A non-cooperative game strategy for provincial hydrogen production capacity planning considering the geographical distribution of renewable energy bases

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**Abstract:** Apart from technical factors such as hydrogen production efficiency, the proper geographical distribution of renewable energy bases is essential for promoting large-scale hydrogen production from renewable energy sources on a provincial scale. This paper establishes a hydrogen production capacity planning method that takes into account the distribution of renewable energy bases. Based on the trading pattern of the hydrogen energy market in regions with a high proportion of renewable energy, a non-cooperative game pattern of hydrogen production capacity is constructed, where energy hubs acts as players, hydrogen production capacity acts as a strategy, and the minimum cost of hydrogen is a payment. On this basis, hydrogen production, transportation and consumption models are constructed by combining renewable energy utilization rate, population, and transportation network. Thereby, a non-cooperative game planning method for provincial hydrogen production capacity is proposed, and the gaming problem is transformed into an optimization problem solved iteratively to minimize the global hydrogen production cost. Furthermore, the provincial hydrogen production capacity planning arithmetic is constructed with the data of Qinghai Province. The equilibrium solution of the game with eight energy hub nodes as players is obtained, and the effectiveness of the model is verified. Finally, the impacts of population changes, installed renewable energy production capacity and industrial electricity prices on hydrogen production capacity planning and regional hydrogen costs are quantitatively analyzed.

1. **| INTRODUCTION**

With the booming development of the renewable energy industry in various countries, the consumption of renewable energy generation needs to be solved [1]. Energy storage systems can effectively solve many problems of renewable energy [2], which has become a research hotspot in energy study. Electrochemical energy storage has been widely used due to its high efficiency [3]. However, the efficiency will continue to decrease with the increase in usage time, so its overall cost is still high [4], and the harm of waste batteries to the environment cannot be ignored. Comparatively, hydrogen energy storage can be produced by electrolysis of water from the waste renewable energy, which has the advantages of relatively low production cost [5], long storage time [6] and combustion without pollution [7]. Hydrogen energy storage has become the most promising environmentally friendly energy storage method.

At present, the hydrogen energy industry is still in the cultivation stage. The lack of infrastructure is considered to be an important reason hindering the vigorous development of the hydrogen energy industry, and the research on the infrastructure planning method for the hydrogen energy industry is also ongoing [8]. Hydrogen energy has a mass, does not require real-time balancing, and takes time to dispatch, which requires a different planning approach than electricity. Determining the production capacity of each party in a hydrogen energy system to balance and optimize the interests of all parties involved is a challenging issue. Some researchers have researched micro-energy networks. In [9], a multi-criteria approach has been proposed to design a hybrid renewable energy system including wind power, photovoltaic power generation, electrochemical storage, and hydrogen storage, which not only increases the flexibility of the system but also significantly improves the intermittency of renewable energy sources. The optimal planning of a microgrid with a hydrogen filling station has been considered in [10], which not only overcomes the uncertainty caused by intermittent renewable energy sources and stochastic loads but also takes into account the multi-objective optimization of the economy and the environment, and proposes a method to maximize the economic benefits and efficiency of the microgrid. Other researchers have proposed new approaches at the national planning level. In [11], a novel modeling approach assesses the infrastructure situation of the hydrogen energy transport network system in Germany up to 2030. It analyses the impact of the hydrogen energy network on the existing energy system in Germany after its completion. A general methodology for identifying hydrogen infrastructure pathways to minimize the total cost of the German hydrogen supply network over the next 30 years has been presented in [12]., Reference [13] further considers the design and decision-making methodology for a hydrogen energy production, storage and distribution network in Germany in 2030 to minimize the total network cost under the supply, demand, and emissions constraints. Reference [14] assumes that the future transport sector in the Netherlands will be fully hydrogen-powered and proposes a general approach to building a hydrogen supply network with multi-cycle optimization.

Considering the transport distance of hydrogen, the distribution of production factors and market policies, hydrogen energy is suitable for promotion and application on a provincial scale. As a result, a large number of scholars have conducted research on provincial hydrogen energy planning. In [15], a strategic plan for a renewable hydrogen supply system using onshore and offshore wind energy as a power source for hydrogen production is proposed, taking Jeju Island region in South Korea as an example. Reference [16] has modeled the hydrogen refueling infrastructure network for hydrogen-powered buses in London, and this study shows that different hydrogen production technologies have a major impact on the hydrogen network planning scheme. A multi-period, three-objective optimization based on the Pyrenees region of southern France is presented in [17] to identify solutions to the problems of more cost-effective hydrogen production methods. Adding the consideration of factors such as GIS and different market penetration rates of hydrogen-powered vehicles in the state of Ohio, Russia, to the planning scenarios for hydrogen infrastructure development and proposes a methodology to optimize the regional hydrogen infrastructure deployment with the support of an economic model in[18]. In[19], a hydrogen infrastructure transition model in Beijing, China is introduced to generate the most economical hydrogen infrastructure construction scenario in time and space through dynamic planning by combining local spatial data. Eleven alternatives for the construction of hydrogen energy infrastructure in Beijing are proposed in[20] based on the current technology level of the hydrogen energy industry in China. Then, evaluation and selection are formed by the best solution by the economic, energy, and environmental benefits indicators.

Previous studies mainly focused on the hydrogen supply chain. However, with the development of large-scale hydrogen production from renewable energy sources, hydrogen planning is inevitably influenced by renewable energy sources. Existing studies ignored the impact of the geographical location of renewable energy sites and the renewable energy price for hydrogen production on hydrogen energy planning. As the installed capacity of renewable energy sources increases, the price forecasting model for waste renewable energy should also evolve. In addition, renewable energy planning and hydrogen energy planning are homogeneous at the provincial level. The conditions for distributing renewable energy and related policies are more uniform throughout the province. Rational planning can keep the price of renewable energy uniform within the province, which is conducive to the industrial development of renewable energy. However, the renewable energy resources used to produce green hydrogen (hydrogen produced by renewable energy) and the demand for green hydrogen are distributed reversely. Large-scale renewable energy bases are mainly located far away from the power load, and green hydrogen from renewable energy bases cannot be consumed locally, which requires production capacity planning that takes into account the geographical location of renewable energy bases and the transport routes of hydrogen-using consumers. Therefore, the geographical location of new energy bases must be considered in provincial hydrogen capacity planning to coordinate the hydrogen transmission network.

