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ANALYSIS AND ASSESSMENT OF CLEAN HYDROGEN PRODUCTION POTENTIALS OF CANADA

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Görkem Kubilay KARAYEL

Signature

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Görkem Kubilay KARAYEL

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LIST OF SYMBOLS

A	Area (m^2)
c_p	Specific heat at constant pressure (J/kgK)
D	Diameter (m)
E	Energy (kJ)
$\dot{E}$	Energy rate (kWh)
ex	Specific exergy (kJ/kg)
$\dot{Ex}$	Exergy rate (kW)
$\dot{Ex}_D$	Exergy destruction rate (kW)
F	Faraday's constant (C/mol)
G	Gibbs free energy (kJ/kmol)
g	Gravitational acceleration (m/s^2)
h	Specific enthalpy (kJ/kg)
I	Solar radiation intensity (kWh/m^2day; W/m^2)
LHV	Lower heating value (kJ/kg)
m	Mass (kg)
$\dot{m}$	Mass flow rate (kg/s)
P	Pressure (kPa)
P	Power (kW)
Q	Heat (kJ)
$\dot{Q}$	Heat rate (kW)
s	Specific entropy (kJ/kgK)
T	Temperature (°C)
t	Time (s)
u	specific internal energy (kJ/kg)
U	Internal energy (kJ)
V	Velocity (m/s)
v	Volume (m^3)
$\dot{v}$	Volumetric flow rate (m^3/s)
w	Work (kJ)
$\dot{W}$	Work rate (kW)

z	Elevation height (m)

Greek Letters

α	Topographic coefficient
Δ	Difference
ρ	Density (kg/m^3)
η	Efficiency

Subscripts and superscripts

ave	Average
D	Destruction
e	Electricity
EL	Electrolyser
en	Energy
ex	Exergy
in	Input
out	Outlet
mech	Mechanical
sep	Seperator
th	Thermal
turb	Turbine
well	Geothermal well

LIST OF ABBREVIATIONS

ALEL	Alkaline electrolyser
AECL	Atomic Energy of Canada Limited
AGR	Advanced gas reactor
AOE	Accumulated ocean energy
APS	Announced pledges scenario
ARAS	Additive ratio assessment
BC	British Columbia
CANDU	Canada deuterium uranium
CanWEA	Canadian Wind Energy Association
CER	Canada Energy Regulator
CI	Carbon intensity
CFS	Canadian Forest Service
CWEEDS	Canadian weather energy and engineering data sets
DC	Direct current
DOE	United States Department of Energy
EU	European Union
GDP	Gross domestic product
GHG	Greenhouse gases
IEA	International Energy Agency
LCSA	Life cycle sustainability assessment
LNG	Liquid natural gas
MHR	Modular helium reactor
MSW	Municipal solid waste
NZE	Net zero scenario
P2G	Power-to-gas

PEM	Proton exchange membrane
PHWR	Pressurized heavy water reactor
PV	Photovoltaic
PRICE	Power reactor information service
ORC	Organic Rankine cycle
SF	Single flash
SMR	Small modular reactor
SMR	Steam methane reforming
SOE	Solid oxide electrolyser
STC	Standard testing conditions
SWARA	Stepwise weight assessment ratio analysis
TOE	Tons of oil equivalent
US	United States
WEICan	Wind Energy Institute of Canada

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ABSTRACT

Analysis and Assessment of Clean Hydrogen Production Potentials of Canada

Görkem Kubilay KARAYEL

Department of Mechanical Engineering

Energy Program

Master of Science Thesis

Supervisor: Prof. Dr. İbrahim DİNÇER

The main objective of this thesis is to design a hydrogen farm concept using Canada's renewable and clean energy sources to produce clean hydrogen. The 13 provinces are examined in terms of their renewable resources, and clean hydrogen production potential was found. According to the calculations, Canada's total clean hydrogen production potential is 693.11 million tons. Clean hydrogen production potential from renewable sources is 205.69 Mt, 439.92 Mt, 29.24 Mt, 2.65 Mt, 13.94 Mt, and 1.66 Mt for solar, wind, geothermal, biomass, hydroelectric-wave-undersea current, and nuclear energies, respectively. Among 13 provinces, hydrogen production potentials found to be 125.71 Mt, 99.66 Mt, 89.08 Mt, 81.96 Mt, 59.09 Mt, 58.85 Mt, 50.95 Mt, 44.94 Mt, 33.70 Mt, 32.05 Mt, 8.14 Mt, 6.88 Mt, and 2.10 Mt for Québec, British Columbia, Alberta, Ontario, Manitoba, Saskatchewan, Nunavut, Yukon, Newfoundland and Labrador, Northwest Territories, New Brunswick, Nova Scotia, and Prince Edward Island, respectively.

Keywords: Green hydrogen, sustainability, electrolyser, renewable energy

ÖZET

Kanada'nın Temiz Hidrojen Üretim Potansiyelinin Analizi ve Değerlendirilmesi

Görkem Kubilay KARAYEL

Makine Mühendisliği Anabilim Dalı

Yüksek Lisans Tezi

Danışman: Prof. Dr. İbrahim DİNÇER

Mevcut çalışmanın temel amacı, temiz hidrojen üretmek için Kanada'nın yenilenebilir ve temiz enerji kaynaklarını kullanarak bir hidrojen çiftliği konsepti geliştirmektir. 13 eyalet yenilenebilir kaynakları açısından incelenmiş ve temiz hidrojen üretim potansiyeli bulunmuştur. Yapılan hesaplamalara göre Kanada'nın temiz hidrojen üretme potansiyeli 693.11 Milyon tondur. Yenilenebilir enerji kaynakları kullanılarak üretilecek toplam temiz hidrojen potansiyeli güneş, rüzgâr, jeotermal, biyokütle, hidroelektrik-dalga-denizaltı akıntısı ve nükleer enerjileri için sırasıyla 205.69 Mt, 439.92 Mt, 29.24 Mt, 2.65 Mt, 13.94 Mt, 1.66 Mt'dur. 13 eyaletin potansiyeli sırasıyla Québec, British Columbia, Alberta, Ontario, Manitoba, Saskatchewan, Nunavut, Yukon, Newfoundland ve Labrador, Northwest Territories, New Brunswick, Nova Scotia ve Prince Edward Island için 125.71 Mt, 99.66 Mt, 89.08 Mt, 81.96 Mt, 59.09 Mt, 58.85 Mt, 50.95 Mt, 44.94 Mt, 33.70 Mt, 32.05 Mt, 8.14 Mt, 6.88 Mt ve 2.10 Mt olarak sıralanabilir.

Anahtar Kelimeler: Yeşil hidrojen, sürdürülebilirlik, elektroliz, yenilenebilir enerji

1
INTRODUCTION

1.1 Energy and Environmental Issues

Climate change mitigation and the execution of appropriate laws and regulations are needed to improve international commitment. On the closely connected energy front, the market has struggled and will continue to struggle to finance the shift away from fossil fuels and into the era of decarbonization. Human health and well-being have been impacted by the substantial rise in atmospheric quantities of anthropogenic carbon dioxide (CO_2) since the industrial revolution. These anthropological effects are inevitable, despite governmental denials and conventional fossil fuel lobbying attempts. This legislation will lead to the adoption of carbon-free fuels in several energy market segments, and hydrogen, which can be used as a feedstock, fuel, and energy carrier, is a crucial component for such a sustainable fuel. Sustainable energy becomes a crucial topic for international competitiveness as well as a huge possibility for economic growth and employment creation. Thanks in large part to the US Inflation Reduction Act, annual solar and wind capacity additions in the United States will more than double by 2030, while sales of electric vehicles will increase sevenfold [1]. China's coal and oil consumption will both peak before the end of this decade as a result of the massive expansion of renewable energy, which is being driven by new targets [2]. In the next decade as a result of the increased deployment of renewable energy and efficiency improvements, the European Union's demand for natural gas, oil, and coal will decrease by 20% and 50%, respectively [2]. This drive is made more urgent by the need to find new sources of economic and industrial advantage beyond Russian gas. India advances toward its domestic renewable capacity goal of 500 gigawatts (GW) by 2030, and renewables satisfy nearly two-thirds of the country's rapidly increasing electricity demand [2]. Figure 1.1 depicts renewable energy investments in advanced economies, China, and emerging and developing countries between 2015 and 2030. There is no visible increase in the investments for emerging and developing countries but by the year 2030 it is expected to more than double the current 0.2 trillion US$. Emissions of greenhouse gases have

resulted in significant human contributions. CO_2 emissions from the combustion of fossil fuels and industrial processes account for 65% of annual human-made greenhouse gas emissions [3].

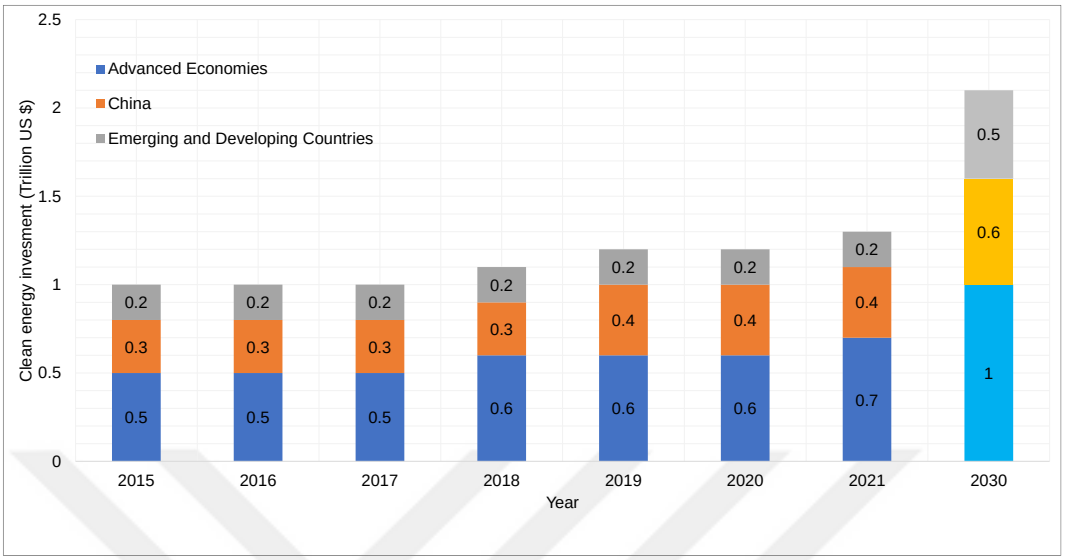


Figure 1.1 Clean energy investments in advanced economies, China, and emerging and developing countries between 2015-2030 (Data from [1])

The amount of CO_2 that is found in the atmosphere has been steadily climbing for more than two hundred years. During glacial eras, CO_2 concentrations were lower, while they were higher during interglacial periods. Nevertheless, its prior historical maximum concentration was at around 300 ppm [3]. The concentration of CO_2 reached 407.2 ppm in 2018, and it is still climbing [3]. In addition, one could argue that the primary sources of hydrogen production today are fossil fuels, which are not necessarily considered to be totally clean (about 50% of the hydrogen generated today comes from natural gas, 30% from oil, and 15% from coal). It can be seen from Figure 1.2, which depicts the life cycle emissions in terms of CO_2 equivalent per kilogram of produced hydrogen, that clean hydrogen is required, and it must be produced by making use of renewable energy sources and nuclear power in order to dissociate water into hydrogen and oxygen in a manner that is less harmful to the environment [4]. The world as a whole would be in a better position if all climate commitments were met, but there is still a significant gap between present expectations and a stability at 1.5 °C. In the year 2022, global energy-related CO_2 emissions reached a new all-time high of nearly 36.8 Gt, representing an increase of 0.9%, or 321 Mt [5]. After two years of extraordinary fluctuations in energy use

and emissions, which were driven in part by the Covid-19 epidemic, the growth rate for the previous year was significantly lower than the rebound rate of more than 6% that was expected for 2021 [5].

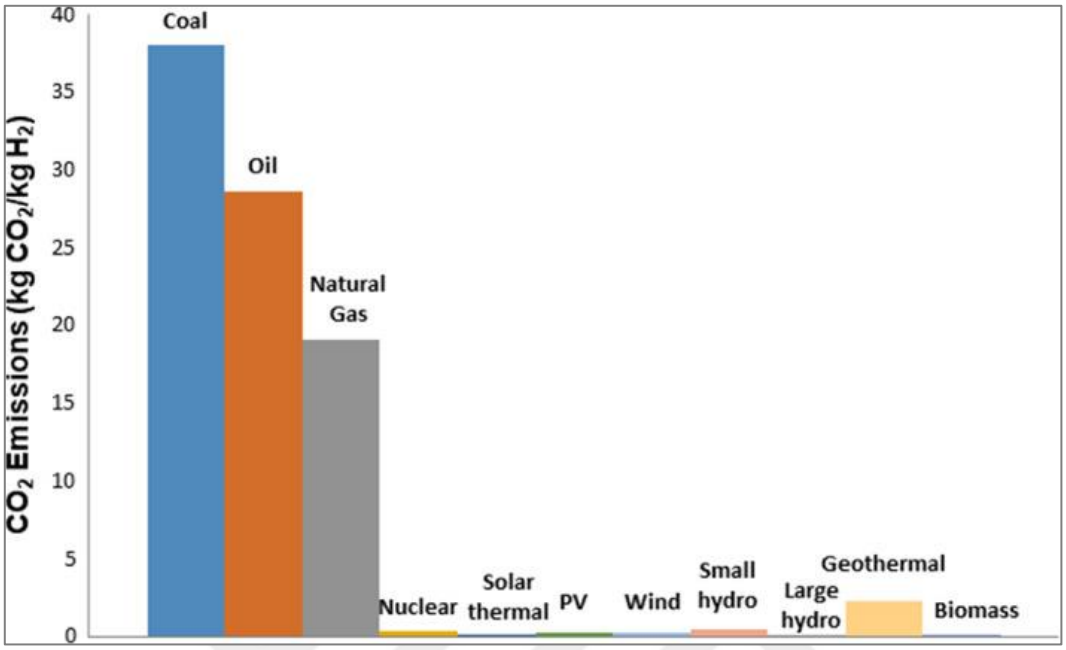


Figure 1.2 Life cycle CO_2 emissions during the production of hydrogen directly from fossil fuels and indirectly by splitting water using nuclear and renewable energy sources [4]

The shift in CO_2 emissions that occurred between 2021 and 2022 is depicted by region in Figure 1.3. The burning of energy sources led to a 423 Mt increase in emissions, while industrial operations led to a 102 Mt decrease in emissions. The difference can be attributed to the combustion of energy sources. The rise in CO_2 levels is due in large part to the huge increase in demand for heating and cooling that was caused by the extreme weather, which accounts for 60 Mt CO_2 of the 321 Mt total increase [5]. The loss of production at nuclear power plants was responsible for an increase of 55 Mt CO_2 in the atmosphere. China's emissions were roughly the same as the previous year in 2022, decreasing by 23 Mt or 0.2% from the previous year's total. The European Union was able to reduce its CO_2 emissions by 2.5%, which is equivalent to 70 Mt despite disruptions in the oil and gas market, hydrological limits brought on by drought, and multiple nuclear reactors going down.

