Strategic Directions for Hydrogen Energy in British Columbia

by

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Abstract

Hydrogen energy is projected to become increasingly important in the coming decades, but most hydrogen is produced by processes that are emission intensive. Green hydrogen is produced using renewable energy resources and has no emissions. B.C. has a comparative advantage in the hydrogen sector due to its cluster of hydrogen and fuel cell firms and abundance of renewable energy resources. By concentrating policy efforts on green hydrogen production, the province could position itself to become a competitive exporter to meet rising global demand with trade partners such as Japan. Through a literature review and multi-criteria analysis of policy options, this paper aims to assess options for B.C.'s strategic hydrogen policy approach in a competitive global context. This paper recommends building hybrid renewable energy plants and creating a public-private hydrogen cluster R&D initiative to focus sector growth on green hydrogen so the province can compete in the global hydrogen market.

Keywords: hydrogen energy; green hydrogen; blue hydrogen; hydrogen economy; energy transition;

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Executive Summary

Jurisdictions around the world are increasingly acknowledging the deleterious effects of the global fossil-fuel based energy economy. Fossil fuels produce harmful emissions which lead to climate change and significant adverse effects that threaten human society. There is a desperate search for new energy alternatives to replace oil and gas. These alternatives must not create harmful emissions and environmental damage while providing a stable energy vector which can satisfy current and future energy needs.

Hydrogen is a promising potential energy replacement that could be used in place of oil and gas. Many countries are dedicating significant resources in efforts to develop hydrogen economies, in which hydrogen becomes the primary energy carrier. This has resulted in a global race worldwide to develop hydrogen production and export capacity. British Columbia is one of the jurisdictions making efforts to strengthen its hydrogen capabilities, but it is not meeting its goals quickly enough to compete with other producers which are investing massive resources into hydrogen. The province must act quickly to build hydrogen capacity and capture growing hydrogen demand in countries like Japan.

To ensure an energy transition that minimizes environmental impact, the type of hydrogen that is produced must be produced from clean energy sources. The majority of global hydrogen production is “grey” and to a lesser extent “blue” hydrogen, which are both produced using natural gas. “Blue” hydrogen is made by capturing harmful emissions created during the production process using carbon capture utilization and storage (CCUS) technologies. Recent studies have cast doubt on the efficacy of CCUS technologies to mitigate environmental impacts when creating “blue” hydrogen. In order to create a clean energy vector using hydrogen, British Columbia should focus on “green” hydrogen production, whereby renewable energy resources are used to create hydrogen. To date, adoption of “green” hydrogen has not been widespread largely due to its high cost compared with other types of hydrogen. These costs are gradually decreasing with technological advancement.

Through a multi-criteria analysis of four potential policy options found through a literature review and jurisdictional scan of other countries developing hydrogen

strategies, this paper recommends a policy bundle of building hybrid renewable energy plants and creating a public-private hydrogen cluster research and development initiative. Policies were assessed based on criteria and measures including effectiveness, cost to government, administrative complexity, and stakeholder acceptance. Due to the globally competitive nature of hydrogen demand and supply, the primary objective used to guide the analysis was to increase green hydrogen production capacity as rapidly as possible. The two policies are the most likely to increase green hydrogen production in the shortest amount of time while reducing costs over time and remaining feasible.

Chapter 1. Introduction

The growing awareness of human caused climate change has been stimulating discourse surrounding the need for clean alternatives to fossil fuels. This is a priority of governments around the world as countries rush to find new fuels. The ideal fuel must not emit harmful by-products such as carbon dioxide while still providing a stable energy that can be used to maintain current standards of living. One of the promising replacements that could assist in eliminating the current dependence on polluting fossil fuels is hydrogen. Hydrogen can be produced by various processes, with each end result referred to as a different colour of hydrogen depending on the production process. The least polluting form of hydrogen is green hydrogen, which is produced by harnessing electricity from renewable energy resources such as wind, solar, and hydroelectric power. The most common colour of hydrogen is currently grey hydrogen, which has highly intensive emissions (Marchant, 2021) and accordingly is an undesirable form of energy when the primary goal is to reduce pollution. There are a variety of production methods that are each used in differing amounts depending on resources and location, but the ideal is green hydrogen.

B.C. has developed its own hydrogen strategy which includes green hydrogen production, but other jurisdictions around the world are increasingly investing massive resources into their own hydrogen plans and becoming more formidable competitors. To varying degrees countries are making plans to transition to hydrogen economies in which hydrogen functions as the primary energy carrier in society. Australia and the United States are two jurisdictions which are making investments into hydrogen production and export; in 2022, Australia exported the world's first shipment of liquid hydrogen to Japan (IEA, 2022a), and the United States announced massive hydrogen subsidies introduced in the Inflation Reduction Act. B.C. is especially falling behind these international peers in the race to develop the requisite hydrogen infrastructure to meet future demand. Indicators of hydrogen adoption proposed in B.C.'s strategy (CleanB.C., 2021) show that the development of hydrogen infrastructure is far behind meeting its set goals. If the provincial government does not act quickly and decisively, the opportunity to position the province to be a globally competitive hydrogen producer is in imminent danger of being lost due to the economies of scale that competitive countries can implement.

A number of countries are seeking to import hydrogen to create hydrogen economies rather than produce it domestically, including Japan. Japan in particular has invested significant resources and directed policy efforts towards building an economy with hydrogen envisioned to make up a core part of the country's energy mix. Japan is not heavily invested into developing its own hydrogen production, but instead is looking to import hydrogen from international peers to meet demand. British Columbia could devise strategies to meet this demand, but competition from other jurisdictions necessitate swift policy implementation to gain momentum and secure a firm position in the supply chain. The International Energy Agency's forecasting (IEA, 2022a) suggests that the cost of green hydrogen will drop significantly by 2030 if current targets are met, which aligns well with B.C.'s natural strengths. Drastically increased investment into the green hydrogen sector is necessary to capitalize on the province's advantage that its hydrogen and fuel cell cluster and abundant renewable energy resources offer. As costs of renewable electricity continue to fall, B.C. can carve a green hydrogen niche and export to international partners that have demonstrated strong policy efforts to create a hydrogen economy such as Japan. The government can accelerate the rate of green hydrogen production and cost reduction while boosting domestic hydrogen sector technological expertise by building hybrid renewable energy plants and creating a public-private hydrogen cluster research and development initiative in collaboration with local hydrogen cluster actors. Results are anticipated to include increased hydrogen production, increased innovation and strength of the high technology domestic hydrogen and fuel cell cluster, and eventual revenue from hydrogen export as the province begins to export.

Chapter 2. Background

2.1. Hydrogen Chemistry

2.1.1. Hydrogen Chemical Composition

Hydrogen is the most abundant element found in the universe, but it is only found naturally on Earth in compound form with other elements which combine to form molecules (U.S. Energy Information Administration, 2022). A common molecule that hydrogen forms is when it is chemically bonded to oxygen; two hydrogen atoms and one oxygen atom form H_2O, which is water. When isolated from other elements, hydrogen is a gas at room temperature (National Center for Biotechnology Information, 2023a). Hydrogen can also be liquefied if it is cooled to below −253°C (Office of Energy Efficiency & Renewable Energy, n.d.a). The compression into liquid allows for much greater density with lower overall volume. In liquid form, hydrogen can be transported much more easily in smaller storage units. At current technology levels, liquefaction consumes more than 30% of the energy stored in hydrogen. Additionally, some hydrogen evaporates when liquefied, particularly in small tanks with large surface-to-volume ratios (Office of Energy Efficiency & Renewable Energy, n.d.a).

