Clean Energy, 2023, Vol. 7, No. 1, 30–40
https://doi.org/10.1093/ce/zkac091
Advance access publication 17 January 2023
Research Article

Economic analysis of hydrogen production from China's province-level power grid considering carbon emissions

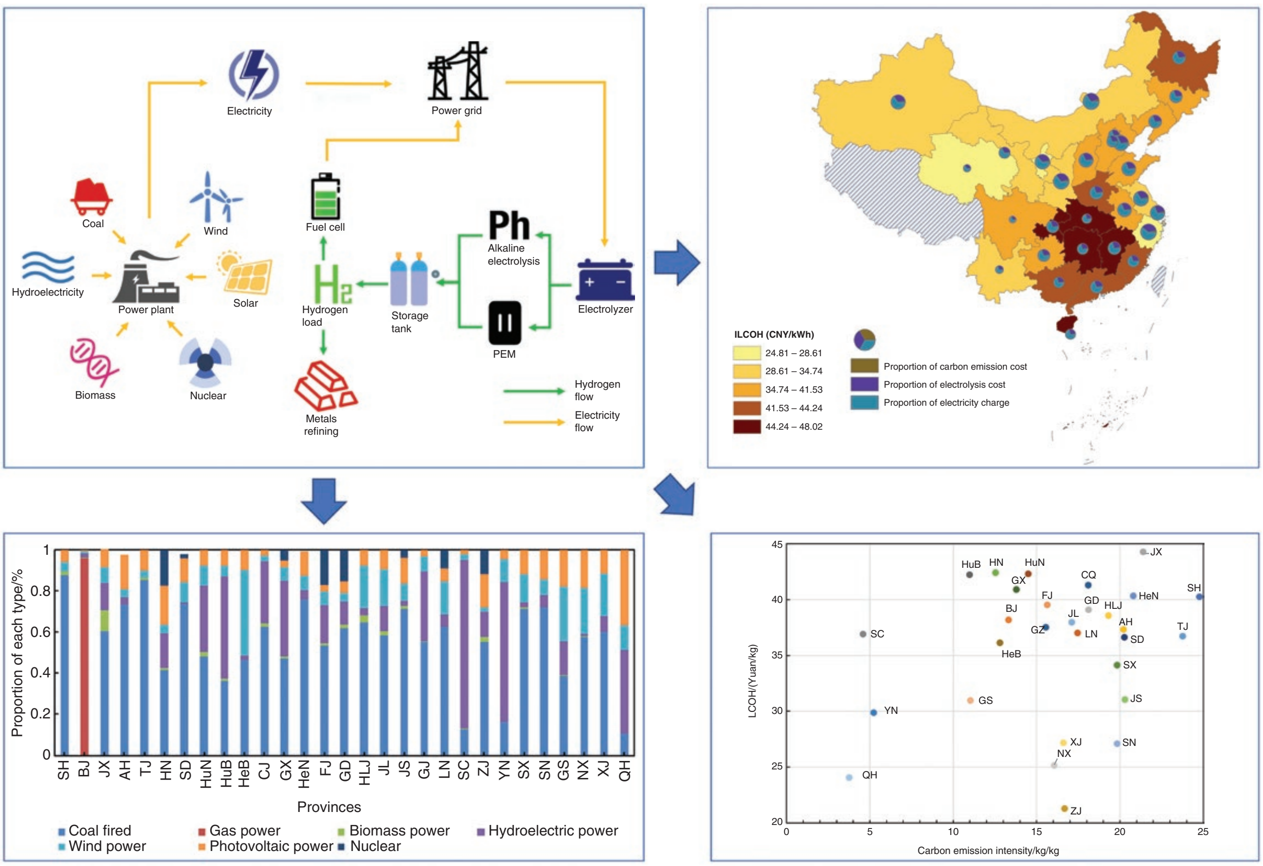
Wenzuo Zhang[1], Xinying Li[2], Jiezhi Yang[3], Jianguo Liu[4] and Chuanbo Xu[1,5,*]

[1]School of Economics and Management, North China Electric Power University, Changping, Beijing 102206, China
[2]School of Economics and Management, China University of Petroleum, Changping, Beijing 102249, China
[3]College of Engineering, University of California, Berkeley, CA 94720 USA
[4]Institute of Energy Power Innovation, North China Electric Power University, Changping, Beijing 102206, China
[5]Beijing Key Laboratory of New Energy and Low-Carbon Development (North China Electric Power University), Changping, Beijing 102206, China
[*]Corresponding author. E-mail: Chuanbo_xu@ncepu.edu.cn

Abstract

Hydrogen energy contributes to China's carbon peaking and carbon neutralization by serving as an important energy carrier. However, the calculation of the cost of hydrogen production by the power grid ignores the current cost of carbon emissions. To measure the cost of hydrogen-production projects in various provinces more comprehensively and accurately, this study incorporates the carbon-emission cost into the traditional levelized cost of hydrogen model. An analysis of the energy structure of the power supply is conducted in each province of China to calculate carbon-emission costs, which are then subjected to a sensitivity test. Based on the results, the carbon-emission costs for hydrogen in each province are between 0.198 and 1.307 CNY/kg, and the levelized cost of hydrogen based on carbon-emission costs varies from 24.813 to 48.020 CNY/kg; in addition, carbon-emission costs range from 0.61% to 3.4% of the total costs. The results also show that the levelized cost of hydrogen considering carbon-emission costs in the Shanghai municipality specifically is most sensitive to the carbon-emission price, changing by 0.131 CNY/kg for every 10% fluctuation in the carbon-emission price.

Graphical Abstract



Received: 18 August 2022. **Accepted:** 15 December 2022

© The Author(s) 2023. Published by Oxford University Press on behalf of National Institute of Clean-and-Low-Carbon Energy
This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial License (https://creativecommons.org/licenses/by-nc/4.0/), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited. For commercial re-use, please contact journals.permissions@oup.com

Downloaded from https://academic.oup.com/ce/article/7/1/30/7043870 by guest on 21 July 2023

Keywords: hydrogen production; levelized cost of hydrogen; power grid; carbon-emission intensity

Introduction

The availability of energy resources is vital to the prosperity of the economy and society, as well as the well-being of the people. In particular, population growth and rapid economic development have resulted in increased daily energy demands at global levels, exacerbating the existing energy crisis [1]. Meanwhile, the extensive use of fossil fuels is also harmful to the environment. Therefore, many countries are seeking to transform their energy sources into ones that are more environmentally friendly and sustainable. One of the best alternatives to those fuels is hydrogen energy, which is a clean secondary energy that can be used for transportation, energy generation and energy storage. Also, as Liu and Li demonstrated, hydrogen can be produced from various domestic resources [2]. Fig. 1 illustrates a simplified view of the hydrogen-production process.

Hydrogen energy is becoming increasingly important in this field. Recently, the National Development and Reform Commission published a medium- and long-term plan for the development of hydrogen energy in China, in which the goals of hydrogen-energy development are outlined. In recent years, the USA, the EU, Japan and other countries and regions have also raised hydrogen energy to a national strategic level and formulated specific action plans, policies and development roadmaps [3]. Recently, there has been large-scale manufacturing of hydrogen and fuel cells [4], which are widely used in the field of hydrogen-energy trams.

However, accurate cost estimates are necessary for large-scale applications of hydrogen energy. Most hydrogen-production methods also release carbon dioxide during the power-generation process, which is not considered in the traditional method for calculating hydrogen-production costs. Carbon emissions will accompany the grey hydrogen produced by fossil-energy hydrogen production and the hydrogen produced as an industrial by-product. These costs are not included in the traditional method of calculating carbon emissions. Furthermore, as countries pay increasing attention to green and low-carbon development, stricter carbon-emission restrictions have been implemented. The Chinese carbon-trading market, which will contribute to reaching carbon peak by 2030 and carbon neutralization by 2060, has just been established and a carbon tax will be imposed on carbon emissions. In the domestic carbon market, the average transaction price reaches 52.78 CNY/t, which is an integral part of the total cost of hydrogen production. Similarly, Australia has also announced plans to reach carbon peak by 2050. The hydrogen-production industry is also increasingly using carbon capture, utilization and storage technology to capture greenhouse gases. It is evident that carbon emissions will continue to increase in price as national attention on carbon emissions and the carbon taxes increases. It is becoming mainstream to price carbon emissions, and it is important to take carbon-emission costs into account when calculating the cost of hydrogen production in domestic hydrogen-production projects.

