Adopting Hydrogen Power to Mitigate Climate Change

Yin Qi

Canadian International School of Beijing, Beijing, 100000, China

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Abstract: The climate change brought by the burning of fossil fuels calls for the development of alternative energy sources, from which hydrogen power has gradually enters public's vision. The purpose of this study is to investigate into the benefits and drawbacks of hydrogen as a alternative fuel, the manifold challenges that China's hydrogen market faces, as well as an analysis of the prospect of hydrogen becoming a full-fledged industry in the next decades from a technological and policy perspective. This paper concluded that hydrogen subsidy is essential due to hydrogen power's PCE and learning potential. However, it should be adjusted over time, and the effect of different market structures should be examined while deciding on preventative actions. Besides, due to various benefits, hydrogen stands out as an attractive option. Via technological advancements and supporting policies, a sound hydrogen energy system which encompasses production, transportation, and end use would boost energy security when executed effectively. Investors, stakeholders, and policymakers who have an interest in the matter of mass-producing and eventually commercializing hydrogen in China will reap the benefit of its findings.

1. Introduction

1.1 Background

In recent years, climate change has received unprecedented levels of attention from governments, social media and the public. Global temperature continues to rise, precipitation patterns change, frequency of droughts and heatwaves increases, extreme weather lasts longer, sea level rises, and the risk of more intense natural disaster increases. However, perspectives on the impact of climate change vary a lot.

On the one hand, many people view climate change as a threat to all life on earth. The threat to food security posed by the chain consequences of climate change is particularly serious. Firstly, according to the future projection of UN, wheats and maize will suffer from serious decline. Given their annual consumption at 700 million metric tons, the demand for them as key components of daily diets should increase by at least 60% to feed 2050's population, predicted at 9.6 billion. Moreover, fisheries are also predicted to experience significant damage, with fresh and salt water fishing at risk, as the global weather pattern is undergoing unpredictable changes. Obviously, some population groups, especially the poor, will be vulnerable to the impacts of inflated prices, failing harvests and malnutrition in the near future. Such multi-faceted crises will not only place greater pressure on other production regions to increase yields, but also decrease living conditions in deprived regions. Hence, the UN has stressed the need for interventions, calling governments to seek for different ways to cope with such threatening impacts.

Because climate change goes beyond national borders, 178 countries in 2016 signed the Paris Agreement, aimed to tackle the negative impacts of climate change through international cooperation, with its long-term goal of considerably reducing greenhouse gas emissions to limit the temperature increase to 2 degrees in this century. After the Paris Agreement, many countries started to set targets and impose policies and regulations to achieve their short-term goals. The measures governments implemented include introducing carbon taxes, raising awareness, and switching to renewable and clean energy via financial and technical support. For carbon tax imposition, the Austrian government and Norwegian government both introduced new carbon taxes, with an increase of $25 per tonne by 2022 and 1410 crowns per tonne by 2030 respectively. For financial support, the German government has decided to spend $44 billion over four years to cut down its carbon dioxide emissions, a policy which is estimated to reduce the global temperature by 0.00018°C within 100 years. Many other countries provide subsidies for renewable energy industries. For awareness dissemination, China encourages people to practice and promote green travel by taking buses, cycling and walking as far as possible, mobilizing citizens to encourage people around them to participate in environmental protection. Apart from that, countries have also set ambitious targets. For instance, the US strives to make a carbon pollution-free electricity sector before 2035; the UK plans to cut carbon emission by 78% by 2035 in comparison with 1990 levels, and to have all electricity go green by the same year. Thus, it can be seen that countries are making efforts to mitigate climate change.

On the other hand, environmentalist Bjorn Lomborg has a relatively optimistic attitude towards climate change, contending that the huge opportunity cost required to achieve such ambitious targets is not worth it. Firstly, he argues that the Paris Agreement is the most expensive accord in history, as it aims to wean the global economy off fossil fuels, in spite of alternative energy sources remaining uncompetitive. Many countries plan to invest heavily in reducing carbon emissions, whilst such budgets could save more than 10 million lives from tuberculosis in developing countries. Secondly, he claims that conforming to such climate policies pose challenges, as developed countries will do little as long as the costs are too high and developing countries will focus more on economic growth to get their citizens out of poverty rather than to invest in costlier energy. Thirdly, Lomborg looked at climate change from several positive aspects. For example, he contends that the rising temperature would save lives because higher temperature averted 10,000 more deaths from cold than from heat. A study points out that there will be a 257% increase in heat death by 2050, whist cold deaths will decline by 2%. All in all, although Lomborg's personal evaluation is quite different from the evaluations of many experts, he also stressed the importance of green energy research and promotion.

The development of clean, renewable energy is a permanent solution to our existing environmental problems, especially global warming. Just as the advent of the steam locomotive during the first Industrial Revolution in London gradually replaced the horse-driven carriages, thus eliminating the environmental problems of that era --horse manure, so a cheaper, cleaner fuel such as hydrogen and solar power would solve the problems that plague us today -- carbon emissions and the resulting global warming. By contrast, any move to neutralize carbon emissions is a temporary solution that has multiple negative consequences, such as pushing more people into poverty and increasing inequality. However, completely clean and cheap technologies may take a long time to arrive, so it is still sensible for the entire human race to reduce carbon emissions.