2.1.2. Molecular Configurations

When discussing hydrogen, it is important to understand the role of other molecules that hydrogen is often bound to. Two other molecules that contain hydrogen are methane (CH_4) (U.S. EPA, 2022) and ammonia (NH_3) (National Center for Biotechnology Information, 2023b). While methane is usually used as a natural source to derive hydrogen from, ammonia can be used to transport hydrogen to end use locations. Methane is a compound of carbon and hydrogen. It is the predominant compound present in natural gas, which is mostly used as a power source (Alternative Fuels Data Center, n.d.). At the same mass, methane causes 86 times the amount of global warming that carbon dioxide does over a 20-year time frame when it is emitted into the atmosphere (Environmental Defense Fund, n.d.). Ammonia is a naturally occurring compound made up of nitrogen and hydrogen that is found on Earth as a colourless gas. The compound has broad applications, the most common of which include the production of fertilizers, as a refrigerant, and making plastics and other products (Royal Society, n.d.). Ammonia can be liquefied under milder conditions than hydrogen (Thomas & Parks, 2006) has a higher volumetric energy density and is easier to store and transport than pure hydrogen, particularly over long ranges (Royal Society, n.d.).

2.2. Hydrogen Energy

Once isolated from other compounds, hydrogen can be used as an ‘energy vector’ to move usable energy from place to place. Hydrogen is a very powerful energy vector. Most stars burn hydrogen to produce energy as their raw fuel through fusion (National Center for Biotechnology Information, 2023a). Hydrogen has the highest energy content of any common fuel by weight (about three times more than gasoline), but the lowest by volume (about four times less than gasoline) (U.S. Energy Information Administration, 2022). Though hydrogen does not emit any carbon when combusted, it does emit nitrous oxide which has the potential for serious environmental consequences (Milford et al., 2020). When hydrogen undergoes a chemical reaction in a fuel cell to create energy, the only by-product is heat, water, and electricity (FCHEA, n.d.). These characteristics make hydrogen energy one of the contenders for a fuel replacement for future energy needs as the world divests from oil and gas.

2.3. Hydrogen Production

Hydrogen can be produced by entirely clean zero-emission energy sources such as hydroelectric dams, wind turbines, or solar panels, but not all methods of hydrogen production are carbon neutral. It can be made by less environmentally friendly means, such as burning fossil fuels like natural gas and storing the released energy in the form of hydrogen. Producing hydrogen this way is much more prevalent than clean production because it is more cost effective, but it is counterintuitive if the end goal is the motivation to switch to hydrogen is to avoid dirty fuels. Emission intensive production is still common in the absence of cost-effective clean energy sources. After production, hydrogen can be cooled and compressed into a liquid form that has greater density than its gaseous counterpart. Pure liquid hydrogen can then be transported in pressurized tanks to be consumed. Ammonia is another storage medium that is more stable than pure hydrogen and can act as an alternative to moving the liquefied element directly.

2.4. Fuel Cells

Regardless of the production process, hydrogen can be used in fuel cells to generate electricity. Fuel cells convert chemical potential energy into electricity by exposing hydrogen and oxygen to a catalyst (CHFCA, n.d.). When the reaction occurs, water and heat are emitted (FCHEA, n.d.) alongside a direct electrical current that can be harnessed for tasks such as turning a motor in a vehicle. Fuel cells can be stacked together to form larger systems (FCHEA, n.d.) similar to how batteries can be combined. There are various types of hydrogen fuel cells that are best suited to different purposes, but almost all function on the same hydrogen-oxygen-catalyst premise (Office of Energy Efficiency & Renewable Energy, n.d.b). Fuel cells can be quickly refueled in a number of minutes (Alternative Fuels Data Center, n.d.) rather than the lengthy amount of time it takes with current technology to charge an electric battery.

2.5. Colours of Hydrogen

Hydrogen is referred to hydrogen as different colours, e.g., green hydrogen, blue hydrogen, etc. The colours do not signify the actual appearance of the element; all hydrogen is physically colourless (Royal Society of Chemistry, n.d.) but the amount of greenhouse gases emitted during the production process determines what colour the hydrogen is referred to as (National Grid, n.d.). The most commonly referenced colours of hydrogen are green, blue, grey, black and brown, and pink.

2.5.1. Green

Green hydrogen is the most environmentally friendly means of hydrogen production, and produces no emissions. Green hydrogen is produced in an electrolyser, which passes electricity through water to separate it into its base hydrogen and oxygen atoms (National Grid, n.d.). Electrolysers are needed for creating hydrogen with renewable energy resources or nuclear electricity (IEA, 2022b). If the electricity used for electrolysis is generated by renewable means, there are no emissions produced throughout the entire production process, and the end result is ‘green’ hydrogen. Any electrical energy generated from a renewable resource can be used with an electrolyser to isolate hydrogen. These resources typically include wind, solar, and hydroelectric energy sources. Like all other colours of hydrogen, it can then be liquefied, used directly in gaseous form, or combined with other elements to form compounds such as ammonia.

2.5.2. Blue

There are several methods to produce blue hydrogen, but the most common method is through a process called steam methane reforming, or natural gas reforming. High temperature steam reacts with methane under high pressure and is exposed to a catalyst which produces hydrogen, carbon monoxide, and carbon dioxide (Office of Energy Efficiency & Renewable Energy, n.d.c). Carbon capture and storage technologies are then used to trap and store the emitted carbon atoms (National Grid, n.d.). Blue hydrogen is described as low-carbon hydrogen but not zero-carbon hydrogen because there are still greenhouse gases emitted during the production process.

2.5.3. Grey

Grey hydrogen is the most common form of hydrogen produced worldwide. Grey hydrogen is usually produced in the same way that blue hydrogen is, but no carbon capture and storage technologies are used so there is no emissions reduction. Over 70% of grey hydrogen is produced with natural gas (Reinsch et al., 2021) and the carbon footprint from grey hydrogen production falls between natural gas and coal.

2.5.4. Black and Brown

Black and brown hydrogen is made with black or brown coal, respectively. Black and brown hydrogen are the most environmentally damaging production methods (National Grid, n.d.) and are the least attractive when considering needs for clean energy alternatives.

2.5.5. Pink

Pink hydrogen, also sometimes referred to as purple or red, is created with electrolysis powered by nuclear energy (National Grid, n.d.). There is no waste produced from pink hydrogen production other than the waste normally created in a nuclear power plant, so it is considered to be zero-emission.

2.6. Use Cases

Hydrogen has several characteristics that make it an effective energy vector. It has applications across a wide range of sectors, including transportation, power generation, heat, and industrial feedstock. Some of the factors that make hydrogen useful are that it can be stored in large quantities for long periods of time (Reinsch et al., 2021), can be refueled quickly compared to battery alternatives, can be transported relatively easily, and has a high energy storage capacity.