The study examines the costs of carbon emissions during hydrogen production in order to quantify the cost and provincial differences of electrolytically produced hydrogen in China. On the basis of the traditional levelized cost of hydrogen (LCOH) and carbon-emission costs, the study proposes an improved levelized

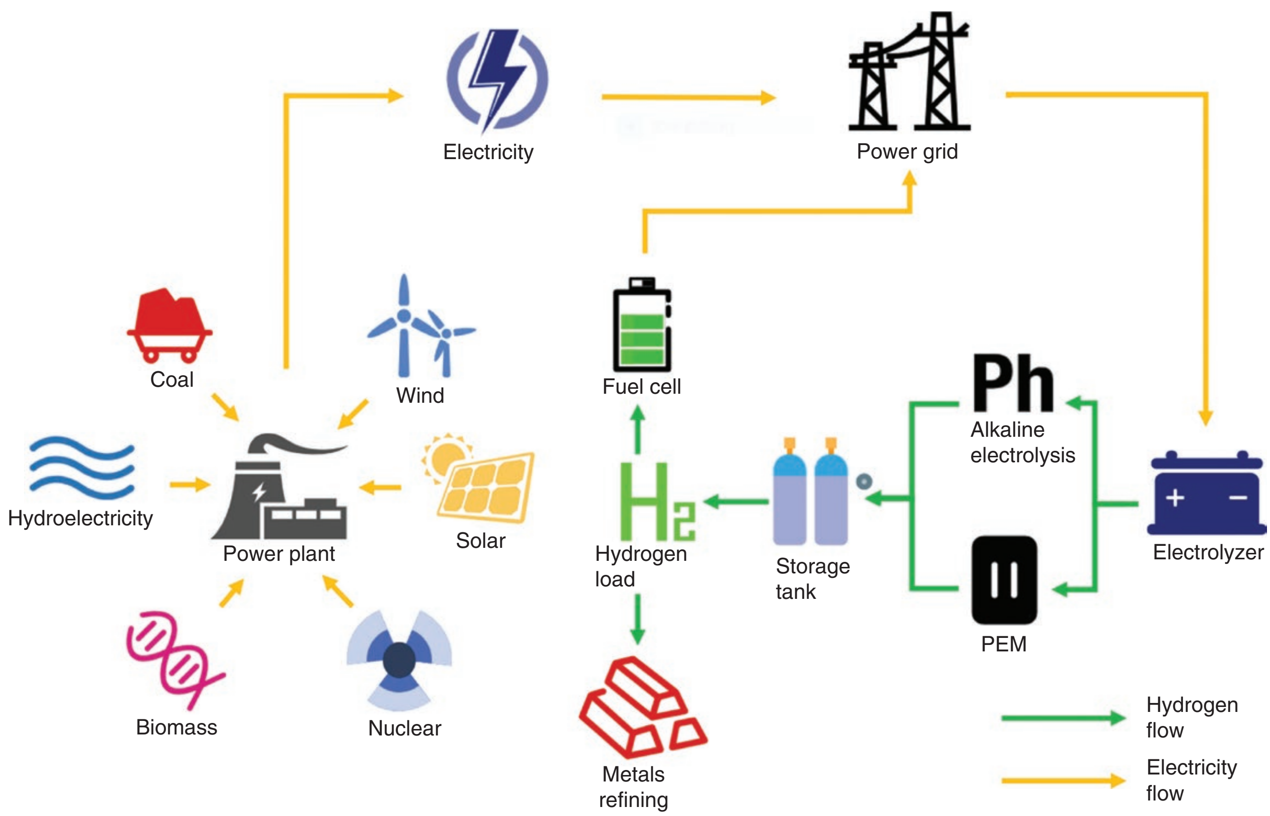


Fig. 1: Structure of hydrogen production from a power grid

Downloaded from https://academic.oup.com/ce/article/7/1/30/7043870 by guest on 21 July 2023

cost of hydrogen (ILCOH) model. In this study, the power-purchase costs of each province are calculated first, followed by the energy structure of each province's power supply to calculate the carbon-emission intensity and cost of carbon emissions. As a final step, carbon-emission costs are added to the LCOH model in order to determine the ILCOH in each province.

A comprehensive literature review is conducted in Section 1, followed by an introduction to the ILCOH model and its calculation model for relevant data in Section 2; then a comparison and analysis of the calculation results follow in Section 3, and this study is concluded in Section 4.

1 Literature review

1.1 Development prospect of the hydrogen economy

Hydrogen energy is a clean, zero-carbon secondary energy. As a key energy source connecting transportation, power generation and energy storage, it has high development potential and a low price. Taking into account different hydrogen supply chains, learning and market penetration rates, Ajanovic *et al.* [5] predicted the cost of hydrogen production through 2050. They used the forecast prices to reflect the potential of hydrogen development and indicated that hydrogen energy will be more competitive. A report by Lazard [6] evaluated the revenue requirement and the sensitivity of LCOH to changes in capital equipment cost, cost of electricity and electrolyser utilization, and showed great potential for development of hydrogen production, despite the current high cost. Yet, it was possible to cut the costs. A report by IRENA [7] outlined the strategies to reduce electrolyser costs through up-scaling and forecasted future cost reductions. The report stated that electrolyser costs could be 40% cheaper by 2030. The sharp drop in electrolyser costs indicates a high potential for the reduction of hydrogen-production costs. Overcoming the disadvantage of its cost, there will be more developments in hydrogen-energy projects.

The hydrogen-energy industry is not only advantageous in terms of productivity and cost, but is also supported by international policies. In China, the 2014 energy-development strategic action plan (2014–20) established 'hydrogen energy and fuel cell' as the strategic direction of innovation in energy science and technology innovation, and the 14th 5-year plan stated that incubation and acceleration plans will be implemented for the hydrogen-energy industry. The national-level plan and the medium- and long-term plan for the development of the hydrogen-energy industry have also just been implemented, defining the development goals and requirements. Hydrogen energy is becoming increasingly important in China and its related industries will be supported. In China, as well as around the world, large-scale hydrogen-energy projects are becoming more widely used because of policy support. Combined with the green-hydrogen standards issued by China and Europe, Liu *et al.* [8] discussed the idea of formulating green-hydrogen standards. It was concluded that Europe and China might have put forward different green-hydrogen standards according to their different main hydrogen-production methods, but these standards and methods were mostly compatible. A report from the Hydrogen Council [9] pointed out that large-scale clean-hydrogen projects have been announced in more countries, projecting >10 million tons of total capacity by 2030, which is approximately a third of the total clean-hydrogen demand growth expected in the next decade.

1.2 Economic analysis of hydrogen production

Existing research on the economics of hydrogen production can be put into two categories. One is to test the cost-effectiveness of hydrogen production for specific projects from a micro perspective. A provincial or national perspective is the other. Numerous studies have been conducted in these fields and some representative ones are listed below.

From the micro perspective, scholars tested the cost-effectiveness of hydrogen production against metrics such as the LCOH in specific projects. For example, Nicita *et al.* [10] analysed the cost-effectiveness of an industry producing green hydrogen in Messina, Italy. The LCOH was ≤30.32 EUR/kg and the payback period was ≥12 years due to the small scale and the short working hours. Based on the previous article, Madeira *et al.* [11] also considered the influences of ecological efficiency, pollution indicators and energy efficiency, which were 93.73%, 19.57 kg CO_2/kg H_2 and 93.73%, respectively. These metrics presented great economic potential and high exegetic yield. At the same time, Macedo and Peyerl [12] verified the economic feasibility of renewable hybrid systems that combine hydrogen production and storage in the Brazilian electricity sector. They concluded that the number of hours of electricity available for hydrogen production directly influenced its cost, and hydrogen production and storage would become feasible only from plants operating for >3000 hours and for electrolysers with a capital expenditure of 650 USD/kW in Brazil. Additionally, Wang *et al.* [13] conducted a parametric analysis of the effects of several key operating parameters on system performance and took total efficiency, cost of producing compressed hydrogen and electrical power output as indicators to measure the economy of the project. Meanwhile, Singlitico *et al.* [14] integrated the hydrogen- and offshore-electric-power infrastructure and determined the levelized costs of both hydrogen and electricity. Song *et al.* [15] combined solar energy, a hydrogen-production system and a combined cooling, heating and power system. And the annual total energy supply, typical daily loads and cost of the optimized system were analysed as the indicators to judge the economy of system. Almutairi *et al.* [16] conducted a case study in different regions in Badakhshan, Afghanistan. They conducted an economic analysis based on indicators of levelized cost of electricity (LCOE), LCOH and payback period. Taghizadeh-Hesary *et al.* [17] analysed the economic feasibility of the hydrogen-production project and concluded that the optimal weight of bank loans for the hydrogen projects in China was calculated at nearly 56%, meaning that the weight of green bonds was ~44%. Abdelrahman *et al.* [18] calculated the LCOH of a 50-MW wind farm in Elkharga, Egypt using the statistical method of the Weibull probability density function and found that the LCOH was 28.15 USD/MWh. These studies tested the cost-effectiveness of hydrogen production for a specific project.