In reality, there are often dozens of renewable energy bases in a provincial area, and multi-subject is a feature that needs to be considered for provincial green hydrogen production capacity planning. Based on the success of game theory [21] in solving multi-subject problems in economics, many scholars have begun to investigate how game theory can be applied to energy systems. A multi-objective optimization of energy networks inspired by cooperative game theory and develops a mixed integer linear programming model to study the impact of revenue sharing constraints is proposed in [22]. In [23], a non-cooperative game can be used to determine the contribution of each fuel cell and battery in a fuel cell and battery hybrid system to obtain the optimized production capacity when the power demand is uncertain. A method of using a non-cooperative game to obtain the optimal bidding strategy among the seller's energy storage devices in two scenarios with different demand responses is proposed in [24]. A method for efficient energy routing using game theory and suggests a strategy for choosing the ideal trading price in case of power surplus and shortage to maximize the profit from energy trading is shown in [25]. Reference [26] presents a hierarchical analysis for production capacity allocation and an economic evaluation of photovoltaic energy storage stations (PESS) based on game theory. In[27], a dual energy planning method is developed to minimize the total energy expenditure of the users based on a non-cooperative game for external energy exchange and internal energy planning for energy internet microgrids. Game theory is expected to be a powerful tool for overcoming the multi-subject-multi-objective optimization problem in hydrogen energy systems planning.

In summary, there is a lack of studies that fully consider the key role of renewable energy bases on green hydrogen production capacity planning, and little research has concerned the competition where different renewable energy bases in the provincial area try to maximize their renewable energy consumption, respectively. As a result, this paper proposes a provincial hydrogen production capacity planning game method based on static non-cooperative game theory, which takes into account the competitive behavior of multiple players under the premise of waste renewable energy power consumption by renewable energy bases in the provincial area. An iterative algorithm based on mathematical optimization is proposed to solve the Nash equilibrium solution for hydrogen production capacity planning to minimize the global cost of hydrogen and determine the optimal hydrogen production solution for each participant. Finally, the reasonableness and practicality of the proposed models are verified by introducing the actual data of Qinghai Province as an example for simulation.

**2 | Provincial hydrogen planning gaming patterns**

**2.1 | Provincial hydrogen sales model**

Traditional hydrogen energy is generally traded locally, and hydrogen is often produced and used locally according to local load demand. However, considering renewable energy production and consumption, the traditional "produce on demand, use locally" model is no longer suitable for the current green hydrogen production scenarios. Provincial hydrogen hubs are no longer energy islands, serving only their own needs, but act as trading partners, producing and transporting hydrogen energy throughout the province. Hydrogen production capacity planning is primarily influenced by the geographical location of renewable energy bases, the installed capacity of renewable energy sources, and local demand. In order to depict the hydrogen sales model in the provincial hydrogen market, this paper divides the provincial area into several secondary regions managed by energy hubs. Renewable energy resources and hydrogen loads are unevenly distributed in the secondary regions (hydrogen hub). Hydrogen energy is being transported within the provincial area via the road network. In any given period, a hydrogen hub with excess hydrogen energy and a hydrogen hub with insufficient hydrogen energy trade hydrogen energy in a hydrogen market. In addition, in practice, there are cases where the maximum amount of hydrogen produced from renewable energy sources in the provincial area is less than the total hydrogen demand in the provincial area. The shortfall can be compensated by local industrial electricity hydrogen production. From an economic point of view, transporting hydrogen over long distances can result in high transportation costs, and trading between neighboring hydrogen hubs is the optimal way to achieve lower hydrogen costs. Therefore, if the cost of hydrogen production plus freight is higher than the cost of industrial electricity hydrogen production in a hydrogen hub with excess renewable energy hydrogen production capacity in a secondary region, a secondary region with insufficient renewable energy hydrogen production capacity may also choose industrial electricity hydrogen production to fill the hydrogen gap to reduce its local hydrogen costs. Each energy hub competes with each other knowing the maximum hydrogen production capacity of the remaining energy hubs, the local hydrogen load, the local cost of renewable energy hydrogen production, and the cost of purchasing hydrogen from one of the hubs. Building a new hydrogen energy market requires rational planning for the production capacity of each hydrogen hub that can meet the supply and demand balance of hydrogen energy within the province. In addition, renewable energy hubs are often located far from load centers, so a new hydrogen supply model is urgently needed to break the reverse distribution of hydrogen production capacity and load. Hydrogen hubs are connected by both physical road routes and virtual information channels. The ideal hydrogen supply model is shown in Figure 1

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Figure 1 Hydrogen network hydrogen sales model

As shown in Figure 1, part of the hydrogen produced by the producer is used for themselves comsumption, and the remaining part is waiting to be purchased by the consumer. The role of the hydrogen transport network, as an intermediate link in the distribution of hydrogen, is to provide a way to purchase hydrogen for other nodes in the provincial area with insufficient hydrogen supply. Figure 1 shows the energy and information pathways. The energy pathway represents the actual physical connection between the energy nodes, while the information pathway is used to transmit the information of each entity and to realize the interaction between the entities.

**2.2 | Non-cooperative gaming landscape for hydrogen production capacity planning**

When a hydrogen transport network connects several energy hubs in a provincial area, the energy hubs have the same characteristics and status in the hydrogen energy market. Furthermore, each energy hub wants to minimize the cost of using hydrogen in their local area to increase their production capacity and expand their markets, and there is competition between each hub. Thus, the competition for production capacity between them can be seen as a non-cooperative game. All energy hubs act as players in the game, with each player using its hydrogen production capacity as a strategy, and players pay for the game by minimizing the cost of hydrogen use.

Consequently, this paper establishes a game landscape based on non-cooperative games, guided by engineering game theory. In the model proposed in this paper, each player competes with the knowledge of the other players' decisions and costs, and the virtual information channel proposed in Figure 1 is the public knowledge in the game. Therefore, the model proposed in this paper is a non-cooperative game model under complete information.

Hydrogen production capacity planning within a province based on a non-cooperative game is envisaged as follows: there is a market consisting of several competing hydrogen hubs that wish to minimize their payments while satisfying the hydrogen load of the current node by rationally planning their hydrogen production capacity. The players in the game are all hydrogen hubs with positive and negative hydrogen demand. Positive hydrogen demand means that the hub has to be purchased from the hydrogen network or replenished with industrial electricity hydrogen, while negative hydrogen demand means that the hub supplies the hydrogen to the network. The set of game players is. In this paper, the local hydrogen production capacity is used as the decision strategy of the players, which is denoted by, so the decision space of players is={ }、={ }、={ } ={ }. Then the set of strategies of the players is = { ，} . 、are the decision space of the players. The minimum unit cost of hydrogen use at each energy hub is used as a payment to the game players, and the set of payments for the game is = { }， are payments for players A、B、C...N respectively. The expression for unit payments is shown in equation (1).