So far, countries have been making breakthroughs in renewable energy, from which hydrogen power has gradually entered the public's vision. Hydrogen was the lifting gas for airships, a type of aerostat or lighter-than-air aircraft that can navigate through the air under its own power prior to the development of fuel-burning airplanes, due to its high lifting capacity and ready availability. [2] Nevertheless, since the hydrogen airship was put into use, explosions have occurred continuously, and countless passengers and crews have been killed. With the Hindenburg Airship's fire during landing in 1937, public confidence in the giant, passenger-carrying airship was shattered, marking the abrupt end of the airship era. In recent years, with the development in renewable energy, hydrogen has been used in other areas, for example in the transport sector, holding many intrinsic advantages as an energy carrier. At present, according to statistics, the global annual hydrogen production capacity is about 75 million tons, and China's hydrogen production capacity is a quarter of it. In foreign markets, hydrogen production is mainly from natural gas, accounting for about 75%; In China, hydrogen production is mainly from coal, accounting for more than 60%.

1.2 Research Question

The research question for this paper is aimed at understanding the potential of hydrogen as a source of energy. This paper will provide an overview of advantages and disadvantages of hydrogen power, analyzing policies that should be implemented, evaluating the prospects of the hydrogen industry in China based on the support from the Chinese government.

2. Pros and Cons of Hydrogen Power

2.1 Advantages Compared to Other Fuels

Climate change and air pollution have become particularly serious problems both to human health and to the environment. This situation is the direct result of considerable and continuous release of combustion products provided from energy systems (especially fossil fuels) in the atmosphere [6]. Hence, the necessity of renewable energies is made apparent, and the importance of making a switch to renewable energy that could allow a reduction in toxic gas emissions is stressed. Among all renewable energy including solar and wind power, lithium iodide, and biomass, hydrogen has some outstanding merits.

To begin with, from the perspective of energy density and costs, hydrogen batteries have more advantages than lithium batteries. In the comparison of energy density, hydrogen batteries are 100 times more efficient than lithium batteries, which indicates a significantly lower power loss per day. Lithium batteries have an energy density of about 220 wh/kg, which can rise to 500 wh/kg only when technology is available for semi-solid and solid batteries. However, this is not possible within five years. Moreover, from the perspective of cost, hydrogen batteries are more suitable for wide scale and long term uses than lithium batteries. Although the cost of lithium batteries has decreased by 80% in the past few years, the cost of energy storage has not decreased linearly. The larger the scale of lithium batteries, the higher the power consumption and cost. On the contrary, the larger the scale and the larger the single tank of hydrogen, the more economical it is to use the compressor.

In addition, hydrogen energy avoids many of the disadvantages of solar and wind energy. First, it is difficult for solar and wind energy to guarantee a stable and continuous power supply. Night weather and cloudy, overcast and stormy conditions limit the amount of light that would otherwise be absorbed by solar panels, and the intermittency associated with fluctuations in insolation availability affects grid stability. Significant wind changes, such as daily and seasonal variations, can also affect grid stability. Therefore, in order to ensure a stable power output, it is necessary to connect to a backup power source such as the local utility grid, or consider the addition of an energy storage or thermal power. Yet, this makes it difficult to escape the dependence on energy sources that generate large amounts of carbon emissions, hence rendering solar and wind power for sourcing electricity less clean due to their instability. In contrast, hydrogen energy is less affected by the fluctuations of the environment, be it the weather or number of daytime hours, because hydrogen is not driven by natural forces, but is a secondary energy made from other energy sources, which are stable and sustainable.

Second, wind and solar energy have negative impacts on the ecology and the environment. The use of land in the solar sector is vast, and it is not feasible to share land for agriculture. The mining and production of materials needed for photovoltaics in solar panel production also affects land use. The metal compounds in solar panels contain many highly toxic elements, including cadmium and lead. Not only that, other toxic and harmful substances are also used in the production process of solar panels, including gallium arsenide, hydrogen fluoride, sulfuric acid, acetone, trichloroethane, etc. Although many photovoltaic products are manufactured in China, the current disposal of these hazardous substances is still inadequate, and manufacturers irresponsibly dump them on farmland, polluting the air, water, and soil. On the other hand, wind farms also have a serious impact on the ecological environment. Wind farms lead to the loss of habitat and the dwindling biodiversity around it, with the impact on birds being particularly pronounced. Studies have shown that bird populations around wind farm sites typically drop by 10 percent; around 80 golden eagles and 400 vultures collide with wind turbines each year around wind farms in Altamont Pass, USA; wind towers built closer to bird migratory pathways were found to cause more bird deaths; in grasslands with no wind turbines or at a distance of more than 80 meters from wind turbines, bird population densities were significantly higher than in wind farm areas. This demonstrates the significant hazards of wind farms to bird survival, migration, and habitat. In contrast, blue and green hydrogen energy has no negative impact on the environment and ecology. According to statistics, hydrogen (blue hydrogen) produced by reforming natural gas will cause carbon emission of 10 - 12 kgCO2 / kgH2, and hydrogen (green hydrogen) produced by electrolyzing water from renewable energy will not cause any carbon emission. Hydrogen production can be carried out in conventional chemical plants, delivered by pipeline and trucks, without disrupting the ecosystem.