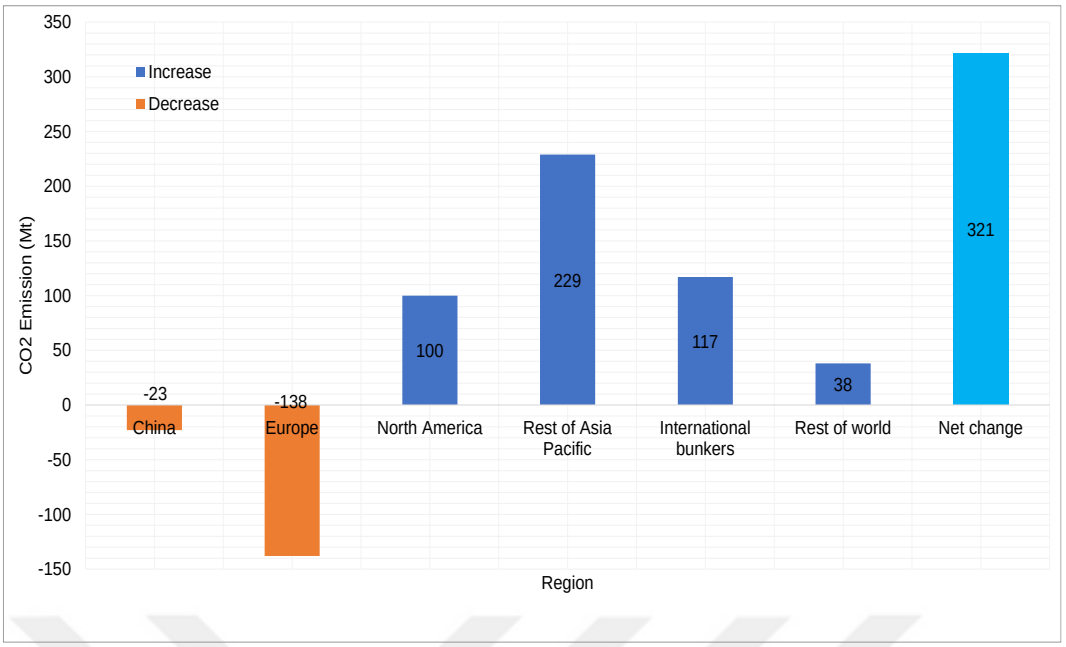


Figure 1.3 The change in CO_2 emissions by region between 2021 and 2022 (Data taken from [3])

1.2 Solar Energy

Supply chains for several essential technologies, such as batteries, solar photovoltaic (PV), and electrolysers, are expanding at rates commensurate with increased global ambitions. If all announced expansion plans for solar PV manufacturing come to fruition, manufacturing capacity would exceed deployment levels in the APS by approximately 75% in 2030 and approach levels required by the NZE Scenario [3]. In the case of electrolysers to produce hydrogen, the prospective excess capacity of all announced projects relative to APS deployment in 2030 is approximately 50% [6]. The expansion of battery manufacturing capacity in the EV sector reflects the ongoing shift in the automotive industry, which has at times moved quicker than governments in establishing goals for electrified mobility. As depicted in Figure 1.4, these renewable energy supply chains are a significant source of employment growth, with clean energy jobs already surpassing those in fossil fuels on a global scale and the APS projecting an increase from approximately 33 million today to nearly 55 million in 2030 [3]. There are presently over 43,000 solar photovoltaic (PV) installations supplying electricity directly to residential, commercial, and industrial rooftops in Canada [10]. Multiple solar panels can be combined to form solar arrays that directly supply electricity to homes and businesses. The majority of solar photovoltaic capacity in Canada consists of

utility-scale solar installations, commonly known as "solar farms." Massive cost reductions and the need for electricity generation that doesn't release greenhouse gases to fight climate change are driving this industry sector's potential for significant growth.

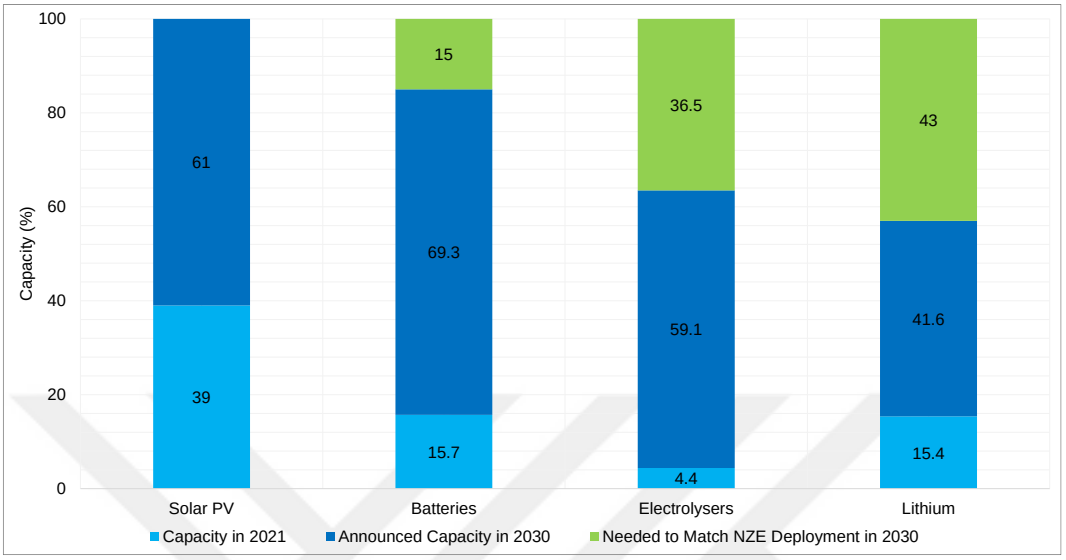


Figure 1.4 Announced manufacturing capacity compared with net zero scenario deployment, 2030 (Data taken from [3])

Because of the magnitude and breadth of its landmass, Canada is home to an abundant supply of solar energy resources. The interior of British Columbia, southern Alberta, southern Saskatchewan, southern Manitoba, southern Ontario, southern Québec, southern New Brunswick, and southern Nova Scotia as well as western Prince Edward Island all have a high solar potential [11]. This is based on the global horizontal irradiation. The parts of Alberta, Saskatchewan, and Ontario that are located the farthest to the south are the ones that include the regions that hold the most potential to gain from solar energy [11-12]. On the other hand, the amount of solar irradiation that hits the country is not very high due of the high latitude of the country. This, when combined with the fact that there is cloud cover, results in a capacity factor that is far lower than the 15% that is observed in the United States [13]. The Northern Territories have a smaller solar potential as a consequence of their even greater latitude, which leads them to receive less direct sunlight. As a consequence of this, the Northern Territories have a lower solar potential. By the year 2040, solar electricity will account for 1.2% of the total

energy production in the United States, as forecasted by the National Energy Board [14].

1.3 Wind Energy

Globally, 77.6 GW of new wind power capacity was added to power grids in 2022, increasing the total installed wind power capacity to 906 GW, a 9% increase from 2021 [15]. In 2022, the top five markets for new installations were China, the United States, Brazil, Germany, and Sweden, in that order. Last year, they accounted for 71% of all global installations, 3.7% less than in 2021. China and the United States, the world's two greatest markets, lost a combined 5% market share compared to the previous year. This is the second consecutive year that both countries have lost market share. The world's newly installed onshore and offshore wind turbines between 2018 and 2022 are depicted in Figure 1.5.

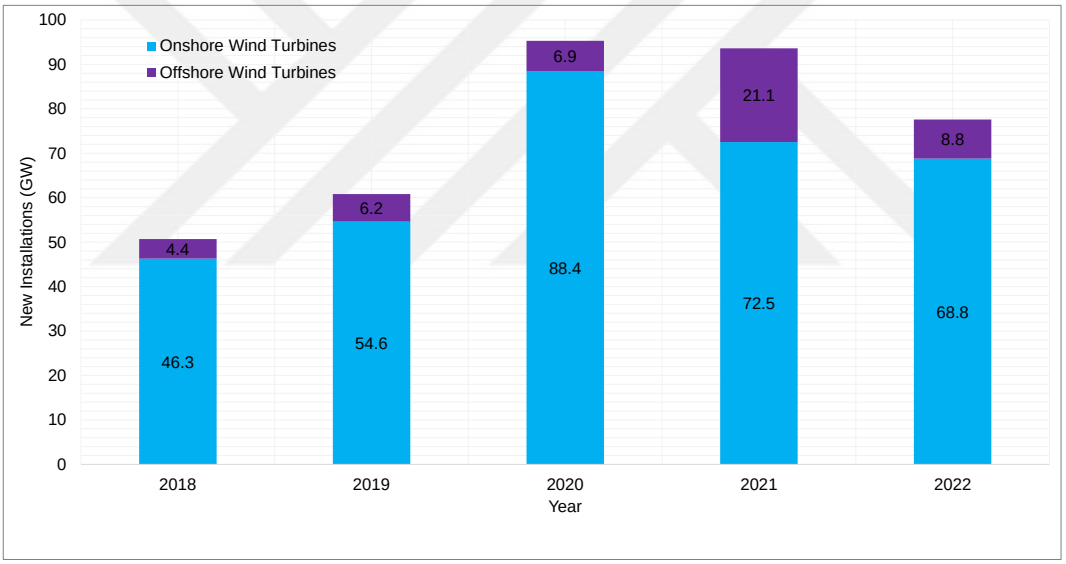


Figure 1.5 Regional outlook for new onshore and offshore wind installations (GW) (Data from [15])

In Canada, wind power has been exploited for several decades, primarily on agricultural lands in the prairies. By the end of the year 2021, the ability to generate electricity from wind was around 14,304 megawatts (MW) [15]. This, in conjunction with the 2,399 MW of solar power generating capacity, accounted for approximately 6.5% of the demand for electricity in Canada in the year 2020 [16]. The Canadian Wind Energy Association (CanWEA) has devised a plan for the future of wind power that aims to increase capacity to 55 gigawatts (GW) by the

year 2025 and meet 20 percent of the country's total energy demands [17]. CanWEA, a non-profit trade group, presented a future plan for wind energy in the year 2008, predicting that it would reach a capacity of 55,000 MW by the year 2025, satisfying 20% of the nation's energy requirements. Wind Vision 2025 [17] has the potential to bring in an annual income of roughly 165 million Canadian dollars and create more than 50,000 jobs. If the goal of CanWEA were to be realized, it would transform Canada into a prominent participant in the wind energy market and result in an investment of around 79 billion Canadian dollars. In addition to this, it would cut annual emissions of greenhouse gases by an estimated 17 metric tons [17]. Canmet ENERGY [18] encourages the research of wind energy technology by offering financial and technical assistance to other partners, such as the Wind Energy Institute of Canada (WEICan) [19]. Their current research focuses on a variety of topics, including the development of novel designs for wind turbine components such as generators, foundations, and towers; the deployment of test equipment for offshore wind applications; the performance evaluation of wind turbines and instrumentation under severe winter conditions; and the effects of integrating wind energy into the existing electrical grid. In addition, they provide oversight for prototype projects, such as the implementation of wind-hydrogen-diesel technologies in rural areas that are difficult to reach and where diesel fuel delivery is both costly and prone to disruptions.

Because of its location, Canada is in a prime position to make use of the enormous amount of wind energy that is available. An increase in the deployment of wind energy results in a decrease in energy consumption, in addition to savings on energy across the entire grid, reductions in greenhouse gas emissions, and decreases in air toxins (including SO_X, NO_X, and mercury). It is expected that a single installation in Newfoundland of six wind turbines with a combined capacity of 65 kW will provide roughly 1 million kWh of power yearly while also reducing CO_2 emissions by approximately 750 metric tons [19]. Using a considerable amount of wind energy demands continuous innovation to increase efficiency, lengthen the lifetime of turbines, and reduce the number of problems associated with interconnection. In order to address some of these challenges, the government works in conjunction

with several international agencies to promote the global sharing of knowledge and experience in the fields of research and development.

1.4 Hydro and Marine Energies

Hydro and marine energies are both forms of renewable energy that have been taken into consideration as part of this research. Hydropower, maritime uses, and their status in the world economy are dissected and discussed in this section. Energy derived from waves, tides, and ocean currents are all considered to have maritime applications. Hydropower is the world's largest source of renewable energy, accounting for about 16% of global electricity generation [20]. Marine energy, on the other hand, is still in its early stages of development, but it has the potential to provide a significant amount of power in the future.

1.4.1 Hydro Energy

In 2021, hydropower produced approximately 4,250 terawatt hours (TWh) of pure electricity globally, a decrease from the record of 4,370 TWh in 2020 [20]. Many regions' below-average precipitation contributed to this generational decline. Hydropower generation is roughly equivalent to the total electricity consumption of the European Union, demonstrating hydropower's sustained significant contribution to low-carbon generation worldwide. Canada is the fourth largest producer of hydroelectricity in the globe in 2021, according to the International Hydropower Association, after the United States, Brazil, and China [20]. Figure 1.6 shows the hydropower plants installed capacity in 2021.

In 2014, Canada was responsible for the consumption of 85.7 Mt of oil equivalent in hydroelectricity, which accounted for 9.8% of the total consumption of hydroelectricity worldwide [20]. In addition, hydroelectricity was responsible for 37.3% of Canada's non-oil energy sources and 25.7% of the country's overall energy consumption. After oil (which accounts for 30.9% of total consumption) and natural gas (which accounts for 28.1% of total consumption), it is the third most common source of energy used in Canada [21]. The generation of more than 90% of the electricity in several provinces and territories, such as British Columbia, Manitoba,

Newfoundland and Labrador, Quebec, and the Yukon, is accomplished through the use of hydropower [22].

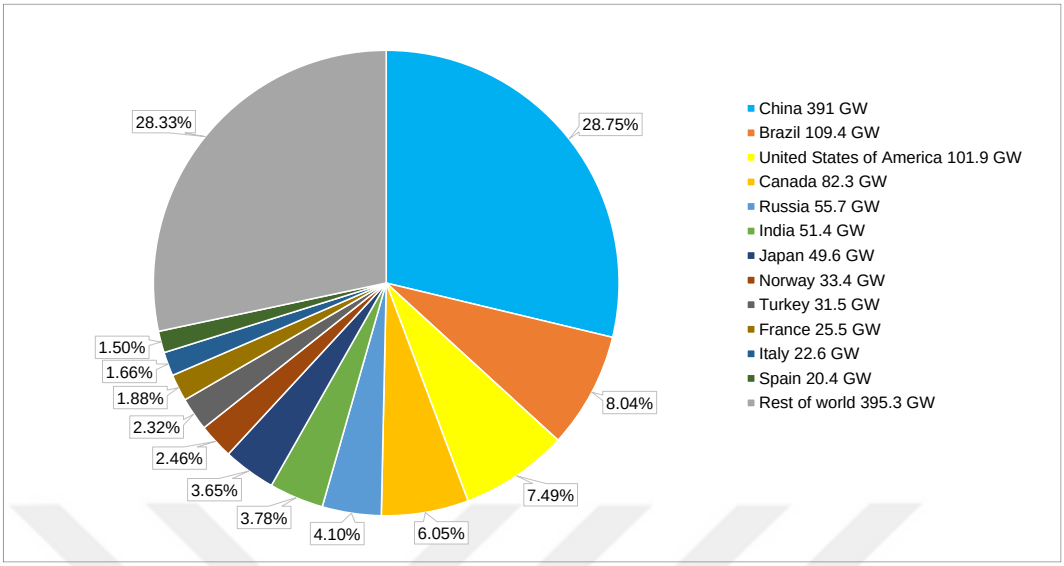


Figure 1.6 Hydropower installed capacity in 2021 (Data from [20])

Since 1990, the majority of development has been comprised of both significant and inconsequential run-of-river projects of varying sizes. The present installed capacity of small hydro is 3,400 MW, with a potential of 15,000 MW, as reported by Natural Resources Canada [22]. Due to a lack of public acceptability, the remaining 40% of hydroelectricity's potential won't be utilized until the year 2050 [23]. The widespread use of hydroelectricity in Canada, including its incorporation into the names of electric utility companies like Toronto Hydro and BC Hydro, has led to the use of the term "hydro" to refer to energy in certain regions of the country regardless of the source of the electricity. As of the year 2019, Canada has an installed capacity of 81 GW for hydroelectric power and produced around 400 TWh of electricity [24].