2.6.1. Transportation

In the transportation sector, hydrogen can be used in a fuel cell to produce electricity which turns electric motors in on-road vehicles such as cars and long-range cargo trucks (Natural Resources Canada, 2022). The most demand for hydrogen in the transportation sector is for road vehicles. Most hydrogen is used in fuel cell powered trucks and buses because of their high annual mileage and heavy weight (IEA, 2022a). By substituting rail engines for hydrogen fuel cells, emissions can be eliminated from trains (Ballard Power, n.d.) while retaining the ability to travel extreme distances without the need for battery recharging or rail electrification. The first fuel cell train fleet of 14 trains was deployed in Germany in August 2022 (IEA, 2022a). It can be used in heavy industry to power various implements; there are already more than 35,000 hydrogen fuel cell powered forklifts in use across North America (Natural Resources Canada, 2022). Hydrogen is a prime replacement for high-emission vehicles in the aerospace industry including passenger planes. Maritime shipping is responsible for about 25% of global transportation sector emissions, and currently almost no low or no carbon fuels are used in the industry (Reinsch et al., 2021).

2.6.2. Power Generation

If retrofitted or built new, power generation plants could burn hydrogen as a fuel to provide power to buildings, homes, and cities. A 485 MW power plant constructed in Ohio was fitted with a gas-powered turbine that is able to run on a mixture of natural gas and hydrogen, with plans to ultimately run the turbine on hydrogen alone (Long Ridge Energy & Power, n.d.).

2.6.3. Heating

Hydrogen is among the candidates for a low-carbon replacement for heating technologies for homes. Instead of burning natural gas to provide heat in winter, hydrogen can be burned (Dodds et al., 2015) and depending on the method of production could be entirely or partially emission free.

2.6.4. Industrial Feedstock

Currently hydrogen is most used worldwide as a feedstock in industrial processes (Natural Resources Canada, 2022). These processes are parts of emission intensive sectors such as oil refining, ammonia and methanol production, and steel production.

Chapter 3. Methodology

The analysis methods of this project were the completion of a literature review which was used to identify barriers to clean hydrogen energy production and adoption, and to inform a jurisdictional scan to understand the global hydrogen economy and hydrogen trade relationships to place British Columbia in an international context.

Scientific information on hydrogen was gathered from public online government data repositories. Policy information was collected from government hydrogen strategies and analysis of jurisdictional hydrogen and energy strategies. A significant amount of hydrogen information was found in the International Energy Agency's 2022 Global Hydrogen Review.

The jurisdictional scan focused on jurisdictions with a demonstrated policy interest and activity in hydrogen energy policy, including Japan, the United States, the European Union, and British Columbia. These jurisdictions were selected due to their explicitly identified hydrogen strategies and their relations to one another regarding hydrogen import, export, or production.

Sources included news articles, consultant reports, academic journals, government and non-government institutions, research institutes, and other peer-reviewed literature. The sources were found by searching Simon Fraser University's library, Google Scholar, and the Google search engine.

A multi-criteria analysis approach was used to assess each policy option. Each policy was compared against criteria and measures including effectiveness, cost to government, administrative complexity, and stakeholder acceptance. Effectiveness was double weighted in consideration of the primary objective to enable production of the most green hydrogen in as little time as possible. Policies were ranked as high, medium, and low according to each measure which was used to inform the policy recommendations.

Chapter 4. Literature Review

4.1. Hydrogen Economy

An end goal for adopting hydrogen is the ultimate creation of what is known as a hydrogen economy, in which hydrogen functions as the main energy vector (Abe et al., 2019). There are a number of benefits associated with broadly replacing current systems with hydrogen as an energy solution including energy security, the ability to store power from local renewable sources, zero emissions, air quality improvements, and the creation of a new industrial/technological power base (Abe et al., 2019). In the late 2000s, there were three major factors identified as driving the movement to hydrogen as a fuel source: reducing CO2 emissions and improving air quality, maintaining security of energy supplies, and creating a new industrial/technological energy base on which the economy can be built (Edwards et al, 2008). The strength of the case for hydrogen as a clean fuel solution suitable for replacing fossil fuels such as oil largely comes from its low to no emissions and high energy density making it suitable for fuel replacement. There is a general trend of hydrogen being used as fuel that is accelerating worldwide (Institute for Breakthrough Energy Emission Technologies, 2019). According to a report from the EU Parliamentary Research Service, the characteristics that make hydrogen attractive as an energy vector include:

"Its use for energy purposes does not cause greenhouse gas (GHG) emissions (water (H2O) is the only by-product of the process); it can be stored over long periods; it can be used for producing other gases, such as methane or ammonia, as well as liquid fuels; existing infrastructure (gas transport and gas storage) can be repurposed for hydrogen, and a certain proportion of hydrogen can be blended with natural gas; it has a higher energy density relative to volume than batteries, making it a suitable fuel for long-distance and heavy-goods transport." (Erbach, 2021).

These characteristics make hydrogen a highly attractive fuel alternative that provides clean energy. Additional benefits include the lack of a need for radical infrastructural changes due to the ability to repurpose natural gas pipelines. There are few problems with converting pipelines to carry hydrogen, and there is no need to start and stop transport because it can be mixed with natural gas to be transported through them at a ratio of 17% with no significant impacts on existing infrastructure (Gondal et al., 2012).

Hydrogen can be used to synthesize ammonia to take advantage of its increased density and ease of transportation (Giddey et al., 2017). Shipping ammonia as an export to be converted back to useable hydrogen at the end-point of use might be a more efficient form of transport in certain circumstances, but in others shipping pure liquid hydrogen is more energy efficient with a lower carbon footprint than shipping ammonia (Ishimoto et al., 2020).

Hydrogen fuel cells provide an attractive long-range fuel source with benefits over conventional batteries, which are another energy vector. Batteries can be powered cleanly, but they have a lower energy density than hydrogen which makes them inefficient for long range transportation, shipping, and aviation (Erbach et al., 2021). Unlike fuel cells, batteries also have reduced performance over time and corresponding end of life cycle concerns. Lithium-ion batteries are currently the most commonly used batteries in electric vehicles (Beaudet et al., 2020). With current materials science, these batteries are unable to be completely broken down and recycled so end up as waste products. This problem is avoided entirely with fuel cells, which can be reused continuously.

4.2. Problems with Hydrogen Energy

4.2.1. Cost Effectiveness

Insufficient technological advancement is greatly hindering the adoption of hydrogen despite its attractive qualities. The most prominent issue is the high overall cost of hydrogen, especially green hydrogen. Despite gradually improving technology, hydrogen remains very expensive compared to gasoline; as recently as 2021, hydrogen cost between $8.50 to $10.80/kg more than gasoline (Yowell, 2022). This is between two and three times costlier than gasoline. The main reason for the disparity is that hydrogen requires a high amount of energy in the conversion process into a useable form (Abdin et al., 2020). Stillwater Associates (Yowell, 2022), a transportation fuels consulting firm, reported that production cost only made up less than 20% of hydrogen's retail cost, and the remainder was due to compression and delivery. However, Stillwater Associates did not specify how the hydrogen was produced. It is likely that the analysis considered grey hydrogen because it makes up the vast majority of production. Other types of hydrogen which are more expensive to produce are likely to have a more even production, compression, and delivery cost ratio. Any colour of hydrogen requires additional energy to complete the liquefaction process and when transported in tankers there is potential for boil-off (Office of Energy Efficiency & Renewable Energy, n.d.a) leading to inefficiency during the transportation process. Both of these inefficiencies drive up the overall cost of liquid hydrogen. Further research and development could remedy liquefaction and storage problems in the future, leading to cost reductions (Office of Energy Efficiency & Renewable Energy, n.d.a) and possibly enabling wider adoption.