From a macro perspective, in order to reflect the status quo of hydrogen production and the hydrogen-production level of a province or country, the following research examined the cost-effectiveness of hydrogen production. Lin *et al.* [19] tested the cost of hydrogen production in western Inner Mongolia in China combined with local wind data. The LCOH result was 0.5–2 USD/kg, which was a competitive price. Using an efficiently sized power-to-gas facility, Glenk and Reichelstein [20] examined the cost of a hybrid hydrogen-production system that combined renewable power with traditional non-renewable power in Germany and Texas. They calculated the LCOH as 3.23 EUR/kg and found that renewable hydrogen was already cost-competitive in these applications. Additionally, Bhandari

Downloaded from https://academic.oup.com/ce/article/7/1/30/7043870 by guest on 21 July 2023

and Shah [21] performed an economic performance analysis for hydrogen production in Cologne, Germany. They concluded that hydrogen produced using a grid-connected solar photovoltaics system coupled with alkaline electrolysers was the cheapest, with the LCOH at 6.23 EUR/kg, which was already market-competitive in Cologne. Guerra *et al.* [22] assessed the average production cost of grid-based electrolytic hydrogen across the USA based on different types of energy and demand charges. They found that hydrogen could already be cost-effective today. Lee *et al.* [23] did an uncertainty analysis in Korea considering the impact of H_2-production equipment, construction, electricity and labour, which showed H_2-production costs of 14.98–17.60 USD/kg. Okonkwo *et al.* [24] investigated the energy cost-effectiveness of available renewable energy sources and concluded that the selling price of hydrogen in 10 years would be 8 EUR/kg and was estimated to decrease significantly in the future. Walsh *et al.* [25] considered the regional differences between hydrogen-production systems. They linked the cost-effectiveness of hydrogen energy with the availability of local energy resources, access to key infrastructure and water supplies, and distance to export ports, and their model could be used to calculate the potential of hydrogen-energy projects in different regions.

1.3 Analysis of carbon emissions from hydrogen production

The assessment of carbon emissions in the hydrogen-production industry has become increasingly important in light of carbon peaking and carbon neutralization.

From a micro view, carbon emissions have been evaluated for specific projects. For example, Li and Cheng [26] compared carbon emissions and energy consumption between two different hydrogen-production methods. Kerscher *et al.* [27] assessed the carbon footprint of a hydrogen-production plant. They showed that low-carbon hydrogen production with life-cycle emissions were between 1.9 and 6.4 kg CO_2/kg H_2. Cetinkaya *et al.* [28] tested the equivalent carbon dioxide emission for a hydrogen-fuelling station in Toronto, Canada. Sako *et al.* [29] analysed greenhouse gas emissions and the depletion of abiotic resources of hydrogen-production systems. Zou *et al.* [30] and Cen *et al.* [31] tested the annual reduction in carbon emissions in hydrogen-production systems. Ravichandran *et al.* [32] calculated the carbon emissions of a 150-MW floating photovoltaic system in an Indian reservoir, showing that it could help reduce 135 918.87 t of carbon emissions annually.

From a macro perspective, researchers have examined the carbon emissions in a province or country as a reflection of the country's overall carbon emissions, but there have been few studies on this topic, especially in China. Almutairi *et al.* [16] assessed the carbon footprint and then the reduction in carbon dioxide in the Badakhshan province of Afghanistan. Meanwhile, Pan *et al.* [33] tested the carbon emissions of electrolytic hydrogen production in China and studied various methods to reduce carbon emissions and the effects of these methods. They concluded that implementing time-of-use electricity rates and subsidizing photovoltaic energy systems can improve the performance of electrolytic hydrogen production in terms of production cost and CO_2 emissions.

1.4 Findings of literature review

Through the literature review, the findings can be summarized as follows:

- The studies of [10–18] and [26–32] remained at the project level, in terms of either economic measurement or carbon-emission measurement, which cannot reflect the overall cost of hydrogen production from the power grid in the whole country or region. There is a need to develop a method to verify the cost-effectiveness of hydrogen production from a macroeconomic perspective.
- The studies [19–25] mainly considered the different factors of electricity price and power structure, but ignored the differences between labour forces. Across provinces, there is a great deal of variation in the average labour force. During the average life cycle of a hydrogen plant, the total expenditure of labour wages is also important. The differences in labour wage levels will result in differences in the cost of hydrogen-production projects, and this cannot be overlooked.
- Cetinkaya *et al.* [28] only calculated the carbon emissions of hydrogen-production projects without taking into account the carbon-emission costs in the cost of hydrogen production. Although carbon-emission levels and green development prospects can be obtained for each province, they do not accurately reflect the cost of hydrogen production at present.

On the basis of these findings, this study provides the following contributions. First, this study investigates a wider range of factors related to hydrogen-production costs. In addition to differences in electricity prices and energy structures, the study examines the impact of labour force differences between provinces in China on hydrogen-energy costs. Second, the traditional LCOH model ignores the cost of carbon emissions, but in the context of global carbon-neutrality, carbon-emission costs constitute a substantial portion of expenditures that cannot be overlooked. Therefore, the improved LCOH (ILCOH) model integrating carbon-emission costs is proposed in this study. Taking into account the different energy structures of the power supply, carbon emissions are calculated for each province and their intensity is converted into carbon-emission prices. Furthermore, this study presents some policy recommendations that are conducive to the development of hydrogen-production projects as a result of the calculated results and analysis.

2 Proposed ILCOH model

The cost of grid-connected electrolytic hydrogen production is reflected in the ILCOH, consisting of three parts: power-purchase cost, the cost of the electrolytic plant and carbon-emission cost.

The ILCOH model is as follows:

$$\mathrm{ILCOH} = \mathrm{N} * \mathrm{E} + \frac{\mathrm{C_{ele,t}} - \frac{\mathrm{R_{ele}}}{(1+r)^t} + \sum_{t=1}^{n} \frac{\mathrm{O_{ele,t}} + \mathrm{F_{ele,t}} + \mathrm{T_{ele,t}}}{(1+r)^t}}{\sum_{t=1}^{n} \frac{\mathrm{H_t}}{(1+r)^t}} + \mathrm{P} * \mathrm{C} \quad (1)$$

where N represents the electricity consumption per kilogram of hydrogen produced by the electrolytic plant; E represents power-purchase price from the power grid; C_{ele} represents capital expenditure of the electrolytic plant; R_{ele} represents the residual value of the capital expenditure of the electrolytic plant; O_{ele} represents the operating expenditure of the electrolytic plant; F_{ele} represents the interest payable by the electrolytic plant; T_{ele} represents the taxes payable by the electrolytic plant; H represents the annual hydrogen production of the electrolytic plant; P represents the carbon-emission price per kilogram of carbon dioxide, which uses the average transaction price of 52.78 CNY/t in China's

Downloaded from https://academic.oup.com/ce/article/7/1/30/7043870 by guest on 21 July 2023

carbon-trading market as the benchmark state; C represents the carbon-emission intensity; n is the start time of the project; and r is the discounted rate. The ILCOH's innovation lies in the third part of the equation $P * C$, which represents the carbon-emission cost per kilogram of hydrogen produced. Thus, the resulting costs include the impact of carbon emissions.