|  |  |
| --- | --- |
|  | （1） |

**3 | Provincial hydrogen production capacity models based on non-cooperative games**

**3.1 | Provincial hydrogen cost model based on non-cooperative game**

In this paper, hydrogen production from renewable energy sources is mainly considered as hydrogen production from waste wind energy and waste photovoltaic energy. In addition, in order to ensure the economy and to meet the loads of the hydrogen hubs, additional industrial electricity hydrogen production facilities is needed.The model takes into account the operation and maintenance costs of the field station, the depreciation and civil installation costs of the water electrolysis equipment, and the costs of electricity and water in the hydrogen production process. Therefore, the hydrogen cost model based on the non-cooperative game is shown in equation (2) to (7).

|  |  |
| --- | --- |
|  | （2） |
|  | （3） |
|  | （4） |
|  | （5） |
|  | （6） |
|  | （7） |

**3.2 | The measurement model of discarded renewable energy tariff**

With the increase in installed capacity of photovoltaic and wind power, the amount of abandoned wind and photovoltaic power that can be used for hydrogen production by water electrolysis is increasing, so the waste energy tariff measurement model plays an important role in accurately calculating the cost of hydrogen use in provincial areas. In this paper, based on the investment, maintenance, and operation costs of renewable energy bases, combined with the current waste rate of renewable energy, a general waste energy tariff model is established by equation (8) to (13).

|  |  |
| --- | --- |
|  | (8) |
|  | (9) |
|  | (10) |
|  | (11) |
|  | (12) |
|  | (13) |

**3.3 | Provincial Shortest Hydrogen Energy Routing Models and Freight Models**

In real road networks, the physical connections between nodes are often not unique, and nodes are not simply connected point-to-point. Modeling the shortest point-to-point transport paths in a hydrogen network to hydrogen hubs within a provincial area is necessary to minimize the freight costs paid by each player when purchasing hydrogen, thus minimizing the overall cost of hydrogen use. Based on data availability such as nodes, edges, paths and path lengths, the distance assignment method is proposed, where a certain percentage scales down the actual distance to facilitate analysis and calculation. The definition of the shortest path is given below: Given an assignment graph M(V,k) and two given vertices and on it. r is a path between and , and its length is denoted as . The set R(M,) consisting of all mutually exclusive paths between and is called the set of paths between and on M, i.e., R(M,)={r| r is the path between and on M }. If the paths are ranked according to their length as ,,…,, and the fact that d()≤d()≤…≤d() exists, then is called the shortest path between and on M.

After constructing the empowerment graph as shown in Figure 2, the shortest path between any two nodes can be determined using the traversal method. The optimal point-to-point hydrogen energy network model is the set of all shortest paths.

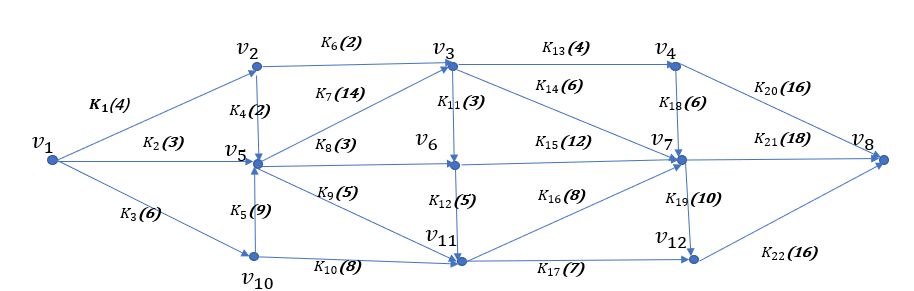


Figure 2 Distance empowerment map

Currently, high-pressure gas-hydrogen transport is the dominant mode of transport. High-pressure gas-hydrogen transport involves storing high-pressure hydrogen in a pressure vessel using a compressor and transporting it in a long-tube trailer. However, due to the low density of hydrogen and the deadweight of the hydrogen storage pressure vessel, the final mass of hydrogen transported by the trailer is only 1-2% of the total mass transported, with a typical single truck hydrogen production capacity of about 260-460 kg. The unit transport cost function is a convex quadratic function that is mainly influenced by the distance between the two energy hubs. In order to simplify the description, it is assumed that i is the starting point of the line, j is the destination of the hydrogen transport, and there are a total of n nodes transporting hydrogen to node j. The unit transport cost is a convex quadratic function that is mainly influenced by the distance between the two energy hubs. Classifying distances into normal and high-speed miles allows a more accurate estimation of the unit transport cost borne by the node where the hydrogen is purchased.

|  |  |
| --- | --- |
|  | (14) |

**3.4 | Provincial Renewable Energy Maximum Hydrogen Production Capacity and Load Measurement Model**

The provincial hydrogen production capacity model is based on the non-cooperative game. Except for establishing a minimum payment model, the maximum production capacity of renewable energy hydrogen production in the provincial area and the prediction of the hydrogen load in the region are also the keys to the rational planning of the hydrogen production capacity of the provincial hydrogen energy network.The maximum hydrogen production capacity of hydrogen production hubs is related to local installed renewable energy capacity.The maximum capacity for hydrogen production at each hydrogen hub can be expressed as follows：

|  |  |
| --- | --- |
|  | （15） |

Regarding actual market demand, the need for hydrogen refueling is seen first in key areas such as densely populated or transit hubs, then gradually expanding outwards to form locally adapted hydrogen energy networks at the provincial level. When designing a hydrogen energy network, the primary consideration is the hydrogen consumption of hydrogen-powered vehicles in the area covered by the node. The hydrogen load of a Hydrogen Energy Hub can be expressed as:

|  |  |
| --- | --- |
|  | (16) |

**3.5 | Solving the non-cooperative game**

The convexity and closure of the minimum payoff set of game subjects with constant load is a sufficient necessary condition for a unique Nash equilibrium solution to the game[28]. Therefore, the linear game of finite strategy type established in this paper (shown in Figure 3) has only one equilibrium solution to the game. The subjects of interest in this paper are the different hydrogen energy hubs in the province. The players are the same type, although there are differences in the set of decision variables and strategies. Therefore, the optimization process of each independent subject is characterized by a unified model. Besides, to ensure that the hydrogen load of each energy hub in the hydrogen network can be satisfied, the hydrogen production capacity of each hydrogen hub must be constrained. Consequently, the established non-cooperative game model is transformed into a generalized model for multi-objective optimization as shown in Eq. (17), with quality constraints as shown in Eq. (18) to Eq. (24)，The objective function is shown in equation (25).The conventional solution is to find the maximum social welfare in a linearly weighted way. However, it can be seen from Eq. (25) that the planning behaviour of hydrogen capacity in the provincial domain may occur several times at the same time. Therefore the current cost of a node is associated with the cost of all nodes with which it has a transfer relationship in the previous time slot. However, the cost of hydrogen for those nodes with which it was shipped to each other in the previous time slot will likewise be correlated with the cost of this node before the shifting took place.Thus, the cost of hydrogen use at a given node is not only associated with the nodes which have the transfer behaviour with it, but also with its cost before this transfer behaviour occurred, and therefore cannot be solved with a general solver, a situation known as the autocorrelation of the function. This study takes into account the fact that in a real hydrogen market trading model, the hydrogen transport also takes place in the order of the actual routes. In order to accurately describe this dynamic transfer process as well as the autocorrelation of the solution function, the planning behaviour of the replica is therefore split up. That is, the planning behaviour is set to perform one transfer at a time at a single node, and the hydrogen costs at all nodes are updated after each completed transfer.In this paper, an iterative algorithm based on mathematical optimization is proposed as equation (26), and in the subsequent simulation analysis, this paper takes the cost of hydrogen production when the rest of the main bodies do not participate in the capacity planning as the initial value of the Nash equilibrium point, and the iterative results after the completion of the transfer act are used to approximate the actual cost of hydrogen used by each hydrogen hub. The improved iterative algorithm can be solved using the CPLEX solver, and the solution process is shown in Fig. 3.

