PTX: The Bridge to a More Flexible Energy System

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Abstract: In order to reduce carbon emissions, increase the utilization rate of renewable energy, and reduce the large-scale abandoned wind and solar energy, the technology of Power to X has become a hot spot in the field of energy research. This paper combines the existing research results and applications of PTX to explore the future development. Firstly, expound the concept and significance of PTX; then through the comparison of European, Japanese and domestic PTX projects and applications, elaborate the development of PTX; then put forward key technologies about energy conversion equipment and cooperative operation method among multi-energy system; then take Shanghai as an example and raise the PTX application path according to the energy environment; finally, prospect the future development PTX.

1 INTRODUCTION

In order to achieve the long-term goal set by the Paris Agreement, China promises to reach the peak of carbon emissions around 2030 including the proportion of non-fossil energy in primary energy consumption will be mentioned as 20% by 2030 and the carbon emissions per unit of GDP will be 60%-65% lower than 2005 (Boqiang Lin, 2014). Shanghai plans to achieve the city peak carbon emissions and per capita carbon emissions by 2025 and by 2035 the total carbon emissions will be reduced by 5% compared with the peak. The energy consumption per 10,000 yuan will be controlled below 0.22 tons coal. State Grid Corporation of China proposed that by 2050 non-fossil energy will account for more than 50% of the primary energy and electricity will account for more than 50% of the terminal energy consumption (Xiaoxin Zhou, 2018). In order to achieve these goals, we should make tremendous changes in energy supply and utilization. It is imperative to accelerate the energy revolution.

At present, the revolution of the energy industry is mostly focused on developing the renewable energy (Pingkuo Liu, 2019), but how to increase the energy efficiency and the usage of renewable energy is a key factor in energy revolution. There are many ways to use renewable energy: directly applied to terminal-user (solar cells, geothermal heating, biomass, etc.) or using renewable energy to generate electricity (Lei Wang, 2019). The latter is an effective means of producing and utilizing renewable energy. However, due to the randomness and uncontrollability of renewable energy (Huan Zhou, 2016), it is difficult to match power supply and demand in real time. What's more, because of the traditional energy storage technology bottleneck, too much new energy is wasted. In addition, demand for clean fuels and raw materials continues to grow, whether in transportation, agriculture, steel production or heating.

To solve the conflict between renewable energy intermittent and clean energy demand, there must be breakthroughs in energy storage, flexible conversion and demand-side management. The conversion of power into other forms of energy (Power to X, PTX) provides a variety of options to solve this problem. PTX is considered by some scholars to be the key to promoting energy revolution (Jan Christian Koj etc., 2019).

2 PTX PROMOTES NEW TECHNOLOGY CONCEPTS FOR ENERGY REVOLUTION

2.1 The Definition of PTX

PTX means Power-to-X. PTX is a general term for technologies that convert power into other forms of

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energy. It was first proposed by Germany, where "X" can be fuel, heat, mechanical energy, chemicals, etc. (Rego de Vasconcelos Bruna etc., 2019). Power can be converted into thermal energy, mechanical energy which can be used as direct source; power can be converted into fuel, chemicals which can provide raw materials for certain industries; power can be stored in hydrogen and methane to meet the peaking demand of the power grid. The concept of PTX is extended by PTG and PTH (PTG: Power-To-Gas; PTH: Power-To-Heat) (Ralf Peters etc., 2019; Feng Zhao etc., 2016).

2.2 The Significance of PTX

The development of PTX has helped to build an energy Internet focused on electricity. PTX is not limited by capacity, time, space and industry. It further enhances the consumption of renewable energy, reduces the abandonment of renewable energy, improves the comprehensive utilization efficiency of energy, and helps to improve the grid's flexibility. Due to the real-time balance of power generation in power systems, a fully renewable energy-based power system will require a large amount of equipment to store energy such as batteries and pumped storage, which can be stored for seconds, hours, days and weeks. Figure 1 is from Sterner et al. (2014) and the analysis of Frontier Economics. It shows the energy storage cycle of different capacities and different modes. The comparison shows that there is a certain advantage in converting electrical energy into fuel storage. In general, PTX technology makes the energy bidirectional flow between the power system and other energy systems, realizes the mutual conversion of electricity and other energy sources, helps multi-energy systems to integrate with each other, strengthens the effective interaction of energy resources and promotes the construction of energy Internet with the power grid as the hub.