Furthermore, the power-purchase cost varies according to different types of pricing in each province. There are mainly four pricing types in each province. The types include time-of-use electricity price and selling price, and each of them can be divided into a two-part-electricity-price scenario and a single-electricity-price scenario. The pricing types and charging standards in each province are shown in Appendices 1–4 (in the online Supplementary Data). The data come from the documents issued by the National Development and Reform Commission, provincial Development and Reform Commissions.

The operating expenditure of the electrolytic plant can be expressed as:

$$\mathrm{OPEX} = \mathrm{F} + \mathrm{S} + \mathrm{M} + \mathrm{B} + \mathrm{W} + \mathrm{Q} \tag{2}$$

where F represents the repair cost; S represents the employee salary and welfare, determined by the per capita annual wage of each province published by the China Urban Statistical Yearbook 2020 from the National Bureau of Statistics; M represents the materials costs; B represents the insurance costs; W represents the water costs; and Q represents the other costs.

In Equation (1), the power-purchase cost is different from the LCOE. The electricity used for the electrolyser to produce hydrogen is from the grid, not from the off-grid power plant. Therefore, the power-purchase cost is calculated according to the time-of-use electricity prices formulated by each province in China. The capacity factor of the electrolytic plant is assumed to be 75% in our model, which means that the annual working hours of the electrolytic plant is 6570 hours. This study assumes that the working hours of the electrolytic plants are only during the lowest 18 hours in the time-of-use electricity price structure. The cost of electrolytic plants is the ratio between the discounted value of the total cost and the discounted value of the total hydrogen production. The capital expenditure of the electrolytic plant is 4410 CNY/kW [34]. Other data required for the calculation are shown in Appendix 5 (in the online Supplementary Data), which is collected from the National Development and Reform Commission and the national and provincial Bureau of Statistics.

The carbon-emission cost is the product of the carbon-emission price per kilogram of carbon dioxide and the carbon-emission intensity. The carbon-emission intensity is calculated by the following formula. This study collected data on the proportion of each type of energy generation in each province and the unit carbon emissions of each type, and used their product to express carbon emissions per unit electricity generated. The final carbon-emission intensity is then obtained by multiplying the power consumption per kilogram of hydrogen production by the carbon emissions of the power generation:

$$\mathrm{C} = \mathrm{D} * \sum (\mathrm{S}_{i,j} * \mathrm{R}_{i,j}) \tag{3}$$

where C represents the carbon-emission intensity; D represents the power consumption per unit hydrogen production; S_{ij} represents the proportion of each energy-generation type in each province from the China Electric Power Statistical Yearbook 2020, namely coal, gas, biomass energy, hydroelectric power, photovoltaic power generation and nuclear energy; and R_{ij} represents the unit carbon emissions of each energy-generation type.

3 Results

The first step in this study is to determine the power-purchase cost of each province with industrial electricity before calculating the ILCOH. Appendices 1–4 summarize the pricing methods and charging standards of each province. According to data from the National Development and Reform Commission and the price bureaus of each province, 12 provinces have implemented time-of-use tariffs in 2020. This study collects the duration and price of each segment of these 12 provinces. The daily working hours of the electrolytic plant are assumed to be 18 hours, so the spike in electricity prices in some provinces is ignored in this study since it only occupies 2–3 hours of 24. The results are shown in Fig. 2. As can be seen, the duration of three segments in most provinces is 8 hours. The time-of-use tariff in Zhejiang province is only two segments as a flat segment is not set up in Zhejiang province. There is a significant difference in electricity prices between provinces. As a result, the average price for the peak segment, the flat segment and the valley segment is 0.7527, 0.4905 and 0.2550 CNY/kWh, respectively. The data about other provinces with selling electricity prices can be seen in Appendices 1–4.

After calculating the cost of carbon emissions, Equations (1) and (3) require the data on carbon-emission intensity and energy structure of each province. To illustrate more intuitively the composition of the energy structure of the power supply in each province, Fig. 3 illustrates the proportion of power generation of each energy source. This database is derived from the 2020 China Power Statistics Yearbook. Due to the existence of small-scale power generation, as well as six main modes of electricity generation, the total installed capacity of the provinces of Anhui, Shandong and Henan does not reach 100%. Of the six types of power generation, coal-fired generation produces the highest unit carbon emissions. Wind, solar and biomass energy are all renewable energy sources and their unit carbon emissions are minimal.

It can be seen that coal-fired power generation dominates all provinces, while hydroelectric power generation and wind power generation also have a significant impact in some provinces. Power generation from gas is the predominant method in individual provinces, whereas biomass power generation and nuclear power generation are constrained by adverse factors, so they represent a lower proportion in all provinces. As a result of the high percentage of coal-fired power generation in the Shanghai municipality, Tianjin municipality, Shandong province, Anhui province, Henan province, Jiangsu province, Shanxi province and Shaanxi province, the carbon emissions per unit hydrogen production in these provinces are also high. These provinces require urgent energy transformation to achieve carbon peaking and carbon neutralization. The Beijing municipality has completely stopped using coal for power generation and switched to gas for power generation, so the proportion of gas power generation is quite high. Benefitting from the advantages of their geographical environment, Hubei province, Sichuan province and Yunnan province are extremely rich in hydroelectric resources. Therefore, hydroelectric power generation accounts for a large proportion and the energy structure is reasonable.

After obtaining the data on the power structure, this study calculates the carbon-emission intensity of each province according to Equation (3). It can be found that the carbon-emission intensity is closely related to the proportion of coal-fired power generation. As can be seen in Table 1, the highest carbon-emission intensities include, from north to south, Heilongjiang province, Tianjin municipality, Shanxi province, Shandong province, Shaanxi province, Henan province, Anhui province, Jiangsu province,

Downloaded from https://academic.oup.com/ce/article/7/1/30/7043870 by guest on 21 July 2023