The improved iterative algorithm can be solved using the CPLEX solver, and the solution process is shown in Figure 3.

|  |  |
| --- | --- |
|  | (17) |
|  | (18) |
|  | (19) |
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|  | (24) |
|  | (25) |
|  | (26） |

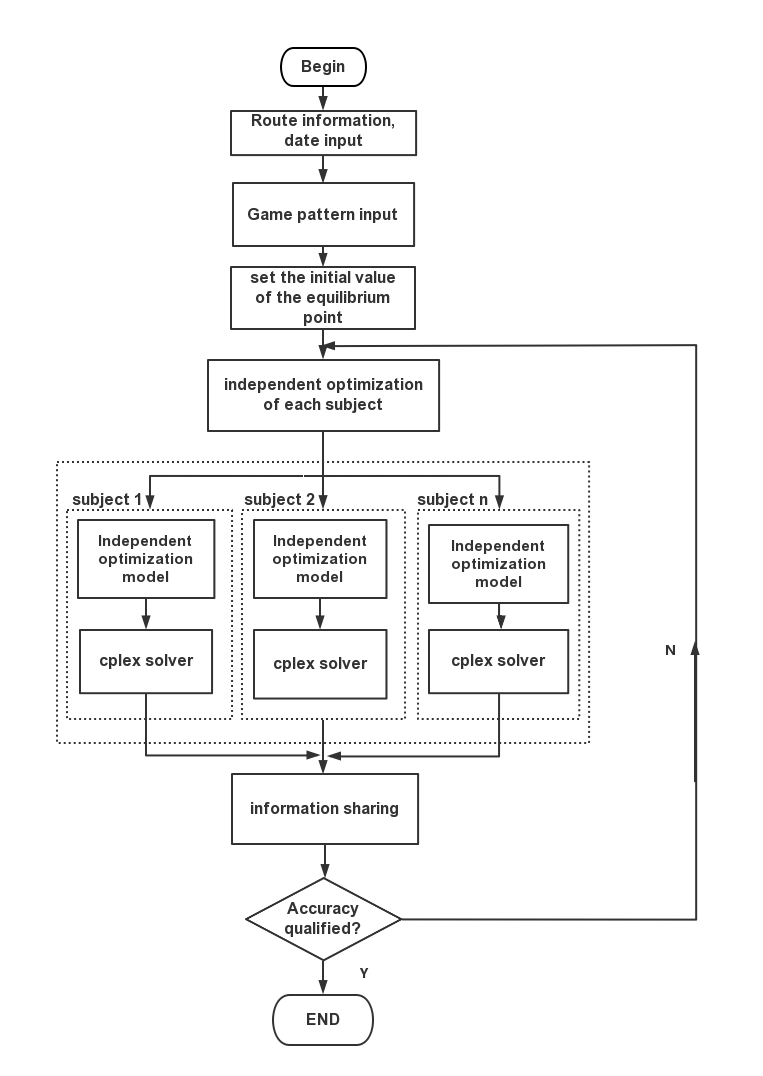


Figure 3 Solution flowchart

**4 | Case study**

**4.1 | Illustrative examples**

Qinghai Province is rich in wind power, photovoltaic, and other clean energy resources. By 2030, the installed capacity of clean energy in Qinghai Province will be more than 140 million kilowatts, accounting for about 10% of China's total installed capacity of clean energy. With the completion of zero-carbon power system in Qinghai, new problems such as the consumption of waste renewable energy need to be solved, so Qinghai Province is chosen as a research example. Referring to the geographical distribution characteristics of renewable energy bases in Qinghai Province, combined with the distribution of hydrogen load demand, therefore, one site is finally set up as a hydrogen hub site in Republican County, Tongren County, Maqin County, Menyuan County, Chengbei District, Ledu District, Golmud and Zhiduo County respectively.

**4.2 | Parameter pre-setting**

According to the Statistical Yearbook of Qinghai Province, the current installed capacity of wind power and photovoltaic in Qinghai Province is shown in Figure 4 below. According to the hydrogen production capacity model, the maximum renewable energy hydrogen production capacity of each hydrogen production station in Qinghai Province can be obtained as shown in Table 1. The other parameters involved in the calculation example are shown in Table 2.



Figure 4 Installed wind and photovoltaic production capacity

Table 1 Maximum hydrogen production capacity of renewable energy sources

|  |  |  |  |
| --- | --- | --- | --- |
| Station | Amount of hydrogen produced from wind power(kg/day) | Amount of hydrogen produced from PV power(kg/day) | Total hydrogen production(kg/day) |
| 1Gonghe | 35918 | 106480 | 142398 |
| 2Tongren | 1514 | 0 | 1514 |
| 3Maqin | 0 | 0 | 0 |
| 4Menyuan | 3582 | 0 | 3582 |
| 5Chengbei | 0 | 0 | 0 |
| 6Ledu | 3306 | 0 | 3306 |
| 7Golmud | 68382 | 62664 | 131046 |
| 8Zhiduo | 0 | 0 | 0 |

Table 2 Table of preset parameters

|  |  |  |
| --- | --- | --- |
| Parameter Name | Parameter Meaning | Preset Value |
|  | Discount rate | 10% |
|  | Periodicity | 24h |
|  | Equipment lifetime | 20years |
|  | Maintenance cost factor | 0.05 |
|  | Electricity consumption-hydrogen volume conversion factor | 5 |
|  | Volume to mass conversion factor of hydrogen | 11.2 |
|  | Feed-in tariff for renewable energy | 0.45 |
|  | Unit water price | 0.77 dollar/ton |
|  | Market penetration of hydrogen fuel vehicles | 20% |
|  | Hydrogen consumption of hydrogen fuel vehicles | 483 kg/year |

The daily load forecast for each hydrogen refueling station in Qinghai Province is closely related to the population, the local car ownership per capita, the market penetration of hydrogen-powered vehicles, and the average daily hydrogen consumption. Considering that Qinghai Province is a tourist city, it is not accurate enough to use only the resident population to predict the hydrogen load, so the indicator of self-driving vehicles entering Qinghai Province is introduced by checking the Statistical Yearbook of Qinghai Province, and the hydrogen refueling demand is predicted by of self-driving vehicles. According to the hydrogen load prediction model, the hydrogen load estimation in Qinghai Province is shown in Figure 5.

