in Fig. 6(b), (c). As we observe, the electrolysis load for hydrogen production mainly occurs around mid-day when the solar PV generates, making the net load "duck curve" reversed and resulting in an improved VRE electricity accommodation as well as a decreased curtailment. Regarding the hydrogen balance, the time period that covers two consecutive months is selected in which the hydrogen demand line bends to show the hydrogen demand monthly change in Fig. 6(b). The hydrogen storage hourly operation is optimized according to the hydrogen production and the derived hourly demand. Similarly, extra hydrogen produced at midday is stored and then retrieved when there is a lack of VRE power for electrolysis to reach a daily balance. The Fig. 6(c) reveals the hydrogen storage capacity utilization rate of each day which is the ratio of accumulated hydrogen storage and the total available storage capacity. In the first three days, a stored hydrogen decrease is observed, which indicates that the previously stored hydrogen is used to make up the shortage of these days. While the stored hydrogen keeps increasing in the last several days, it means that more hydrogen has been produced than the daily demand, and the exceeding part is stored for future use. It should be noticed that the VRE curtailment is allowed in the hydrogen shortage days. It is actually the trade-off between the VRE power utilization and the investment cost of electrolysis and storage of hydrogen, which is the result of coordinated optimization for approaching the lowest system cost.

Detailed calculation results are shown in Fig. 7 and Table 1. Similar to the electricity scheme, the Northwest and Southwest, which are power sending regions, are also hydrogen sending regions, indicating that both regions produce excessive hydrogen over local demand and the extra portion is transported outbound through hydrogen pipeline network.

Generally speaking, the hydrogen transportation direction presents similar pattern as that of electricity, as shown in Fig. 7. The detailed data are summarized in Table 1. To be specific, 21% of the local hydrogen demand in the central regions and 23% in the southern regions are met by direct transportation