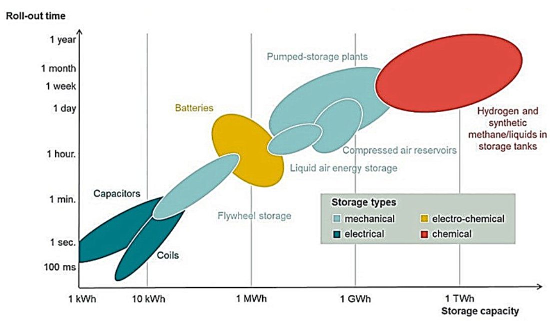

Figure 1. Comparison of different energy storage forms.

PTX helps companies to break through the development bottleneck. Electric utility companies are facing challenges. Their traditional profit models for power generation, transmission and distribution are threatened. On the one hand, renewable energy and energy storage solutions such as solar and cogeneration (Ceguo Wu, 2017) are less dependent on traditional power grids; on the other hand, users upgrade their equipment to reduce energy consumption (Bin Hu, 2017). PTX not only connects other energy carriers to store the electric power, but also connects non-energy materials to make electric energy directly used as industrial raw materials, and gradually forms an electricity-centered energy supply structure. Through PTX, we will continue to expand the varieties of energy, enrich application scenarios, promote the reorganization and extension of the energy value chain, promote the comprehensive non-regulatory services such as integrated energy services and promote new business models as well as profit growth points. On the one hand, PTX can achieve cross-industry communication between the power industry and other energy fields; on the other hand, PTX can break the industrial barriers of public utilities.

PTX contributes to the improvement of social energy efficiency. From the perspective of energy consumption, the economic efficiency of electric energy is 3.2 times of oil and 17.27 times of coal (Lijing Qiu, 2018). In China, the proportion of energy consumption in terminal energy consumption increases by 1 percentage point, and the energy consumption per unit of GDP can be reduced 2 - 4 percentage points (Zhengmin Yin, 2013). From the perspective of energy supply, at present, different systems such as electric power, heat and gas are integrated and complemented, but the degree of utilization is not high which reduces the overall efficiency of energy systems. PTX provides cooperation opportunities for different kinds of energy companies, helps to extend the interconnection between the power Internet and the petrochemical industries and helps to promote efficient coordination of power production and related industries. The application of PTX technology can increase the proportion of electric energy among the terminal energy consumption, break the traditional application mode of different energy types. It also can improve the comprehensive utilization efficiency of energy, promote the transformation and upgrading of the industry, optimize the urban infrastructure construction plans and improve the overall energy efficiency level of the society.

3 THE DEVELOPMENT OF PTX AT HOME AND ABROAD

Frontier economics have targeted some of the countries and regions with renewable energy advantages and have classified their production and exports (Figure 2). The role of each country in PTX global market and the timing of its entry are determined by its own resource and market environments. The following is a detailed description of the development of PTX in Europe, Japan and China.

Type	PtX motivation and readiness	Selected example
Frontrunners	● PtX already on countries (energy) political radar ● Export potential and PtX readiness evident ● Uncomplicated international trade partner ➢ Especially favourable in early stages of market penetration	Norway
Hidden Champions	● Fundamentally unexplored RES potential ● Largely mature, but often underestimated, (energy) political framework with sufficiently strong institutions ➢ PtX could readily become a serious topic if facilitated appropriately	Chile
Giants	● Abundant resource availability: massive land areas paired with often extensive RES power ● PtX readiness not necessarily precondition, may require facilitation ➢ Provide order of PtX magnitudes demanded in mature market	Australia
Hyped Potentials	● At centre of PtX debate in Europe with strong PtX potential ● Energy partnerships with Europe foster political support ➢ Potential to lead technology development; may depend strongly on solid political facilitation	Morocco
Converters	● Global long term conversion from fossil to green energy sources ● PtX to diversify portfolio as alternative long-term growth strategy ➢ Strong motivation for PtX export technology development; may requires political facilitation and partnership with the EU/DE	Saudi Arabia
Uncertain Candidates	● Partially unexplored RES potentials, possibly paired with ambitious national climate change policies ● PtX export in competition with growing national energy demand ➢ PtX export motivation and potential unclear – may drive PtX technology development, however export uncertain	China

Figure 2. Type of possible PTX producers/exporters and selected example country.