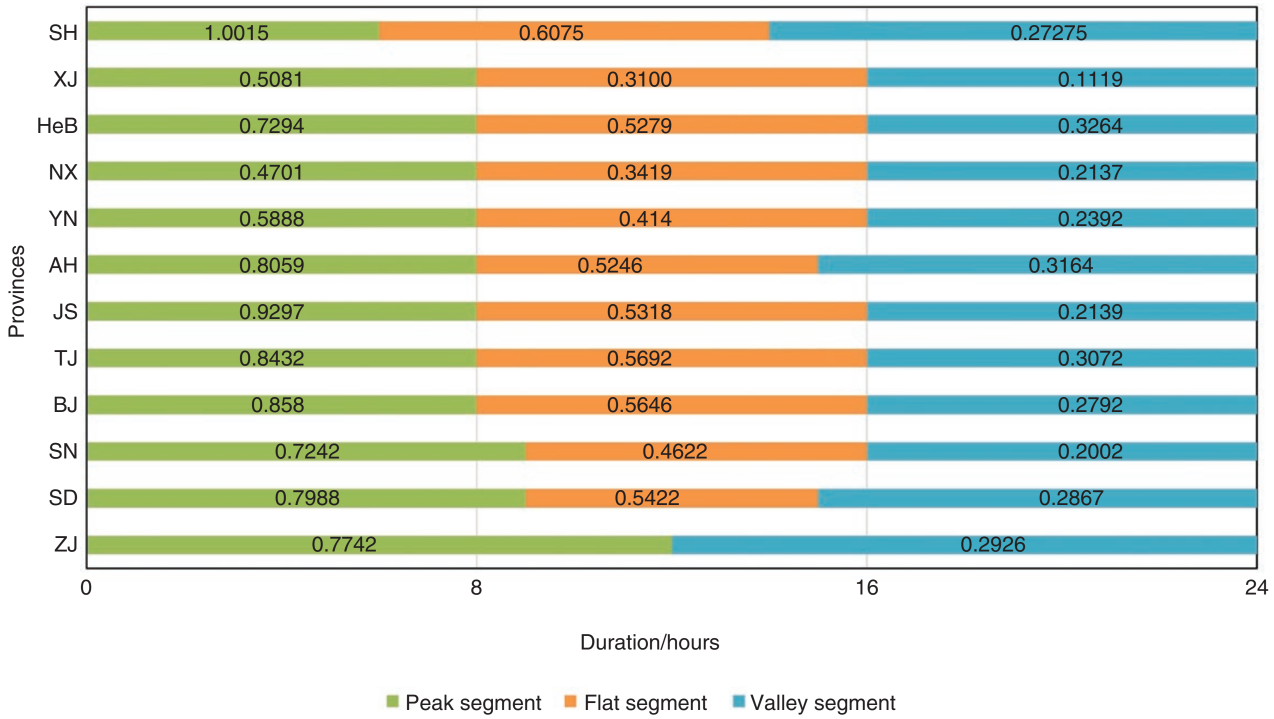


Fig. 2: Duration and price of each stage of time of use. Each segment's electricity price is represented by the numbers in the rectangle (CNY/kWh). SH, Shanghai; BJ, Beijing; JX, Jiangxi; AH, Anhui; TJ, Tianjin; HN, Hainan; SD, Shandong; HuN, Hunan; HuB, Hubei; HeB, Hebei; CQ, Chongqing; GX, Guangxi; HeN, Henan; FJ, Fujian; GD, Guangdong; HLJ, Heilongjiang; JL, Jilin; JS, Jiangsu; GZ, Guizhou; LN, Liaoning; SC, Sichuan; ZJ, Zhejiang; YN, Yunnan; SX, Shanxi; SN, Shaanxi; GS, Gansu; NX, Ningxia; XJ, Xinjiang; QH, Qinghai; IM, Inner Mongolia.

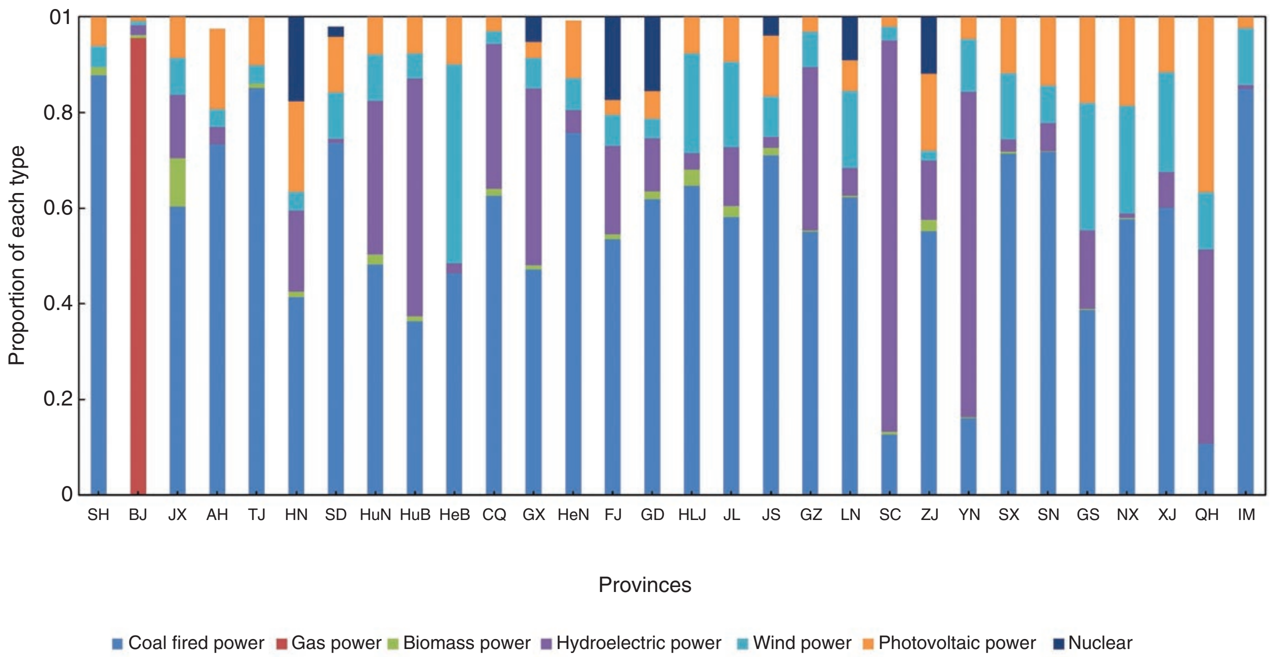


Fig. 3: Proportion of various power-generation types

Shanghai municipality, Jiangxi province and Guangdong province. Combined with Fig. 3, coal-fired power generation accounts for >60% in these provinces. A high proportion of coal-fired power generation produces an excessive amount of carbon dioxide. As a consequence of small-scale coal-fired power generation and large-scale new-energy power generation, Sichuan, Yunnan and Qinghai provinces have extremely low carbon-emission intensities. The proportion of hydroelectric power generation in Sichuan province, Yunnan province and Qinghai province is large, and the proportion of photovoltaic power generation in Qinghai province is also high. The higher the proportion of new-energy power generation, the lower the intensity of carbon emissions. In contrast, the higher the proportion of coal-fired power generation, the higher the intensity of carbon emissions. To calculate

Downloaded from https://academic.oup.com/ce/article/7/1/30/7043870 by guest on 21 July 2023

Table 1: Carbon-emission intensity of each province

Provinces	Carbon-emission intensity (kg CO_2/kg H_2)
Shanghai	24.76
Beijing	13.32
Jiangxi	21.39
Anhui	20.21
Tianjin	23.75
Hainan	12.54
Shandong	20.26
Hunan	14.49
Hubei	10.97
Hebei	12.79
Chongqing	18.09
Guangxi	13.79
Henan	20.80
Fujian	15.64
Guangdong	18.10
Heilongjiang	19.30
Jilin	17.11
Jiangsu	20.30
Guizhou	15.53
Liaoning	17.45
Sichuan	4.59
Zhejiang	16.67
Yunnan	5.22
Shanxi	19.82
Shaanxi	19.83
Gansu	11.03
Ningxia	16.05
Xinjiang	16.61
Qinghai	3.75

the costs of carbon dioxide emissions, the carbon-emission price of carbon dioxide is taken as 0.05278 CNY/kg in China's carbon-trading market. According to Equation (1), the carbon-emission intensity of each province ranges from 3.75 to 24.76 kg, so the carbon-emission costs range from 0.198 to 1.307 CNY.

After obtaining the power-purchase cost of each province and the carbon-emission costs, the ILCOH of each province is calculated according to Equation (1). The results of the ILCOH calculations are shown in Fig. 4, which shows the ILCOH in 2020 under the assumption that the installed capacity of electrolytic plants is 10 MW in 30 provinces in China, excluding Tibet for the lack of extensive power grid and the few hydrogen-production systems there. Tibet and Taiwan are indicated by slashes.

As can be seen in Fig. 4, the darker the yellow, the higher the ILCOH. The ILCOH in the central and southern regions is generally higher than in western and northern regions, which is in line with the current level of economic development in China. In general, provinces with a high ILCOH are the most developed, as these provinces have higher power-purchase costs and higher carbon-emission costs. Provinces with a low ILCOH are generally those that apply new energy more effectively. For example, Shanghai municipality, with a higher ILCOH, reaches 44.263 CNY/kg, while Qinghai province, with the second-lowest ILCOH, is 26.875 CNY/kg. The low level of ILCOH in Qinghai is due to the fact that only 10% of its power comes from coal-fired power generation and nearly 90% comes from renewable-energy power generation. Unexpectedly, ILCOH in Zhejiang province is at the lowest level in the country when calculating the power purchase, because there is no flat segment in the time-of-use price in the province as shown in Fig. 2. However, the daily working time of the electrolyser is 18 hours and this study assumes that it will rest at the time of the highest-electricity-price segment; therefore, most of the expense comes from the valley segment cost, which is lower than the selling price in other provinces. Similarly, the ILCOH in Shanghai municipality is the sixth-highest in China. Its highest electricity price in the peak segment does not make it the highest ILCOH because Shanghai adopts the time-of-use electricity price. The highest ILCOH is 48.016 CNY/kg in Jiangxi province because it does not implement the time-of-use electricity price, so the selling price used is higher than that in provinces with the time-of-use price. Fan *et al.* [35] calculated the LCOH of hydrogen production via water electrolysis with coal-fired power generation as 16.43–23.96 CNY/kg without carbon-emission costs, while those with wind and photovoltaic power generation were 26.63–35.56 and 40.91–51.80 CNY/kg, respectively, which is close to the data in our study considering that the power sources in our study include both coal-fired power generation and renewable-energy power generation. Li *et al.* [36] also calculated the LCOH in China. Their calculation result was much higher than that of this study, which was 80 CNY/kg, possibly due to the small scale and high cost of the off-grid hydrogen-production mode. Furthermore, the ILCOH in Zhejiang province in this study is 24.813 CNY/kg. If the cost of hydrogen distribution per 300 miles of pipeline is ~15 CNY/kg [37], then the cost of hydrogen sent from Zhejiang province to Jiangxi province is 39.813 CNY/kg, which is far lower than the cost of hydrogen production in Jiangxi province at the present stage of 48.016 CNY/kg. This means that hydrogen transportation and distribution have great cost advantages.