1.4.2 Marine Energies

Wave energy is a method of producing electricity from the movements of waves that entails converting the kinetic energy present in the waves of the ocean into a form that can be consumed by people. In contrast to topping converters, which make use of height discrepancies, oscillating body converters use wave motion. A turbine can be powered by shifting water columns that trap air pockets, and oscillating body converters, among other types of converters. Turbines are driven by all of these

different converter types. The several marine-related applications that contribute to the production of electrical power are broken out globally for the years 2010 through 2020 in Figure 1.9. There is a potential for 35,700 megawatts (MW) of tidal energy in Canada, according to estimates [25]. This amount of renewable energy is sufficient to avert the emission of over 113 Mt of CO_2, which is the same as taking more than 24 million cars off the road [25]. Tides are caused when the gravitational pull of the sun, moon, and the earth's rotation all act together. Both their orbits and the amount of tidal energy that is available may be predicted.

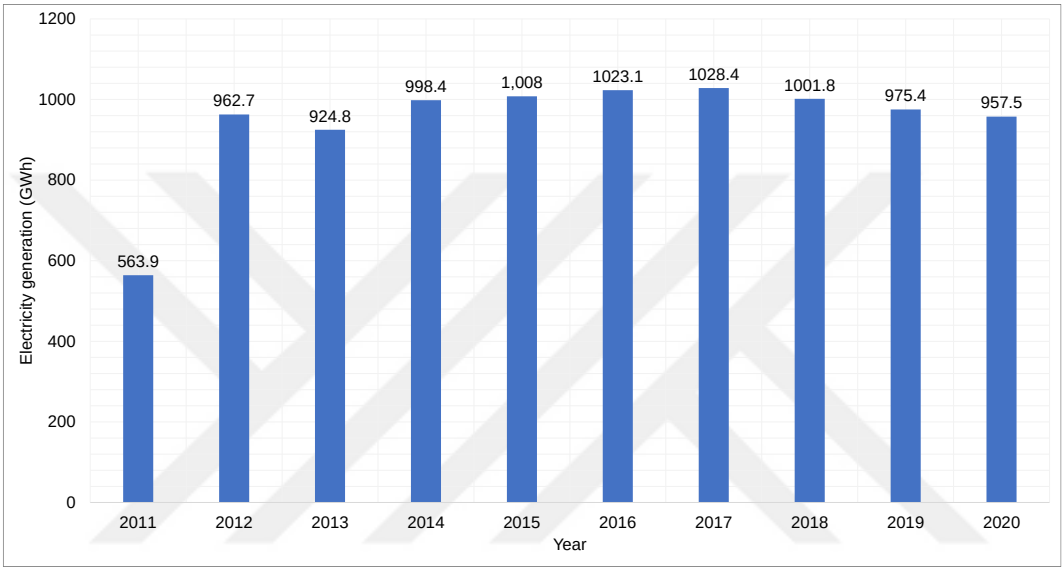


Figure 1.9 The global electricity generation from marine applications around the globe between 2010 and 2020 (Data from [25])

The Ocean surges have a tremendous amount of potential energy. Wave energy devices can derive energy from the surface motion or pressure fluctuations of ocean waves. Canada is a wave energy potential juggernaut. The National Round Table on the Environment and the Economy estimates that wave power has an extractable potential of up to 16,000 MW [26]. While the east coast of Canada has significant wave energy potential, the near-shore wave potential on the west coast represents the largest and most practicable development opportunity in the near future. British Columbia (BC) is home to a number of wave energy technology developers, such as Accumulated Ocean Energy (AOE) [27] and Neptune Wave Power [28]. Multiple additional prospective wave farm development sites in the province are being investigated. Wave energy resources are plentiful in the waters off the coasts of both the Pacific and Atlantic oceans that Canada possesses. There are over

37,000 MW of generating capacity off the coast of Canada's Pacific region, which is comparable to more than 55% of the total yearly demand for energy in the country [26]. It is estimated that the area off the coast of the Atlantic coast of Canada has a potential capacity of approximately 146,500 MW, which is more than double the total amount of power that is now required [26]. However, not all of these wave energy resources can be converted into useful power due to socioeconomic issues, the hostile conditions of the ocean, energy conversion losses, and the expenditure that is involved.

1.5 Geothermal Energy

In 2021, geothermal electricity generation attained a total installed capacity of approximately 15.96 gigawatts of electric (GW_e) at an annual growth rate of approximately 3.5% [29]. Globally, geothermal still accounts for less than 0.5% of installed renewable capacity for electricity generation, heating, and ventilation. In contrast, geothermal deployment for heating and ventilation increased by an average of 9% per year between 2015 and 2020, reaching 107 gigawatts thermal (GW_{th}) in 2020 [29]. Geothermal energy is used to generate electricity in over 30 countries. Per country, installed capacity ranges from less than 1 MWe to 3.7 GW_e [29]. The primary electricity generation technologies are dry steam, flash steam, and binary power plants. The global installed capacity for geothermal electricity generation at the end of 2021 is depicted in Figure 1.7 as 15.96 GW_e, distributed across five major regions [29]. Asia and Oceania, North America, and Eurasia have the highest installed capacity, with 5.9 GW_e, 3.7 GW_e, and 3.5 GW_e, respectively.

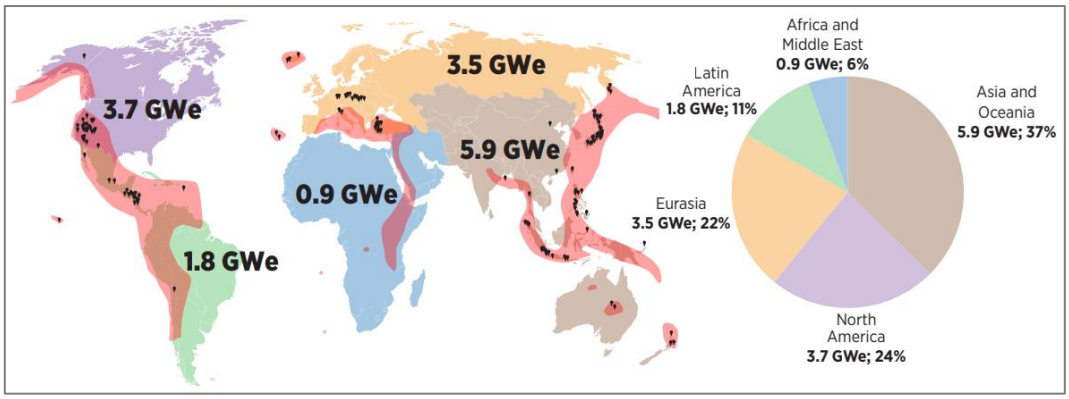


Figure 1.7 Installed geothermal capacity by regions in 2021 [29]

Geothermal energy systems have been in operation since 1911. To date, however, Canada has only constructed a scattering of direct heat-use initiatives. Several geothermal energy projects are in various phases of development, including DEEP Corp's 25-megawatt (MW) project in southern Saskatchewan, which is expected to become operational soon [30].

While the majority of Canadians are connected to regional electricity infrastructure, the vast majority of Northern Canadian communities and industrial sites rely on diesel for heat and electricity. This is expensive and has significant environmental impacts. Geothermal energy is particularly attractive for such locations, particularly if the surplus heat is reused for another purpose, such as powering greenhouses, which would also help resolve food security in the North. Parts of the North are overlain by high-temperature resources that can be utilized for high-efficiency geothermal electricity generation.

Reasonable excavation depths are necessary for high-temperature resources in order to generate utility-scale electrical power using classic dry steam and flash steam power stations. According to the findings of a recent study [31], areas that have a temperature of 150 °C (302 F) and a depth of 5 km (3.1 miles) or fewer have a great potential for high-temperature geothermal systems, such as the generation of power. These requirements are satisfied in the territories of British Columbia, the Northwest Territories, far northern Alberta, and southeastern Yukon.

For utility-scale electricity generation using binary cycle power stations, areas that have thermal springs and temperate sedimentary basins with temperatures between 80 °C and 150 °C (176 and 302 °F) must be provided at tolerable drill depths [32]. This encompasses the territories of the Yukon, Northwest Territories, southern Saskatchewan, southern Alberta, and western and southern Alberta in Alberta [32].

Geothermal heat pumps require places with sedimentary basins and/or fractured rock that may rapidly produce water or that are easy-to-dig shallow well systems for circulation loop installation. These regions must also have a temperate and cold temperature range. Those listed provinces are Alberta, British Columbia, southern parts of Ontario, Manitoba, Saskatchewan, and Quebec, northern parts of Ontario,

Nova Scotia, and Northwest Territories, Yukon, Nunavut, New Brunswick, and Prince Edward Island.

Other regions of the North, however, are composed of frigid granite, necessitating the need for enhanced geothermal systems. To reach minerals with sufficient heat to generate electricity, at least 4-5 km of excavation is required. At this depth, the rock must be artificially fractured to generate sufficient permeability. Such systems are still in the experimental phase, but a 6,500 m deep system in Finland is nearly finished [29]. Hydrothermal reservoirs are geothermal resources with enough natural permeability to produce sufficient water at an appropriate temperature for commercial power or heat production. In Canada, hydrothermal reservoirs exist in volcanic rock in British Columbia and the Yukon, as well as in sedimentary basins in the Prairies and parts of the North [32].

1.6 Biomass Energy

Bioenergy can be derived from a variety of biofuels. These include liquid biofuels used to power automobiles and forest wood residues utilized to power fiber mills and other industrial processes. The forest biomass used to produce bioenergy comes from a variety of sources, including trees of harvestable age but unsuitable for lumber, material from stand thinning, harvest residues, trees killed by disturbances such as fire, disease, or insects, and trees are grown specifically for the purpose of providing biomass for bioenergy conversion. Industrial forest byproducts are an additional source of biomass for bioenergy production. Among these by-products are things like wood wastes (like sawdust, bark, and shavings) and pulp remnants (such as lignin-rich "black liquors") from the pulp and paper industry [33]. Figure 1.8 illustrates the global bioenergy supply on the assumption of a net-zero scenario from the years 2010 to 2050. More than 60% of the 100 EJ of global bioenergy supply that would be available in 2050 under the NZE scenario will be produced from waste streams that do not call for the utilization of dedicated land [34]. This includes leftovers from the agricultural and municipal food processing industries, as well as those from the forestry sector. In the NZE scenario, by the year 2050, 20 EJ of bioenergy will be produced from the forest residues that are left over after the processing of timber and the harvesting of forests [34].

Before biomass can be used to produce energy in an effective manner, there are a few prerequisites that need to be satisfied first. These include the provision of biomass at a cost that is competitive with that of other available options, as well as the exploitation of biomass for the generation of energy in a manner that has a minimal impact on the natural environment. Both of these conditions need to be satisfied. In addition, for the objectives of converting biomass into energy and using it as an end product, the quality of the biomass must be as good as it can possibly be. In order to satisfy these requirements, unique harvesting techniques and post-harvest procedures have been developed [32].

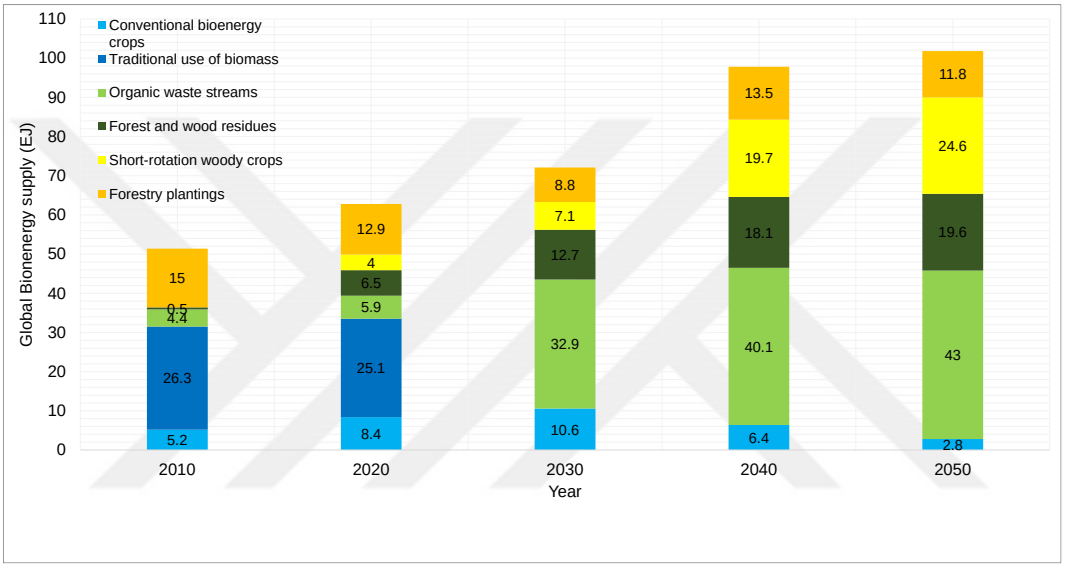


Figure 1.8 The global bioenergy supply in the net zero scenario between 2010 and 2050 (Data from [34])

In addition, research conducted in this field by the Canadian Forest Service (CFS) [32] continues to focus on:

- locating additional existing and novel biomass sources;
- developing effective cultivation, harvesting, and collection techniques for biomass;
- transportation and conversion of it into biofuel;
- proving the ability to sustain an increased biomass output over time.

As a result of improvements made to the cultivation system, the amount of biomass produced by these "dedicated energy crop" farms is on the rise. Plantations in Canada are capable of producing 10–15 oven-dry tons of biomass per hectare per

year as a result of improvements in fertilization, irrigation, and insect management [33].

The International Energy Agency, known as the IEA, Bioenergy is an organization whose mission is to improve collaboration as well as knowledge sharing between nations that have national bioenergy research, development, and deployment initiatives [34]. Canada is one of seventeen countries that participate in International Energy Agency (IEA) Bioenergy research activities.