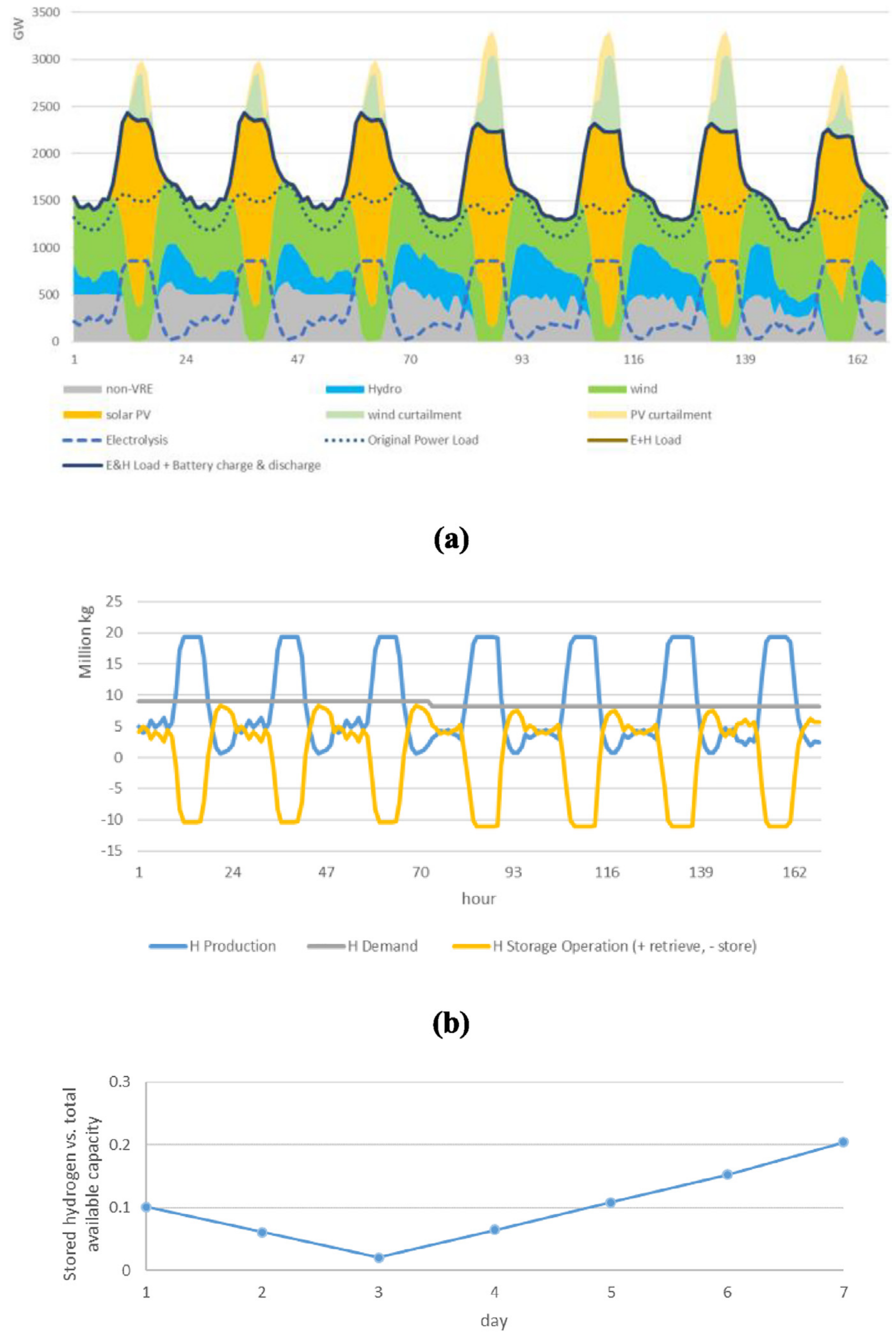

Fig. 6. (**a**) Hourly power balance of benchmark case (**b**) Electrolysis load and schematic storage operation (**c**) stored hydrogen out of total available capacity .

through hydrogen pipeline network, which mainly consists of two hydrogen transportation channels, Southwest China to South China (Channel I) and Northwest China to Central China (Channel II). The annual hydrogen transportation volume of Channel I is 28.3 billion m^3 under the 10 MPa pressure condition, converted from 2.55 million tons. Channel II has carried an annual hydrogen transportation volume of 21.6 billion m^3 under the 10 MPa pressure condition, converted from 1.94 million tons. In the early stage of development, the existing *West–East Gas Transmission Infrastructure* can be fully utilized by mixing hydrogen with natural gas in an appropriate and secure proportion. Local hydrogen production in the northern and eastern regions is cheaper than direct hydrogen imports, leading to none hydrogen pipeline network connection, and more than half of the local hydrogen demand is met by local hydrogen production from inbound VRE electricity. In order to meet the needs of extra power transmission for hydrogen production, an expansion of the capacity of the cross-regional power flow, which is expected to be 660 GW and more than 4000 TWh electricity delivery, is necessary. The capacity of the new transmission channels is about 100 GW, which is equivalent to that of 10∼12 new ±800 kV UHV DC transmission projects. In conclusion, from the perspective of the hydrogen energy transportation, it will cover 42% of the hydrogen total demand, in which, the delivered electricity for hydrogen

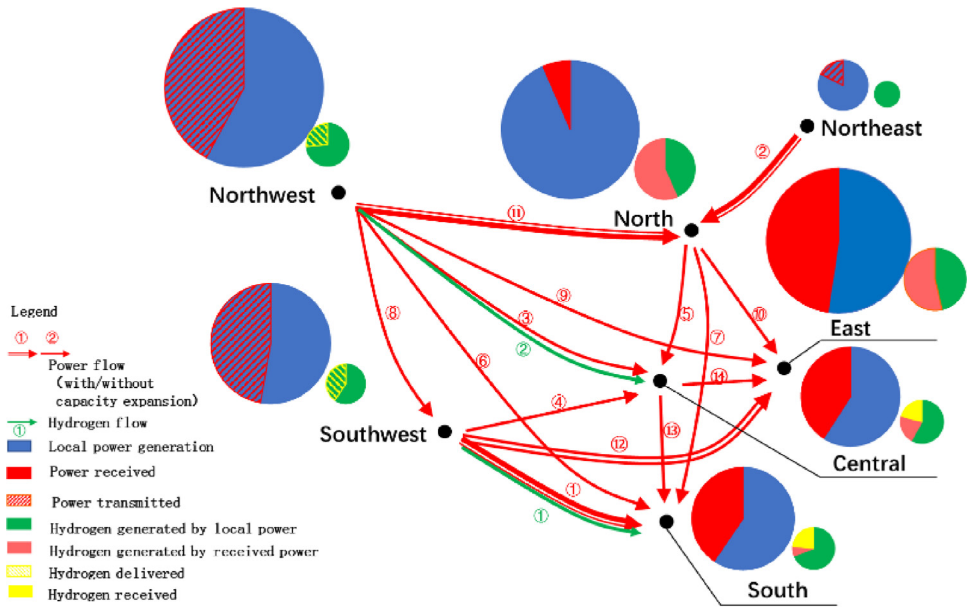

Fig. 7. Power transmission and hydrogen transportation scheme of benchmark case.

Table 1
Summary of power transmission capacity and VRE power installation scheme of benchmark case.