4.2.2. Blue Hydrogen Emissions

When developing hydrogen policy with the motivation of reducing environmental impact, it is critical to assess the greenhouse gas emissions produced during the hydrogen production cycle. Blue hydrogen is marketed as a low-carbon alternative fuel to polluting oil, coal, and natural gas. There are varying reports on how much carbon can be captured by carbon capture technology, but estimates typically range from between 50% to 95% (Reinsch, 2021) (Royal Society, n.d.). At least some large active producers in the blue hydrogen sector do not publicly share that there is carbon leakage: the multinational oil and gas corporation ExxonMobil does not acknowledge on its website that not all carbon can be captured with current technology (ExxonMobil, n.d.). Further, it was found in a 2021 study that fugitive methane released from natural gas during the steam methane reforming process may entirely negate the benefits of carbon capture. Howarth et al., discovered that the greenhouse gas footprint of blue hydrogen is more than 20% greater than burning natural gas or coal for heat and 60% greater than burning diesel oil for heat (Howarth et al., 2021). This indicates that at least for heating purposes, it would be environmentally cleaner to simply burn natural gas directly rather than produce blue hydrogen at additional expenditure only to emit more greenhouse gases.

4.2.3. Green Hydrogen Costs

Green hydrogen produced with electrolysers using renewable energy produces zero-emissions, but this technology is still not as cost-effective as hydrogen produced with emission intensive fuels (Erbach, 2021). An additional cost specific to water electrolysis for green hydrogen is the water itself, which must be desalinated if it is not fresh water. Desalination costs are very low and only marginally more expensive than using fresh water (IEA, 2022a) but desalination plants and the necessary capital to build them is required. Technologies are in development for direct seawater electrolysis but are not yet viable (IEA, 2022a). As technology improves, further reductions in the cost of renewable energy including wind and solar power have made the generation of hydrogen through electrolysis more feasible, garnering increased interest in the element as a viable energy vector replacement (Abdin et al., 2020).

4.3. Supply and Demand

As of 2021, hydrogen production was dominated by natural gas without carbon capture and storage technologies (IEA, 2022a). Coal was the second most common source of hydrogen, but almost all of this production was concentrated in China (IEA, 2022a). Green hydrogen produced by water electrolysis made up a very small portion of total production but still increased by 20% from 2020 to 2021 because of the additional deployment of electrolysers (IEA, 2022a). Over the same amount of time, the installed capacity of electrolysers increased greatly by 70% from 2020 to 2021 (IEA, 2022a). 32% of announced electrolyser projects set to be completed by 2030 are in Europe, 28% are in Australia, and 12% are in Latin America (IEA, 2022a). 80% of global electrolyser manufacturing capacity is split between Europe and China (IEA, 2022a).

The International Energy Agency’s 2022 Global Hydrogen Review estimated that global hydrogen demand reached 95 million tons in 2021, which made up 2.5% of energy consumption (IEA, 2022a). Most of the increase in production was in grey hydrogen, and only 1 million tons of low-emission hydrogen was produced (IEA, 2022a). Global hydrogen demand in industry is mainly for the production of ammonia, methanol, and DRI in the steel industry (IEA, 2022a). Countries which have access to plentiful renewable energy sources are more easily able to produce green hydrogen, but when a cheaper grey alternative exists, it can be economically unfeasible to dedicate production to green hydrogen. The IEA also estimates that the build out of green hydrogen over the next decade depends on government targets being translated into real-world projects beyond what is currently planned (IEA, 2022a). The agency identifies that there is a need to provide early support for green projects so they can meet targets. As current fossil fuel energy costs are very high, renewable hydrogen may already be able to compete with hydrogen from fossil fuels in many areas that have renewable resources and need to import fossil fuels for hydrogen production (IEA, 2022a). If current projects and timelines maintain momentum, costs for electrolysers could fall by around 70% by 2030 compared to now (IEA, 2022a).

The majority of hydrogen refueling stations are located outside of North America, and there is a particular concentration in China, Europe, and to a lesser degree Japan (IEA, 2022a). The stock of FCEVs does not mirror this distribution. This could indicate the difference in strategy between jurisdictions regarding infrastructure deployment and demand vs. supply-oriented policies. Despite slow growth overall growth, Japan has maintained a fairly even ratio of FCEVs relative to refueling stations indicating the rate of infrastructure construction is matching the adoption of hydrogen vehicles. The United States is seeing an increase in the number of FCEVs but construction of refueling stations is not keeping pace. Korea has been greatly increasing both the number of FCEVs and refueling stations in the country, moreso than any other jurisdiction.

4.4. Policy Interest

Hydrogen is projected to play a critical role in replacing batteries and other energy vectors in critical use cases such as long-range transportation and heating (Institute for Breakthrough Energy Emission Technologies, 2019). A sector in which hydrogen would function well as a direct replacement of oil is in the transportation industry. In addition to the other benefits, hydrogen fuel cells are highly efficient compared to internal combustion engines, (Edwards, 2008), though there has historically been difficulty in matching internal combustion engine's cost-effectiveness and reliability. Policy interest in hydrogen has existed since at least the 1970s, but consistent attention to developing hydrogen policy has not been universal in the international community. Depending on advancements in research, government interest has been strong in different countries at different times. In addition to the unique challenges that can make developing hydrogen economies in each jurisdiction difficult due to varying practical, geographical, and political factors, the ongoing problem of cost-effectiveness of producing hydrogen fuel has been hindering adoption. Japan and the European Union were early proponents of a hydrogen energy transition, and Canada has been host to several innovative companies driving technological advancement. Recently, there has been a strong renewed movement in the hydrogen policy landscape mostly driven by increased attention to climate change and gradually improving cost effectiveness. More countries have been adopting specific hydrogen strategies, and stronger emissions targets, a focus on driving technological innovation, and the decrease in renewable energy generation costs may propel the hydrogen energy transition now in ways that were not possible in the past. It remains to be seen whether this will be another fleeting moment for large scale hydrogen adoption or signal a more permanent shift.

4.4.1. Energy Security

Unlike regionally constrained fossil fuels, hydrogen can theoretically be produced anywhere that there is sufficient renewable energy or access to technologies to separate hydrogen from compounds like natural gas and ammonia. Fossil fuels can only be extracted from where it occurs naturally. This has major geopolitical implications for the energy security of countries. The current era of energy revolves primarily around the extraction and refinement of oil, and to a lesser extent coal. States without these resources must import them from others that do. Fossil fuel rich countries can have leverage over other countries without them and withhold the supply of energy to their own gain. When states are on amicable terms with one another, the trade of fossil fuels can be but one part of a productive and mutually beneficial relationship. On the contrary, fuel export can be a geopolitical tool to influence countries that depend on imports. Resource poor countries such as Japan are dependent on importing coal, oil, and gas (Behling et al., 2015) from international trade partners, some of whom may be geopolitical rivals. At scale hydrogen production allows countries to develop new trade relationships with allies and like-minded countries that have the ability to reliably produce fuel without the possibility of running out of resources.