In order to illustrate the ratio of power-purchase cost, the cost of the electrolytic plant and the carbon-emission cost, and to confirm whether the electricity price is dominant in the ILCOH, this study draws the proportion between the three costs in each province as pie charts in Fig. 4. As can be seen from the figure, the proportions of the three costs of the provinces are not different except for Beijing. In all provinces, power-purchase costs account for ~70% of the total cost, with Zhejiang province having the lowest at ~65%. This shows that power-purchase costs account for the majority of the total cost and they have the greatest impact on the ILCOH. In addition, the size of the pie chart indicates the percentage of carbon-emission costs in the ILCOH. Inner Mongolia accounts for 3.65% of the total cost of carbon emissions, while Sichuan province accounts for 0.611%. Carbon emissions account for a relatively small proportion of the overall; however, they range between 0.198 and 1.307 CNY/kg H_2, which is an important aspect of the economics of hydrogen production. It is also possible to reduce the cost of large-scale hydrogen-production projects by reducing the cost of carbon emissions.

The LCOH and carbon-emission intensity are indicators for measuring the cost-effectiveness of hydrogen-production projects. To enable a clearer understanding of the relationship between the LCOH and carbon emissions, and to reflect the development potential of green energy more clearly in each province, the carbon-emission intensity and LCOH without carbon-emission costs are presented separately in Fig. 5, with the *x*-axis indicating the carbon-emission intensity and the *y*-axis indicating the LCOH. As shown in Fig. 5, the provinces with high LCOH and carbon emissions are in the upper-right corner of the figure, while the provinces with low LCOH and carbon emissions are located in the lower-left corner, and most provinces are located in the middle. Qinghai province is a province with low carbon emission and low

Downloaded from https://academic.oup.com/ce/article/7/1/30/7043870 by guest on 21 July 2023

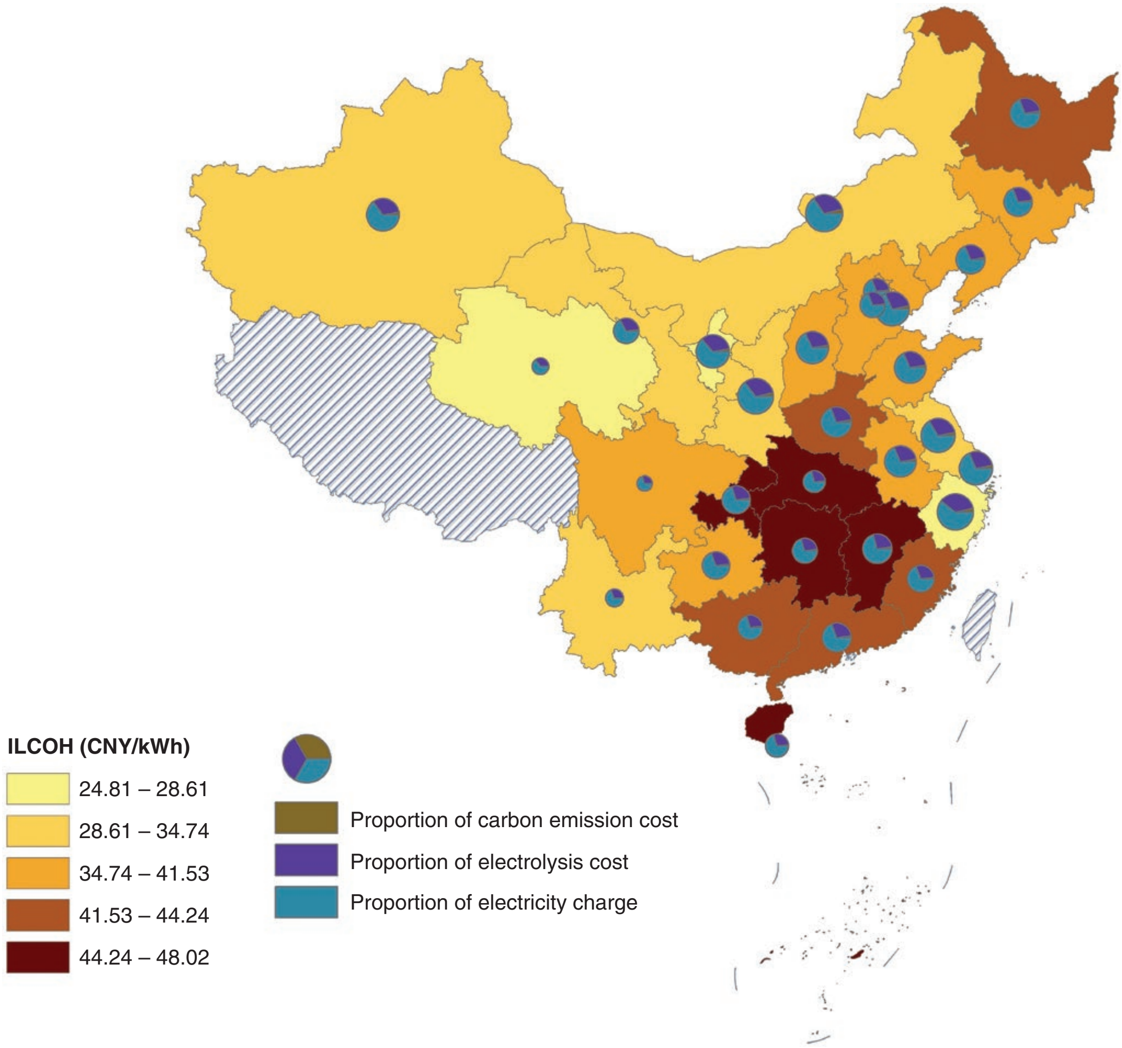


Fig. 4: ILCOH of each province in China and proportions of electricity charge and electrolysis cost

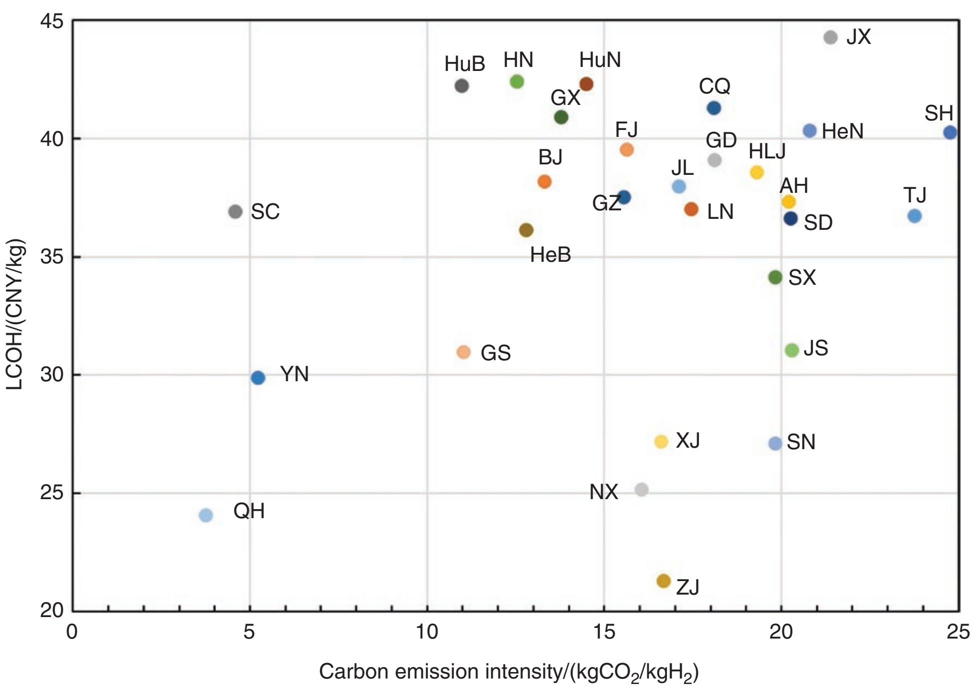


Fig. 5: Scatter plot of carbon-emission intensity and LCOH of each province

Downloaded from https://academic.oup.com/ce/article/7/1/30/7043870 by guest on 21 July 2023