To sum up, hydrogen energy has more advantages than lithium battery, wind energy and solar energy. Compared with lithium batteries, hydrogen batteries have much higher efficiency and less power loss; in addition, hydrogen energy is more suitable for large-scale and long-term use. Compared with wind energy and solar energy, hydrogen energy is cleaner and more stable, as it overcomes the limitations of solar energy and wind energy: they do not guarantee a stable, continuous power supply, and they do not reduce our dependence on carbon. Secondly, the carbon emissions of grey hydrogen (after the use of carbon capture technology), blue hydrogen and green hydrogen are less; production will not damage the ecosystem. In contrast, the highly toxic elements used in the production of solar energy are usually not well disposed of, and the turbines in the wind farm have led to the reduction of biodiversity around it.

2.2 Advantage: Growing Market Demand and Declining Production Costs

Hydrogen is used in refining oil and producing fertilizers, methanol and steel. In recent years, there has been a growing demand for hydrogen as a fuel for vehicles and factory uses, and with this comes great market potential.

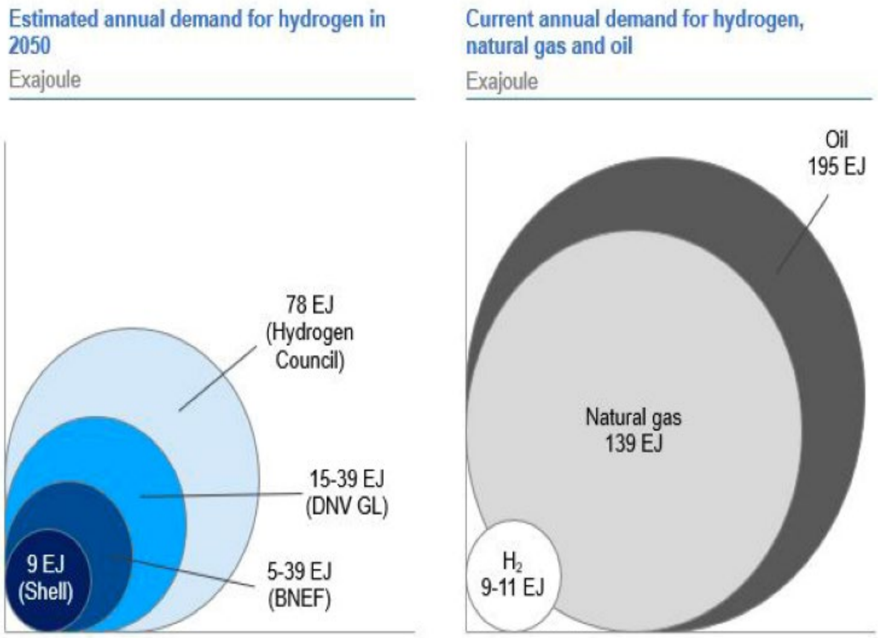

Figure 1 Hydrogen Market in 2050. (Hydrogen Council 2017, Bnef 2019, Dnagl 2018, Shell 2018, Iea 2019, Bp 2019) [1]

As shown in Figure 1, China's current demand for hydrogen is very limited, at between 9 and 11 Exajoule, compared to 139EJ for natural gas and 195 EJ for oil. [1] By 2050, it is estimated that the world's demand for hydrogen will grow exponentially. Excluding the most conservative prediction by Shell, other estimates put the demand for it at 39EJ (by BNEF), 39EJ (by DNV GL) and as high as 78 EJ (by Hydrogen Council). [1] If the hydrogen industry is allowed to grow, it will surely become a major supplier of energy in 2050, so there is great potential in tapping into this market.

Although in the last few years electric vehicles that are powered by batteries have gained momentum in China, they pose a serious problem: traditional batteries, which store electric energy by using lithium ions, pollute the environment. As a result, the government of China has decided to make the production of fuel cell vehicles an option.

At the same time, there are good reasons to believe that the costs associated with the processes of hydrogen production will decline. Currently, China's coal-based method remains the lowest-cost one, but as coal is a source of pollution, contributing roughly 20 tons of CO_2 for every ton of H_2 [1], it is critical for China either to reduce the carbon emissions from this method or to change to renewable energy. At present, the government regards nuclear power as a source of clean energy that can help combat air pollution and achieve its carbon neutrality goals. As a result, it is constructing or planning 50 more nuclear plants. Research and development are also under way to achieve technological innovation and mass production. State-own companies are already investing in relevant technologies, for example by adjusting pipelines transporting natural gas to accommodate the transmission of hydrogen.

2.3 Disadvantages: the Availability of Freshwater and a Lack of Infrastructure

One disadvantage is the availability of freshwater. A nation's supply of freshwater is deemed scarce if its annual freshwater supply is below 800m^3 per resident. For such a nation, the dominant uses for water should be for drinking, domestic consumption, and irrigation.