In return for the contributions of its expertise, experience, and financial resources to the IEA Bioenergy program, Canada is given permission to access the findings of research and scientific exchanges carried out by other member nations. Moreover, IEA Bioenergy has made a contribution to the study that has been carried out in Canada [34]. The information gathered was helpful to efforts that were exploring the practicality of using forest leftovers for the production of bioenergy as well as the prospective repercussions on land use of transitioning to greater bioenergy production. These initiatives were looking into both of these topics.

The International Energy Agency's Bioenergy Task 43 [34] and the Biomass Feedstocks for Energy Markets project [35] are two of the nine various bioenergy endeavors that Canada is currently engaged in. Task 43's goal is to encourage businesses, the government, and other sectors to make decisions based on reliable information so that the bioenergy industry can expand in a manner that is socially and environmentally responsible. Participants in this job for the IEA Bioenergy endeavor to help decision-making by providing timely and topical analyses, syntheses, and general data on all domains associated with biomass feedstock. This support can be provided in a number of different ways. Markets for biomass, as well as the social and environmental implications of feedstock production, are included in these areas of study [33].

1.8 Nuclear Energy

In the years to come, the global energy mix may include a large contribution from nuclear energy, which has the potential to play a significant role. It is a source of electricity that has a minimal carbon footprint and can contribute to the reduction of emissions of greenhouse gases. The usage of nuclear power has resulted in a

reduction of CO_2 emissions of over 60 Gt over the course of the past 50 years, which is equivalent to approximately two years' worth of global energy-related emissions [36]. However, in rich economies, nuclear power has started to decline, with facilities closing and very little new investment being made—just at a time when the world needs more electricity that is low in carbon emissions. On the other hand, the average age of the nuclear fleet in advanced economies is 35 years, and several reactors are getting very close to reaching the end of the lifetimes for which they were intended. The following information is taken from World Nuclear Association Power Reactor Information Service (PRICE) [36]. Because of their advanced age, facilities are starting to shut down, and it is anticipated that 25% of the existing nuclear capacity in advanced nations will be shut down by the year 2025. In 2021, nuclear reactors produced a total of 2,653 TWh of electricity, which is an increase of 100 TWh over the 2,553 TWh generated in 2020. This is the third-highest total ever for global generation from nuclear, falling just short of the 2,657 TWh output of 2019 and 2,660 TWh in 2006 [36]. As can be seen in Figure 1.10, the generation of nuclear power grew in 2021 in the regions of South America, East Europe, Russia, Africa, and Asia. These gains carried on the growing trends that have been observed in those locations over the past few years. Even if there was a rise in generation in Western and Central Europe, the general trend in this region is still declining. China remained the primary driving force behind the expansion of the nuclear power generation industry. In the year 2021, China's fleet was expanded with the addition of two additional reactors, and the country has plans to construct dozens more in the years to come. As a result of the retirement of multiple nuclear reactors, nuclear power generation in the United States saw a drop. Despite this, the United States continues to be the world's second-largest producer of nuclear electricity. Quite a few nations, such as Germany and Belgium, have recently made public their intentions to wind down their nuclear projects. This level of uncertainty over the trajectory of nuclear power presents a significant obstacle for the business. The 19 commercial reactors in Canada, which have a combined net capacity of 13.5 GW, are responsible for the generation of a total of 95.6 TWh of electricity in 2015, which is equivalent to 16.6% of the country's overall output of electric energy [37].

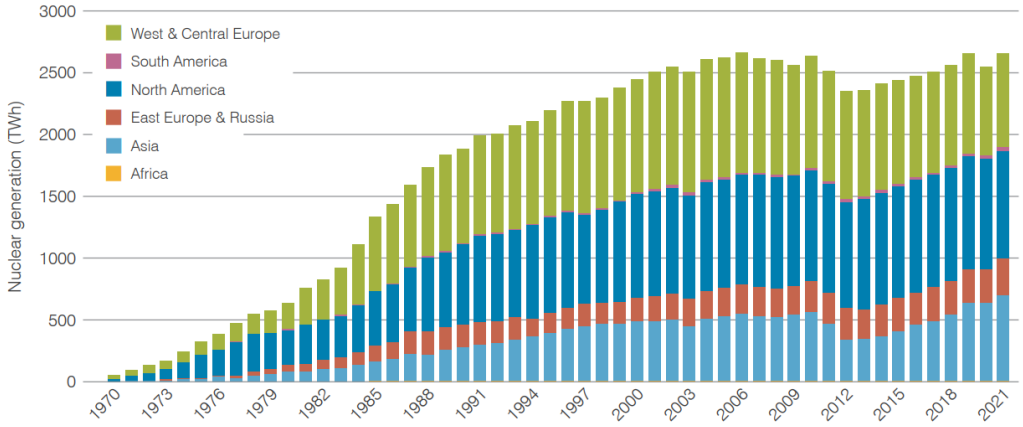


Figure 1.10 Nuclear energy production between 1970-2021 [36]

These reactors, with the exception of one, are all situated in Ontario, and in 2019, they were responsible for producing 61% of the province's total power (90,4 TWh) [37]. The Canada Deuterium Uranium (CANDU) [38] pressurized heavy-water reactor (PHWR) is the only type of nuclear reactor that is currently operational in Canada. CANDU reactors are being shipped to countries such as India, Pakistan, Argentina, South Korea, Romania, and China. Even if there are no current plans for the construction of any new CANDUs anywhere in the world as of the year 2022, Canada remains a technology frontrunner in the field of heavy water reactors and natural uranium-fueled reactors in general.

1.9 Objectives

The primary objective of this thesis is to propose a concept for a hydrogen farm that makes use of renewable and clean energy sources to produce clean (or sustainable) hydrogen via electrolysis. These types of energy sources are referred to as "green" sources of energy. There is a significant need, in the context of research on a national scale, for an extensive investigation of the possible renewable resources and integration of those resources with effective methodologies, with the end goal of determining the green hydrogen potential. Previously, Dincer et al. [39] conducted a comparable study for Turkey. An original method for approaching the idea of the hydrogen core gave a new point of view to the area of research being investigated. The many provinces of Canada are governed by similar principles. An application study is being carried out for 13 Canadian provinces, each of which has the ability to make use of a different type of renewable energy source for the

production of hydrogen. As a result, the development of this study's concept makes it one of a kind, and its potential applicability to Canada's provinces is extremely dynamic. In addition to this, it intends to illustrate the significance of hydrogen farms and supply an overview of the possibilities for the generation of hydrogen. It has a positive impact on the economy of the region as a whole, as well as on the transportation and manufacturing sectors, as well as the building and construction business. This strategy for utilizing renewable energy sources speeds up the process of decarbonization on a worldwide scale, which is an efficient method for preventing global warming and reversing its effects.

It is essential to conduct research into hydrogen storage systems that are both cost-effective and efficient in order to allow the transfer of associated technologies to a nation that has established a hydrogen center. The main objectives of the thesis are as follows:

- To develop and analyze clean energy-based hydrogen production systems considered including, solar, wind, hydropower, geothermal, wave, undersea current energies, and nuclear energy
- To prepare hydrogen maps based on available clean energy potential for the country
- To assess the green hydrogen production potential of provinces from their available electric energy
- To show the hydrogen production difference among three commercially available electrolysers.
- To compare the onshore and offshore hydrogen production potential of different regions of Canada
- To identify the regions with the highest green hydrogen production potential in Canada
- To help strategists dealing with the implementation of green hydrogen production technologies in hydropower plants

With this study, an assessment of clean hydrogen production of Canada from renewable and clean energy resources will be found. It will show what kind of sources and methods Canada has and what is not will be revealed.

2
LITERATURE REVIEW

2.1 Green Hydrogen Production

The hydrogen demand is anticipated to exceed 1.94 Mt/year by 2030 and 5.26 Mt/year by 2040, according to the hydrogen map of South Korea [40]. By 2030, Japan wants to cut its GHG emissions from the residential and commercial sectors by 39% and 40%, respectively [41]. California in the United States of America has the most advanced hydrogen delivery infrastructure for fuel cell automobiles. Approximately 7,800 fuel-cell electric cars and 28,000 forklifts powered by hydrogen fuel cells are in operation in the United States right now [42]. Countries should adhere to certain policies and roadmaps in order to create a sustainable energy future on a global scale. Turkey, for instance, is developing a roadmap for the development of hydrogen energy technologies [43].

Algeria's potential for producing green hydrogen was looked at by Rahmouni et al. [44]. They have taken wind and solar energy into account. The hydrogen is subsequently produced using the water-splitting technique using the obtained renewable energy. The potential for producing hydrogen has been demonstrated in many zones. It is determined that a good example of a large-scale hydrogen manufacturing facility is the Algerian Sahara. Many nations are motivated to address the CO_2 emission problem during conventional hydrogen generation from fossil fuels because of the significance of producing green hydrogen. When discussing the significance of hydrogen as a potential future energy source, it will be pointless if the life cycle analysis of hydrogen production is not fully addressed.

Germany has developed a national hydrogen strategy and projects that by 2030, it will need 90–110 TWh of hydrogen [45]. It is anticipated that the necessary hydrogen will be imported from the Netherlands, Denmark, and Russia in order to accomplish this goal and take into account the restricted hydrogen resources. Germany's natural gas network features a sophisticated infrastructure. The pipelines that are not in use will be used to transport hydrogen, according to the plan [45].

A consortium in Hassfurt is constructing a power-to-gas prototype using extra renewable energy. Siemens-made proton exchange membrane (PEM) electrolysers with a 1.25 MW input power produce hydrogen [46].

Additionally, Australia is researching the potential advantages of producing environmentally friendly hydrogen from an abundance of wind and solar energy and then selling it to Japan and Korea [47].

In the Karachi region of Pakistan, researchers Mohsin et al. [48] looked at the production of hydrogen using wind energy. Baghan, Nooriabad, Golarchi, and DHA Karachi are some of the areas that have been researched since they have available meteorological data. According to the findings, all of those locations are suitable for the generation of hydrogen from wind energy on a commercial scale. The amount of hydrogen that can be produced at these four locations ranges from 10,545 kg/day to up to 51,917,390 kg/day during the summer months when 660 kW turbines are used. Wind speed, air density, the size of the wind turbine, and the size of the electrolyser all have a role in determining how much hydrogen can be produced.

A comprehensive statistical analysis was performed by Ashrafi et al. [49] to assess wind-hydrogen technologies at high elevations in Iran by extrapolating wind data. Evaluating the variables that are part of the Weibull distribution function was done for every wind site that was analyzed by applying the Standard Deviation Method, the Empirical Method of Lysen, and the Power Density Method that was found to be the most appropriate. According to the findings, a wind turbine with a hub height of 80 m has the highest possible efficiency in terms of capacity ratio and yearly energy production.

The F-AHP, MCDA, and DEA approach technologies were utilized in Zhao et al.'s [50] investigation, which also looked into potential sources of hydrogen production in Pakistan. Wind energy is the most effective method for creating hydrogen in Pakistan, according to the results that were based on the DEA methodologies ranking efficiency ratings; biomass was the second most effective method. Solar energy comes in third place, while geothermal energy comes in last place, according

to this rating, with scores of 0.756 and 0.662, respectively, for solar, geothermal, and geothermal energy.

Chapman et al. [51] examined the findings of four separate case studies that investigated the possible use of hydrogen and its impact on the energy system of the future. The international energy model, social welfare economics assessment, hydrogen as an energy carrier for motor vehicles in the United States, and reducing GHG emissions from the gas grid using hydrogen were the topics of these case studies. According to the findings of recent research, boosting the utilization of hydrogen can be good for reducing energy consumption while also contributing to the decarbonization of the global energy system. A reduction in CO_2 emissions of around 10–30% can be achieved in on-road transportation in the United States through the utilization of hydrogen as an energy carrier.

More than 50,000 rivers in China irrigate an area that is 100 km^2 in size, and the country's total number of rivers is around 3,886 [52]. Each of these rivers has a hydroelectric potential that is greater than 10 MW. China has a significant number of rivers. The entire theoretical potential is greater than 6,000 TWh/yr, the practical potential is approximately 2,474 TWh/yr, and the economic benefit potential has been estimated at 1,753 TWh/yr in all rounds, which places China in front of every other country in the world [52].

Even though Malaysia has a large number of hydroelectric power plants, and its total capacity is stated to be 29,000 MW, the country only utilized approximately 2,091 MW of that potential in 2008 [53–55]. This was due to the significant amount of capital expenditure as well as socio-economic concerns. The current Bakun hydroelectric project in Micronesia has a capacity of 2,400 megawatts (MW), making it the largest hydropower project in the country at the moment. The Bakun Dam would become the world's second-tallest concrete-faced rockfill dam once construction is complete. Greece possesses approximately 50 smaller hydropower stations that have a combined power rating of 70 MW, in addition to 15 big hydropower plants that have a total capacity of 2,950 MW. There are four further big hydropower plants located between western Greece and the center of Macedonia. These stations include Kremasta (440 MW), Polifito (375 MW), Kastraki (320 MW), and Pournari-I (300 MW) [56].

Nepal has a hydroelectric capacity of over 43,000 MW, however, only 2.64% of it was used up till 2019 [57]. New pipes with a 6,000 MW capacity are built in order to boost the hydropower production potential. The capacity balance prediction reveals a significant discrepancy between supply and demand. By 2030, an excess of about 3,000 MW of power is anticipated. It has been noted that using surplus energy at 20% and 100%, respectively, is projected to change the potential hydrogen production between 63.07 kt and 3.15 Mt. By 2030, this can meet 20% of the demand for fossil fuels [57].

According to the findings of Chang and colleagues [58], conventional operation diagrams might no longer be adequate for directing the management of reservoirs as a result of recent changes in the global climate. A new simulation method is applied in order to fit the operation rules of the hydropower plant into the adaptive management diagram in order to facilitate the discovery of an alternate solution. The Shiquan-Xihe-Ankang cascade reservoirs have been selected for the purpose of the case study in order to analyze and demonstrate the efficiency of new operating charts. In order to validate the rationality and superiority of the present system, three brand-new operation charts were implemented. Cascade power generation increased by 4.4%, 9%, and 7.3% in rainy years, normal years, and dry years, respectively, when compared to the traditional operation chart's recommendations. The newly adopted optimal adaptive operating chart was responsible for this improvement.

Between the years 1991 and 2010, De Faria et al. [59] investigated the relationship that existed between socioeconomic conditions and the development of hydropower in Brazil. To capture the temporal course of development effects, identical methodologies to those employed in the evaluation of countries' plans to construct hydropower plants were utilized. These methods include the event study and the difference-in-differences panel econometrics. There are four primary pieces of evidence. First, the construction of hydropower plants raises the value of the nation's gross domestic product (GDP), but it lowers the value of the nation's agricultural GDP. Second, the public benefits follow a matching criterion with federal tax transfers. Thirdly, smaller hydropower facilities have a significantly more favorable influence on the Gross Domestic Product and tax income than larger

hydropower plants, and the most recent research suggests that there are no notable effects on socioeconomic variables.