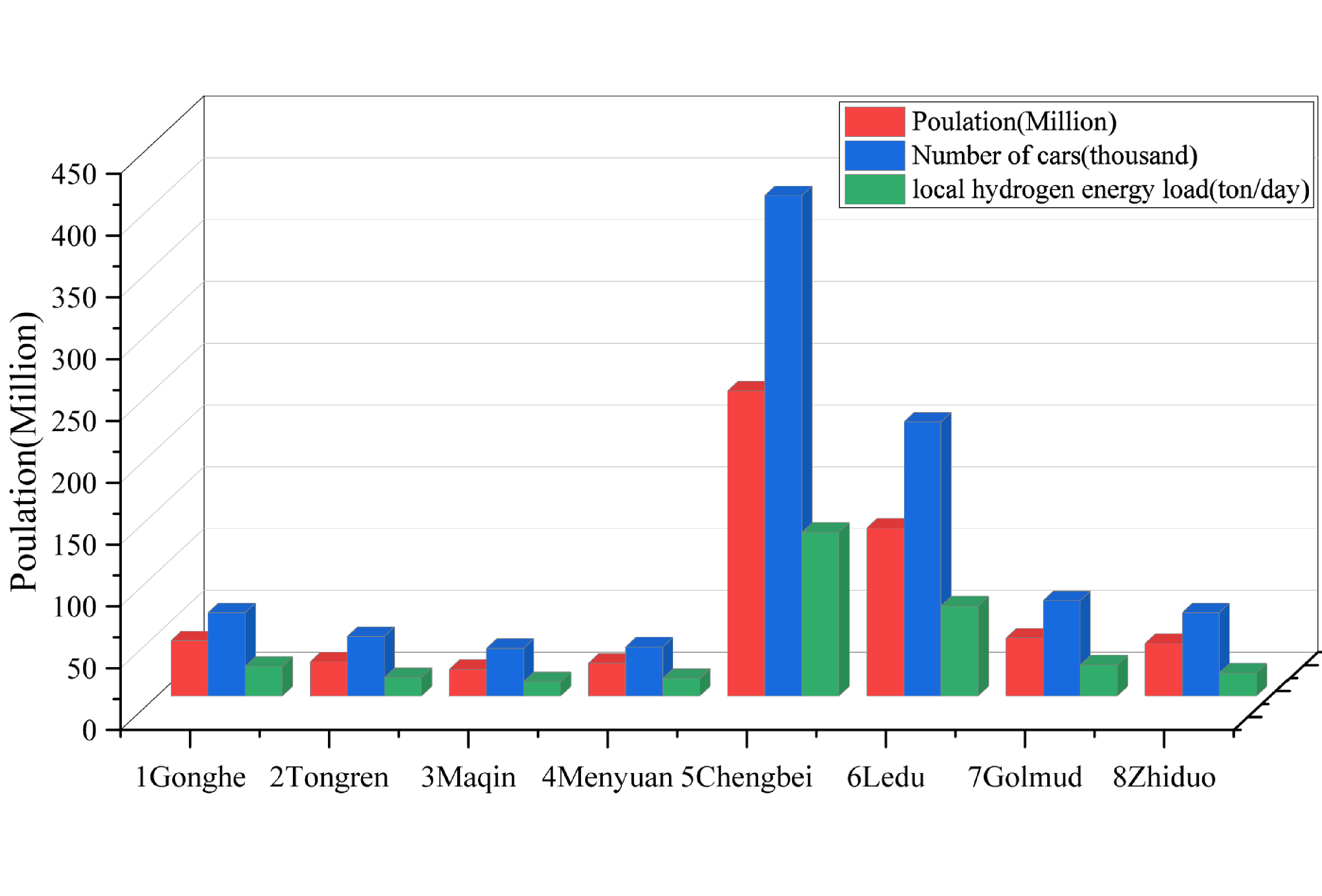


Figure 5 Hydrogen refueling station load diagram

Referring to the distance empowerment model and combining with the highway network of Qinghai Province as shown in Figure 6, the hydrogen supply network model of Qinghai Province is constructed as shown in Figure 7. Route specific information is shown in Appendix 1.