No.	Channel	Capacity (MW)	Increased capacity (MW) after adding hydrogen demand	Hydrogen daily max. transportation capacity (kton)	Hydrogen annually transported (Million ton)
1	SW-S	86 115	2155	9.58	2.55
2	NE-N	35 115	8115	–	–
3	NW-C	89 110	0	5.42	1.94
4	SW-C	29 000	0	–	–
5	N-C	15 000	0	–	–
6	NW-S	36 000	0	–	–
7	N-S	16 000	0	–	–
8	NW-SW	57 800	0	–	–
9	NW-E	72 000	0	–	–
10	N-E	69 300	0	–	–
11	NW-N	51 720	34 480	–	–
12	SW-E	92 002	54 402	–	–
13	C-S	710	0	–	–
14	C-E	10 200	0	–	–
	Sum	660 073	99 153	15.00	4.49

production and direct transported hydrogen will account for 35% and 7% respectively of the hydrogen total demand.

An optimized VRE installation distribution among these seven regions is formed to adapt and support the energy transportation pattern, as demonstrated in Fig. 8. Compared with the reference case shown in Appendix A, 60% of the new installed capacity of the wind power and solar PV power is distributed in the energy-receiving regions such as the northern, eastern, central, and southern China for local generated electricity to realize direct hydrogen production. While 40% of the new installed capacity is distributed in energy-sending regions such as the northwestern, southwestern, and northeastern China, being that the hydrogen demand in these three regions only accounts 20% of total. Regarding the hydrogen storage, 237 ktons storage capacity is required. The sending-regions need 62% of the total hydrogen storage capacity, and the rest is for the other regions. Furthermore, the hydrogen storage capacity accounts for 0.4% of the total hydrogen consumption and 130% of the daily hydrogen demand on average. Therefore, it can solve the hydrogen short supply problem derived from insufficient VRE power output caused by extreme weather lasting more than one day.

It is concluded that, the hydrogen energy development will form a pattern of hydrogen production based on electricity transmission through a strong power grid, supplemented by direct hydrogen pipeline transportation. Therefore, large-scale cross-regional power grids combined with on-site production will dominates the energy transportation in the electric-hydrogen coordinated optimized energy system. A moderate utilization of West–East Gas Pipeline and construction of new hydrogen pipeline between the southwest and southern regions are favorable for further pushing downward the energy system cost. At the same time, the VRE power development trends within each region will be optimized according to the energy transportation pattern to support the energy system coordinately optimized on production–transportation–storage.

The electric-hydrogen coordinated configuration fully combines the advantages of easy transmission of electricity and wide-area configuration capability, as well as the characteristics of large-scale storage of hydrogen. On the one hand, when the hydrogen transmission technology is not yet mature, the early development of the hydrogen energy industry can be promoted with the help of mature power transmission technology. On the other hand, in the electric-hydrogen coupled energy system, the flexible load function of hydrogen production and the large-scale

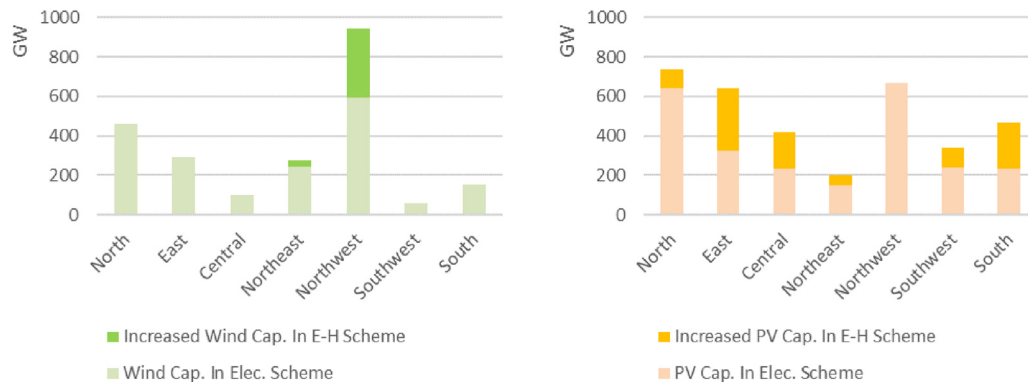

Fig. 8. VRE power installation scheme of benchmark case.

and long-term energy storage function of hydrogen storage can be fully utilized, and the utilization rate of hydrogen production equipment and transmission channels has been significantly improved. The utilization rate of the newly-built hydrogen transmission channels in the northwest-central and southwest-south China is around 80%, and the average utilization hours of the national power transmission channels will increase by 700 h.