3.1 The Development of PTX in Europe

Europe uses PTX to solve energy resource imbalances and focus on its value-added services (Benoit Decourt, 2019). By January 2016, there are 49 PTG pilot projects in the world. And 44 of them are located in Europe which mainly located in Germany and Denmark with a large proportion of renewable energy and low electricity prices (Ming Che, 2017). Netherlands and France also pay attention to PTX. It is related to their lower electricity prices and the proportion of renewable energy. In 2017, the proportion of renewable energy in Denmark reached 47% (Ning Wang, 2019), and in Germany it was 36% (Ning Wang, 2019).

In Danish, Aarhus completed the capacity expansion of the existing cogeneration plant in 2015, while solving the problem of excess wind power and heating demand. North Jutland and Orr has signed a cooperation agreement. It is expected to complete the country's first fuel-cell bus system in October 2019. The region also signed a contract for the intentional electrolysis system with Aalborg, using the excess power to produce hydrogen. In addition, Danish has carried out a project named Hybalance to use the excess wind energy to produce hydrogen in order to balance the grid load. Meanwhile, the hydrogen can also be used in transportation and industry.

In Germany, many researches about PTX has be conducted (Christian Schnuelle, 2019). The German Power-to-X Alliance will invest 1.1 billion euros to promote the production of green hydrogen and synthetic methane (Shanshan Fan, 2019). The REFHYNE project will provide the required hydrogen through a 10MW electrolytic cell. Replacing the existing two steam methane reformers, it can balance the in-plant power grid and can provide first-level control and backup services for German transmission operator. The project also includes some research for the 100MW electrolytic cell of the

Rhineland Refinery. Siemens has completed a set of PTX solutions covering the hydrogen energy industry chain (Figure 3). In the upstream, Siemens can provide power generation equipment and solutions suitable for renewable energy. In the middle reaches, Siemens has the core technology for hydrogen production by electrolyzing water. Downstream, Siemens can provide hydrogen equipment for industrial applications. The core PEM technology and related product series have been successfully commercialized in the world first megawatt electric hydrogen production plant in Germany by 2015. The Baden-Württemberg Solar and Hydrogen Energy Research Center (ZSW) proposes a combination of high-temperature biomass oxidation and high-temperature electrolysis to reduce the amount of electricity needed to produce renewable hydrogen.