The water resources map, as issued by China Water Risk Project in 2017, shows that generally China's water supply per capita is high in the south and north, but is low in central China where there is a large population. However, China's water distribution is not even, and freshwater varies significantly across the country. In the north, urban and industrial needs for water are considerably high, affecting water availability for hydrogen production. This situation is compounded by the fact that China is undergoing urbanization and industrialization at a high speed. As a result, many provinces including Beijing, Gansu, Shanghai, Liaoning among others are already facing freshwater shortages. In the southwestern and southeastern regions of China, the availability of freshwater is high. However, these are the regions where there is a lack of proper infrastructure.

Statistically speaking, the impact of the amount of water used for producing hydrogen is limited when compared to the amount of total fresh water available worldwide. Only 9 kilograms of water should be consumed to generate one kilogram of hydrogen; globally, 20.5 Gt of fresh water, or 20.5 billion m^3 is required to produce 2.3 Gt of hydrogen annually, making up merely 1.5 ppm of the Planet's freshwater. [1] However, if China is to develop a completely green economy based on hydrogen, it must take into consideration many freshwater factors such as the locations and delivery of freshwater across the country as well as the possibility of obtaining it from seawater through desalination facilities. There is concern that obtaining freshwater to produce hydrogen would be too costly and demanding from an economic perspective.

Besides, lack of infrastructure and technology is also a problem. In order for China's hydrogen industry to mature, a sound infrastructure is needed for varied purposes, such as production, transportation, and refilling. Although there are projects underway to build infrastructure, they are far from enough if this country is to possess a hydrogen economy of scale.

Currently, China has only a few factories that are capable of producing hydrogen, and these facilities are not technologically advanced enough. On the one hand, they produce hydrogen from coal, and lack the proper facilities to capture the carbon emitted from the production processes. This means pollution. On the other hand, they lack the economic incentive to innovate new technologies as the market is currently small.

In terms of transportation facilities, there are a few state-owned companies that are adapting natural gas pipelines to transport hydrogen, but they are small in number and their carrying capacity is limited. The main means of transportation in China is by trucks, which have huge containers that are specially designed to hold liquid hydrogen. But this means of transport has proved inefficient. If China is to develop the hydrogen industry, it will have to invest a large amount of capital for that purpose, and that depends on political willingness.

Equally important are refilling stations, facilities that can improve consumers 'confidence and satisfaction in using hydrogen. At present, the fueling time can be shortened to as little as 5 minutes, making the process as efficient as that of a petrol-powered car. However, there is a dearth of fueling stations around the country, a concern for the owners of electric cars powered by hydrogen fuel cells.

2.4 The Biggest Challenge--Hard to Obtain Renewable Energy

Although hydrogen is the most plentiful element in the solar system, it is difficult to obtain on Earth as it exists mainly in compounds such as water. Normally, there are three ways to produce hydrogen from their compounds: thermo-chemical reaction, biochemical reaction, and water electrolysis.

However, the specific production processes are not always clean. Hydrogen derived from renewable energy such as biomass, solar and wind and from water electrolysis is clean, with the resulting carbon emissions standing at zero or below 5 kilograms for every kilogram of hydrogen produced; by contrast, hydrogen derived from fossil fuels such as natural gas, coal, and oil is called gray or black hydrogen because these fuel sources, when used to produce hydrogen, also release carbon. In the case of China, coal is its main fuel used to produce hydrogen because it is easily available and 30% cheaper than from natural gas. The amount of carbon emitted for hydrogen production processes that use coal or grid electricity can reach as high as 25-30 kilograms per kilogram of hydrogen [1].

According to Wang Cheng, an expert in the field of hydrogen production, China's ability to produce completely green hydrogen is hampered by low-level technology, small-scale production, and high costs. Green hydrogen is obtained by using renewable energy sources, by electrolysis or chemical reactions. Although electrolysis is technologically advanced for producing hydrogen, it requires large amounts of electricity. To produce 1 kilogram of hydrogen, 60 kilowatt-hours are required. In order for green hydrogen to become competitive with gray hydrogen, the price of electricity would have to go as low as 0.2 yuan per kilowatt-hour.

Therefore, the biggest challenge facing China is how to shift from a carbon-based production process to one based on renewable energy or nuclear energy. In the middle term, coal, along with facilities that can capture and sequester carbon, will remain the most economically viable source for producing hydrogen. In the long term, as China is committed to its carbon neutrality goals set forth in its Five-Year Plan and as China is supporting this industry with policies, it is likely that the production of hydrogen will be clean, not resulting in carbon emissions.

3. Governmental Policy Analysis (Subsidy)

When hydrogen industry expands and numerous producers enter in and compete with others, a competitive market forms and externalities occurs. Currently, it could be said that subsidies are being enacted for two reasons: to correct positive externalities caused by the consumption of hydrogen power and increase consumers 'knowledge and exposure to hydrogen so as to better accept them as a replacement. However, the degree to which both reasons make up for the subsidies remains uncertain, because over time subsidies for the sake of increasing exposure should plateau, leaving behind only the externalities as a reason. Hence, subsidies should be adjusted over time.

Today, hydrogen power can be used for electricity, transportation, and heating. Taking the transportation sector as an example, fuel cells can be put into use. For consumers, they could enjoy the efficiency of it: a 50% reduction in fuel consumption, a 30% increase in electricity generating compared with traditional fossil fuels, a faster charging time (only takes five minutes to be recharged) and a longer usage time. In terms of spillover effects to the society, fuel cells present powerful advantages. For families, every member can enjoy the convenience of fuel cells transportation, and will not have to worry about charging and duration. For the society, as the byproducts of fuel cells are simply water and heat, no adverse environmental impacts will be entailed. With almost zero emissions, fuel cells do not generate greenhouse gases, thus having no carbon footprint while using and improving air quality, which benefit the society as a whole.

