Pathway Towards Integration of Green Hydrogen Into Society

A Research Paper submitted to the Department of Engineering and Society

Presented to the Faculty of the School of Engineering and Applied Science

University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements for the Degree

Bachelor of Science, School of Engineering

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Spring 2024

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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STS Research Paper

1. *Introduction*

As climate change continues to harm communities and environments, it is increasingly important to engineer solutions to power the world which assist ongoing decarbonization efforts. More specifically, policy makers and engineers have aimed to accomplish this goal through reducing cultural reliance on carbon-emitting fossil fuels as our predominant source of energy. As a replacement, a clean, carbon-neutral energy source such as hydrogen should be adopted. This shift, from fossil-fuel based to hydrogen-fueled power, is outlined in the Paris Agreement, which plans to reduce global carbon emissions by 40% by the year 2030 (Alanne et al., 2021). Ultimately, this plan was designed to keep the Earth below an 1.5^{o} C temperature increase, at which environmental disaster would occur. This disaster may include exacerbation of the current economic crisis, loss of biodiversity, increased forest fires, hurricanes, droughts, and beyond. Unfortunately, the current global rate of carbon emissions is projected to result in this 1.5^{o} increase by the year 2040 (Hodgson, n.d.). Therefore, immediate attention and efforts are required to mitigate this ongoing crisis.

Green hydrogen, as a solution, has attracted substantial interest as an energy source because it is both, by definition, carbon-neutral in production and carbon-neutral in its usage as a fuel. With the introduction of a “green hydrogen economy” to replace fossil-fuel reliance, comprising 84% of the current energy consumption market (Ma et al., 2023), environmental disaster could be avoided by decreasing carbon emissions between 90-99% (University of Reading, n.d.). Novel processes such as green hydrogen, however, are required to mitigate economic, social, and governmental barriers associated with this process. Therefore, green hydrogen faces multiple challenges which must be overcome before the development of a hydrogen-centric society. Firstly, there is a severe lack of governmental legislation, incentives and regulations to facilitate the initial development of green hydrogen facilities. This lack of information, necessary for both companies and governments, leads to safety concerns, large inefficiencies and consequently monetary losses in production, further dissuading the start-up of green hydrogen processes. Governments have also placed an underwhelming effort into educating the public on hydrogen as an energy source, leading to misconceptions and unnecessary concerns about its function. As a result, many people currently believe that hydrogen poses a hazard to their safety as a fuel and is not worth paying for as a form of renewable energy. Finally, minimal to no large-scale hydrogen infrastructure exists, further prohibiting the development of a hydrogen-centric economy. Because of this, the sociotechnical component of this paper will discuss how governments can facilitate the implementation of green hydrogen as fuel through development of regulations, new usage of infrastructure, efforts to change public perceptions as well as in reducing reliance on fossil fuels. Additionally, this paper will explore how the creation of legislature surrounding hydrogen production can influence other governments, increasing the rate of development of a green hydrogen based economy.

2. *Background and Significance*

As briefly explained above, implementation of green hydrogen as a clean, alternative energy is as critical as it is challenging to combat global warming and other societal implications. Current reliance on fossil fuels as sources of energy is the main contributing factor to carbon emissions, accounting for around 75% of total greenhouse gasses released into the atmosphere (United Nations, n.d.). These fossil fuels, specifically referring to coal, oil, and natural gas, are burned for energy, releasing carbon dioxide, methane, and other gasses into the atmosphere. As carbon dioxide is responsible for the greatest warming effects in our atmosphere, greenhouse gas emissions are often used interchangeably with carbon (dioxide) emissions. These gasses effectively work as a blanket, trapping sunlight reflected off the Earth within the atmosphere, damaging our environments and resulting in what we know as "global warming".