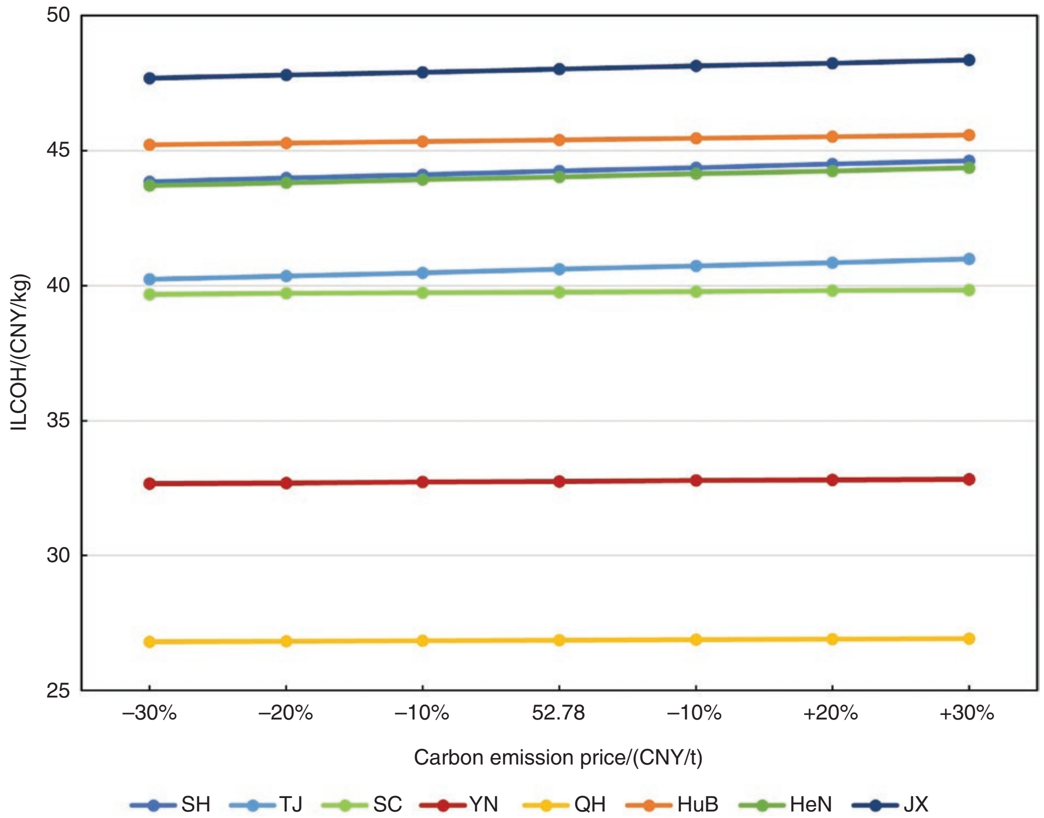


Fig. 6: Stress test on carbon-emission price

LCOH, which shows promising potential. Sichuan province and Yunnan province are medium LCOH and low carbon-emission provinces, which also have good prospects for development. As a result of continuous restrictions on carbon emissions and the rise of carbon taxes, the cost of carbon emissions is expected to increase, which could benefit low-carbon-emission provinces. On the other hand, Zhejiang province, Ningxia province, Xinjiang province and Shaanxi province are provinces with low LCOH and high carbon emissions. Although their LCOH is low because the electricity price in these provinces is rather low, high carbon emissions mean that their energy structure is unreasonable. Some provinces such as the Beijing municipality and Hebei province belong to high-LCOH and medium-carbon-emission provinces, since they have high power-generation costs. Despite this, their energy structure is more reasonable and promising because they do not rely heavily on coal. Shanghai municipality, Tianjin municipality and Jiangxi province are provinces with the highest LCOH and highest carbon-emission intensity. These provinces have relatively low development potential, and thus energy-structure transition is more imminent.

Then, to reflect the impact of the carbon-emission price on the ILCOH, a sensitivity test on the carbon-emission price is conducted. The sensitivity analysis is to test the impact of factor changes on the ILCOH, so this study selected eight provinces with extreme levels of carbon emissions. This study selected the four provinces with the highest carbon-emission intensity and the four provinces with the lowest carbon-emission intensity for the sensitivity analysis. In Fig. 6, the x-axis represents the carbon-emission price and the middle of the x-axis, 52.78 CNY/t, is the benchmark state. This study calculates the ILCOH under seven scenarios: benchmark state, 10%, 20%, 30% lower than the benchmark state, and 10%, 20%, 30% higher than the benchmark state. Among the eight provinces listed in the figure, Shanghai, Tianjin, Henan and Jiangxi represent the provinces with the highest carbon-emission levels. Sichuan, Yunnan, Hubei and Qinghai represent provinces with the lowest carbon-emission levels. The results show that, in the Shanghai municipality for the greatest variation, for every 10% increase in the carbon-emission price, the ILCOH increases by 0.131 CNY/kg, and in Qinghai province, for the smallest variation, every 10% change in the carbon-emission price results in a fluctuation in the ILCOH of 0.02 CNY/kg. A region with a higher carbon-emission intensity is more sensitive to fluctuations in the carbon-emission price than a region with a greater application of new energy, such as Sichuan province, Yunnan province or Qinghai province.

4 Conclusion and policy suggestion

Taking into account China's carbon-peaking and carbon-neutralization policy, this study incorporates carbon-emission costs into the cost of hydrogen production in order to determine a more accurate estimation of the cost of provincial hydrogen-production projects connected to the power grid. First, this study calculates the power-purchase cost of each province. After that, the study calculates the carbon-emission cost and the energy structure of the power supply of each province is collected. The carbon-emission intensity of each province is then calculated to obtain the carbon-emission cost. Finally, the cost of the grid-connected hydrogen-production project is obtained considering the carbon-emission cost. The results show that the ILCOH of the southwest coastal provinces is generally higher than that of the western regions. The ILCOH of Shanghai municipality, Beijing

Downloaded from https://academic.oup.com/ce/article/7/1/30/7043870 by guest on 21 July 2023

municipality and Jiangxi province is the highest, reaching 48.016 CNY/kg, and the ILCOH in Zhejiang province is only 24.813 CNY/kg. In addition, this study also conducts a sensitivity test on the carbon-emission price, showing that the ILCOH will change by 0.131 CNY/kg for every 10% change in the carbon-emission price in the Shanghai municipality. Provinces with a better economy and greater development potential for grid-connected hydrogen-production projects are often those with better applications of new energy, where the carbon-emission intensity is at a low level. The carbon-emission cost of Qinghai province is the lowest, at only 0.198 CNY/kg. Considering the cost of hydrogen production and carbon-emission intensity, the development potential for hydrogen-production systems in Qinghai province, Sichuan province and Yunnan province is optimistic.

Based on the above conclusions, the following three policy implications can be obtained:

- As coal-fired power generation constitutes a large portion of each province's power-supply structure, resulting in high carbon emissions, provinces need to adjust the power-supply structure and increase the generation of renewable-energy power to reduce the ILCOH.
- Provinces with a low ILCOH should play the role of surrounding radiation. A province with a low ILCOH can transport hydrogen via pipelines or trucks to a province with a high ILCOH.
- Electricity prices account for the largest portion of the cost composition of the ILCOH. Hydrogen-production enterprises purchase large industrial power from the power grid at an expensive cost, so provinces should subsidize the price of electricity for hydrogen production to reduce the cost of hydrogen production.

Supplementary data

Supplementary data is available at *Clean Energy* online.

Funding

This work was supported by the National Key Research and Development Plan (2021YFB4000101); the Social Science Foundation of Beijing (22JCC092) the Fundamental Research Funds for the Central Universities (No. 2021MS022, 2021PT013); and North China Electric Power University Interdisciplinary Innovation Special Project.