Sensitivity analysis

Considering the uncertainty of technology route, scalability and marketization, a sensitivity analysis of related parameters alteration impact on the optimization result should be carried out, which involves the energy demand and technic-economic prediction of electricity and hydrogen. In this section, because the electricity-related aspects are relatively mature and stable, we take the hydrogen-related techno-economic parameters, water electrolysis efficiency and long-distance hydrogen transportation cost, as the objects of study due to their high uncertainty. The optimization results alteration of power transmission capacity, hydrogen transportation volume, VRE power capacity, hydrogen production and storage are presented and discussed. The variables assembly to be optimized maintains the same as those of benchmark case.

Based on the input data of previous benchmark case, the hydrogen transportation cost goes down by 30% (adapting to natural gas and hydrogen mix transportation condition) and increases by 30% (same as current natural gas transportation cost condition) respectively. Meanwhile, the comprehensive electrolysis efficiencies are set to 60%, 70%, and 80%, apart from 90% that is adopted in the benchmark case, to have water electrolysis conservative technological progress scenario included. The analysis of hydrogen storage cost impact is excluded in this study since diversity of the actual form of hydrogen storage, which could be tank storage in centralized station or integrated storage with hydrogen transportation pipeline, complicates the prediction of the cost. Optimization calculation results regarding energy transportation, VRE power capacity installation and hydrogen production and storage are shown in Figs. 9 to 11.

(1) **Power transmission and pipeline transportation**

With the decrease in hydrogen transportation cost, the power transmission capacity expansion slightly shrinks and the amount of the transported hydrogen increases correspondingly for any electrolysis efficiencies, as we can observe in Fig. 9(a) (b). While generally more transportation pipes construction is favored with more regions included into hydrogen transportation network, i.e., northern and eastern regions as hydrogen receiving regions and northeastern region as sending regions, as summarized in Table 2. The cost competition between these two forms of energy transportation explains that along with the cost decrease in hydrogen pipeline construction, direct hydrogen transportation becomes more competitive and partly replace the electricity transmission.

From the perspective of electrolysis efficiency, energy cross-regional transportation is inclined to be further enhanced and power transmission dominance weakens along with the electrolysis efficiency drop, as revealed by Fig. 9(c). On one hand, in order to meet the hydrogen demand increase induced by the hydrogen producing efficiency degradation, extra electricity should be generated. Similar to the previous study, exceeding VRE power generators to the local energy demand are deployed in the western and northeastern regions to make full use of the abundant resources although the transmission cost being added. Increasing total energy is outbound delivered despite the slight shrink of power transmission capacity, as demonstrated in Fig. 9(c). On the other hand, with the electrolysis efficiency drops, the energy transported in form of hydrogen is gradually increasing while the electricity transmission still dominates, which is consistent to the results of benchmark case. It is because the utilization rate of hydrogen transportation rises faster than that of power transmission. In fact, the hydrogen is balanced by day while the hydrogen daily demand is much more steady than electricity, thus the hydrogen is more favored than electricity to facilitate the cross-regional energy balance. Next, hydrogen can be stored much longer than electricity, providing short term and seasonal flexibility simultaneously. Therefore, the hydrogen transportation utilization rate rises faster when larger energy need to be transported. To conclude reversely, the higher the comprehensive efficiency of hydrogen producing is, the more favored will be replacing hydrogen pipeline transportation with power transmission.

(2) **VRE power installation**

In terms of the VRE power capacity installation optimization which is demonstrated in Fig. 10, from the perspective of comprehensive electrolysis efficiency, total VRE power capacity increases along with the hydrogen producing efficiency under any hydrogen transportation cost condition. It is because that when hydrogen producing efficiency drops, more wind and PV power installation is required to compensate energy loss in the electrolysis process. It is notable that the wind and PV power are unequal in increase rate due to their cost of electricity generation differs.

Regarding hydrogen transportation cost, PV power capacity generally changes consistently with it while wind power changes reversely. The decrease in PV power capacity is more significant than the increase in wind power when hydrogen transportation cost drops, resulting in a decrease in total VRE power capacity. According to the calculation results, wind power capacity increase only occurs in the Northwest regions. Thus, it is evident