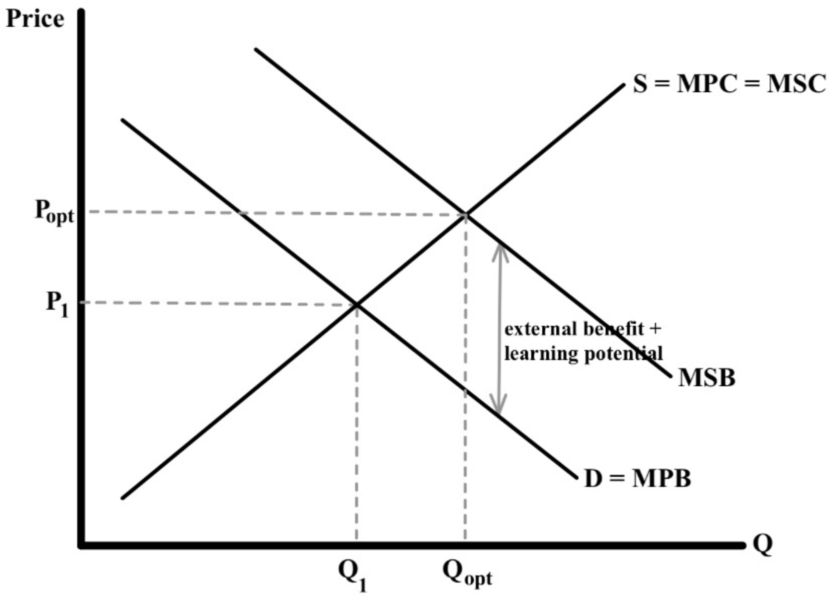

Figure 2 Positive Consumption Externality and Learning Potential in the Hydrogen Fuel Cells Industry under Perfect Competition

Figure 2 shows the positive consumption externality and learning potential of hydrogen fuel cells industry under perfect competition. MPC and MSC are equal because there are no positive or negative eternality generated in production (assuming hydrogen used are produced by natural gas, electrolysis from renewable electricity, as an industrial byproduct, or the carbon dioxide emission during production is cancelled out). The MSB curve lies above the MPB curve, due to the positive spillover effect of hydrogen fuel cells in terms of environment and efficiency [2] and the learning potential for getting customer more used to hydrogen power and realize its benefit. The point where MPB and supply curve intersect represents the quantity produced in the market currently at P1. The socially optimum quantity, Q_{opt}, is the point where MSB equals to MSC at P_{opt}. As $Q_{opt} > Q_m$, resources are under-allocated by the market to hydrogen fuel cells, and too little of it is produced to reach the social optimum.

Hence, a subsidy should be granted. According to Ellie Tragakes, a subsidy refers to “the assistance by the government to individuals or groups of individuals, such as firms, consumers, industries or sectors of an economy.” [3] It allows firms to increase their productions and enables consumers to purchase hydrogen products with a lower price and thus to buy more.

China is now striving to kickstart its hydrogen economy and reaching the goal of 1 million hydrogen fuel cells and more than 1000 hydrogen filling stations by subsidies. In February 2018, China adjusted subsidies for new energy vehicles and established that fuel cell passenger vehicles are subsidized according to the rated power of the fuel cell system. The government will provide ¥6,000 subsidy per kW with an upper limit of ¥200,000 subsidy per vehicle. In September of 2020, the Chinese government said they would subsidize the value chain for hydrogen fuel cells around the three qualified city clusters: Beijing, Shanghai, and Guangdong. Within the four years demonstration period, each of these clusters could receive up to ¥1.5 billion for fuel cells and another ¥200 million for hydrogen supply chains.

Economically speaking, such subsidies could help with the full expansion of hydrogen industry in China. Because subsidies can assist firms to cover some of their production costs and thus increase the quantity of output produced, it makes hydrogen products more affordable for lower income people (as it lowers consumer paying) and promote the overall growth of hydrogen industry.