Issues with modern fossil fuel usage extend beyond carbon emissions and climate effects. Excessive fossil fuel burning often leads to smog and hazardous air quality levels, killing 4.2 million people (Koch & Klitzman, 2023) around the world yearly. Moreover, fossil fuels are finite in their usage as a natural resource. Estimates between sources vary, but it is generally predicted (using current consumption rates) that there are only 70 remaining years of coal, 50 years of oil, and 40 years of natural gas left (Stanford University, 2023). As the population on Earth grows and develops, energy usage will continue to increase, meaning fossil fuels will no longer be a sustainable solution to meet future energy requirements.

Beyond supply limitations, the finite nature coupled with cultural reliance on fossil fuels also poses as a method for countries to gain and utilize political leverage over others. This dynamic was recently observed in February of 2022 during the Russian invasion of Ukraine. In response to this invasion, most European countries sided with Ukraine, imposing Russian economic sanctions to condemn this activity. However, Russia is a heavily net gas-exporting country for most of Europe, with the European Union (EU) importing over $100 billion of Russian energy in 2022 (Cooban, 2022). Consequently, the EU was unwilling to stop purchase of gasoline from Russia, as this type of instability could have exacerbated high inflation rates at the time. The cutoff of supplies, additionally, could have sent the more heavily Russia-reliant countries (such as Germany) into a recession. The presence of fossil fuels in Russia, therefore, wields the country political power to assist or harm the economy of other countries.

Conclusively; fossil fuels have many issues associated with their use, extending far beyond simply climate change, and society should transition towards a greener, more sustainable solution.

Unfortunately, renewable, or green, energy as a whole is an extremely novel industry. Although significant progress has been made, with a 50% increase in electrical capacity from 2022 to 2023, renewable energy still only produces around 29% of current energy globally (IEA, n.d.). Of this renewable energy, the majority is produced through methods such as hydropower, wind energy, solar energy, or bioenergy. However, despite the benefits of clean electricity, each of these technologies has significant drawbacks. Hydropower, for example, is the largest source of renewable energy in the electricity sector, but has unfortunately been known to damage surrounding marine wildlife and local ecosystems. Solar panels required for solar energy are extremely bulky and contain heavy metals considered as "hazardous waste", creating expensive specialized labor costs. Bioenergy, ironically, releases carbon dioxide in use, in addition to consuming up to a copious 20,000 liters of water in processing per liter bioenergy produced. This dilemma proves to be similar to the most prevalent and cheapest hydrogen production method, gray hydrogen, which uses fossil fuel-derived electricity in production. Consequently, in use as a renewable energy source, it releases greenhouse gasses.

These drawbacks bring light green hydrogen as a promising energy alternative. In this technology, hydrogen is produced through a process called electrolysis, where water is split into hydrogen and oxygen components using a clean, renewable energy source as electricity. This electricity is commonly sourced from wind turbines. This hydrogen is then supplied to a fuel cell, where it is split into protons and electrons. These electrons then flow through an external circuit, producing electricity to be (potentially) used within applications such as cars, power plants, and beyond. Green hydrogen fuel cells offer numerous advantages over existing renewable energy sources. The only byproducts released are water and heat, making the process entirely pollutant and carbon-free. Hydrogen-based fuel cells have the potential to be over 2 times more efficient compared to traditional systems, and do not require “re-charging” as an energy storage system as is needed for batteries or capacitors (Connecticut Hydrogen Fuel Cell Coalition, n.d.). Intermittency issues, as seen with other renewables such as wind and solar energy, do not apply to green hydrogen. The small size of the fuel cells, additionally, allows for flexibility and portability in installation and operation. For these reasons, green hydrogen is the renewable energy solution which should be implemented into today’s society to mitigate ethical and environmental issues.

3. *Methodology*

This paper will use multiple STS analytical frameworks to answer the presented research question of how to implement green hydrogen into society as a replacement for traditional fossil fuels. The first framework which will be utilized is the “Technological Momentum” framework. This framework explains that, for societies to adopt a new technological system, it must first align with the current social goals and context (Hughes, 1983). As large sociotechnical systems gain “momentum” in society, they are increasingly resistant to change and difficult to replace. It is, therefore, preferable for corporations, governments, consumers, etc. to innovate these existing sociotechnical systems “around the edges” rather than starting from scratch (IEEE, n.d.). To foster development of new technologies, societies must invest money, effort and resources into acceptance of these new systems; for example, governments investing money in the creation of supportive infrastructure to allow new technologies to grow and gain momentum over pre-existing systems. Green hydrogen currently has an extreme lack of infrastructure, including storage and transportation, in addition to facing the massive momentum of societal reliance on fossil fuels. In analysis, literature reviews will be conducted to understand the existing state of green hydrogen's development, and what specific investments and innovations are required to facilitate acceptance of this technology.