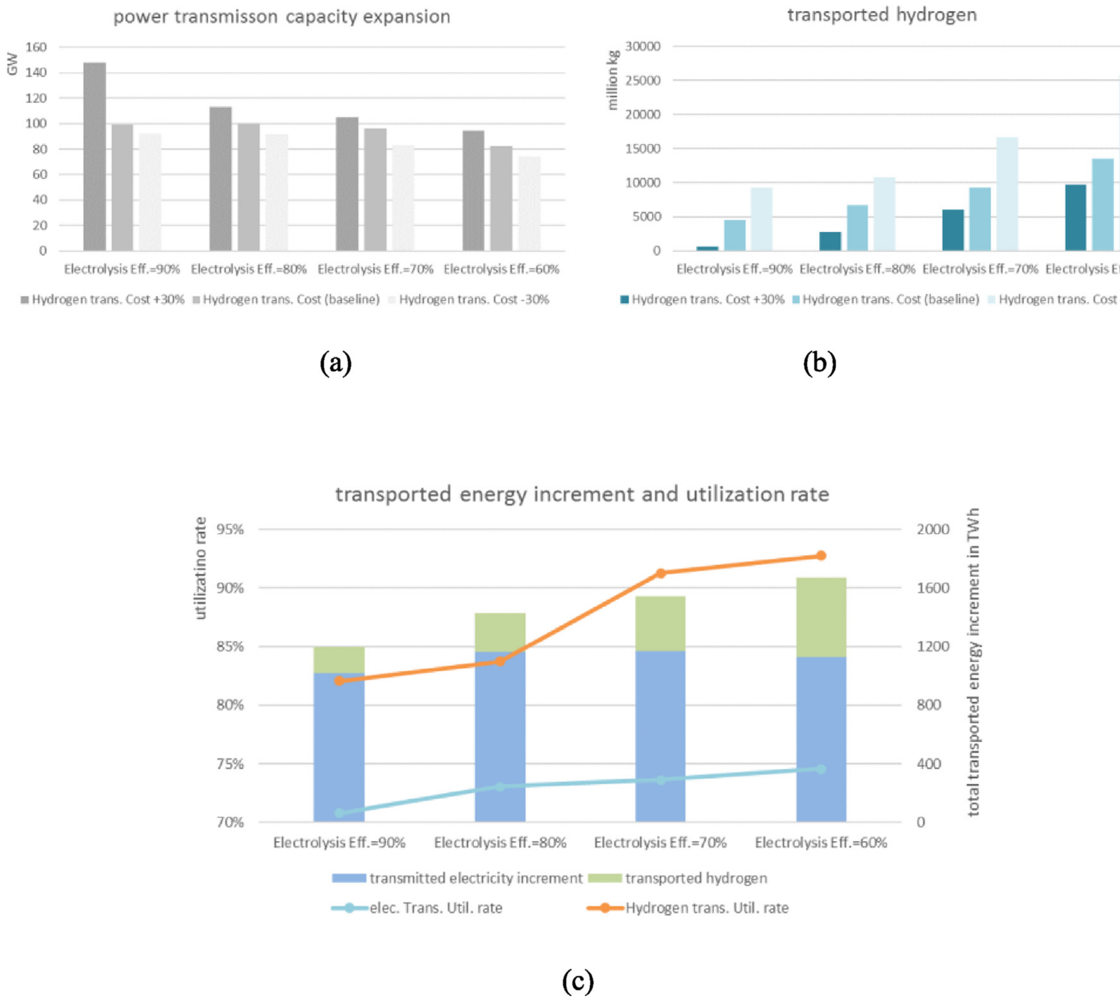

Fig. 9. (a) Power transmission capacity and transported hydrogen (b) transported hydrogen (c) transmitted electricity increment, transported hydrogen and utilization rate in case of unaltered hydrogen transportation cost.

Table 2
Hydrogen transportation pipeline scheme.

	Hydrogen trans. Cost +30%	Hydrogen trans. Cost (baseline)	Hydrogen trans. Cost -30%
Electrolysis Eff. = 90%	SW-S	SW-S,NW-C	SW-S,NW-C,NW-N
Electrolysis Eff. = 80%	SW-S,NW-C	SW-S,NW-C,NW-N	SW-S,NW-C,NW-E,NW-N
Electrolysis Eff. = 70%	SW-S,NW-C	SW-S,NW-C,NW-E	SW-S,NE-N,NW-C,SW-C,NW-E,NW-N
Electrolysis Eff. = 60%	SW-S,NW-C,NW-E	SW-S,NW-C,NW-E	SW-S,NW-C,NW-E,NW-N

that as the hydrogen transportation cost drops, wind power becomes more favored especially in the energy sending regions. It is because the resource endowment difference of wind energy between energy sending and receiving regions is more significant than that of solar energy, so it is with the difference in power generation cost, thus an exploitation of wind energy in sending regions instead of solar energy should be enhanced to fully utilize the advantage of wind power cost. Because of the higher fill factor of wind power generation, less PV power capacity is required eventually. It is concluded that the higher the comprehensive efficiency of hydrogen producing is, the less VRE power installation is required, and the cost competition between power transmission and hydrogen transportation will influence the VRE power installation in each region to achieve an optimized deployment.

(3) **Hydrogen production and storage**

The electrolysis equipment capacity varies along with its efficiency change in the similar trend as the VRE power capacity does, as revealed in Fig. 11. When the VRE generation penetration rises, the power generation fluctuates more severely, then expanded capacity of electrolysis needs to be equipped to fulfill the hydrogen demand at the expense of lower utilization rate.