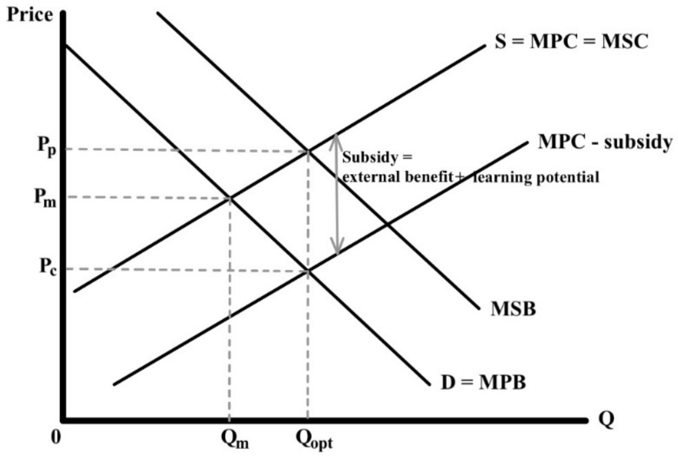

Figure 3 Subsidy for Hydrogen Fuel Cells and Hydrogen Supply Chain in China

As shown in Figure 3, the pre-subsidy equilibrium represented by the intersection of demand curve(MPB) with supply curve(S=MPC=MSC), both determined by the market, bringing about the equilibrium price P_m and quantity Q_m. A subsidy that is granted to the producers of hydrogen fuel cells and supply chain could correct the positive consumption externality and increase hydrogen power's exposure to customers by shifting the supply curve rightward. Provided that the subsidy equals to external benefit of consumption, the new supply curve will be MPC - subsidy (using subtraction as subsidy works to lower the cost of production), and optimum level of output is produced. [3] Allocative efficiency is achieved as subsidy is designed correctly, with price falling from P_m to P_c and quantity demanded increasing from Q_m to Q_{opt}. [3]

In the short-run, demand for hydrogen products is price elastic as it's not a necessity and there are plenty of substitutes; any changes in price will result a relatively large response in quantity demanded. Supply for hydrogen products is price inelastic, as its production requires high technical skills and the amount of time needed to shift factors of production is relatively long. However, in the long run, demand and supply will both be elastic with sufficient time for consumers to change their purchasing habits and all factors of productions can be adjusted.

In terms of impacts to stakeholders, consumers, producers, and workers are all better off. For consumers, they are able to enjoy the lower price P_c, which allow them to purchase more hydrogen products. For producers, they receive the price at Pp, which includes consumer paying and subsidy per unit of output, and therefore allow them to produce at the socially optimum quantity. For workers, as producers are willing and able to produce more hydrogen fuel cells, more employees should be hired to help them increase their production, and thus making people who find new jobs better off.

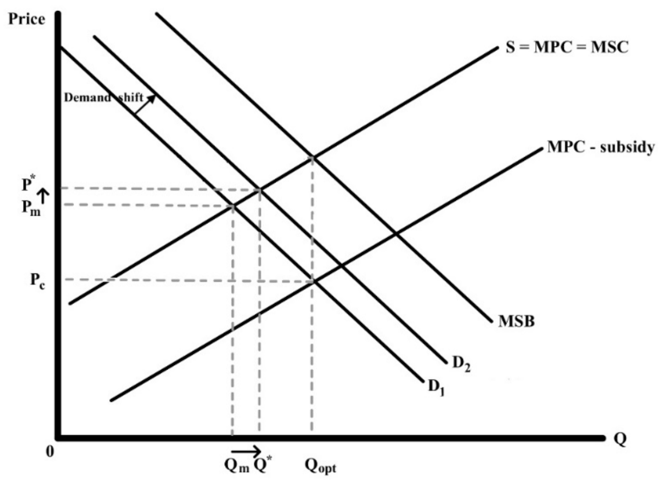

Figure 4 Subsidy for Hydrogen Fuel Cells and Hydrogen Supply Chain in China in the Long-Run

In Figure 4, hydrogen subsidies cause more consumers to learn about the product and encourages them to switch to hydrogen as an alternative energy, shown in how demand shifts to D_2. Currently, hydrogen is unheard of to many consumers who may be wary of its utility as a replacement for traditional energy sources. However, with decreased prices, this would encourage more consumption, and with more consumers having learnt of hydrogen, over time, they would be more comfortable with using it and demand would shift right, with price increase from P_m to P^*, and quantity demanded increase from Q_m to Q^*. The subsidy can be reduced accordingly. However, as recipients of hydrogen may consider subsidies as their right and entitlement, its difficult for governments to adjust it. Thus, when governments want to remove such subsidies, they will be likely to face oppositions by the beneficiaries, who will fight hard to keep subsidies, which forms a dilemma.

Experts hold different views toward hydrogen fuel cells subsidies not only considering it from merely the pros and cons of subsidies, but from long term perspective. While some experts think that hydrogen program is "an attempt to establish an industry chain and promote fuel-cell vehicle development" [4], others suggest that Chinese government should seek better approaches to create a hydrogen market in the long term, as subsidies are not only justifiable during the infant stages of the industry, but also for the improvement of health and reduction of negative externalities in the long-run. [4]

Additionally, it may also be difficult to correctly measure the size of external benefit and therefore to determine the level of support. If there is too much subsidies, there may be overproduction or increased inefficiency and dependence, and considering subsidies may become more difficult to adjust over time as firms may demand continual subsidies for the sake of profit and other private interests, this may deter efficiency to both private sectors and the economy over time. Hence, the right amount of subsidy needs to be ensured, so that the firms which survive should be the efficient ones, and there should be invest interest to keep subsidy and make the entry for these subsidies more difficult over time. as show in Fig.5.