Recent research conducted by Y. Bayazt [60] demonstrates that a hydropower plant has a beneficial impact on the amount of carbon emissions produced. The SIMAHPP 5 Professional program was utilized for analysis in the instance of CO_2 emissions from the Eskişehir province. This software was taken into consideration by the Gokcekaya Hydroelectric Power Plant for the study. The findings indicate that if the same 597.85 Gwh/year quantity of energy that is generated by the Gokcekaya dam is generated from fossil sources, then it will result in an average of 408,533.57 tCO_2/year. The power plant's production of electricity results in a reduction of carbon emissions that have a market value of 2,479,833 dollars. This is an economic benefit.

Bødal et al. [61] evaluated the impact of hydropower on the expense of hydrogen produced in the system and a model for optimization of a system using large-scale production of hydrogen from wind power. According to the study, with 24 hours of flexibility, raising hydropower levels can cut the system's energy loss by up to 56%. This flexibility reduces the electrolyser's need for electricity by 27% and can bring down the price per kilogram of hydrogen produced from 1.83 to 1.32 euros.

An operational 7.5 MWe binary geothermal power station in Tuzla, Istanbul was investigated by Coskun et al. [62], who found that energy and exergy losses occur in the saline reinjection unit.

Osamah et al. [63] conducted research on geothermal power plants that used a single flashing stage to four flashing stages. It was discovered that increasing the number of flashes in a cycle from one to two results in an increase in the output power. However, if the number of flashing processes is increased from two to three or more, the power growth rate will not remain the same and will actually decrease. This is because more flashing processes mean greater power consumption.

The several geothermal power plant configurations were investigated by Fallah et al. [64] from both a thermodynamic and a thermoeconomic point of view. The amount of electricity that can be produced by double-flash staged power plants is 27.7% higher than that which can be produced by single-flash staged power plants.

In addition, both the first- and second-law efficiencies improve, with the former increasing by 3.6% and the latter by 2%. In addition, utilizing a triple-flash cycle rather than a double-flash geothermal system will result in a 10% improvement over the latter.

Mostafaeipour et al. [65] conducted research on Afghanistan's potential for the manufacture of hydrogen using geothermal energy. Evaluation and ranking of the hydrogen production capacity of Afghanistan's provinces is accomplished through the utilization of multi-criteria decision-making approaches such as Stepwise Weight Assessment Ratio Analysis (SWARA) and Additive Ratio Assessment (ARAS). Out of the 17 provinces that were looked at, the ones that are best suited for producing hydrogen from geothermal energy are Sari Pul, Balkh, and Herat. On the other hand, Zabul, Ghowr, and Kandahar are the provinces that are least suited.

The design of a submersible electrical pump system for geothermal wells was examined by Aydın and Merey [66]. The fast expansion of operations in the same basins is causing a high-pressure decrease in Turkey's geothermal reservoirs. As a result, ESP devices are being used more frequently, especially in the Gediz and Buyuk Menderes Grabens. To maximize production potential, an ESP must be designed as efficiently as possible. They showed that the proposed design may enhance production by 165 t/h and that the installation of REDA L43000 N pumps increases production.

An innovative intergenerational system using a biomass gasification system was proposed by Parsa et al. [67] for the production of hydrogen and other commodities. The authors demonstrated that the system's first-law and second-law efficiencies rely on the biomass feedstock using energy and exergy analysis. When sugarcane bagasse served as the biomass source, the system's exergy efficiency was at its highest.

Puga [68] conducted research on the production of hydrogen using photocatalysis using feedstocks obtained from biomass. Substances such as carboxylic acids, aldehydes, alcohols, and saccharides, when subjected to selective light-induced photo reforming into H_2 and CO_2 under conditions of ambient temperature and pressure, generate side products and cause problems that are associated with

degradation. In this photo-reforming process, the range of substrates that exhibit the highest H_2 activity is typically nanocomposites of titanium dioxide and metal-supported co-catalysts. This is because these nanocomposites are the most prevalent type of substrate used.

The life cycle sustainability of hydrogen derived from the gasification of biomass was investigated by Valente et al. [69]. Comparisons are made between the standard method of producing hydrogen from natural gas and the more environmentally friendly method of producing hydrogen from the gasification of biomass using a method called Life Cycle Sustainability Assessment (LCSA). According to the findings, the first alternative cannot unqualifiedly be redeemed as a sustainable hydrogen replacement option for the second option. The gasification of biomass, on the other hand, has a good possibility of becoming a more environmentally friendly alternative to the traditional methods of producing hydrogen as technology continues to advance.

The researchers Solowski et al. [70] looked into the synthesis of hydrogen from biomass and the separation of it using membrane technology. Bacteria that meet certain requirements must be in possession of a specialized enzyme known as hydrogenase in order to create hydrogen. The production of hydrogen by strict bacteria, such as Clostridium, is the most efficient, whereas the creation of hydrogen by facultative bacteria is the second most efficient. This type is capable of producing hydrogen, although at a lower efficiency, it has a stronger resistance to oxygen. Hydrogen is likely what these bacterial metabolites are composed of given that they continue to hold onto carbon and work toward reestablishing contact with the immune systems of their victims, such as antibodies. Therefore, bacteria need to be pretreated utilizing stress factors such as heat, physical stress, or chemical stress in order to increase the efficiency of hydrogen production.

The development of a hythane-based cogeneration system that is integrated with gasification and landfill subsystems was researched by Sorgulu et al. [71]. They demonstrated that the system had an energy efficiency of 76.30% and an exergy efficiency of 35.17%. When hythane, a mixture of hydrogen and methane, is utilized as the input fuel for the combined cycle, the energy efficiency of the cycle drops to 51.64%, while the exergy efficiency rises to 70.29%. It has been

determined that hythane has a lower heating value (LHV) of 52,153 kJ/kg. The mole fraction of hydrogen in hythane is 20%, which results in an increase of 4.26% in the amount of methane. In addition, approximately 0.13 kg/s of hythane is necessary in order to meet the electrical load requirements of 3.5 MW and the heating load requirements of 1.55 MW for 12,000 dwellings.

An investigation into the creation of hydrogen from an innovative biomass-based integrated system for multigeneration was carried out by Safari et al. [72]. Analyses of energy and exergy were performed on the digester, the Brayton cycle, the organic Rankine cycle (ORC), the multi-effect desalination (MED), and the electrolyser. The overall efficiencies for energy and exergy were calculated to be 63% and 40%, respectively, whereas the performance rate of the MED system was calculated to be 4.25. According to the findings, the total energy and exergy efficiencies, as well as the production rates of hydrogen and other valuable outputs, are significantly improved when there is a greater molar proportion of CH_4 in the biogas.

Taamallah et al. [73] investigated the impacts of syngas fuels with a high hydrogen content in a gas turbine and compared them to the effects of CO and CH_4. In a fuel that is rich in hydrogen, the stability of combustion and the emissions of nitrogen oxides are both enhanced as the proportion of hydrogen in the mixture is increased.

Additionally, there have been several studies conducted in the literature on Türkiye's potential [43]. Besides perspective, research on the hydrogen hub concept [39], road map [74], and comprehensive assessments had been done for Turkiye's green hydrogen production potential from solar [75], wind [76], geothermal [77], hydropower [78], and biomass energies [79]. Based on these studies, the green hydrogen production potential of Turkiye from solar energy, wind energy, geothermal energy, hydropower, and biomass energy are listed as, 415.48 Mt, 248.56 Mt, 559.76 kt, 2.26 Mt, and 1.66 Mt, respectively.

2.2 Hydrogen Production in Canada

The International Energy Agency (IEA) [2] has suggested to governments throughout the world that they give hydrogen and other alternatives for clean energy the highest priority in their respective stimulus programs. In order for Canada to meet its post-pandemic financial turnaround, sustainable development, and climate

change objectives, it is essential to make investments in environmentally friendly infrastructure. The rapid deployment of centers will prepare Canada for broad utilization in the middle to long term, which is necessary so that the full decarbonization potential of hydrogen may be realized. Canada is one of the top ten producers of hydrogen in the world because of the steam methane reformation (SMR) of natural gas [80]. Each year, the country produces an estimated 3 metric tons of hydrogen. Despite the fact that SMR is not regarded as a green hydrogen path without capturing carbon, Canada is in a good position to make the switch to more environmentally friendly methods in the not-too-distant future. In recent years, Canada has created production supply chains, mostly in the province of Alberta, for the upgrading and refining of petroleum as well as the manufacturing of nitrogen fertilizer. These chains can be leveraged in the relatively near future. It is possible for Canada's production to rise by a factor of seven, reaching over 20 Mt of hydrogen with a low CI content yearly, in order to satisfy domestic needs by the year 2050 [81]. There is also the potential for major expansion in order to satisfy worldwide demand.

Canada, a significant player in the hydrogen market on a global scale, is an affiliate of several international organizations that deal with hydrogen. In December 2020, Canada made public its call-to-action hydrogen strategic plan. This strategy advocates the use of hydrogen as a means of achieving Canada's net-zero greenhouse gas emission objective by the year 2050 and positioning the nation as the global leader in renewable energy sources [80]. As part of the Paris Agreement, Canada has agreed on bringing its emissions of greenhouse gases down to levels 30% lower than those in 2005 by the year 2030 [81]. In addition to this, it has joined the ranks of the 72 other countries that have made the ambitious promise to achieve net-zero emissions by the year 2050 [81]. The economy of Canada will be fueled by electricity and renewable energy sources in a future with a net-zero carbon footprint, with low-carbon fuels supplying at least 60 % of the country's total energy requirements [81]. The new hydrogen strategy plan for Canada is the product of a process that spanned three years and involved the participation of over 1,500 industry professionals and stakeholders in engagement sessions [81]. There are numerous incentives in Canada. These can be listed as:

- Canada has a low carbon intensity (CI) power supply, placing it among the top nations with the lowest CI around the globe thanks to its hydroelectric-producing capabilities and position as a Tier-1 nuclear territory. Canada also has a huge amount of fossil fuel reserves, some of the best geology in the world for CO_2 storage, the ability to expand variable renewable energy, an immense amount of biomass, and abundant sources of freshwater. Each of these has an opportunity to be used in the hydrogen-generating process.
- Hydrogen and fuel cell technologies are two areas in which Canada is recognized as having world-leading firms and knowledge. As of the year 2017, there were over a hundred well-established businesses that employed over 2,100 people and generated over 200 million dollars in revenue [82].
- As of 2019, the energy sector in Canada was responsible for 832,500 direct and indirect jobs, and its assets were valued at 685 billion Canadian dollars [82]. Due to its highly qualified workforce and essential infrastructure, Canada is in a position to quickly change its energy currency to include at-scale hydrogen.
- The government of Canada, industry in Canada, and academic institutions in Canada are all participating in worldwide collaborations linked to hydrogen, which positions Canada as a leader not only in terms of innovation but also in terms of commercialization.
- California, the UK, Germany, and all of Europe, coupled with Canada's export advantages like deep-water ports, established transportation networks, and a developing liquefied natural gas (LNG) sector, prepare Canada to be a hydrogen exporter as the world economy changes [82].
- Canada is a hub for technical know-how, intellectual property, and cutting-edge goods and services, and it is considered an international leader in both the hydrogen and fuel cell industries. One of the biggest 10 hydrogen generators in the world right now is Canada [81]. Natural gas is used to produce about three megatons each year. The largest facility in the world for creating clean hydrogen from natural gas, including carbon capture and long-term storage of the accompanying CO_2 emissions, is located in Canada.

Ontario requested a discussion paper on the province's first hydrogen strategy in November 2020 [83]. The paper solicited feedback from public and sector-specific experts regarding the use of hydrogen as a reformer in the province's energy sector. Enbridge Gas Inc. [84], a Canadian behemoth in the energy transportation industry, has announced a hydrogen blending pilot project in the midst of these tremendous efforts by local and federal officials. Through this $5.2 million initiative, hydrogen will be incorporated into the company's existing natural gas network in Markham, Ontario [85]. By adding hydrogen to the mixture, it is hoped to improve the combustion ratio of natural gas; consequently, greenhouse gas emissions will be reduced. In this regard, the initiative, which is supported by Sustainable Development Technology Canada [86], is North America's first hydrogen blending project. Each province's hydrogen potential is depicted in Figure 2.1.

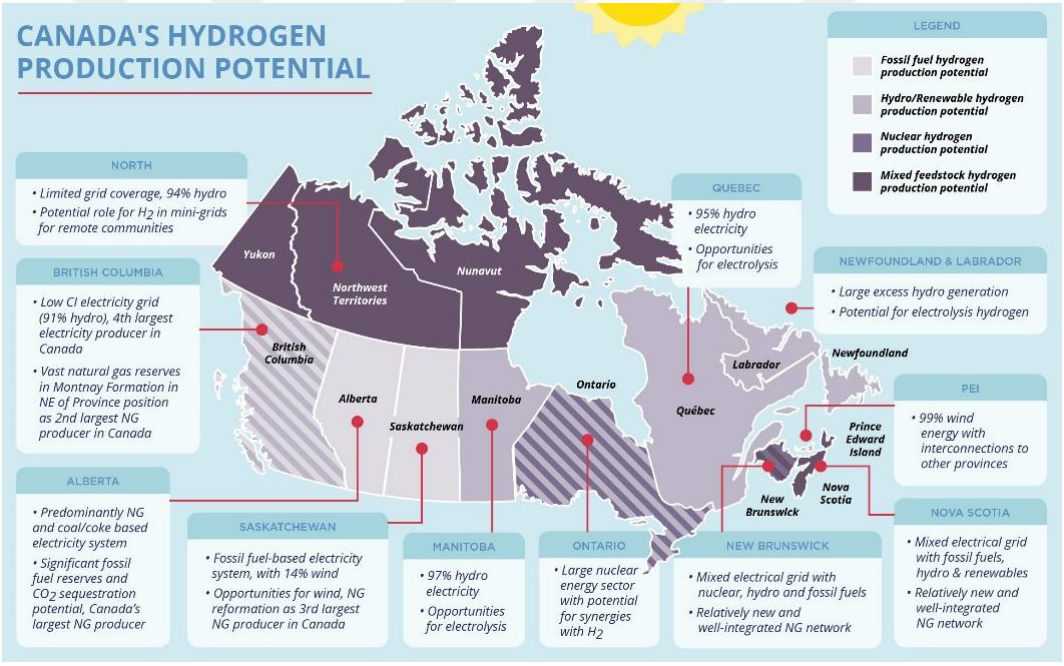


Figure 2.1 Canada’s hydrogen production potential [81]

The next five years will be dedicated to laying the groundwork for Canada's transition to a hydrogen-based economy. In order to support Canadian demonstrations of developing applications as well as the early deployment of centers in established applications, this includes the creation of new infrastructure for the transport and delivery of hydrogen. Early measures are vital for promoting investment in the industry, as are the implementation of rules and policies such as carbon pricing, which are required to take Canada closer to achieving its net-zero.

goals. Both of these are essential. Regulations like the Clean Fuel Standard [82] will be crucial in promoting immediate investment in the sector, in addition to adopting novel legislation and regulatory measures that will promote Canada's goal of achieving net-zero emissions by 2050. Early innovation investments are essential in order to meet medium- and long-term goals. Early-stage creative research and development may require an additional ten to fifteen years to mature. For even later-stage support, which may be required to improve the effectiveness of processes or save expenses, it may take years, followed by additional time for testing and presentation.