Chapter 5. Jurisdictional Scan

The potential of hydrogen as a sustainable fuel of the future has been widely recognized since at least the 1970s. A timeline of hydrogen fuel cells and the accompanying economic policy necessary to stimulate their innovation in Sweden between 1978 and 2005 was mapped in 2012 (Hultman et al., 2012). Establishing hydrogen policy roadmaps has been a common approach used by governments when considering energy alternatives. In the early 2000s, the United States, the European Union, and Japan had recognized the potential of hydrogen and fuel cells and accordingly allocated resources to the technologies (Behling et al., 2015). Japan spent significantly more resources than its western counterparts; from 2002-2015, Japan spent $4.1 billion while the US and EU spent roughly $1.9 billion each on hydrogen (Behling et al., 2015). Belief in hydrogen energy has not stopped growing, as there is still a growing number of countries that are recognizing the value that a hydrogen energy transition could create. Some of the prominent countries that are demonstrating significant interest in hydrogen include China, Germany, Japan, South Korea, Australia, and the US (Cuevas et al., 2021). The European Union has also had detailed hydrogen strategies in place since the early 2000s (Cuevas et al., 2021). Policy focus is differentiated between jurisdictions; whereas EU states like Germany have focused more on policies to increase the readily available supply of hydrogen fuel directly, other countries such as Japan have employed demand-centric policy (Jensterle et al., 2019) to boost consumption of hydrogen to build a hydrogen economy. Japan has also made large investments into R&D so production organically rises to meet demand. Despite having a smaller economy than these other countries, Canada is one of the top 10 producers of hydrogen in the world (Razi et al., 2022).

5.1. Japan

Japan has a strong strategic focus on hydrogen and shares three main drivers for hydrogen development with Germany: climate change mitigation and other environmental goals, energy supply diversification, and technological leadership (Jensterle et al., 2019). In 2015, Japan developed a sweeping new energy policy to eventually place hydrogen at the forefront of energy consumption across sectors in the country (Behling et al., 2015). The strategy was conceived due in large part to energy security; the country's reliance on external fuel sources such as coal, oil, and gas, and the perceived instability of its nuclear energy after the Fukushima disaster (Behling et al., 2015) lead the government to seek new sources of energy. Japanese policymakers have identified hydrogen as the core fabric of the energy powering their society in the coming decades because of the country's lack of access to energy resources; hydrogen can be produced anywhere with renewable electricity, whereas most of Japan's oil is shipped from the Middle East through the South China Sea (Okutsu et al., 2020). Amidst heightening tensions with China, alternative forms of energy that can be imported from anywhere are a solution to establish Japan's energy security. If there are specialized hydrogen exporters that align with Japan as political allies, there is cause to believe that Japan would seek to import hydrogen from them to establish its new hydrogen economy. Japan's movement towards hydrogen policy implementation began in the 1990s with fairly limited initiatives inspired by technological developments in fuel cells in the United States and the EU (Behling et al., 2015). The most significant of these initiatives was the 1995 Science and Technology Basic Law which strengthened R&D and private-academic partnerships (Behling et al., 2015). Motivated by impressive fuel cell research in Canada by the company Ballard, in 1992 the Japanese government undertook its own fuel cell research, but a study concluded that to meaningfully adopt the technologies they would need to be made more cost competitive (Behling et al., 2015). This aligns with the struggles the European Union has continuously experienced over time in widespread hydrogen adoption due to issues with cost effectiveness. Between 2005 and 2009, 58% of global patents related to hydrogen fuel cell technology were filed by Japan (Behling et al., 2015). Several commercialization initiatives have since been created by private companies and supported by the government (Jensterle et al., 2019). Unlike countries such as Germany, which focus on supply-side stimulation, Japan is more concentrated on boosting demand (Jensterle et al., 2019) and building a market that will buy hydrogen. Further R&D initiatives in Japan developed fuel cell vehicle technology and more policy was formed to further commercialization prospects (Behling et al., 2015). Japan is also trying to maximize its potential in exporting domestically produced technologies that it gains from its investment into fuel cell R&D (Jensterle et al., 2019). The country aims to capitalize as much as possible on the technology. Japan is now interested in importing cheaper blue hydrogen but would likely import green hydrogen if the price became more competitive (Vijayakumar et al., 2022). Japanese companies have begun to invest in green hydrogen projects abroad, indicating there is future potential for increased green activity (Vijayakumar et al., 2022).

5.2. United States

The US has had several iterations of some form of hydrogen roadmap in recent decades; in 2003, then-President George W. Bush announced a $1.2 billion hydrogen fuel initiative (Council on Environmental Quality, 2003) to spur investment and research into hydrogen and fuel cell technology. The vision at that time was to create a secure domestic fuel source so the country would not have to rely on oil exports and at the time same build hydrogen fuel cell powered vehicle technology. There were, as there still are now, questions over the chicken-egg paradox of hydrogen demand and supply in the American government at that time (Andrews et al., 2004). Since the early 2000s, the US has substantially increased its policy attention to hydrogen and clean energy. In 2022, US Congress passed the Inflation Reduction Act, abbreviated as the IRA. The act is sweeping and is designed among other inflation reduction policies (Badlam et al., 2022) to combine many clean energy tax incentives into one single bill. With the act, the US government is aiming to grow domestic hydrogen supply. There is a specific stimulus designed to boost hydrogen by providing a clean hydrogen production tax credit. There is also an investment tax credit aimed at making it more attractive for private capital to flow into the sector. In the act, clean hydrogen is defined as hydrogen that emits less than 4 kilograms of carbon dioxide per kilogram of hydrogen produced (Monahan et al., 2023); in other words, the credits do not specifically target only green hydrogen but do exclude dirty production methods such as grey, brown, and black.

5.3. European Union

The European Union's primary motivation in pushing hydrogen adoption is to meet climate targets that call for the reduction of carbon intensive fuels. Policy is broadly targeted at achieving climate neutrality (Erbach et al., 2021). In the early 2000s, the EU created an ambitious roadmap detailing its hydrogen energy transition strategy into the coming decades. Iterative framework programs built continued support for the hydrogen industry and fuel cell development across the EU. Through the European Hydrogen and Fuel Cell Platform established in 2004, the roadmap set targets of 1 GW of hydrogen fuel cell power generation capacity by 2015 and between 400,000 to 1.8 million hydrogen fuel cell vehicles sold annually by 2020 (Edwards et al, 2008). In 2021, only 3885 new fuel cell vehicles were registered (Clean Hydrogen Partnership, 2022) showing that the EU's strategic policy dramatically overestimated fuel cell vehicle adoption rates. The initial strategy was designed to build commercially viable hydrogen and the corresponding infrastructure needed to begin transitioning (Cuevas et al., 2021). Out of this policy came the establishment of the Fuel Cells and Hydrogen Joint Undertaking (FCH-JU), which was a public-private partnership that is composed of the European Commission, Hydrogen Research Europe, and Hydrogen Europe. The partnership is considered by some to be the most important EU tool in driving hydrogen development and policy (Cuevas et al., 2021). In 2021, the FCH-JU was succeeded by the Clean Hydrogen Joint Undertaking which aims to build on the work completed for the FCH-JU (Clean Hydrogen Partnership, n.d.). Policy is also continually evolving within the EU. In 2020, it released an updated hydrogen strategy concentrating mainly on the development and innovation of hydrogen technology (Erbach et al, 2021). Specifically, the EU is prioritizing the development of clean hydrogen in an effort to make zero-emission production cost-effective enough to be widely adopted (Erbach et al., 2021). Continentally, EU policy "strongly supports the implementation of a hydrogen-based energy system as one of the key tools to achieve the European Green Deal and Europe's clean energy transition" (Cuevas et al., 2021). Implementing hydrogen remains a primary tool in the journey to meet ambitious climate targets across the region. The strongest national policies are being developed by France and Germany (Cuevas et al., 2021), but almost all member states acknowledge the importance of hydrogen in the coming decade. Roughly half have distinct transport and industry sector hydrogen adoption goals (Erbach et al., 2021). The most current EU roadmap targets one quarter of the growing renewable electricity sector to be allocated to clean hydrogen production between 2030 and 2050 (Cuevas et al., 2021). There is also a target of producing 10 million tonnes and importing 10 million tonnes of renewable hydrogen by 2030 (European Commission, n.d.).