The next theory which will be used to analyze the research question is "Diffusion of Innovation". This framework allows readers to determine the speed at which different societies accept new technologies and ideas, and requires understanding of the target populations to understand who will be the slowest and fastest adopters of new technologies (Boston University School of Public Health, 2022). A literature review will be conducted on the expected adoption pathway of green hydrogen, primarily within the context of different countries due to differing economies, and resource levels. In addition to this, a case study will be performed on the adoption of green hydrogen regulations, its expected pioneer countries, and the expected diffusion pattern. This will be primarily based on current hydrogen capabilities that exist within a country-to-country basis.

The final STS analytical frameworks that will be used are the "Relational View" and "Cultural Lag". The "Relational View" helps to explain how relationships between people and technology are affected by external factors (Leonelli, 2015), and "Cultural Lag" discusses the lag in time between development of new technologies and societal acceptance, in terms of social norms, values, and public perceptions about these new technologies (Godin, 2010). These frameworks, together, will focus on understanding how public opinion of green hydrogen can be improved. Primarily, this will be done through the use of interviews and surveys. These interviews and surveys will be taken from multiple populations to avoid biasing results towards certain groups. In addition, a case study on nuclear energy developments will be performed. This case study will provide insights on why this technology has received negative social opinions, as a "risky" innovation for energy production, and how lessons learned from experiences with nuclear energy can facilitate a smoother pathway for green hydrogen's implementation.

4. Literature Review and Discussion

Using the analytical techniques described above, the research question will be better understood and answered, proposing the most effective methods and changes which are necessary to successfully implement green hydrogen into society as a primary source of energy. The largest obstacles which green hydrogen must overcome are a lack of infrastructure due to reliance on fossil fuels, a lack of cohesive and global legislature, as well as an unfavorable public opinion towards green hydrogen and renewable energy as a whole.

Infrastructure is a part of our daily lives which is often taken for granted within first world countries; a massive amount of work and energy has been put into developing the infrastructure and countries that exist today. Using the United States as an example of a developed and first world country, real infrastructure and "modern" machinery began development around the 1750's during the (first) Industrial Revolution. At the time, these systems were mostly reliant on water and steam-powered energy. This all changed with the discovery of coal during the second Industrial Revolution in the 1850's (National Grid, n.d.), paving the way towards nearly complete reliance on fossil fuels, currently cashing in at around 81% of the US' energy production (EIA, 2023). So, how do we stop this 175-some years of reliance on fossil fuels, and eventually transition towards a "green hydrogen economy"?

From the “Technological Momentum” framework, we understand that motivation to keep fossil fuels predominantly stems from the desire to keep “business-as-usual” and it is more preferable to change fossil fuel systems “around the edges” to ultimately de-incentivize their usage in the long-term. In the grand scheme of things, these small changes all tie back to money. Currently, for every dollar spent on renewables, six are subsidized towards fossil fuels, a strategy designed to stabilize fuel prices for consumers and corporations (Environmental Defense Fund, 2019). However, ironically, these subsidies continue monopolization of fossil fuels over cleaner energy sources. The phasing-out of these subsidies, although a slow and complex process, is considered a pivotal step in the de-reliance of fossil fuels.