Between the years 2030 and 2050, Canada will begin to fully experience the benefits of an economy based on hydrogen, which will continue until the year 2050. This will take place when the number of installations and the range of new business uses both develop, both of which will be enabled by the infrastructure that is currently in place in Canada to deliver and distribute hydrogen. It is expected that as cell and charging technology advances, there will soon be a clearer separation between the use of batteries and fuel cells in vehicles in Canada, particularly for the purposes of transportation. This is one of the reasons why it is important for Canada to continue investing in these technologies. Applications that have a larger power demand and are more concerned with utility will choose hydrogen energy storage, whereas applications that have a lower power demand and are more concerned with efficiency will favor battery energy storage. The newly developed applications for transportation will enter the stages of commercialization and rapid expansion during this time period. The proportion of hydrogen that may be found in natural gas (NG) networks is expected to continue rising, which means that the utilization of specialized hydrogen pipelines will become an increasingly appealing alternative.

3
METHODOLOGY

Electrolysis is quickly becoming one of the most widely used technologies for creating high-purity hydrogen from the splitting of water molecules. The electrolysis of water is predicated on the movement of electrons across an external circuit, which is maintained throughout the process [87]. The types of electrolysers that are available for purchase on the market are as follows: alkaline, solid oxide electrolysers (SOEL), and proton exchange membrane electrolysers (PEMEL).

In order to split water, a certain amount of direct current needs to be passed across two electrodes that are physically separated from one another by an aqueous electrolyte that possesses a higher ionic conductivity. This is true for all three of the electrolyser systems covered in this study, with the general reaction

$$H_2O_{(l)} + electrical\ energy \rightarrow H_{2(g)} + 1/2O_{2(g)} \quad (3.1)$$

Considering the Alkaline electrolyser, which can be considered the oldest technology for water splitting by electrolysis and hydrogen production, the employed electrolyte is deterministic. The electrolyte is mainly based on potassium hydroxide (KOH) or sodium hydroxide (NaOH). Therefore, the reactions for Anode and Cathode electrodes in alkaline electrolysers for hydroxyl (OH_) ionic transportation can be shown as:

$$Anode: 2OH -_{(aq)} \rightarrow \frac{1}{2}O_{2\,(g)} + H_2O_{(l)} + 2e^- \quad (3.2)$$

$$Cathode: 2H_2O_{(l)} + 2e^- \rightarrow H_{2\,(g)} + 2OH -_{(aq)} \quad (3.3)$$

In terms of commercial ones, PEM electrolysers can be preferred, especially for mobility. Although they are much newer and less developed compared to alkaline electrolysers, they are easier to work with and generate hydrogen with higher purity.

$$\text{Anode: } H_2O \rightarrow 2H^+ + \tfrac{1}{2}O_2 + 2e^- \quad (3.4)$$

$$\text{Cathode: } 2H^+ + 2e^- \rightarrow H_2 \quad (3.5)$$

$$\text{Overall reaction: } H_2O_{(l)} \rightarrow H_{2\,(g)} + \tfrac{1}{2}O_{2\,(g)} \quad (3.6)$$

The specifications and differences among these three types of electrolysers are tabulated in Table 3.1. Three different commercially available electrolysers are considered in the calculations. While alkaline and PEM electrolysers considered in general applications, solid oxide electrolyser are also considered in high-temperature applications regarding geothermal energy. The efficiency of the chosen electrolysers is 66.10%, 64.63%, and 67.95% for alkaline electrolyser, PEM electrolyser, and solid oxide electrolyser, respectively.

Table 3.1 Typical specifications of alkaline, proton exchange membrane (PEMEL), and solid oxide electrolyser (SOEL)

Specification	Alkaline electrolyser (ALEL) [88]	Polymer electrolyser (PEMEL) [89]	Solid Oxide electrolyser (SOEL) [90]
Model Name	Nel-A1000	Nel-MC500	Sunfire-Hylink
Net Production Rate (Nm^3/h)	600	492	750
Production Capacity Range (%)	15-100	10-100	5-100
Power Consumption at Stack (kWh/Nm^3)	4.4	4.5	3.3
Delivery Gauge Pressure (bar)	1-200	30	1-40
H_2 Purity (%)	99.9	99.999	Up to 99.999
Ambient Temperature (°C)	5-35	20-40	20-40
Efficiency (%)	66.10	64.63	67.95

Regarding produced and consumed electricity, there are few assumptions considered in the calculations. First, total electricity production of a renewable source is equal to total sum of already existing power plants of that type and theoretical potential of it. In some cases, such as nuclear energy, only current production capacities are considered. Other sources like solar, wind, and hydroelectric energies, total capacity is total of both current power production and considered calculations. The second factor is the energy consumption of households, utilities, enterprises, and any other auxiliary consumers. Energy consumption of each province in Canada tabulated in Table 3.2. This data is taken from the Government of Canada, Statistic [91]. While producing clean hydrogen, two different scenarios considered. First scenario is all of the produced electricity from renewable and clean energy resources fully committed to produce hydrogen. In this case, power demand is discarded, and maximum hydrogen production potential is found. In the second scenario, electricity demand of each province is

met and after that clean hydrogen production potential is found by using the excess electricity.

Table 3.2 Energy consumption (PJ) of each province in Canada in year 2019

Province	Energy consumption in 2019 (PJ)
Alberta	4,160
British Columbia	1,346
Manitoba	340
New Brunswick	235
Newfoundland and Labrador	180.6
Northwest Territories	18
Nova Scotia	175
Nunavut	5.8
Ontario	3,150
Prince Edward Island	26.7
Quebec	1,975
Saskatchewan	686
Yukon	8.7
Total	12,305

3.1 Utilization of Solar Energy

Environment Canada's CERES CD (le disque canadien des énergies renouvelables éolienne et solaire, The Canadian Renewable Energy Wind and Solar Resource CD) [92] was the source for monthly values of global solar insolation (in MJ/m^2) on horizontal and variously inclined surfaces. At 144 locations across Canada, CERES provides a variety of summary statistics in graphical and tabular formats regarding solar radiation, wind speed, and wind energy potential. The solar data comprises global, direct beam, and diffuse solar radiation on a horizontal surface as well as 31 tilted surface orientations, one of which is a sun-tracking surface known as FTS (follow the sun) [92]. The hourly solar radiation data used by CERES was obtained from the governmental database [92]. This database is compiled from national climatological archives and contain standard meteorological observations such as temperature, humidity, wind speed and direction, sky conditions, weather occurrence, solar radiation, etc. Up to four observed cloud layers are considered, with each cloud layer's specific transmissivity taken into account. Multiple reflections between the ground and cloud base are considered, taking into account the albedo of the ground and the cloud type of each stratum. The orientation of a photovoltaic array has a substantial effect on the amount of electricity it can produce

and how this varies throughout the year. The optimal orientation for a fixed surface is determined by the intended use and the available orientations for PV system installation. From the 32 orientations presented in the CERES database [92], five surface orientations of particular relevance for photovoltaic applications were selected, and the daily average global insolation for each month and the entire year was obtained for these five orientations. Four of the five orientations are fixed, while the fifth orientation follows the sun along the East-West and North-South axes. The four fixed surfaces face south (equator) because the sun is due south at solar noon in Canada when irradiance is typically at its peak. Their tilts (angle of inclination away from the horizontal toward the South) are as follows: 90 tilt (vertical), latitude tilt (L), tilt = L-15°, tilt = L+15°. Figure 3.1 shows an illustration of different PV array selections used in the calculations. Photovoltaic modules are rated by manufacturers according to their nominal power, which is the power output corresponding to standard testing conditions (STC):1,000 W/m^2 irradiances with normal incidence, 25°C module temperature, and air mass 1.5. Under these conditions (and assuming no losses), a 1 kW PV system is expected to produce 1 kW of electric power.

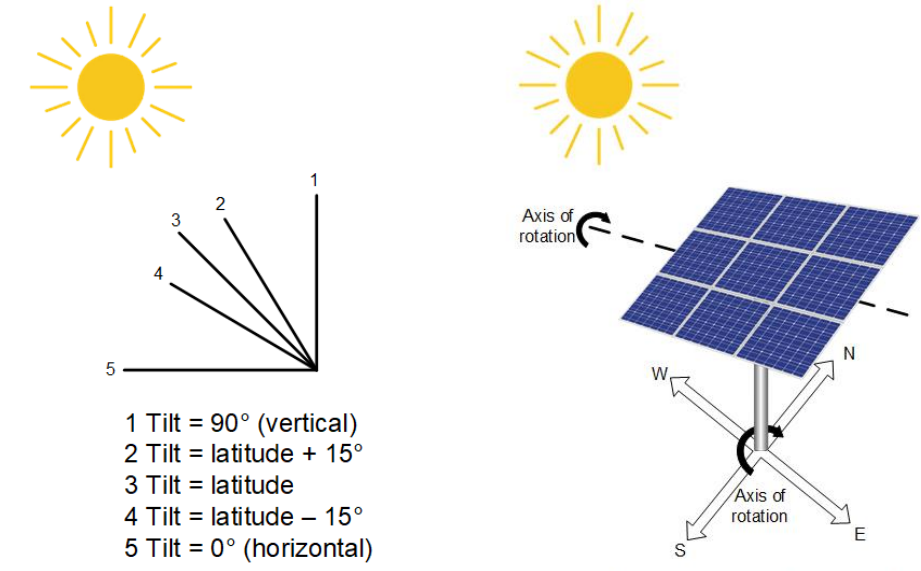


Figure 3.1 Illustration of (a) south facing PV panels with 5 different tilts and (b) 2-axis tracking PV panels used in the calculations (Modified from [10]).

The main assumptions for clean hydrogen production potential from solar energy are as follows:

- Six different PV panel arrays with different tilts and configurations are considered for the calculations. These are mentioned above and illustrated in Figure 3.1
- To estimate the potential monthly/yearly electricity production per kilowatt of a typical PV system with the orientations examined here, a fixed performance ratio of 0.75 was assumed.
- The entire acreage for each province is gathered from official sources in order to assess the country's overall potential for green hydrogen [85]. The useable net area has been determined since the objective is to utilize onshore and offshore areas for solar energy. From the entire area of each province, the urban, industrial, forestry, natural park, and agricultural regions are subtracted.
- It is envisioned that solar panels will be installed on 10% of the rooftop surface. 90% of the land received from the calculated net area for the areas is used to build solar farms.
- Alkaline electrolyser with an efficiency of 66.10% is used for onshore and offshore solar systems.
- For calculating the applicable offshore area, each province with access to the seashore selected and transport routes, private areas, public beaches, marinas, and harbors excluded from the total usable offshore land.
- For onshore applications, mono-facial PV panels are considered while for offshore applications floating bifacial PV panels are used whenever possible.
- The amount of undeveloped land that is available in various regions is constrained by topological issues and natural limitations. An ‘α’ coefficient is used in the calculations to reflect the topographic limitations and roughness of the terrain of each province.
- Generated electricity from the solar energy in the province is first used to provide the power demand of the region, then sent to electrolyser for hydrogen production. Only excess electricity is considered in the calculations.

Based on the assumptions mentioned above and calculations, power generation from solar energy for each province was found. Using water electrolysers, this generated power is used to produce green hydrogen. Despite being one of the largest countries in the world, Canada only utilizes around 10% of the total land. 90% of the country's land is not used due to harsh conditions, extreme temperatures, topography, or simply there is no need. Figure 3.2 shows the annual solar radiation intensity (kWh/kWp) of each province in Canada.

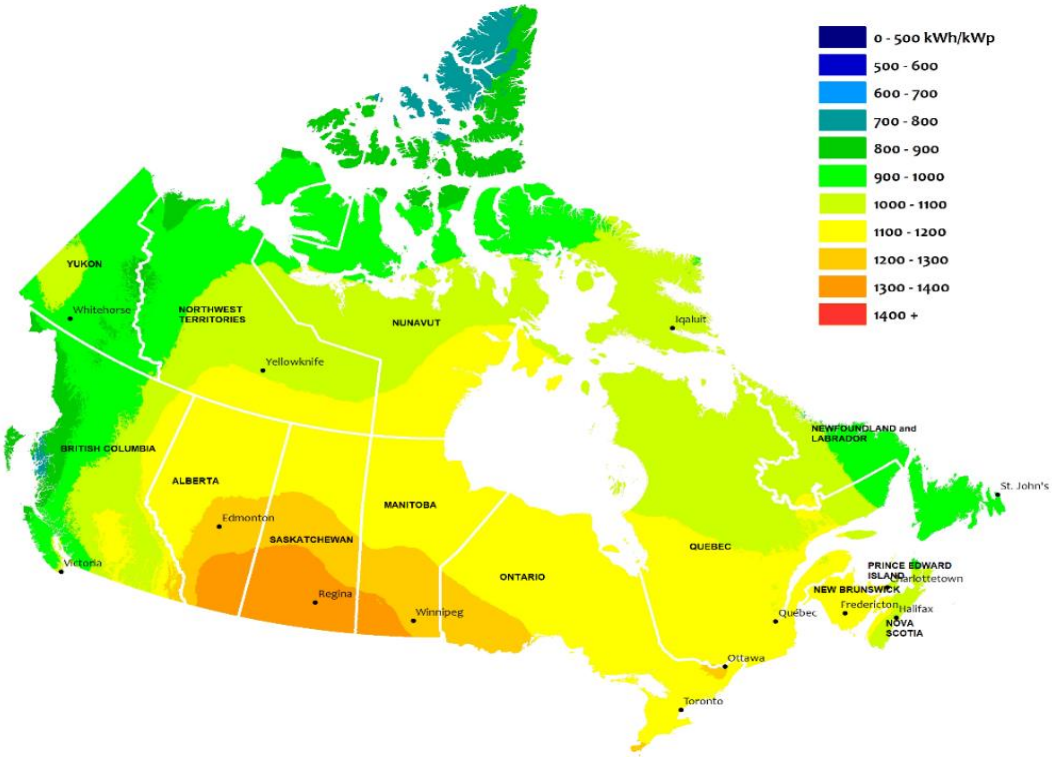
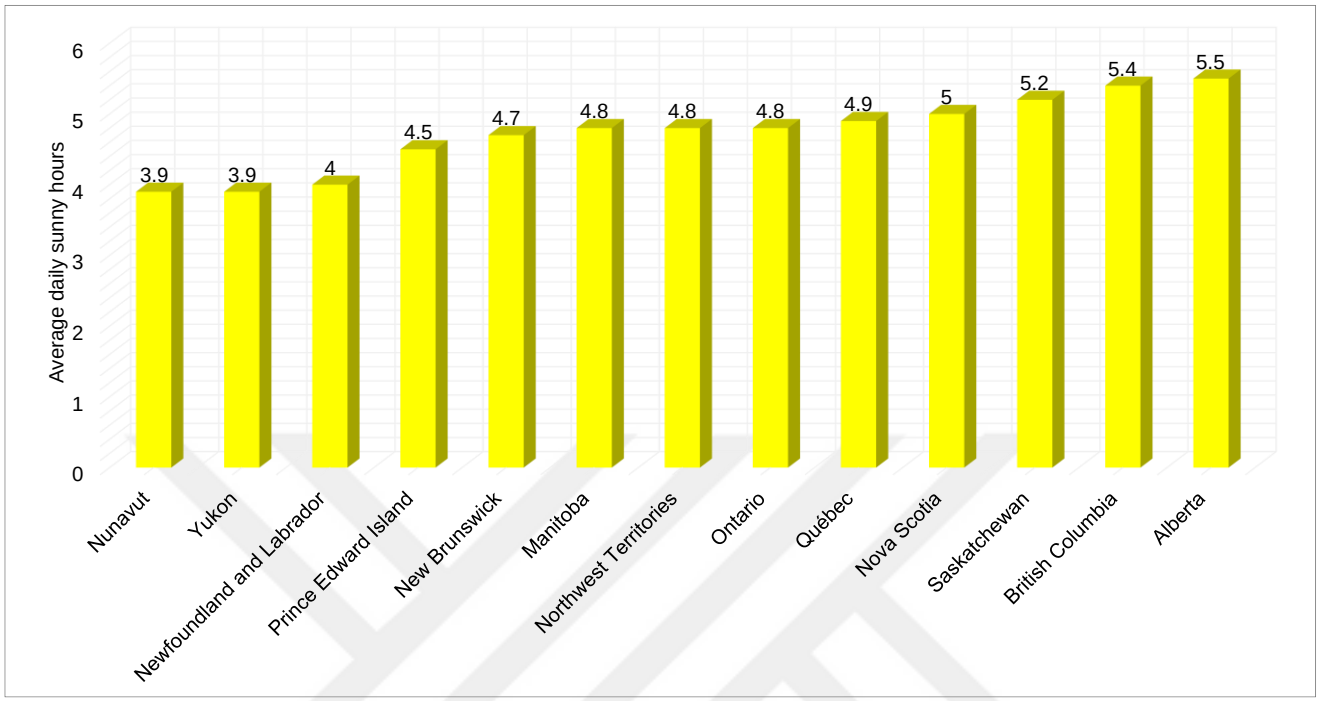