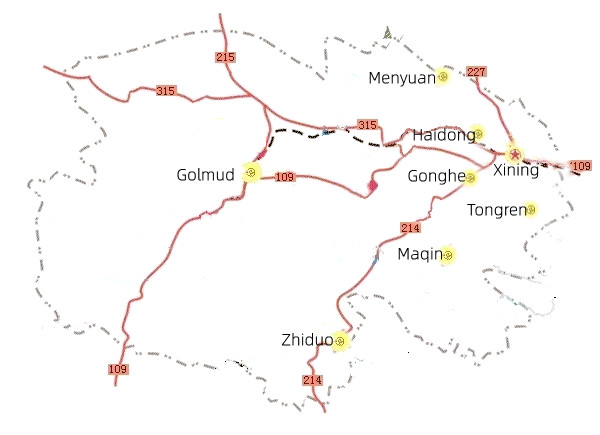


Figure 6 Highway Network Map of Qinghai Province

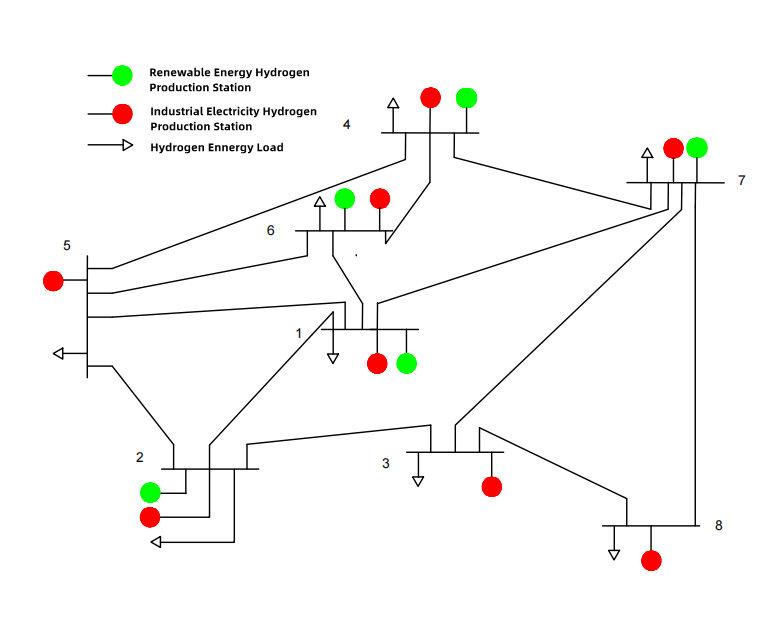


Figure 7 Hydrogen energy network map of Qinghai Province

**4.3 | Hydrogen production capacity Planning results**

Based on the above model and parameter settings, the planning of hydrogen production capacity in Qinghai Province and the cost price of hydrogen energy in each city and province are obtained in Table 2. The more waste renewable energy is used to produce hydrogen from renewable energy, the better from a renewable energy consumption perspective. From an economic point of view, the cost of hydrogen production from industrial electricity power is much higher than that of renewable energy sources. Therefore, all renewable energy bases are fully committed to hydrogen production in the current scenario. Nodes where local new energy hydrogen production cannot meet local hydrogen load demand need to bring in hydrogen from other surplus nodes by paying the freight. Suppose the hydrogen from the rest of the nodes cannot meet the local load demand even after transporting hydrogen to the nodes. In that case, the local industrial electricity hydrogen production is used to make up the hydrogen demand gap. The planning of hydrogen transport between nodes and industrial electricity hydrogen production is shown in Figure 8.

Table 3 Hydrogen production capacity planning and cost of hydrogen in Qinghai province

|  |  |  |  |
| --- | --- | --- | --- |
| Station | Renewable Energy  Hydrogen Production(kg) | Industrial Electricity  Hydrogen Production(kg) | The Cost of Hydrogen(dollar/kg) |
| 1Gonghe | 142398 | 0 | 3.5022 |
| 2Tongren | 1514 | 0 | 3.5796 |
| 3Maqin | 0 | 0 | 3.6382 |
| 4Menyuan | 3582 | 0 | 3.5296 |
| 5Chengbei | 0 | 0 | 3.8175 |
| 6Ledu | 3306 | 31534 | 4.2528 |
| 7Golmud | 131046 | 0 | 3.5022 |
| 8Zhiduo | 0 | 0 | 3.6072 |

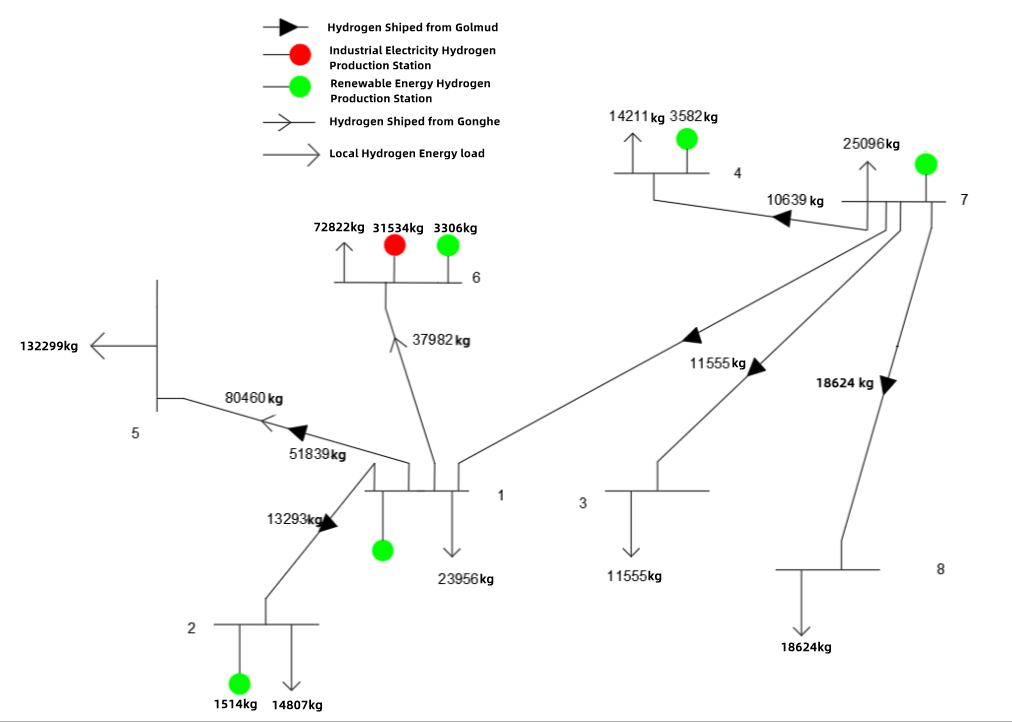


Figure 8 Map of actual hydrogen energy transportation in Qinghai Province

As shown in Figure 9, the price of each hydrogen station converges after two iterations, indicating that only two hydrogen hubs with excess production capacity, namely Gonghe and Golmud, have transferred hydrogen to the remaining nodes with insufficient production capacity. Gonghe hydrogen station, Tongren hydrogen station, Maqin hydrogen station, Menyuan hydrogen station, Chengbei hydrogen station, Ledu hydrogen station, Golmud hydrogen station, and Zhiduo hydrogen station achieved stable convergence at US$3.5022/kg, US$3.5796/kg, US$3. 6382/kg, US$3.5296/kg, US$3.8175/kg, US$4.2528/kg, US$3.5022 US$/kg, US$3.6072/kg reached a stable convergence.Ledu is located in the region of hydrogen energy cost price is significantly higher than other cities and provinces because of the Ledu District geographical location of special more, it local new energy installed capacity is small, the local load demand is larger. Part of its shortfall is shipped in from the Republican node, but the Golmud node does not prioritise the option of transferring the remaining shortfall of hydrogen to the Ledo node based on economics in the game, so the rest of the following hydrogen shortfall is produced by the utility.The unit price of industrial electricity is much higher than the price of waste new energy electricity, so the unit cost of hydrogen energy in Ledu is significantly higher than that in other cities and provinces in Qinghai Province.The Gonghe and Golmud are located in areas where the price of hydrogen refuelling is the same and the lowest in the province, because they are both areas with large installed capacity of new energy sources, and the capacity of hydrogen production from waste new energy sources far exceeds the local hydrogen load. They do not need to bring in hydrogen from other hydrogen refuelling stations, do not incur freight costs, and do not need to use industrial electricity to produce hydrogen, so the cost per unit of hydrogen energy for the Republican and Golmud hydrogen refuelling stations is the cost of hydrogen production for hydrogen production from waste new energy sources.