In a similar vein, the creation of a “social cost” associated with greenhouse gas emissions from gasoline in cars allows electric vehicles to become financially competitive. This concept can also be applied towards renewable energy tax incentives. China recently demonstrated this strategy through the incentivization of importing clean energy technologies “not yet matured” in China, ultimately lowering the cost of electricity used in these technologies (Qadir et al., 2021). By lowering this cost, these technologies become competitive with power generation sources reliant on oil and gasoline. Both of these ideas create feasible scenarios where fossil fuels are not the clear-cut financial option, and both of these can and should be applied using green hydrogen as the environmentally-friendly technology of choice.

However, the usage of green hydrogen is moot without adequate investment in research and development of the technology and compatible infrastructure. This being said, there are (at least) 228 ongoing government subsidized hydrogen research projects currently underway, with over half taking place in Europe (Ma et al., 2023). Unfortunately, the majority of these countries have failed to invest in the assessment of critical details of how to integrate this innovation into society, excluding factors such as scale, storage and transportation. Projects under construction are almost exclusively within the pre-commercial phase, and proposed plants have extremely limited electrolyzer (the instrument which produces the hydrogen) capacities relative to those of gray hydrogen. The majority of green hydrogen projects have electrolyzer capacities well below 50 MW, plateauing at around 100 MW for large plants, both of which are well under half of the 220 MW capacity observed for gray hydrogen processes (PricewaterhouseCoopers, n.d.). Other issues with these projects include a lengthy timeline associated with new, large-scale infrastructure development such as hydrogen pipelines, import, and export terminals; creating a pipeline alone, for example, may take between 7 to 12 years. With the overarching goal of reducing 40% of carbon emissions by 2030 in mind, per the Paris Climate Agreement, a more realistic solution must be deployed to begin green hydrogen usage as quickly as possible.

Rather than relying on development of these extensive projects, green hydrogen should use a similar "around the edges" strategy as described above. Instead, green hydrogen should follow a three-phase integration process. This utilizes the hydrogen economy which, according to Oliveira, Beswick, and Yan (2021), is here, but gray. Because of this, green hydrogen should first be used as a replacement for gray hydrogen in the chemical synthesis industry, comprising 96% of current production means. Gray hydrogen plants already contain many of the required pipelines, transportation and storage facilities which would otherwise require new construction. In this scenario, green hydrogen would not be used as an energy source, but in its usage has the potential to save 1.5 gigatons of carbon emissions annually. Equally importantly, introduction of green hydrogen into the chemical synthesis market would provide ample opportunity to rapidly increase the efficiency, safety, and productivity of green hydrogen.

The resultant innovations lead to phase two: decarbonization of the transportation center, specially for heavy-duty and long-range fuel, as well as for the heating and buildings sectors. In this phase, improvements in technology have allowed green hydrogen-based fuel cells to become commercially viable for long-range trucks, although not yet smaller cars. Additionally, green hydrogen begins to serve as a “transition fuel” in heating and building emissions to lower carbon emissions by supplementing traditional methods, utilizing existing natural gas pipelines to avoid the creation of new infrastructure when possible. Finally, in phase three, green hydrogen’s importance within the chemical and transportation industry has facilitated its penetration into the power sector as a seasonal energy storage method for renewables. From this point, as a fully developed technology, green hydrogen can continue to increase its presence within the power sector until it has the capacity for total de-carbonization.

With this outlined pathway for the implementation of green hydrogen, countries can begin to adopt this technology. Green hydrogen costs are expected to drop around 50% by 2030; however, as resources and economies differ greatly between geographic regions, certain countries will have lesser financial barriers in its usage. The lowest anticipated costs are expected to occur in various parts of the Middle East, Africa, Russia, China, the US and Australia, where renewable energy sources used to supply electricity in green hydrogen production are abundant (PricewaterhouseCoopers, n.d.). These are likely to be the pioneer countries in green hydrogen adoption. As the price of green hydrogen lowers in coming years, countries with limited renewable resources, such as large parts of Europe, Japan or Korea, will be able to import green hydrogen at a competitive price. Densely populated areas with land constraints will also be required to import, as renewable electricity production required for green hydrogen is limited by space. Following this, large countries will begin trading hydrogen resources, creating export and import hubs similar to those used within the current oil and gas market.