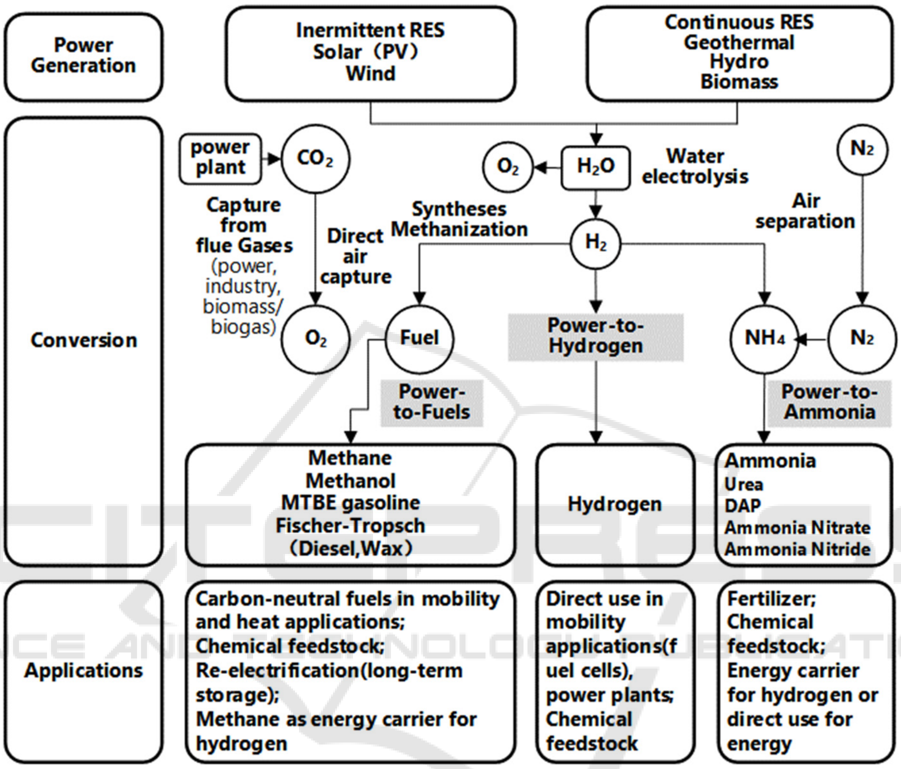

Figure 3. Conversion of renewable power into various forms of chemical energy carriers.

The Netherlands has conducted an electric-to-gas project named HyStock which includes a 1MW proton exchange membrane (PEM) and a 1MW solar energy field that will supply some of the electricity needed to produce hydrogen from the water. The hydrogen produced is injected into the gas cylinder and transported to the terminal user. The project also includes the research about how the cell can provide benefits to the power industry by providing auxiliary services to the grid.

In Austria, the project named H2Future consists of a 6MW electrolyzer and is planned to be installed in a steel plant. While supplying hydrogen to the steel plant, it will also use the electrolytic cells to provide various levels of backup balancing services for the grid. The hydrogen fuels are produced by off-peak electricity.

In France, a hydrogen storage project named GRHYD has be conducted. The goal of GRHYD Project is to convert the remaining energy produced by renewable energy into hydrogen and mix it with natural gas to form ethane for reuse in existing natural gas infrastructure.

In Sweden, the utility company Vattenfall has invested about 100 million euros to build three cogeneration units with a total heating capacity of 120 megawatts. These units will use excess wind energy to heat the water. It is expected to be put into use in 2019 to replace one of the 330MWh coal-fired plant. It can reduce the use of fossil fuels in heating.

In Scotland, one content of Heat Smart Orkney project is a plan to convert wind power into heat which received £1.2 million through the Scottish government's Local Energy Challenge Fund. Users will receive energy-efficient heating equipment that is connected to the Internet and is activated when the wind turbine receives a power limit signal. It can produce heat only by using the remaining power from the fan in community.

3.2 The Development of PTX in Japan

The "hydrogen energy society" concept proposed by Japan (Jie Zhou, 2019) hopes to diversify energy supply by using hydrogen, increase energy self-sufficiency rate and complete Japan's independent emission reduction targets.

In the latest Energy Basic Plan, Japan has positioned hydrogen energy as a core secondary energy in parallel with electricity and heat. It hopes to realize the application of hydrogen energy in homes, industry, transportation and even the whole society through hydrogen fuel cells. So real energy security and energy independence can be realized. Japan hopes to seek new growth points in economy relying on hydrogen energy (Guang Jia, 2019).

Japan has put forward the development strategy of “utility 3.0” by combining PTX technology with “three-type” enterprise construction. On the one hand, Utilities 3.0 is the next generation of social sharing platform. The Tokyo Electric Power Research Institute proposed that Uber, Lyft and DiDi are shared transportation platforms, Airbnb is a housing sharing service platform and public utilities will have a next-generation sharing platform. On the other hand, Utilities 3.0 not only promotes the restructuring and expansion of the energy value chain, but also covers a variety of infrastructure services such as transportation, communications, gas, water, hydrogen and other utilities.

At the same time, Utilities 3.0 is based on the needs of future infrastructure construction. In the industrial economy era, the most important infrastructure is the fundamental infrastructure, but the most important infrastructure for the development of the new economy and the digital economy in the future is the “cloud network”.