Conflict of interest statement

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.

References

[1] Mohr SH, Wang J, Ellem G, *et al*. Projection of world fossil fuels by country. *Fuel*, 2015, 141:120–135.
[2] Liu Z, Li Y. Study on critical technologies and development routes of coal-based hydrogen energy. *Clean Energy*, 2019, 3:202–210.
[3] Shao ZG, Yi BL. Developing trend and present status of hydrogen energy and fuel cell development. *Bulletin of Chinese Academy of Sciences*, 2019, 34:469–477.
[4] Ajanovic A, Haas R. Prospects and impediments for hydrogen and fuel cell vehicles in the transport sector. *Int J Hydrog Energy*, 2021, 46:10049–10058.
[5] Ajanovic A, Haas R, Nakicenovic N. Economic analysis of production and use of hydrogen from solar energy, wind, hydropower and biomass. In: Goswami DY, Zhao Y (eds). *Proceedings of ISES World Congress 2007* (Vol. I–Vol. V). Berlin: Springer, 2008, 2496–2500.
[6] Lazard. Lazard's Levelized Cost of Hydrogen Analysis. June 2021. https://www.lazard.com/media/451779/lazards-levelized-cost-of-hydrogen-analysis-vf.pdf (13 December 2022, date last accessed).
[7] IRENA. Green hydrogen cost reduction. December 2020, https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction. (27 April 2022 date last accessed).
[8] Liu W, Wan Y, Xiong Y, *et al*. Green hydrogen standard in China: standard and evaluation of low-carbon hydrogen, clean hydrogen, and renewable hydrogen. *Int J Hydrog Energy*, 2022, 47:24584–24591.
[9] Hydrogen Council. Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness. February 2021. https://hydrogencouncil.com/en/hydrogen-insights-2021. (31 October 2022 date last accessed).
[10] Nicita A, Maggio G, Andaloro APF, *et al*. Green hydrogen as feedstock: financial analysis of a photovoltaic-powered electrolysis plant. *Int J Hydrog Energy*, 2020, 45:11395–11408.
[11] Madeira JGF, Oliveira EM, Springer MV, *et al*. Hydrogen production from swine manure biogas via steam reforming of methane (SRM) and water gas shift (WGS): a ecological, technical, and economic analysis. *Int J Hydrog Energy*, 2021, 46:8961–8971.
[12] Macedo SF, Peyerl D. Prospects and economic feasibility analysis of wind and solar photovoltaic hybrid systems for hydrogen production and storage: a case study of the Brazilian electric power sector. *Int J Hydrog Energy*, 2022, 47:10460–10473.
[13] Wang Q, Liu C, Luo R, *et al*. Thermo-economic analysis and optimization of the very high temperature gas-cooled reactor-based nuclear hydrogen production system using copper-chlorine cycle. *Int J Hydrog Energy*, 2021, 46:31563–31585.
[14] Singlitico A, Østergaard J, Chatzivasileiadis S. Onshore, offshore or in-turbine electrolysis? Techno-economic overview of alternative integration designs for green hydrogen production into offshore wind power hubs. *Renewable and Sustainable Energy Transition*. 2021, 1:100005.
[15] Song Y, Mu H, Li N, *et al*. Techno-economic analysis of a hybrid energy system for CCHP and hydrogen production based on solar energy. *Int J Hydrog Energy*, 2022, 47:24533–24547.
[16] Almutairi K, Dehshiri SS, Dehshiri SJ, *et al*. Technical, economic, carbon footprint assessment, and prioritizing stations for hydrogen production using wind energy: a case study. *Energy Strategy Reviews*. 2021, 36:100684.
[17] Taghizadeh-Hesary F, Li Y, Rasoulinezhad E, *et al*. Green finance and the economic feasibility of hydrogen projects. *Int J Hydrog Energy*, 2022, 47:24511–24522.
[18] Abdelrahman MA, Abdel-Hamid RH, Abo Adma MA, *et al*. Techno-economic analysis to develop the first wind farm in the Egyptian western desert at Elkharga Oasis. *Clean Energy*, 2022, 6:211976–211225.
[19] Lin H, Wu Q, Chen X, *et al*. Economic and technological feasibility of using power-to-hydrogen technology under higher wind penetration in China. *Renew Energy*, 2021, 173:569–580.
[20] Glenk G, Reichelstein S. Economics of converting renewable power to hydrogen. *Nat Energy*, 2019, 4:216–222.

Downloaded from https://academic.oup.com/ce/article/7/1/30/7043870 by guest on 21 July 2023

[21] Bhandari R, Shah RR. Hydrogen as energy carrier: techno-economic assessment of decentralized hydrogen production in Germany. *Renew Energy*, 2021, 177:915–931.

[22] Guerra OJ, Eichman J, Kurtz J, *et al*. Cost competitiveness of electrolytic hydrogen. *Joule*, 2019, 3:2425–2443.

[23] Lee B, Heo J, Choi NH, *et al*. Economic evaluation with uncertainty analysis using a Monte-Carlo simulation method for hydrogen production from high pressure PEM water electrolysis in Korea. *Int J Hydrog Energy*, 2017, 42:24612–24619.

[24] Okonkwo PC, Farhani S, Belgacem IB, *et al*. Techno-economic analysis of photovoltaic-hydrogen refueling station case study: a transport company Tunis-Tunisia. *Int J Hydrog Energy*, 2022, 47:24523–24532.

[25] Walsh SDC, Easton L, Weng Z, *et al*. Evaluating the economic fairways for hydrogen production in Australia. *Int J Hydrog Energy*, 2021, 46:35985–35996.

[26] Li J, Cheng W. Comparative life cycle energy consumption, carbon emissions and economic costs of hydrogen production from coke oven gas and coal gasification. *Int J Hydrog Energy*, 2020, 45:27979–27993.

[27] Kerscher F, Stary A, Gleis S, *et al*. Low-carbon hydrogen production via electron beam plasma methane pyrolysis: techno-economic analysis and carbon footprint assessment. *Int J Hydrog Energy*, 2021, 46:19897–19912.

[28] Cetinkaya E, Dincer I, Naterer GF. Life cycle assessment of various hydrogen production methods. *Int J Hydrog Energy*, 2012, 37:2071–2080.

[29] Sako N, Koyama M, Okubo T, *et al*. Techno-economic and life cycle analyses of battery-assisted hydrogen production systems from photovoltaic power. *J Clean Prod*, 2021, 298:126809.

[30] Zou X, Qiu R, Yuan M, *et al*. Sustainable offshore oil and gas fields development: techno-economic feasibility analysis of wind–hydrogen–natural gas nexus. *Energy Rep*, 2021, 7:4470–4482.

[31] Cen S, Li K, Liu Q, *et al*. Solar energy-based hydrogen production and post-firing in a biomass fueled gas turbine for power generation enhancement and carbon dioxide emission reduction. *Energy Convers Manage*, 2021, 233:113941.

[32] Ravichandran N, Panneerselvam B. Performance analysis of a floating photovoltaic covering system in an Indian reservoir. *Clean Energy*, 2021, 5:208–228.

[33] Pan G, Gu W, Hu Q, *et al*. Cost and low-carbon competitiveness of electrolytic hydrogen in China. *Energy & Environmental Science*, 2021, 14:4868–4881.

[34] Gu Y, Chen Q, Xue J, *et al*. Comparative techno-economic study of solar energy integrated hydrogen supply pathways for hydrogen refueling stations in China. *Energy Convers Manage*, 2020, 223:113240.

[35] Fan JL, Yu P, Li K, *et al*. A levelized cost of hydrogen (LCOH) comparison of coal-to-hydrogen with CCS and water electrolysis powered by renewable energy in China. *Energy*, 2022, 242:123003.

[36] Li J, Liu P, Li Z. Optimal design and techno-economic analysis of a hybrid renewable energy system for off-grid power supply and hydrogen production: a case study of West China. *Chem Eng Res Des*, 2022, 177:604–614.

[37] Brown D, Reddi K, Elgowainy A. The development of natural gas and hydrogen pipeline capital cost estimating equations. *Int J Hydrog Energy*, 2022, 47:33813–33826.

Downloaded from https://academic.oup.com/ce/article/7/1/30/7043870 by guest on 21 July 2023