Regarding the hydrogen storage, as we can observe in Fig. 11, more storage capacity is required when the hydrogen producing comprehensive efficiency is lower. The storage equipment provides flexibility for the whole energy system. When the VRE generation penetration rises due to the low hydrogen producing efficiency, more flexibility resources, i.e., the storage capacity, is required. Especially, when the installation as well as its generation penetration of wind power dominates, and its generation fluctuates more greatly, such as in cases of 80% and 90% efficiencies, more storage is needed. It can be stated that the storage requirement is highly depends on the system flexibility shortage induced by the high fluctuating power generation. The higher the efficiency of energy conversion between electricity and hydrogen is, the stronger the long-term adjustment ability can be to provide hydrogen storage.

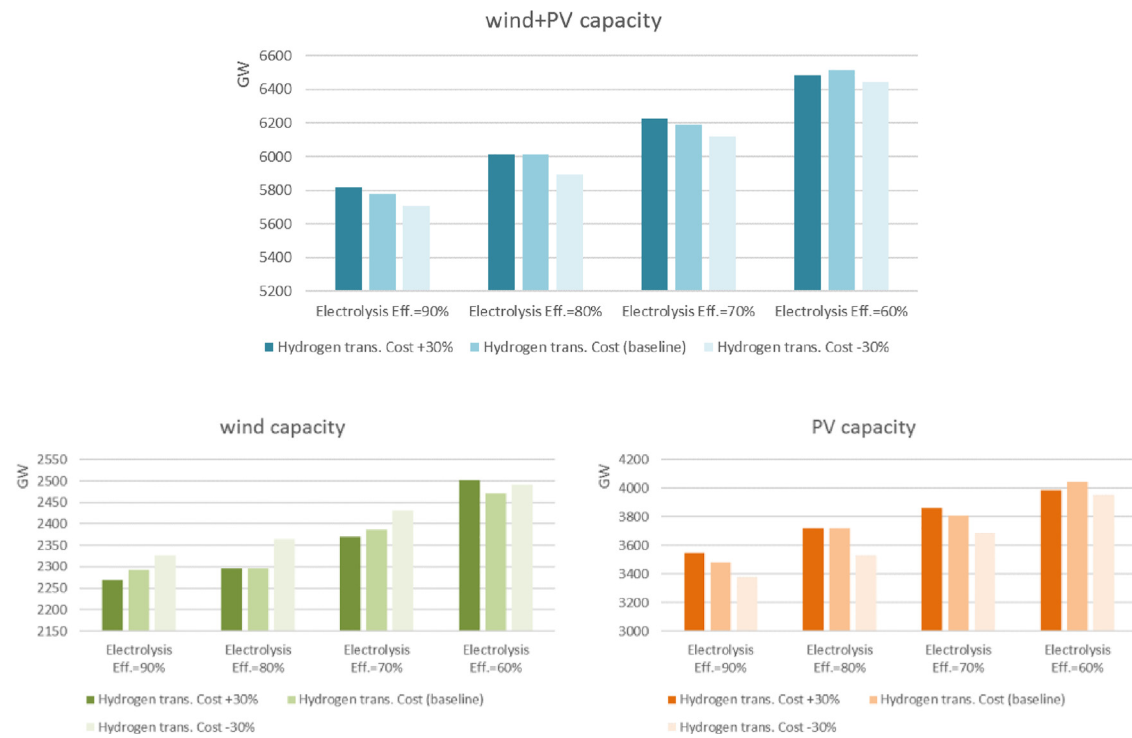

Fig. 10. Wind and PV power capacity installation.

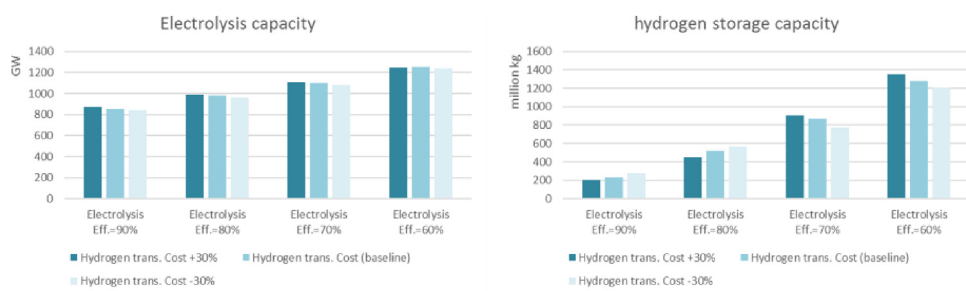

Fig. 11. Hydrogen production and storage capacity.