3.3 The Development of PTX in China

At present, there is no systematic PTX concept in China, but the development in the hydrogen energy industry and fuel cell vehicles is good (Meng Qingyun, 2013; Hongshuai Shen, 2018; Wen Ling, 2019). Now the national energy industries are paying more and more attention to the developments of PTX (Shil Song, 2017).

In policy perspective, the National Clean Development Council and the National Energy Administration jointly issued the Clean Energy Dissipation Action Plan (2018-2020) in October 2018. The plan explicitly mentioned the need of "explore the transformation of renewable energy surplus power for the other types of energy which can be used in an efficient way". In the 2019 "Government Work Report", "Promoting the construction of facilities such as charging and hydrogenation" was written. The National Development and Reform Commission as well as other ministries have issued relevant subsidy support policies for fuel cell vehicles. National Energy Group, Sinopec and other enterprises invest hydrogen energy to utilize the entire industrial chain. They also participate in the research and development of hydrogen fuel cells to promote international cooperation.

In technology perspective, the team of He Yijun from Shanghai Jiaotong University has conducted a series of research on the key technologies of PTX (Jiani Shen, 2016&2018; Guobin Zhong, 2019, Wei Su, 2019). The research mainly focuses on PTX system design and operation optimization technology under multi-time scale and multi-class product uncertainty environment.

In project perspective, at the end of 2010, the first demonstration project for hydrogen production from off-grid wind power in China was completed in Dafeng, Jiangsu. The project consists a wind turbine, a non-grid wind/network intelligent coordinated power controller, a fan controller, a new electrolyzed water system, etc., and one 30kW and one 10kW fan jointly supply power to the hydrogen production device. The demonstration project is small in scale and has a hydrogen production capacity of only 120m3/d (Zhuoyong Yan, 2015). In 2016, the world largest wind power hydrogen production comprehensive utilization demonstration project in Zhangjiakou City has been connected to the grid for power generation, including 200MW wind power generation, 10MW electrolysis water hydrogen production system and hydrogen comprehensive utilization system. The wind turbine with a single unit capacity of 2MW has an annual production capacity of 17.52 million m3 of hydrogen. The total investment of the project is 2.03 billion yuan, covering an area of 116 mu (about 77,000 m2). It is estimated that the annual sales income will be 260 million yuan and the profit and tax will be 0.8 billion yuan. The project effectively solved the problem of large-scale abandoned wind and solved the bottleneck of the development of wind power industry in Hebei

Province. In September 2016, Dalian built the first 70MPa hydrogen refueling station (Tongji-Xinyuan Hydrogen Station) that uses hydrogen from wind and solar hybrid power generation. The hydrogen refueling station is the research result of the 863 project “Research and Development and Demonstration of 70MPa Hydrogen Refueling Station Based on Renewable Energy System/Hydrogen Storage” undertaken by Tongji University.

4 APPLICATION OF PTX IN URBAN ENERGY INTERNET

4.1 Multi-energy Collaborative Model in Urban Energy Internet

There are many different forms of energy that can be used to transform in urban energy Internet. The most common and practical ones are Power to Gas, Power to Heat, Power to Food, and Power to Mobility.

Power to Gas. Hydrogen is the raw material for all power to X and is the most promising storage solution. Hydrogen can also directly enter the natural gas pipeline network in a certain proportion, providing buffer and regulation mechanisms for the grid and gas network. It is expected that in the future, large-scale wind power consumption can be achieved by integrating wind power hydrogen production into power plant CO2 capture technology to manufacture methane and supplement natural gas demand to create a true energy router.

Power to Heat. The current level of electrification in Shanghai is still at the middle and lower reaches of the country, with a large space for improvement. The traditional electric heating, heat pump, electric refrigeration, heat storage, cold storage and other safeguard projects are the basic scenarios of PTX technology in Shanghai.