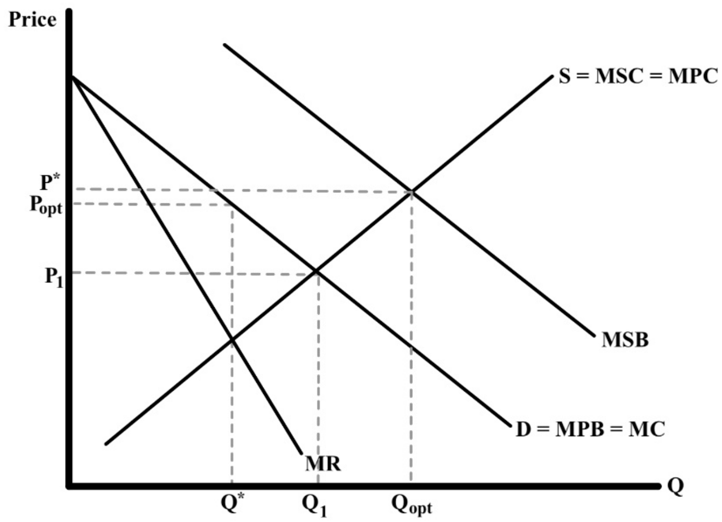

Figure 5 Positive Consumption Externality and Learning Potential of Hydrogen Fuel Cells in a Monopolist Industry

However, the above mentioned may differ depending on the market structure of the hydrogen fuel cell industry in the country, such as in monopolistic industries where there are fewer producers and barriers to entry in the industry is heightened.

In a monopolist industry, the government would designate a firm to produce hydrogen fuel cells and grant this firm a subsidy to cover part of the cost of production. Even when there is no negative externality, the producers would still produce at a quantity at Q^*, that is lower than both Q_{opt} and Q_1 (perfect competition), because their monopoly power allows them to produce at where marginal revenue intersects marginal cost. Likewise, this would also occur even when subsidies are present, as shown in Fig.6:

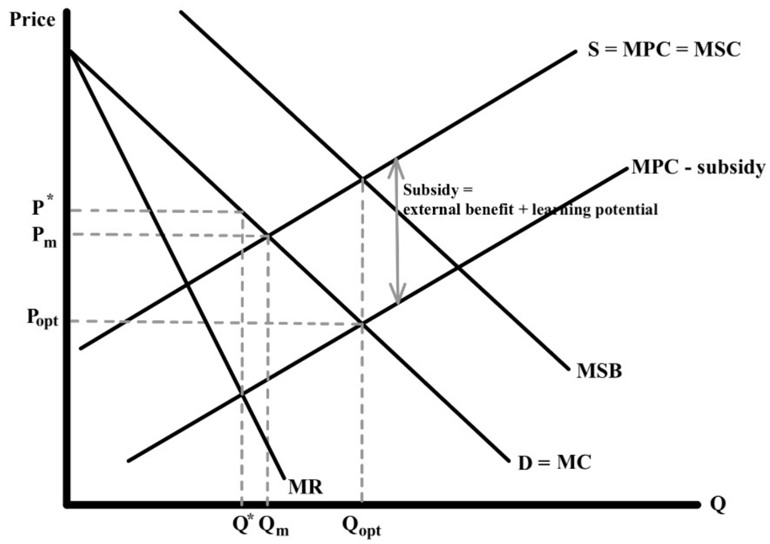

Figure 6 Subsidy for Hydrogen Fuel Cells in China in a Monopolist Industry

This means they will limit the production of hydrogen fuel cells due to the nature of their industry. Meanwhile, the monopolist would also choose to charge at a higher price at P* instead of Popt or Q1, because they are able to receive an increased price at where D=AR rather than at MR=MC due to their price-setting power.

This difference in effect between the two extremes of the market structures suggests to government decision and policy-makers that the interventions they choose should take into consideration the market structure. In addition to subsidies, regulation is also essential. Grey hydrogen produced from coal must be carbon captured, otherwise it will create negative production externalities, which frustrate the objective of mitigating climate change.

4. Prospect of Hydrogen Power

The prospects of the hydrogen industry becoming a competitive source of energy are high in many of the world's major countries including China. Possibly 30 years from now, technology will progress to a point where mass production of hydrogen is possible and where hydrogen will be made affordable for commercial car use. Two factors are essential for its success: supporting policies and technological advances.

In 2018, a total of 64 million tons of hydrogen was produced globally, and China's production accounted for 26.6% of this amount [5]. In the world, the main source of hydrogen production was natural gas. However, China relied heavily on one of its most easily available, yet nonrenewable sources--coal, so hydrogen production in this country is not clean and may make climate issues more severe. China therefore needs to upgrade and transform its hydrogen production process.

ure 7. Source of hydrogen in 2018 [5]

The pie charts clearly show that while hydrogen production relied mainly on natural gas (at 48%) worldwide, China's coal-derived hydrogen accounted for as much as 59%. Burning coal to produce hydrogen surely has a greater impact on the environment than using other natural resources, and runs counter to the carbon neutrality goals set in China's 14th five-year plan. Indeed, apart from increasing investment in hydrogen as it is a renewable and cleaner source, China has inked the hydrogen industry into its 2021-2025 period plan, and juxtaposed it with another five main industries[6].

China is committed to the carbon reduction goals set by the United Nations, and the following moves are thought to be able to promote the hydrogen industry.