5. Conclusion

The joint GTSEP-EH model established in the work can include multi-node network and different balance timescales respectively for electricity and hydrogen. By applying this model, an optimization calculation in the seven large regions all around the country was carried out, and a national-wide scheme of the large-scale and cross-regional energy production, storage and transportation for both electricity and hydrogen was provided. This work responds to the question of how to configure electricity and hydrogen production–storage–transport among various regions in the most cost-effective way. It can be concluded that under the predicted scenario of power and hydrogen demand, the energy cross-regional transportation capacity will be further enhanced, and more than 40% of the hydrogen demand is fulfilled by transported energy in forms of either power transmission or direct hydrogen transportation, among which, the power transmission pathway accounts for 80%. It will form a pattern that power transmission dominates and direct hydrogen transportation supplements. Further, the most uncertain variables, the hydrogen producing efficiency and transportation cost were applied to carry out sensitivity analysis research. It is found that the progress of hydrogen producing efficiency will promote power transmission's replacement for hydrogen pipeline transportation, and cut down the installation requirement of VRE power, electrolysis equipment, and hydrogen storage. Moreover, the changes of cost competition between power transmission and hydrogen transportation will influence the cross-regional energy transportation form preference as well as the VRE power installation in each region to achieve an optimized deployment. In this paper, the author hopes that the quantitative calculation and results discussion could provide suggestion and reference to energy-related companies, policy-makers and institute researchers in formulating strategies on related energy development.

CRediT authorship contribution statement

Chen Jin: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Jinyu Xiao:** Conceptualization, Resources. **Jinming Hou:** Conceptualization, Resources. **Han Jiang:** Resources. **Jinxuan Zhang:** Investigation, Visualization. **Xunyan Lv:** Visualization. **Wei Sun:** Conceptualization. **Haiyang Jiang:** Methodology, Software. **Ershun Du:** Software, Project administration, Resources, Funding acquisition. **Yuchen Fang:** Writing – review & editing. **Yuanbing Zhou:** Supervision. **Xunpeng Shi:** 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 will be made available on request.

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Appendix A

The power installed capacity, except wind and PV, of the seven regions are shown in Fig. A.1. Regarding hydropower, the southwestern region of China has the richest water resources that provide a large amount of clean electricity to be delivered to the power consumption center regions through multiple cross-regional interconnection power channels. It constitutes an important source of flexible resources for the power system not only in local or neighbored regions but also in the East China and South China in the distance. The characteristics of hydropower output are profiled by the historical statistics of monthly power generation in each region.

With progressive fossil fuel power plants withdrawal, only natural gas thermal power plants will participate in the power system in 2060, with a total installed capacity of about 400 GW. The natural gas power is mainly used as peak shaving power sources. The nuclear power plant, mainly located in coastal regions of China, is estimated to be 250 GW in tall while other novel energy power capacities including biomass and geothermal power are summed up to be 332 GW.

Appendix B

See Tables B.1–B.4.

Table B.1
The adjustment ability of power generation and energy storage.

Power type	Adjustment capabilities
Natural gas	0.1∼1
Hydropower	0.3∼0.1
Pumped-storage	−1∼1
Nuclear	0.9∼1
Biomass and others	0.9∼1
Batteries	−1∼1

Table B.2
Cost of technologies.

Technologies	Items	Investment (yuan/kW or kWh)
Generation	Wind	3150
	Solar PV	1225
	Hydrogen	1800
Storage	Electricity	700/150
	Hydrogen	6/1.2
Transmission	HVDC	[a]
	Hydrogen	10 million yuan/km

[a]Details presented in Table B.3.

Appendix C

The electricity consumption of the whole society is expected to reach 14,000 TWh. Referencing the predicted data (GEIDCO, 2020) of none-VRE power installation such as thermal power, pumped storage and the basic power flow scheme, it is focused on the optimization of VRE power installation and the power transmission performance for these seven regions. The results are summarized in Appendix C, Fig. C.1.

According to our observation, the eastern, central and southern regions are the energy-receiving regions due to the large energy demand, while the northeast, northwest and southwest are energy-sending regions due to their excessive energy production capacity and their economically competitive generation costs, even including transportation costs.