**5 Analysis of influencing factors**

Taking the hydrogen energy network in Qinghai Province as an example, the three influencing factors of population, total installed capacity of new energy and changes in utility prices are analysed and quantitatively calculated, and then in the case of changes in the magnitude of change of the influencing factors (the initial magnitude of change of the three influences is predicted based on historical data, and changes in the magnitude of change are obtained by referring to the changes in the initial magnitude of change), the impact of the three influencing factors on the price of hydrogen is analysed by using the control variable method, so that the impact of the three influencing factors on the price of hydrogen is obtained by using the control variable method, and the changes in the magnitude of change are obtained by referring to the changes in the initial magnitude of change), the impact of the three influencing factors on the price of hydrogen is analysed using the method of controlling variables, in order to examine factors that have a greater degree of influence on the planning of hydrogen production capacity and the cost of hydrogen in each city and state.

**5.1 Impact of demographic factors**

In recent years, the national birth rate is decreasing, but with the gradual development of Qinghai Province, the foreign population is increasing, and the future trend of the population of Qinghai Province is not yet clear, so let the population of Qinghai Province change by 2%, and the hydrogen production capacity planning and the change of the price of hydrogen used in each city and province in the province are shown in Figure 9. There is no change in the price of hydrogen for the Gonghe and Golmud nodes, because the hydrogen production in Republican and Golmud far exceeds the local hydrogen load, and the price in these two nodes has always been related only to the price of waste new energy, regardless of population changes.The Machin node's hydrogen energy is always supplied only by Golmud and Republic under this demographic change, which keep the price constant, so the average hydrogen price in Machin minus the average transportation cost is always equal to the hydrogen price in Republic and Golmud.Changes in the population of the remaining nodes affect their respective sources of hydrogen, as the load decreases when the population decreases and the amount of hydrogen that needs to be shipped decreases, and conversely the load increases when the population increases, and the amount of hydrogen that needs to

be shipped or the amount of industrial electricity needed to produce hydrogen increases, so that the prices of the remaining nodes are positively correlated with the population.The change in hydrogen at the Ledo Hydrogen Station is particularly noticeable because its hydrogen source is mainly from industrial electricity and transferred hydrogen, and the cost of hydrogen from industrial electricity is significantly higher than the cost of hydrogen from new energy sources, so the price of hydrogen at the Ledo Hydrogen Station varies significantly with the changes in population.





Figure 9 Impact of Demographic Changes on Hydrogen Capacity Planning in Qinghai Province

**5.2 | Impact of the increased installed capacity of renewable energy sources**

As the installed capacity of renewable energy bases in Qinghai Province increases, the total amount of waste renewable energy that can be used for hydrogen production shows an increasing trend. Therefore, it is assumed that the total amount of waste renewable energy that can be used for hydrogen production in Qinghai Province will increase by 5% (assumption is made only in existing renewable energy bases, and newly const renewable energy bases will not be considered). The hydrogen production capacity planning in the province is shown in Table 3. It can be seen that the maximum total hydrogen production from new energy sources will exceed the hydrogen load when the installed capacity of new energy sources is increased by 10%. The Golmud node is the furthest away from the load center and has the highest transmission cost. Hence, nodes that need to bring in hydrogen have a preference for nodes other than the Golmud. The remaining nodes with renewable energy installations（except for Golmud node）are fully committed to hydrogen production. The variation in hydrogen energy cost in each city and province is shown in Figure 10. When hydrogen produced by renewable energy sources increases, the amount of hydrogen produced by industrial electricity in the Ledu node decreases. When renewable energy hydrogen production exceeds the hydrogen demand in Qinghai Province, the amount of industrial electricity hydrogen production in the Ledu node is zero. The load in Ledu is only met by local renewable energy hydrogen production and renewable energy hydrogen production from other nodes. Hence, the cost of hydrogen energy in Ledu decreases significantly. There is a slight decrease in the cost of hydrogen energy at some nodes, such as Tongren and Menyuan. The load in such nodes remains the same but the amount of local renewable energy hydrogen production increases. Hence, the hydrogen shipped from other nodes decreases, leading to lower freight. Then the cost of hydrogen energy per unit decreases by a small amount. The cost of hydrogen energy at the remaining nodes, such as Gonghe and Golmud, remains the same, as the local load is always satisfied by local renewable energy hydrogen production.

Table 4 Planning table for hydrogen production capacity in Qinghai Province

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Increment  Nodes | | 5% increase | 10% increase | 15% increase | 20% increase | 25% increase |
| Gonghe | Maximum production(kg) | 149518 | 156638 | 163758 | 170878 | 177998 |
| Actual production(kg) | 149518 | 156638 | 163758 | 170878 | 177998 |
| Tongren | Maximum production(kg) | 1590 | 1665 | 1741 | 1817 | 1893 |
| Actual production(kg) | 1590 | 1665 | 1741 | 1817 | 1893 |
| Maqin | Maximum production(kg) | 0 | 0 | 0 | 0 | 0 |
| Actual production(kg) | 0 | 0 | 0 | 0 | 0 |
| Menyuan | Maximum production(kg) | 3761 | 3940 | 4119 | 4298 | 4478 |
| Actual production(kg) | 3761 | 3940 | 4119 | 4298 | 4478 |
| Chengbei | Maximum production(kg) | 0 | 0 | 0 | 0 | 0 |
| Actual production(kg) | 0 | 0 | 0 | 0 | 0 |
| Ledu | Maximum production(kg) | 3637 | 3741 | 3802 | 3967 | 4233 |
| Actual production(kg) | 3637 | 3741 | 3802 | 3967 | 4233 |
| Golmud | Maximum production(kg) | 137598 | 144151 | 150703 | 157255 | 163808 |
| Actual production(kg) | 137598 | 144151 | 139960 | 133242 | 124778 |
| Zhiduo | Maximum production(kg) | 0 | 0 | 0 | 0 | 0 |
| Actual production(kg) | 0 | 0 | 0 | 0 | 0 |



Figure 10 Hydrogen Energy Costs by City and State in Qinghai Province

**5.3 | Impact of the price change in industrial electricity**

If the renewable energy installed in Qinghai Province increases, based on the energy supply and demand relationship, this paper estimate that the price of industrial electricity in Qinghai Province will decrease at a rate of 2% per year. The hydrogen price changes in each city are shown in Figure 11. With Figure 10, it can be seen that the hydrogen production capacity planning in the region is not affected due to the renewable energy in the initial scenario is in full force to produce hydrogen, therefore, in terms of regional hydrogen energy unit cost, except for the Ledu station, which contains a large number of hydrogen production by industrial electricity, its hydrogen price is positively correlated with the industrial electricity price, and the rest of the nodes of the hydrogen price are unaffected.