Firstly, it is seeking to establish a coordinated infrastructure and network at the national level that meet the needs of the production, transportation, and use of hydrogen. At the production end, hydrogen has long been successfully produced and has a niche market. Though the facilities for producing, storing, transporting, and using hydrogen are not advanced enough, frontier technologies are being developed. At the transportation end, there are plans to create a network that delivers hydrogen nationwide. Pipelines would be the most efficient way of delivering hydrogen nationwide, compared to other modes of transport such as trucks. China is willing and able to build a pipeline network that fulfills this purpose. In 2021, the China National Petroleum Pipeline Engineering Corp successfully won the bid to design a hydrogen transportation pipeline that runs 7.4 kilometers and that blends hydrogen and natural gas. Also, another state-owned company--PipeChina--has included hydrogen pipeline research in the national 14th Five-Year Plan. Other companies like China Petroleum and Sinopec are also planning on building infrastructure including filling stations. Currently, China has two hydrogen pipelines that are in operation. Also, it is predicted that more pipeline projects are likely to be initiated in the following years. The per-kilogram cost of pipeline transport will be six times lower in 2050 than in 2030 because the utilized capacity will increase and there will be economies of scale[7].

Secondly, as technology improves, hydrogen will be able to be mass-produced at the commercial level, and its price is predicted to go down to compete with today's dominant fuel--petrol. Hydrogen prices have been increasing slightly in recent year, due to the effects of COVID19 pandemic. Indeed, given today's technology, hydrogen production costs are high, and compounded by inaccessible and expensive storage and delivery, hydrogen that is used to power a fuel cell car in China costs as much as 70 yuan per kilogram. Normally, the cost of hydrogen as a fuel in the Chinese market ranges between 40 and 70 yuan per kilogram, much higher than diesel and petrol[8].

However, it is predicted that if the costs of solar and wind production drop to $20 per MWh, and if the costs of electrolyzers decrease by about 40%, then the cost of producing hydrogen from renewables will decrease by over 50% to around $2.5 per kilogram by 2030. [3] If so, hydrogen will be a viable energy source. According to Jiang, by 2025, the costs of hydrogen used to power trucks will be competitive against gas and oil because by then hydrogen derived from renewables will be less than 30 yuan a kilo. [9]

In the future, the transportation cost will go even lower, and the cheapest hydrogen will be made from cryogenic liquid. If it is delivered within a radius of 800 km, given the transportation demand is 30 tons a day, the lowest possible hydrogen cost for fuel cell vehicles will be as low as 2.15 USD per kilogram[10].

5. Conclusion

Hydrogen as a fuel has grown in popularity because it will be a permanent, fundamental solution to our current environmental problems resulting from the burning of fossil fuels and from global warming.

Hydrogen has a multitude of advantages over other forms of energy. It is more stable and cleaner than wind and solar energy because it guarantees a steady supply of energy and its production processes have minimal impact on the ecosystem. It is more energy intensive and loses less energy when burned than lithium-batteries, and therefore are more suitable for large-scale and long-term uses. Besides, the market for hydrogen is expected to grow exponentially, and at the same time the costs associated with producing hydrogen are projected to further decrease thanks to the Chinese government's subsidies in this market. However, the path to a hydrogen-economy is fraught with problems. One would be the scarcity of freshwater, whose uneven distribution across China poses challenges to hydrogen production. Another would be a poor infrastructure, a lack of high technology, and a lack of economic incentive; these factors mean low efficiency in transporting hydrogen and difficulty in commercializing hydrogen products. The greatest challenge would be a shift from a coal-based hydrogen industry to one based on renewable energy, due to high costs, inadequate production capacity, and simple technology.

Subsidies for the hydrogen sector are vital to its long-term survival. There is evidence that hydrogen products, such as hydrogen fuel cells, having positive externalities in terms of the environment and increase efficiency. The hydrogen industry's market resources are insufficiently distributed, and supply is not effectively encouraged. Furthermore, as prices fall, demand will rise, and people will be better educated about hydrogen and embrace it as a viable alternative to traditional fuels. Subsidies should be adjusted over time, especially when the industry has developed or when monopoly emerges. Heavy subsidies, on the other hand, will only stifle the growth of this industry. Furthermore, the hydrogen industry's market structure has an impact on output and pricing. Monopolies, for example, will offer hydrogen items at a higher price than equilibrium due to their market power. As a result, while deciding on preventative actions, policymakers should examine the effects of market structure.

In summary, in the next three decades or so, hydrogen is likely to become China's next significant source of energy. Because hydrogen is currently the primary viable solution to climate change and greenhouse emissions, the Chinese government will continue to support this field. China is determined about expanding its hydrogen sector with subsidies and favorable policies; it also committed to build coordinated infrastructure and network to meet the needs of hydrogen production, transportation and application. Also being researched and developed are technologies that can assist decreasing manufacturing costs and consumer prices, and will eventually be mature enough to allow economies of scale.

In the future, investigation into hydrogen power could be carried out from other perspectives. Firstly, due to the difficulty in obtaining data, current research is mainly carried out from two perspectives of economic theory and qualitative analysis. In the future, mathematical models can be used to quantitatively analyze the factors hindering the development of hydrogen energy, so as to judge the prospects of it. In addition, the research can also dig into the micro enterprise level and analyze the possibility of existing enterprises to transform to produce hydrogen power and flourish. Finally, the advantages and disadvantages of developing and developed countries in producing and using hydrogen energy can be compared, so as to analyze how should they develop their hydrogen industry.

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