5.4. Australia

The Australian National Hydrogen Strategy was released in 2022. Australia is working at the strategic policy level to increase hydrogen penetration in its domestic market, and has targeted the markets of Japan, South Korea, and China as export targets (Kar et al., 2022). The country identified that it has abundant renewable resources including wind and solar that make it well suited to produce more hydrogen than needed domestically, and to benefit from export relationships with other countries. Australia is looking into developing green and blue hydrogen infrastructure to capitalize on its renewable resources and natural gas (COAG Energy Council, 2019). In February 2022, Australia exported the world's first shipment of liquid hydrogen to Japan (IEA, 2022b), however, the export was of brown hydrogen (Paul, 2022), the most environmentally damaging colour of hydrogen. Australia also seeks to reduce its own dependence on fossil fuels to secure the country's energy security, including in remote areas (COAG Energy Council, 2019). Like British Columbia, Australia also generally has not built sufficient infrastructure to drive domestic hydrogen adoption (Kar et al., 2022).

5.5. British Columbia

British Columbia is a site of significant hydrogen activity within Canada. Canada has had both a history of national policy objectives related to establishing a hydrogen economy and industry actors who have been world leaders in the development of hydrogen and fuel cell technologies (Solomon et al., 2006). Canada numbers in the top ten of hydrogen producers worldwide and demonstrates promise in realizing sustainable development (Razi et al., 2022). In 2020, the National Research Council of Canada released a national hydrogen strategy mapping out the key role that hydrogen will play in reaching net-zero emissions by 2050 (National Research Council Canada, 2020). The strategy details the economic and environmental benefits of capitalizing on Canada's lead on hydrogen production. The report notes that cooperation between levels of government is necessary to meet goals. British Columbia in particular has had a historically sustained strong hydrogen fuel cell industry; Ballard, a fuel cell manufacturer based in Burnaby, British Columbia, was an industry leader in driving fuel cell innovation (Solomon et al., 2006) (Behling et al., 2015). The B.C. government created its own strategy in 2019. In order to meet net-zero emissions by 2050, the B.C. government has targeted hydrogen as an alternative energy vector that can help to reduce reliance on fossil fuels. The B.C. hydrogen strategy contains 63 actions to be completed in short-, medium-, and long-term stages. Actions include incentivizing the domestic hydrogen economy, infrastructure supports, creating the new B.C. Centre for Innovation and Clean

Energy to drive commercialization, and establishing carbon intensity targets (Government of British Columbia, n.d.). The strategy goes into minute detail and covers a broad range of both supply and demand side policy. The B.C. government has commissioned studies on the approximate locations and numbers of public fast charging sites, ports, and hydrogen refueling stations in the province. Alongside the number of fast charging sites needed to traverse all major roads in the province, it also forecasts that the province will need 82 sites with 141 hydrogen stations. As of 2021, only three of the planned 141 had been completed (CleanB.C., 2021). A lack of infrastructure, including refueling stations, is leading to insufficient domestic demand to sustain hydrogen production locally.

The British Columbian city of Vancouver is home to a high-tech hydrogen and fuel cell cluster comprised of several companies and research institutions. There is some research suggesting that high-tech clusters such as the Vancouver hydrogen fuel cell cluster are different from regular industrial clusters in that they compete on an international scale, or not at all (Holbrook et al., 2010). Outputs from high-tech clusters like the one in Vancouver are usually too specialized to operate solely in regional, national, or even continental markets (Holbrook et al., 2010) and are dependent both on global markets and global talent. Studies on the cluster also determine that it makes up the majority of activity in the sector in Canada, and on a more granular level the company Ballard conducts the most activity (Holbrook et al., 2010). The cluster has sufficiently developed to the point, however, that even if one of the major firms were to exit the sector the cluster would be able to continue. In almost all of the clusters that have been studied in Canada, public research institutions are key components of cluster development (Holbrook et al., 2010) that are tools that government can use to support innovation. To boost cluster effectiveness, it is important to create and maintain a triple helix structure of academia, industry, and government relations (Holbrook et al., 2010).

Chapter 6. Policy Options

Due to its small market size and subsequent difficulty in increasing demand for hydrogen relative to other, larger countries focused on growing demand like Japan, British Columbia is better suited to position itself as a producer and exporter of hydrogen than it is to attempt domestic market growth. Though competing with cheaper blue hydrogen from countries such as the United States and brown hydrogen from Australia, B.C. can make significant investments to bring its costs of green hydrogen to parity with these other types of hydrogen. Australia is already exporting liquid brown hydrogen to Japan, but there is the greatest interest from Japan in green hydrogen compared to other types of hydrogen (Vijayakumar et al., 2022) and if costs were the same it would be willing to import from a clean producer like British Columbia.

The International Energy Agency has undertaken research that indicates hybrid renewable energy plants powered by multiple energy sources could be paired with electrolysers to increase green hydrogen production rates (IEA, 2022a). As explored in the jurisdictional scan, jurisdictions other than British Columbia have developed various policies to spur domestic hydrogen production. Promising options include tax credits based on the United State's Inflation Reduction Act hydrogen policies to assist private investment, allocating funding for basic hydrogen research to bring production costs down similar to Japan's R&D investment strategy, and the creation of a public-private cluster R&D initiative like the European Union's Clean Hydrogen Joint Undertaking. With modifications, these policies can be altered from their respective origin countries to suit British Columbia's hydrogen strategy.

6.1.1. Policy Option 1: Build Hybrid Renewable Energy Plants

This policy option is an infrastructure project which proposes building hybrid renewable energy plants with wind and solar generators paired with electrolysers. Wind and solar power generation are both dependent on fluctuating sources of energy, and when used to produce hydrogen with an electrolyser, inefficiency arises when wind slows and the sun is blocked. This can result in the value of the electricity generation being insufficient in recouping capital costs incurred during installation, meaning the overall cost per unit of hydrogen produced is higher (IEA, 2022a). Though not a complete solution, the variability of solar and wind generation can be partially mitigated by installing hybrid plants with both wind and solar generators. On-site electrolysers allow for electricity generated by the renewable resources to store energy by splitting the water molecules and capturing the hydrogen. When there are multiple sources of potential electrical generation the electrolyser has a better utilization rate with less non-productive time, and ultimately more stable hydrogen production and lower costs (IEA, 2022a). The province could task the Ministry of Energy, Mines, and Low Carbon Innovation with constructing the new infrastructure which BC Hydro could then administer and maintain.

6.1.2. Policy Option 2: Subsidize Private Green Hydrogen Projects

This policy option proposes providing subsidization to private enterprise to accelerate green hydrogen production by alleviating private risk, similar to the large clean hydrogen investments in the form of tax credits announced in the United States' Inflation Reduction Act. Unlike the US which subsidizes blue and green hydrogen, British Columbia could provide more substantial tax credits for companies and projects that are focused specifically on green hydrogen spurring production and investment. The province could utilize the Ministry of Jobs, Economic Development and Innovation to provide direct project funding to green hydrogen companies.