Although the majority of green hydrogen projects are being conducted within Europe, on a country-level scale, China is currently holding a dominant lead over other countries in terms of green hydrogen capacity, both in construction and operational (Canary Media, 2024). As the world's largest producer of hydrogen, mostly fossil-fuel based, China has large plans to upgrade and decarbonize these facilities. Consequently, with the greatest investment in the market, China can be expected to pioneer green hydrogen regulations and legislation (as discussed above). China's policies can, therefore, be expected to spread to the pioneer countries listed above, following a similar adoption trend.

Public opinion is a critical factor in successful development of new technologies, renewable energy as a whole, and passing of legislation. Unfortunately, there is significant progress to be made in that front; in a study conducted in the United Kingdom, 64% of respondents were unable to demonstrate basic knowledge of hydrogen, and 34% believed that hydrogen was dangerous (Armstrong, 2022). An estimated 77% of the public also claims that they would be "unable or unwilling" to pay more for electricity. These statistics demonstrate the need for governments to provide education to the public on green hydrogen energy, and to reiterate the importance of incentives to lower cost and therefore improve public opinions. Surveys have shown that the most effective and desirable government initiative to educate the general public on renewable energy is through social media, supported by about 90% of people (Zakaria et al., 2019). Social media can be used as a tool to promote technical content on how hydrogen functions as a fuel, using content suitable and understandable to the general public, rather than just those highly educated in the fields of STEM (European Commission, 2015).

A form of renewable energy which faces fundamentally similar backlash is nuclear energy, often stereotyped as dangerous and misunderstood by the majority of the public. However, despite incidents such as the 2011 Fukushima Daiichi accident in Japan, public support has (relatively) steadily increased over the last 40 years, according to a study conducted within the United States (American Nuclear Society, 2023). It was concluded that the most effective strategy in improving public opinion was educating about the simplicity of controlling nuclear radiation systems. This study also found that, of the 14% of respondents who feel they are “very well informed” on nuclear energy, 74% were in strong support of nuclear energy, further reiterating the need to inform the public on novel technologies to gain public support. Green hydrogen should adapt the lessons learned from nuclear energy, in educating the public and squashing misconceptions, to better facilitate acceptance and implementation within society.

5. Conclusion

Green hydrogen is a carbon neutral fuel which is a critical solution in the fight against climate change. It has shown to be a unique and promising renewable energy source, which lacks the intermittency issues faced by other renewables, has a high energetic efficiency, and is easily portable. To prevent environmental disaster, carbon emissions must be reduced 40% by the year 2030, with the hopes of keeping the Earth from increasing above the infamous 1.5^{o} C global temperature threshold. This is a result of years of global reliance on fossil fuels continually releasing greenhouse gasses into the atmosphere, an existing infrastructure which is incompatible with clean technologies required to mitigate a future climate crisis. This leads into the current issues faced in transitioning away from fossil fuels, towards a green hydrogen economy: a lack of infrastructure, lack of applicable regulations, and unfavorable public opinion. These major challenges were analyzed using multiple STS methodologies, including "Technological Momentum", "Diffusion of Innovation", "Relational View", "Cultural Lag", in conjunction with literature reviews and case studies. Through these analyses, the pathway towards integration of green hydrogen in society was defined. Green hydrogen should utilize existing gray hydrogen infrastructure, rather than creating new developments, to speed up timelines and save money. Through this, green hydrogen will be used as the standard within the chemical process industry, allowing for improvement in production means, decrease in cost, and eventually transitioning towards the power grid. Due to abundance of renewables and plentiful land, the Middle East, Africa, Russia, China, the US and Australia, will be pioneer locations in green hydrogen's adoption. China will likely be the pioneer country in pushing out regulations and legislation, with existing hydrogen financial incentives and the greatest capital investment, and the others will follow suit. Finally, governments should focus on educating the public on hydrogen through social media to decrease misconceptions, increase awareness, and therefore support levels. These solutions will create an environment where green hydrogen can thrive as a financially feasible, publicly supported, and globally adopted energy alternative.

6. Resources

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