Regarding the power flow pattern, the reverse distribution of energy demand and resource endowment which determines the pattern of "West-to-East" and "North-to-South" has relieved a national-wide energy supply–demand imbalance. The calculation results suggest that the country's cross-regional power flow will reach about 560 GW and the cross-regional transmission of electricity will exceed 3000 TWh in 2060, as summarized in Table C.1

The required VRE power installed capacity is 1908 GW of the wind power and 2488 GW of the solar PV power, as summarized

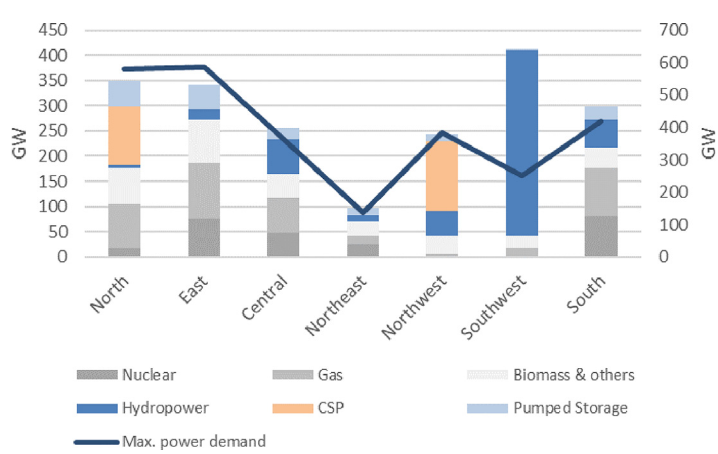

Fig. A.1. The power installed capacity (except wind and PV) of the seven regions.

Table B.3
Power transmission cost.

Voltage class	Capacity (MW)	Single substation (100 million $)	Unit length investment (10,000 $/km)
±1100 kV	12,000	11.8	108
±800 kV	8000	6.7	63
±500 kV	3000	2.4	31

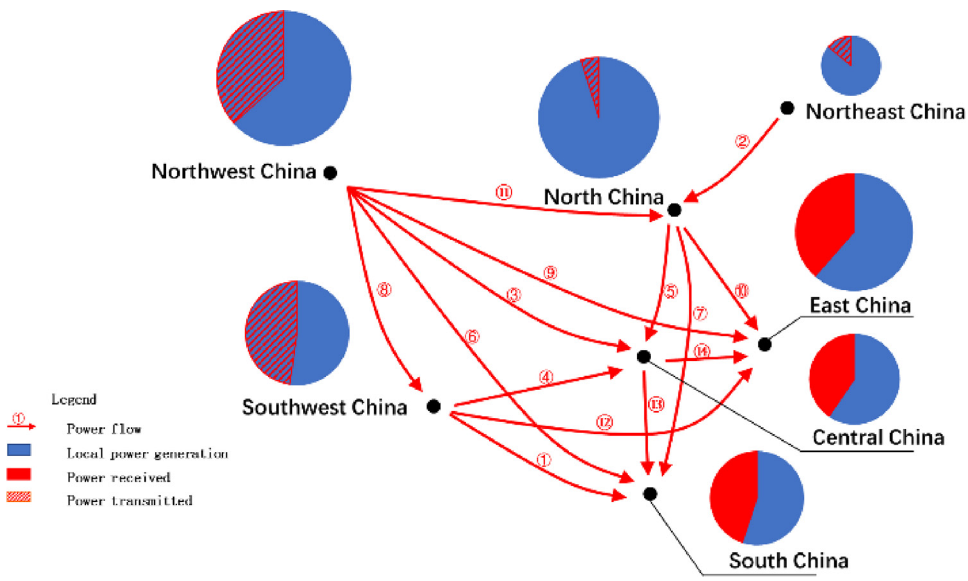

Fig. C.1. Power transmission scheme of reference case.

Table B.4
Conversion and storage efficiency.

Conversion	Eff. (%)
Electricity to H_2	90
Battery storage.	90
H_2 storage.	90

Table C.1
Summary of power transmission capacity scheme of reference case.

No.	Channel	Capacity (MW)	Electricity (GWh)
1	SW-S	83 960	695 200
2	NE-N	27 000	127 800
3	NW-C	89 110	512 300
4	SW-C	29 000	222 600
5	N-C	15 000	31 500
6	NW-S	36 000	183 700
7	N-S	16 000	43 400
8	NW-SW	57 800	40 900
9	NW-E	72 000	522 800
10	N-E	69 300	272 500
11	NW-N	17 240	88 900
12	SW-E	37 600	289 900
13	C-S	710	2100
14	C-E	10 200	40 000
	Sum	560 920	3 073 600

Table C.2
Summary VRE power installation scheme of reference case.

Region	Wind (GW)	PV (GW)
North (N)	463	641
East (E)	294	322
Central (C)	104	237
Northeast (NW)	242	147
Northwest (NW)	594	668
Southwest (SW)	57	238
South (S)	154	235
Sum	1908	2488

in Table C.2. Generally, the western region is rich in renewable energy resources. As large-scale and low-cost VRE exploitation is allowed in the region, it turns out that nearly one-third generation from the northwest region and half from the southwest region are outbound delivered.

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