Figure 11 Impact of industrial electricity price changes on unit hydrogen energy costs

5 **| CONCLUSION**

By combining the ideas of non-cooperative game theory with energy planning, this paper establishes a planning model based on static non-cooperative strategies, which aims to solve the problems of planning, operation, and pricing in the early stage of hydrogen energy market formation. Besides, this paper provides guidance and suggestions for constructing hydrogen energy networks, planning production capacity, and determining the global minimum cost in a particular region. The model is applied in the Qinghai province which the main conclusions from the results are presented as follows:

●Improved iterative algorithms based on mathematical optimization and non-cooperative game planning can transform planning problems with complex coupling terms into linear problems with good convergence.

●Simulation results indicate that a node with a sufficient renewable energy supply can achieve a low hydrogen production cost, while long-distance transportation and the utility of industrial electricity lead to a high cost.

●With the increase of renewable energy installed capacity,the cost of hydrogen produced from abandoned renewable energy in Qinghai Province is expected to continue to reduce in the future.

●The model can effectively form planning strategies for different hydrogen hubs under the general hydrogen sales scenario, which can provide reference suggestions for the planning, pricing, and subsequent development of hydrogen production capacity in the provincial hydrogen network.

**NOMENCLATURE**

|  |  |
| --- | --- |
|  | the cost of hydrogen production |
|  | the cost of investment |
|  | the cost of operation and maintenance |
|  | the cost of hydrogen energy transported into the node. |
|  | the tariffs of wind,/PV/ industrial electricity power under strategy s |
|  | electricity consumption of the wind turbine, PV system, and industrial electricity at strategy s |
|  | the water consumption of wind turbine/PV system,/industrial electricity at strategy s |
|  | the conversion coefficients of electrolytic water to hydrogen for game player i when choosing strategy s |
|  | unit operating costs of wind, PV, and industrial electricity field stations under strategy s |
|  | the number of hydrogen production equipment types in the system |
|  | production capacity of the jth unit |
|  | the unit production capacity price of the unit |
|  | operating unit maintenance cost coefficients for wind turbines, PV, and utilities under strategy s |
|  | the unit civil investment cost and unit equipment investment cost of water electrolysis equipment |
|  | the unit equipment investment cost of water electrolysis equipment |
|  | the unit freight cost of player i under strategy s |
|  | amount of hydrogen mobilised by player i under strategy s |
|  | the local renewable energy hydrogen production cost for player i under strategy s |
| */* | the cost for abandoned wind/PV power generation |
|  | expected annualised cost |
| */* | the average annual wind/PV power abandonment rate |
| */* | the annual abandoned wind/PV power generation |
|  | the annualised investment cost of system equipment |
|  | the cost of system maintenance |
|  | the annual running cost;I is the number of equipment types in the system |
|  | production capacity of the i-th device |
|  | the price per unit production capacity of the equipment |
|  | the discount rate |
|  | A given period |
|  | the equipment lifetime |
|  | maintenance cost factor |
|  | the number of scenarios |
|  | probability that the ith device is switched on |
|  | electricity consumption-hydrogen volume conversion factor for hydrogen production by electrolysis of water |
|  | the volume-to-mass conversion factor for hydrogen; s the power consumption |
|  | the current feed-in tariff for that renewable energy source |
|  | the unit freight cost to be shipped from other nodes into node j |
| */* | he high-speed/common mileage unit freight rate between node i and node j |
| */* | the highway/common mileage unit freight rate between node i and node j |
|  | toll for that route |
|  | the full production capacity of the hydrogen transport vehicle |
|  | time span of a single scene |
|  | total amount of hydrogen produced by the industrial electricity at node i during the time period |
|  | the unit electricity consumption for hydrogen production by electrolysis of water |
| // | the total amount of PV/industrial electricity/wind power generated by node i during the time period |
| / | the local abandoned rate of PV/wind power |
|  | hydrogen demand in the area under the jurisdiction of the hydrogen hub j |
|  | the population in the area under the jurisdiction |
|  | car ownership in the area under the jurisdiction |
|  | market penetration of hydrogen fuelled vehicles |
|  | the expected average annual hydrogen use per vehicle |
| / | Inequality/equational constraint |
|  | the industrial electricity production/dispatch decision variables |
| / | the amount of hydrogen ship into/out of energy hub i |
|  | the amount of hydrogen from local industrial electricity hydrogen production at node i of the energy hub |
| / | the actual/maximum amount of hydrogen produced by the local renewable energy at node i |
|  | the amount of hydrogen load in the area covered by energy hub i |
|  | global cost of hydrogen production at node j when iterating to generation t+1 |
| 、 | the cost of hydrogen production including investment and operation and maintenance costs for renewable energy / industrial electricity power |
|  | the freight rate representing the unit of hydrogen energy transported into point j by other nodes |
|  | total mass of hydrogen energy transferred from other nodes to point j at the t-th iteration |
|  | the cost of renewable energy hydrogen production at all nodes where hydrogen is shipped to node j for the t-th time |
|  | is the total mass of hydrogen energy at node j after the completion of the t-th transfer |

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Appendix 1

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Route number | total distance traveled | toll | highway mileage | common mileage |
| ①② | 296 | 66 | 281 | 14 |
| ①③ | 398 | 145 | 336 | 62 |
| ①④ | 287 | 22 | 171 | 116 |
| ①⑤ | 143 | 3 | 134 | 9 |
| ①⑥ | 208 | 24 | 199 | 9 |
| ①⑦ | 627 | 150 | 596 | 31 |
| ①⑧ | 839 | 183 | 456 | 383 |
| ②③ | 361 | 0 | 0 | 361 |
| ②④ | 307 | 100 | 240 | 67 |
| ②⑤ | 167 | 62 | 152 | 15 |
| ②⑥ | 159 | 64 | 116 | 43 |
| ②⑦ | 918 | 216 | 879 | 39 |
| ②⑧ | 1130 | 250 | 738 | 392 |
| ③④ | 687 | 203 | 621 | 66 |
| ③⑤ | 544 | 184 | 530 | 14 |
| ③⑥ | 609 | 205 | 594 | 15 |
| ③⑦ | 591 | 196 | 565 | 26 |
| ③⑧ | 1127 | 156 | 565 | 562 |
| ④⑤ | 153 | 36 | 90 | 63 |
| ④⑥ | 213 | 44 | 154 | 59 |
| ④⑦ | 902 | 169 | 819 | 83 |
| ④⑧ | 1115 | 202 | 678 | 437 |
| ⑤⑥ | 74 | 23 | 65 | 9 |
| ⑤⑦ | 759 | 156 | 728 | 38 |
| ⑤⑧ | 971 | 189 | 587 | 384 |
| ⑥⑦ | 824 | 175 | 793 | 31 |
| ⑥⑧ | 1035 | 210 | 617 | 418 |
| ⑦⑧ | 536 | 0 | 0 | 536 |