Power to Food. The electric stove equipment has no noise, no radiant heat, and the cooking environment is more comfortable. It is more conducive to energy saving and emission reduction. According to estimates, heating the same food, electrical stoves 61% faster than liquefied gas, saving 72.6%. Based on the current situation that cooking is still dominated by gas in large-scale canteens such as schools, hospitals, military, hotels, restaurants and residents' kitchens. We will vigorously promote the all-electric kitchen model represented by electromagnetic stoves. It can effectively reduce nitrogen oxide emissions while effectively improves the kitchen environment.

Power to Mobility. Electric vehicles not only consume excess energy, but also store this part of energy and then recharge it to the grid as needed. Use batteries or indirectly use hydrogen fuel to replace fossil fuels. At the same time, Shanghai as an international shipping center and an international metropolis, the transportation uses a large amount of oil, which can be replaced by clean energy (Figure 4).

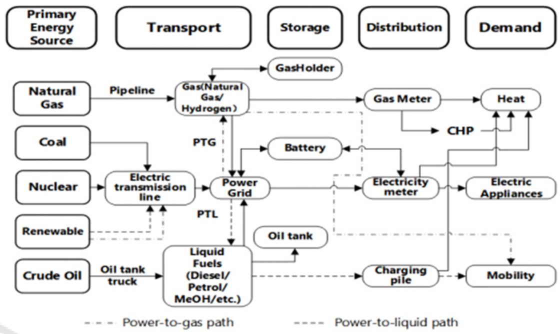

Figure 4. Energy supply value chain from power generation to end users (take power to mobility as an example).

Using PTX technology to build a complete urban energy Internet architecture model is important for future energy planning and development. Figure 5 combines electrical energy, thermal energy and gas energy to build a multi-energy complementary system for a small community. It is the basis of the large-scale energy Internet architecture and can also be used as a pilot project for PTX.

Considering the multi-energy planning of large cities, figure 6 builds a large urban energy Internet architecture model that includes the coupling of multiple sources of energy such as cold, heat, electricity, gas, and biomass.

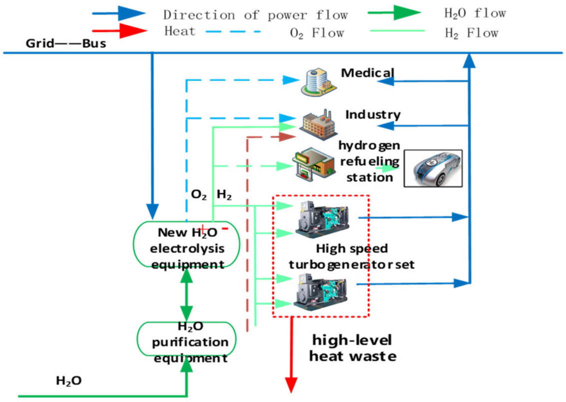

Figure 5. The small multi-energy complementary system.