6.1.3. Policy Option 3: Allocate Funding for Basic Hydrogen Research

This policy option proposes increasing investment into the research institutions in B.C. that are active in hydrogen research. The University of Victoria's Institute for Integrated Energy Systems, University of British Columbia's Clean Energy Research Centre, and Simon Fraser University's Fuel Cell Research Laboratory are three major provincial academic institutes that are focused on hydrogen research. By increasing funding through grants administered by the Ministry of Post Secondary Education and Future Skills, technological development can be steered to work towards commercialization avenues for cheaper hydrogen technology. This strategy has been employed by Japan in recent decades to further hydrogen uptake (Jensterle et al., 2019).

6.1.4. Policy Option 4: Create Public-Private Hydrogen Cluster R&D Initiative

This policy option proposes investment into a public-private hydrogen cluster research and development initiative like the European Union's Clean Hydrogen Joint Undertaking to enable collaboration between public institutions and their researchers and the network of hydrogen firms in the province, such as Ballard Power Systems. The Canadian Hydrogen and Fuel Cell Association has a presence in BC and could act as the centrepiece for organizing collaboration and research activities. Investments could include funding for research and R&D infrastructure to be shared by academia and industry made through the Ministry of Energy, Mines and Low Carbon Innovation with federal support from Pacific Economic Development Canada. Over time, the initiative will result in new green hydrogen technological advancements and commercial partnerships that strengthen the sector, making the region more globally competitive.

Chapter 7. Criteria and Measures

To assess the strengths and limitations of the different policy options, evaluation criteria and measured were defined based on their ability to assess the probable success of each policy option in achieving the ultimate goal of increasing green hydrogen production. In addition, a scoring system was added to be able to better illustrate the nuance between each policy option. Effectiveness was determined to be the primary objective because it directly measures the most important result of policy. Cost to government, administrative complexity, and stakeholder acceptance were chosen to assess whether each individual policy would be feasible to implement.

7.1. Effectiveness (x2)

This criterion is the primary policy objective and receives a x2 multiplier because of the time-sensitivity of the race between jurisdictions to develop green hydrogen production capacity to capture global markets. Measures are based on how effective the policy is at accelerating the estimated cost reduction rate of green hydrogen production over time. By reducing costs quickly, production will increase and B.C. will be able to export green hydrogen to meet global demand resulting in large economic benefits. This criterion is measured by the speed at which the policy is expected to reduce the cost of production. The reduction rate measures are high, medium, and low.

7.2. Cost to Government

This criterion assesses the anticipated budgetary cost to government of each policy. Policies are measured based on an estimation of how expensive they are to implement. Measures are low, medium, and expected cost.

7.3. Administrative Complexity

This criterion assesses the administrative burden to government the policy imposes, measured by how much direct government intervention will be required to administer the policy option with additional staff, teams, departments, and so on. Measures are low, medium, and high levels of expected government intervention.

7.4. Stakeholder Acceptance

This criterion assesses how the policy is likely to be received by stakeholders, which has implications for political feasibility. Stakeholders include the public, whose opinion may change depending on perception of unfair corporate assistance or environmental impacts, and the private hydrogen industry, which may lobby for or against particular policies that influence the domestic hydrogen market. Measures are high, medium, and low anticipated support.

7.5. Criteria and Measures Summary

Table 1: Summary of Criteria and Measures

Criteria	Measure	Rating
Effectiveness (x2)	Estimated rate of green hydrogen production cost reduction	**High (3) x2**
		Medium (2) x2
		Low (1) x2
Cost to Government	Expected budgetary cost of policy implementation	**Low (3)**
		Medium (2)
		High (1)
Administrative Complexity	Expected level of direct government intervention	**Low (3)**
		Medium (2)
		High (1)
Stakeholder Acceptance	Anticipated support of the public and private hydrogen industry	**High (3)**
		Medium (2)
		Low (1)

Chapter 8. Evaluation

Policy options were given high, medium, or low scores based on how successful they were estimated to be according to each measure. Each policy that was analyzed had pros and cons, and no single policy entirely satisfied all criteria and measures. The options were assessed as to how comprehensively they were able to meet the primary objective of quickly reducing the cost of green hydrogen production while remaining feasible. The scores for each measure were added together to result in a final score for each policy option, which informed the policy recommendations.

8.1. Effectiveness

Building hybrid renewable energy plants was rated as high for effectiveness because they directly increase the number of green hydrogen generating stations in the province, leading to a rapid reduction of the cost of producing green hydrogen due to greatly increased supply that can then be exported to meet demand.

Subsidizing private green hydrogen projects was rated as medium because providing incentive for the private market to produce more green hydrogen relies on the business case of production. Industry will likely increase production and firms that are already involved in green hydrogen projects will gain increased financial capacity, but if there is insufficient demand for green hydrogen new firms are unlikely to enter the supply chain.

Allocating funding for basic hydrogen research was rated as low for effectiveness. Though basic academic research is needed to improve hydrogen specific technologies such as liquefaction (Office of Energy Efficiency & Renewable Energy, n.d.a), significant time is expected to see impacts bring costs down.

Creating a public-private hydrogen cluster R&D initiative was rated as medium because while increasing public-private collaboration is likely to increase the rate of technological progress more than strictly academic funding and commercial project development could occur, there could be a significant delay before technological improvement greatly reduces costs.

Table 2: Effectiveness Evaluation

Policy	Score
Build Hybrid Renewable Energy Plants	**High (3) x2 = 6**
Subsidize Private Green Hydrogen Projects	**Medium (2) x2 = 4**
Allocate Funding for Basic Hydrogen Research	**Low (1) x2 = 2**
Create Public-Private Hydrogen Cluster R&D Initiative	**Medium (2) x2 = 4**

8.2. Cost to Government

Building hybrid renewable energy plants was rated as high because they have the highest cost to government of all policies. There will be large amounts of capital expenditures necessary for constructing new plants, and salaries will be required for new jobs operating and maintaining the new energy infrastructure.

Subsidizing private green hydrogen projects was predicted to have a medium cost in order to sufficiently incentivize private investment, though the cost was not anticipated to be as high as building new infrastructure.

Allocating funding for basic hydrogen research was rated low cost in comparison to other policy options because there are already three academic institutes dedicated to hydrogen research in the province which would simply receive increased direct funding.

Creating a public-private hydrogen cluster R&D initiative was rated medium cost; building new research infrastructure would require capital expenditure, but having industry buy-in reduces the amount of public money needed to accelerate later development and fund projects.

Table 3: Cost to Government Evaluation

Policy	Score
Build Hybrid Renewable Energy Plants	**High (1)**
Subsidize Private Green Hydrogen Projects	**Medium (2)**
Allocate Funding for Basic Hydrogen Research	**Low (3)**
Create Public-Private Hydrogen Cluster R&D Initiative	**Medium (2)**

8.3. Administrative Complexity

Building hybrid renewable energy plants was rated as high administrative complexity because the policy would require entirely direct government intervention. There will be many new staff and teams needed to physically construct the infrastructure, and thereafter maintain and repair it as needed. Further, administration of the pre-existing energy grid will need to be scaled up.

Subsidizing private green hydrogen projects has medium administrative complexity because there will be government oversight required to administer and monitor funding to avoid hydrogen producers from misrepresenting their production methods.

Allocating funding for basic hydrogen research was ranked as low complexity because additional research funding does not require much government intervention. There are already grant systems and personnel in place for funding the three research institutions and projects that they undertake.