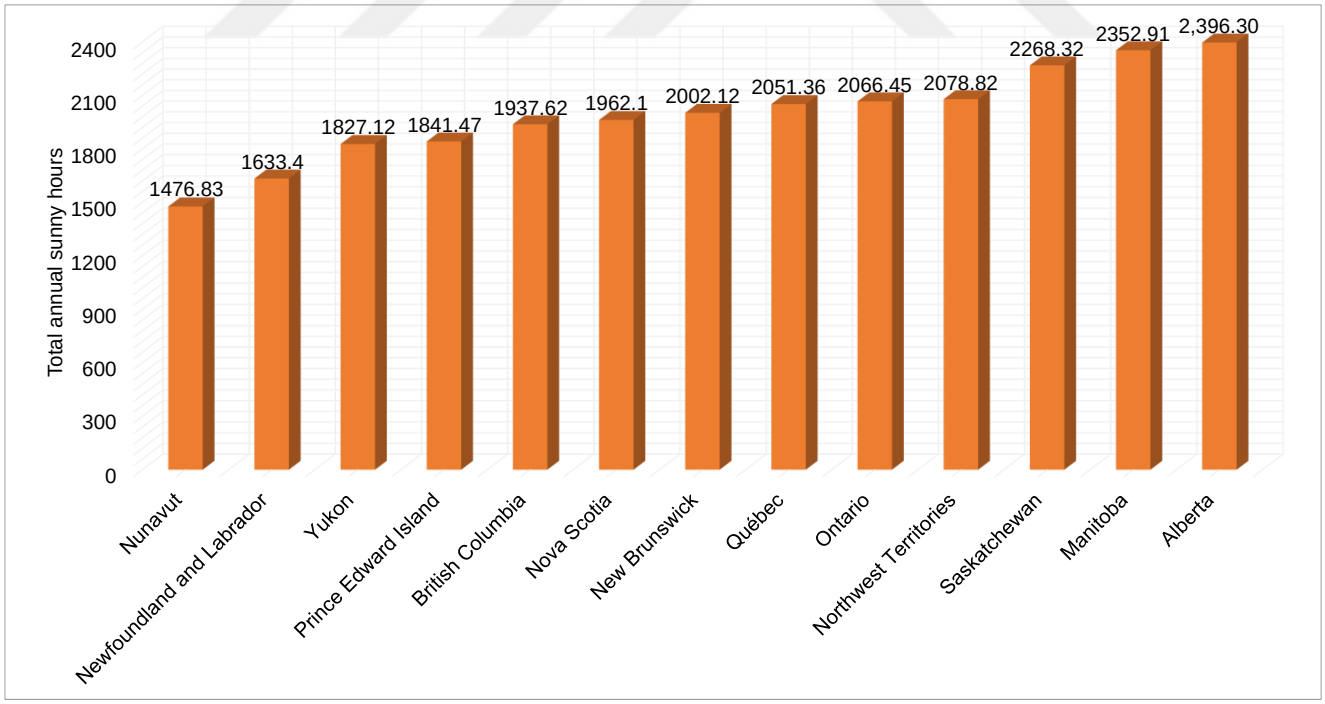
Figure 3.2 Solar radiation intensity (kWh/kWp) of each province in Canada [11]

Figure 3.3 shows the daily average sunny hours (a) and total annual sunny hours (b) for each province in Canada. Data and the following information are taken from CWEEDS [92]. The sunniest cities in Canada are Calgary, Edmonton, Regina, and Saskatoon, which all receive an average of over 300 days of sunshine per year. These cities are located in the prairie provinces, which are known for their sunny skies. Other cities in Canada that receive a lot of sunshine include Winnipeg, Vancouver, and Victoria. The sunniest month in Canada is July, with an average of 275 hours of sunshine. The least sunny month in Canada is December, with an average of 65 hours of sunshine. Total annual sunny hours differ between 1,476.83 and 2,396.30 hours with Nunavut listed as last place while Alberta listed as first

place. Annual daily sunny hours for provinces in Canada are between 3.9 and 5.5 hours/day. For total annual sunny hours, Nunavut is listed as last and Alberta is listed as the first province, respectively.



(a)



(b)

Figure 3.3 Canada provinces' (a) daily average sunny hours and (b) total annual sunny hours (Data from [92])

3.2 Utilization of Wind Energy

In terms of wind power, all of the data come from the Canada Energy Regulator (CER) [93], and the figures for wind speed are derived from a height of 60 m above the ground. Because of its location, Canada is in a prime position to make use of the enormous amount of wind energy that is available. In addition to savings in energy across the grid, decreases in emissions of greenhouse gases, and reductions in air contaminants (such as SO_X, NO_X, and mercury), the increased deployment of wind energy offers the benefit of reducing overall energy consumption. For example, a single installation of six wind turbines with a combined capacity of 65 kW in the province of Newfoundland is predicted to create around 1 million kWh yearly while simultaneously reducing CO_2 emissions by approximately 750 kilos [94]. As of the year 2022, the amount of wind power capacity already installed in Canada is equal to 14,304 megawatts (MW) [95]. This quantity is adequate to supply electricity to around 3.5 million dwellings. The Canadian Wind Energy Association (CanWEA) has devised a plan for the future of wind power that aims to increase its capacity to 55 gigawatts (GW) by the year 2025 [17]. This would be sufficient to meet 20% of the country's need for energy at that point in time. There is a wide variation in the speed of the onshore wind in Canada, ranging from 3.5 to 14.8 m per second [94]. The speed offshore is steadily growing to be far greater than the speed onshore. This value is something in the neighborhood of 5.10 to 16.26 m per second [94]. The Canadian government has made available the technical details of all of the wind turbines that have been built in the country [95].

Figure 3.4 depicts the average annual wind speed [94] at three different heights above the ground: (a) 60 m, (b) 120 m, and (c) 200 m. Because there is insufficient data, grey areas are assigned a value of zero. These regions are inhospitable, and the extreme conditions make it impossible to construct any power stations that run on renewable resources. The average wind speed rises from white to dark blue as the color progresses. The areas of the coasts of British Columbia, Quebec, Newfoundland and Labrador that are most suited for the installation of offshore wind turbines are located on the west coast of British Columbia. Ontario, Quebec, and Alberta are the three provinces that have the most potential for harnessing wind energy. Because these provinces experience high wind speeds throughout the year

in a continuous manner, they are excellent locations for the generation of wind power.

Wind turbines of the horizontal type have a better overall efficiency compared to wind turbines of the vertical type. In the course of this research, in addition to the wind farms and wind turbines that are already in operation, horizontal wind turbines are also taken into consideration. A survey of the relevant literature reveals that the typical capacity of wind turbines erected in the United States is 1.8 MW [96]. In light of this, Vestas V90-2.0 MW wind turbines are utilized for onshore application calculations, whilst Vestas V117-4.2 MW wind turbines are utilized for offshore application calculations [97-98]. The calculations take into account the technical specifications of the turbines, which are provided in Table 3.3.

Table 3.3 Technical specifications of onshore and offshore wind turbines

Specification	Onshore wind turbine	Offshore wind turbine
Model name	Vestas V90-2.0 MW [97]	Vestas V117-4.2 MW [98]
Rated Power (kW)	2,000-2,200	4,000-4,200
Cut-in wind speed (m/s)	4	3
Cut-out wind speed (m/s)	25	25
Rotor diameter (m)	90	117
Swept area (m^2)	6,362	10,751

The main assumptions for the calculation of the clean hydrogen production from wind energy are listed as:

- The entire acreage for each province is gathered from official sources in order to assess the country's overall potential for green hydrogen [99]. The useable net area has been determined since the objective is to utilize onshore and offshore areas for solar energy. From the entire area of each province, the urban, industrial, forestry, natural park, and agricultural regions are subtracted.
- For calculating the applicable offshore area, each province with access to the seashore selected and transport routes, private areas, public beaches, marinas, and harbors excluded from the total usable offshore land.

- For offshore applications, the coastline of each province is considered. The data for the applicable cities' coastlines are considered with a 2 km net width assumption.
- The amount of undeveloped land that is available in various regions is constrained by topological issues and natural limitations. An ‘α’ coefficient was used in the calculations to reflect the topographic limitations, roughness of the terrain of each province.
- Generated electricity from the wind energy in the province is first used to provide the power demand of the region, then sent to electrolyser for hydrogen production. Only excess electricity is considered in the calculations.
- The wind turbines are considered to be operational for 14 hours per day.
- Due to the greater wind speed offshore, larger wind turbines are utilized for offshore applications [98].
- In addition, only 90% of the net area is utilized due to topological constraints, unforeseen land issues, and similar factors.
- The vertical and horizontal distances between two wind turbines have been determined to be five and four times the diameter of the wind turbine blades, respectively, based on the already installed wind farms.
- The electricity generated by wind turbines is first used for the power demand of the provinces and then utilized in PEM electrolysers to produce renewable hydrogen.

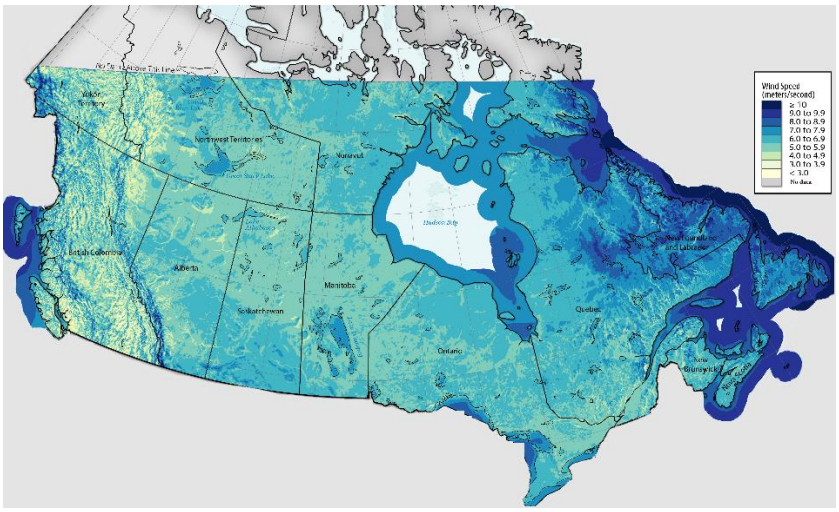
The mechanical energy of a flowing fluid can be described as:

$$\dot{E}_{mech} = \dot{m}\left(\frac{P}{\rho} + \frac{V^2}{2} + gz\right) \tag{3.7}$$

Wind power potential equation used for calculating commercial wind turbine is.

$$\dot{W}_{available} = \frac{1}{2}\rho A V^3 \tag{3.8}$$

where V is the velocity of the wind, ρ is for air density, and A is the disk area of rotating blades of the wind turbine.



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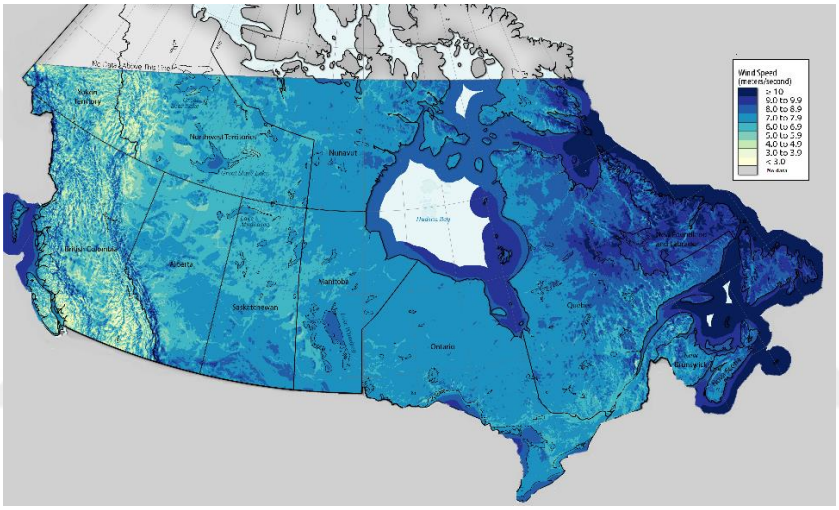

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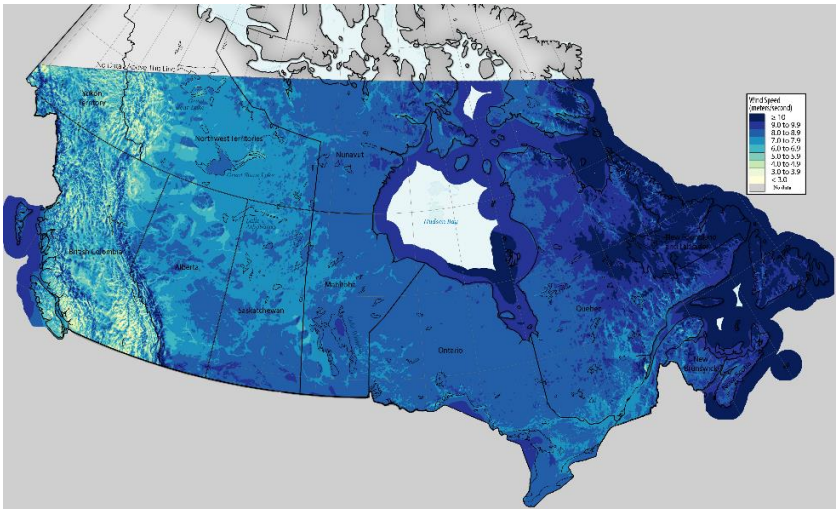


(c)

Figure 3.4 Annual wind speed (a) at 60 m, (b) 120 m, and (c) 200 m above the surface level of each province in Canada [94]

3.3 Utilization of Hydro and Marine Energies

Canada possessed 81 GW of installed hydroelectric capacity in 2019, with 74,000 MW of installed capacity generating an estimated 355 TWh of electricity [20]. Hydroelectricity is the main source of energy in Canada, accounting for 60% of the country's power [22]. British Columbia, Manitoba, Newfoundland and Labrador, Quebec, and the Yukon generate more than ninety percent of their electricity from hydropower. Figure 3.5 depicts each hydroelectric power plant operating in Canada. The Peace and Columbia River watersheds contain more than 80% of British Columbia's operational power generation capacity. As of early 2020, approximately 97% of Manitoba's electricity generation is hydroelectric [23]. Current hydroelectric facilities in Ontario are primarily located in southern Ontario. Despite the fact that the installation of hydroelectric stations in northern Ontario could potentially satisfy rising energy demands, the public is concerned about the environmental damage caused by hydroelectric activities. The three largest hydroelectric facilities in Canada are Centrale Robert-Bourassa in Quebec [100] with 5,616 GW capacity, Churchill Falls in Newfoundland and Labrador [101] with 5,428 GW capacity, and Mica in British Columbia [102] with 2,805 GW capacity.