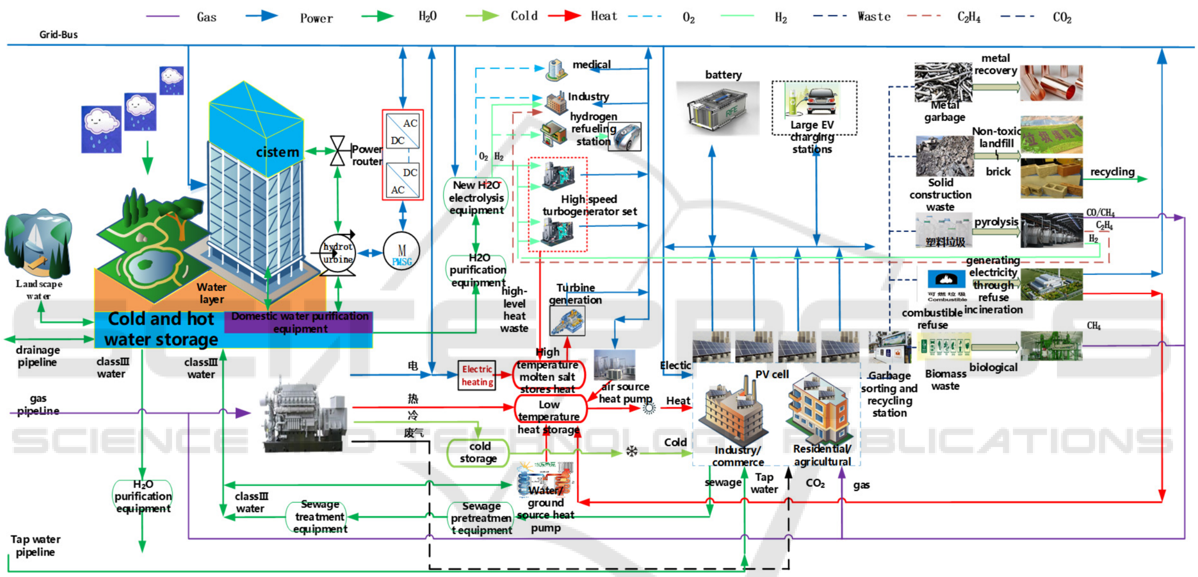

Figure 6. Large-scale urban multi-energy network model.

5 CONCLUSION AND FUTURE WORK

Technology, demand and market, investment and supply will drive the development of PTX. First, technological breakthroughs and expansion of scale will make the costs significantly reduce. The existing PTX projects are both small in scale. Some of the projects don't fully utilize renewable energy to generate electricity, and the applied scenarios are limited. Next step is to expand the scale of the experimental unit and increasing the applied scenarios. Second, carbon emission requirements and exact subsidy policies will drive the expansion of market demand. Long-term stable market demand is a key factor in ensuring investors to enter the market, which means that PTX products must meet the needs of consumers, and their prices can cover costs. The pressure of energy saving and emission reduction as well as the supporting subsidy policy guidance can reduce the entry barrier of the PTX market. Third, a good business environment and a sound agreement system will help increase investment and cooperation. Establish a multi-party cooperative energy partnership with PTX as a focus, and lead a multi-party agreement to scale the PTX market, reduce investment risks, and ensure the stable supply of renewable energy.

5.1 Using Hydrogen to Produce Electricity as a Demonstration

Large-scale wind power hydrogen production projects can be considered. On the one hand, the wind power hydrogen production project includes three subsystems: electrolytic hydrogen production, high-voltage hydrogen storage and fuel cell power generation. It can be implemented in various modes such as "electricity-hydrogen-electricity" and "electric-hydrogen-use". However, the overall conversion efficiency of the "electric-hydrogen-electric" mode is low, and the cost of the fuel cell power generation equipment is high, so it's not available to promote and apply in large-scale. On the other hand, the cost of producing hydrogen from wind power is much better than wind power connected to the grid. The difference in technology and cost is very large, especially in manufacturing costs. When wind power is connected to the grid, it not only needs to meet strict technical specifications, but also requires additional phase control equipment, which costs about 50% of a wind turbine. For example, the current price of a 1000kW wind turbine is about 800~10 million yuan/unit. If the wind turbine only to produce hydrogen, its cost is about 300~5 million yuan/unit, and there is still room for decease the cost. The demonstration project could focus on offshore wind power. The demonstration of wind power hydrogen production could use the surplus power (excessive power exceeding the national regulations) of offshore wind power at a lower price (such as 0.2 yuan or below).

5.2 Expand "X"

The extension of X does not only contain chemicals such as methane and methanol. It that can be converted into various forms such as heat. It is possible to consider the construction of all-electricity parks, schools, factories and communities to improve the replacement of fossil energy by coal, oil and gas. Expand the type and scale of terminal energy consumption. Based on the traditional electricity to heat and heat storage projects, learning the example of Tokyo Electric Power, it can be considered that provide efficient energy solutions in the super high-rise buildings, large residential areas, key industrial parks to improve the value of grid service products.

5.3 Targeted Technical Research

The Targeted technical research can be the robust design and operation optimization of multi-type energy product systems based on renewable energy/surplus power, as well as the design of modular demonstration devices for PTX systems which are suitable for different application scenarios, including hydrogen integrated energy system integration technology and PTX energy router technology.

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