Creating a public-private hydrogen cluster R&D initiative was ranked as low complexity because a public-private initiative only requires the initial convening of academia and industry partners; thereafter, the initiative will be overseen by a selected cluster manager such as the Canadian Hydrogen and Fuel Cell Association and would not require much further government intervention than funding.

Table 4: Administrative Complexity Evaluation

Policy	Score
Build Hybrid Renewable Energy Plants	**High (1)**
Subsidize Private Green Hydrogen Projects	**Medium (2)**
Allocate Funding for Basic Hydrogen Research	**Low (3)**
Create Public-Private Hydrogen Cluster R&D Initiative	**Low (3)**

8.4. Stakeholder Acceptance

Building hybrid renewable energy plants was rated as likely to have high support from the public without much pushback from the private sector. Building energy infrastructure would create new jobs for British Columbians, which is likely to generate popular support. It will also contribute to hydrogen demand over time, a positive for industry. However, public infrastructure that creates hydrogen at low cost does represent competition to industry.

Subsidizing private green hydrogen projects was rated low is due to the risk of appearing as corporate welfare. The private sector would be supportive, but there is a risk of conflict based on which companies are granted subsidization and which are not which may be viewed as unfair.

Allocating funding for basic hydrogen research was rated as high because both public and private are likely to support the reduction in cost of a new energy source, with additional promise of increased exports in the future.

Creating a public-private hydrogen cluster R&D initiative was rated as high. The public would likely be supportive because costs are shared with industry, and the private sector would likely be supportive because there is public funding helping to subsidize research and development while building a stronger local cluster.

Table 5: Stakeholder Acceptance Evaluation

Policy	Score
Build Hybrid Renewable Energy Plants	**High (3)**
Subsidize Private Green Hydrogen Projects	**Low (1)**
Allocate Funding for Basic Hydrogen Research	**High (3)**
Create Public-Private Hydrogen Cluster R&D Initiative	**High (3)**

8.5. Evaluation and Scoring Summary

Table 6: Evaluation and Scoring Summary

Criteria	Policy			
	Build Hybrid Renewable Energy Plants	Subsidize Private Green Hydrogen Projects	Allocate Funding for Basic Hydrogen Research	Create Public-Private Hydrogen Cluster R&D Initiative
Effectiveness	**6**	**4**	**2**	**4**
Cost to Government	**1**	**2**	**3**	**2**
Administrative Complexity	**1**	**2**	**3**	**3**
Stakeholder Acceptance	**3**	**1**	**3**	**3**
Total Score	**11**	**9**	**11**	**12**

Chapter 9. Recommendations

It is recommended that the provincial government implement the complementary policy options 1 and 4 by constructing hybrid renewable energy plants and creating a public-private hydrogen cluster research and development initiative. In order to quickly act on the current gap in the global market of sufficient green hydrogen supply, developing the strongest base of hydrogen supply as quickly as possible is the priority, and options 1 and 4 are the most likely to stimulate production now while reducing costs over time and remaining reasonably feasible.

Through the multi-criteria analysis above, the policy option with the highest score was found to be the creation of a public-private hydrogen cluster research and development initiative, which received a medium score for the speed of reducing green hydrogen costs but will still increase industry and academic collaboration and research progress. The policy also poses medium cost to government and is rated highly on administrative complexity, meaning that the policy will be relatively easy to implement. Though it is not the policy that will bring down green hydrogen costs and increase supply the fastest, the long term research and development opportunities that the initiative will likely create will reduce the costs of green hydrogen over time. The government of British Columbia should also increase spending on renewable energy infrastructure in the province by implementing policy 1, building hybrid renewable energy plants. The construction of the new plants with attached hydrogen electrolysers will enable the supply of green hydrogen to be immediately increased the most out of all the policies, without needing to wait for technological innovation to bring costs down enough to make production viable for private industry. The increased production will likely bring green hydrogen costs down to compete with blue hydrogen, and open the possibility to begin substantial international trade. The infrastructure is the most expensive of the policies, but it is a necessary cost that can be partially mitigated over time by investing in the public-private R&D initiative. British Columbia can take advantage of its geographic position on the Pacific Ocean and broker trade deals with Japan, which is likely to import the green hydrogen if costs are brought to parity with other forms of hydrogen by these policy actions.

Positive knock-on effects not included in the multi-criteria analysis will also occur. The construction, administration, and maintenance of renewable energy infrastructure and any public-private R&D facilities constructed as part of the initiative will create many high-quality jobs for British Columbians. Furthermore, the additional concentration and funding made available for hydrogen will feed the hydrogen and fuel cell industry in the province, strengthening B.C. as a global hydrogen centre. British Columbia will secure economic growth and cement its place in a cross-Pacific hydrogen supply chain while contributing to the worldwide reduction of greenhouse gases and further development of clean technology.

Chapter 10. Considerations and Limitations

There were several limitations which impacted the study over its duration. Though establishing a hydrogen economy has been an object of policy curiosity for several decades, no jurisdiction yet successfully created a hydrogen economy anywhere in the world, so only estimations for how successful policy options will be are possible. Hydrogen technology has greatly developed and the costs of renewable energy resources have dramatically fallen since early hydrogen strategies, so the field and policy direction is in a new context.

Policy interest in hydrogen has also greatly accelerated in only the last few months, and several new strategies and developments occurred during the completion of this project including the introduction of the large hydrogen subsidies in the US Inflation Reduction Act and the first shipment of brown hydrogen to Japan from Australia. This influenced the paper late into its development, and it may not be current for a great deal of time past its publishment date due to the rapidly evolving global hydrogen movement.

Finally, though China is a growing hydrogen market and was projected in the B.C. hydrogen strategy as the largest export market for hydrogen by 2050 at 70 million tonnes (Government of British Columbia, n.d.), China was excluded from this study as an export option because of Canada's current unstable geopolitical relationship. For now, this warrants concentrating export efforts on Japan, the second largest potential export market.

Chapter 11. Conclusion

British Columbia is facing a rare opportunity to meet an unmet global market demand for hydrogen, and it is in a strong position to develop its green hydrogen capacity to export to target markets such as Japan. The main reasons that make hydrogen energy an alternative in the move away from fossil fuels revolve around energy security and diversification, meeting climate goals, its superior performance as an energy vector in comparison compared to battery technologies, and its efficiency when used in fuel cells.

Governments have been experiencing difficulties in establishing hydrogen for several decades despite keen policy interest that has been sustained over time. The single most common issue preventing widescale hydrogen economy adoption is the challenge with cost-effectiveness of converting energy into hydrogen. As technology improves and costs go down, the feasibility of replacing existing emission-intensive infrastructure increases. Japan, the United States, the European Union, and British Columbia have all identified hydrogen as a critical component to accomplish energy transition but interact with one another in different export, import, and innovation relationships. Major roadmaps and strategies have been established to lay the foundation for further policy development. Furthermore, significant resources have been allocated across the coming decades to allow for hydrogen energy to take root. As previous hydrogen energy transition targets worldwide have not been met, governments are betting significantly on technological improvements that will bring costs down sufficiently to enact real change.

The government of British Columbia is recommended to build hybrid renewable energy plants and create a public-private hydrogen cluster research and development initiative in order to meet the ultimate goal of gaining a foothold in the international green hydrogen market. By enacting this policy bundle, the province can quickly produce large amounts of green hydrogen while enabling cost reductions over time and strengthening its hydrogen industry.

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