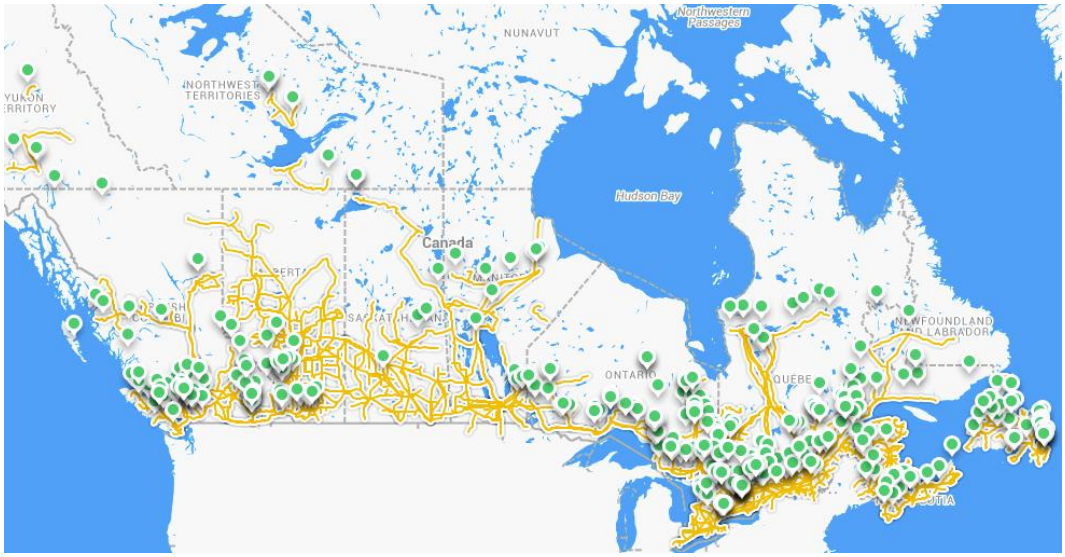


Figure 3.5 Hydroelectric power plants in Canada [20]

Canada is surrounded by oceans, gulfs, and currents, making it a viable source for the production of renewable hydrogen. There are various methods for exploiting wave energy, ranging from gravitational tide energy to subsea turbines. Due to the

location of the provinces, several of these strategies are inapplicable. Underwater turbines and wave energy are the two primary methods employed in this study.
Hydropower may be used to produce hydrogen in essentially two different ways. First method is a certain percentage of the economic hydropower potential is used to generate hydrogen using electrolysers, based on research is done in Venezuela [103]. The second method is to evaluate the potential for hydrogen production by looking at the increased output or decreased power consumption of run-of-river facilities as a result of higher water inflows during the spring and rainy seasons. The main assumptions for calculating clean hydrogen potential from hydropower, wave, and undersea current are listed as:

- The installed capacity of large, minor, and micro hydroelectric generators, run-of-river systems, and new hydroelectric power stations with a total capacity installed of more than 100 MWe is considerd for each Canadian region.
- The assumed sea depth for wave energy is 75 m, and the wave height is calculated from sea level.
- Typical wave energy harvesting Pelamis turbines have a capacity of 2.62 GWh/year (750 kW power output), a capacity factor of 0.40, and a length of approximately 150 m [106] considered for wave energy applications.
- In the calculations for the undersea current, commercial undersea turbines were used. In order to circumvent the wake regions of subsequent turbines, they are separated by 20 m.
- Electricity generated from marine applications is first used for power demand from the provinces, then sent to an alkaline electrolyser to produce clean hydrogen.

3.4 Utilization of Geothermal Energy

Unfortunately, there aren't any geothermal wells in Canada, and the temperatures deep down aren't very high, thus this has a huge negative effect on the country's potential for using geothermal energy. It is likely that geothermal heat and power systems will be limited to larger settlements in the Canadian North. This is because larger populations have higher energy demand, which is required to make

geothermal energy economically viable. They may yet be economically competitive in some remote northern villages despite the exorbitant cost of diesel energy. They will be more competitive if they make use of waste heat, and even more so if they are integrated with shallow geologic heat storage. This is a process in which heat is collected during the warmer months (when it is not required) and stored in the shallow subsurface; heat is then produced during the cooler months using ground-source heat pumps. Figure 3.6 depicts the subterranean temperature [107] (°C) at depths of (a) 3500 m, (b) 4500 m, and (c) 5500 m. Technically, 117,650 kJ is required to produce one kilogram of hydrogen via electrolysis. The effectiveness of the alkaline electrolyser is estimated to be 66.10 percent. Therefore, the energy required for unit mass hydrogen production (W_{actual}) would be as $\frac{117{,}650\ \text{kJ}}{0.661}$ or 177,987 kJ.

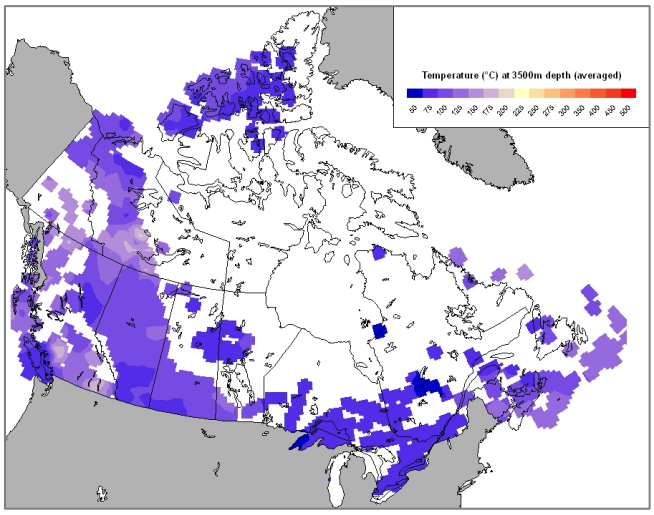
Energy input can be calculated as the enthalpy difference between the two phases of geothermal water at the plant's inlet.

$$\dot{E}_{in} = \dot{m}_{well} h_{well} \tag{3.9}$$

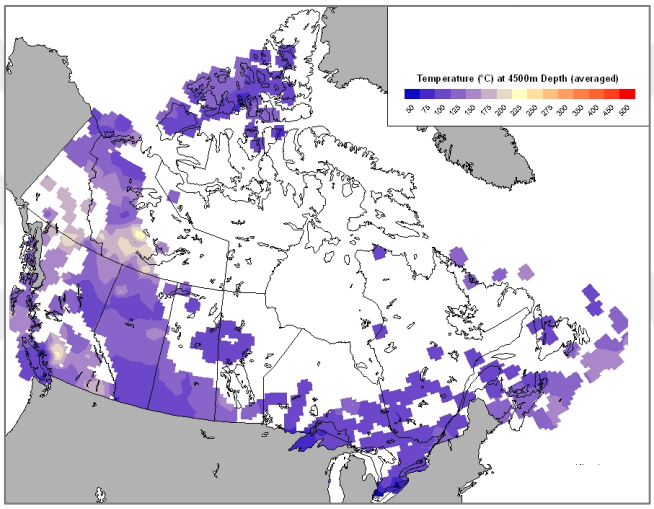
The current work examines single-flash geothermal power plant. The production well supplies saturated geothermal saline. The flash valve cools the liquid. Thus, it is a quality saturated liquid-vapor composition. The separator separates liquid and vapor from new mixture. Separate valves release vapor and saturated liquid. The liquid is pumped into a reinjection well, while the vapor goes to the steam turbine to generate energy. After power generation at the steam turbine, the saturated vapor combination exits at a lower pressure and temperature, enters the condenser, where heat is rejected, and is redirected to the reinjection well as a saturated liquid. The following equations are used to calculate energy and exergy efficiencies of a single-flash power station.:

$$\eta_{en,SF} = \frac{\dot{W}_{T1}}{\dot{m}_{well} h_{well} - (\dot{m}_{sep} h_{sep} + \dot{m}_{turb} h_{turb})} \tag{3.10}$$

$$\eta_{ex,SF} = \frac{\dot{W}_{T1}}{\dot{m}_{well} ex_{well} - (\dot{m}_{sep} ex_{sep} + \dot{m}_{turb} ex_{turb})} \tag{3.11}$$



(a)



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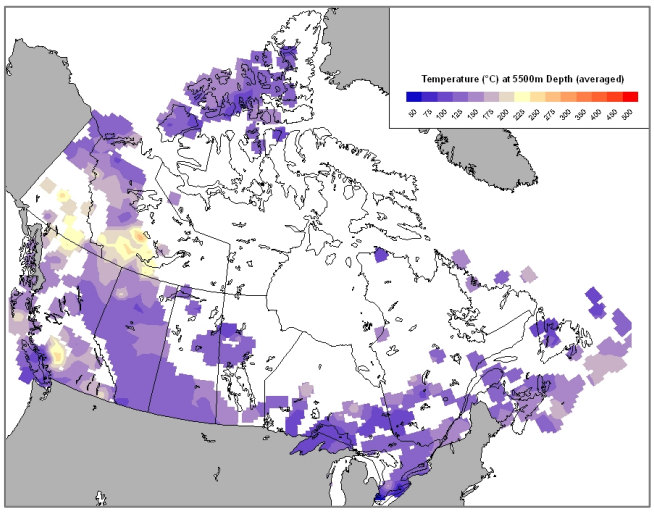


(c)

Figure 3.6 Average temperature (°C) at (a) 3500 m, (b) 4500 m, and (c) 5500 m depth [107]

Assumptions considered in the calculation of clean hydrogen from geothermal energy are as follows:

- Since there are currently no installed geothermal power plants only theoretical potential is found from using governmental resources.
- Alkaline and high-temperature solid-oxide electrolysers are considered in the current thesis for low and high-temperature sources.
- Single-flash steam cycle and binary cycle geothermal power plants are considered for benefitting from underground sources.
- The coefficient (α) varies between is assumed to vary from 0.65 to 0.90, representing the flatness and surface availability of the useable net area of a region.
- The heat is assumed to be transported only by conduction.
- Thermal conductivity (K_s) is assumed 2.5 W/mK.
- Up to 10 km depth temperature values calculated with 1 km intervals. Density (ρ) and specific heat capacity (c_p) of intervals assigned.
- High temperature solid oxide electrolyser considered in the calculations.

3.5 Utilization of Biomass Energy

Despite the inherent differences that exist between bioenergy and other forms of renewable energy, it is still considered to be a source of renewable and sustainable energy. This is because bioenergy is derived from biomass. Because of its widespread availability and exceptionally low levels of pollution, it has the potential to become a substantial alternative energy source. The output of solar and wind energy is electrical energy, while the products and byproducts of bioenergy can be biofuels that are used in power plants, transportation, and other energy-related businesses. These fuels include biodiesel, bioethanol, and any other liquid fuels that are derived from bioethanol. Syngas is the gaseous form of biomass energy output, while solid pellets are one of the solid fuels that may be created from biomass resources [108-109]. The gasification method is one of the most effective options for creating syngas from biomass. For the gasification process, a downdraft gasifier is chosen. In terms of the reaction, the general chemical formulation for the

raw components included in the biomass may be represented as $CH_aO_bN_c$, and from there, the generalized gasification reaction equation can be written as:

$$CH_aO_bN_c + mH_2O + w(O_2 + 3.76N_2) \rightarrow n_{H_2}H_2 + n_{CO}CO + n_{CO_2}CO_2 + n_{C_2O}H_2O + n_{CH_4}CH_4 + (\frac{c}{2} + 3.76w)N_2 \quad (3.12)$$

In contrast to coal, however, biomass is more difficult to gasify, and the mixture of gases that are created as a result of the gasification process includes the byproducts of other hydrocarbon compounds that are produced by the biomass. Coal is much easier to gasify. As a consequence of this, an additional step is often necessary to reform such hydrocarbon gases to produce a clean syngas combination consisting of CO, hydrogen, and CO_2 by making use of a catalyst. This is done in order to accomplish the goal of reforming the hydrocarbon gases. The generation of syngas is what happens when biomass is gasified, and this syngas can then be put to work in several different ways in order to generate energy. The Brayton cycle, a heat recovery steam generator followed by the steam Rankine cycle, and a steam turbine are some of the processes that are included in this category. The electrolyser makes use of the electricity that is acquired through the gasification of biomass, which ultimately culminates in the production of hydrogen.

There are many different types of biomass energy, some examples of which are animal waste, plant waste, trash from forests, and waste from cities. This energy can be utilized in a variety of different ways. The Canada Energy Regulator (CER) [105] ensures that people have access to sources of biomass in each of the country's provinces. The percentage of total biomass that is present in each Canadian province is depicted in Figure 3.7 [108]. Because of the hazardous conditions and severe weather, white zones are seen as being on par with zero. When moving from orange to blue, there is a gradual rise in the number of trees and shrubs as well as the overall density of the forest. One of the provinces that is considered to be among the best in terms of the biomass resources it possesses is British Columbia. Both the southern part of Canada and the region that is close to the border with the United States have a plethora of biomass resources available to them. In the course of this line of investigation, we have taken into consideration several sources of urban waste, including waste from municipalities and industry, livestock, forestry residue, agricultural residue, and crops that were specifically grown for their energy content.

The electricity that was generated, in addition to the power that was gained from several other sources, was fed into an alkaline electrolyser that had an efficiency of 66.10 percent so that hydrogen could be manufactured.

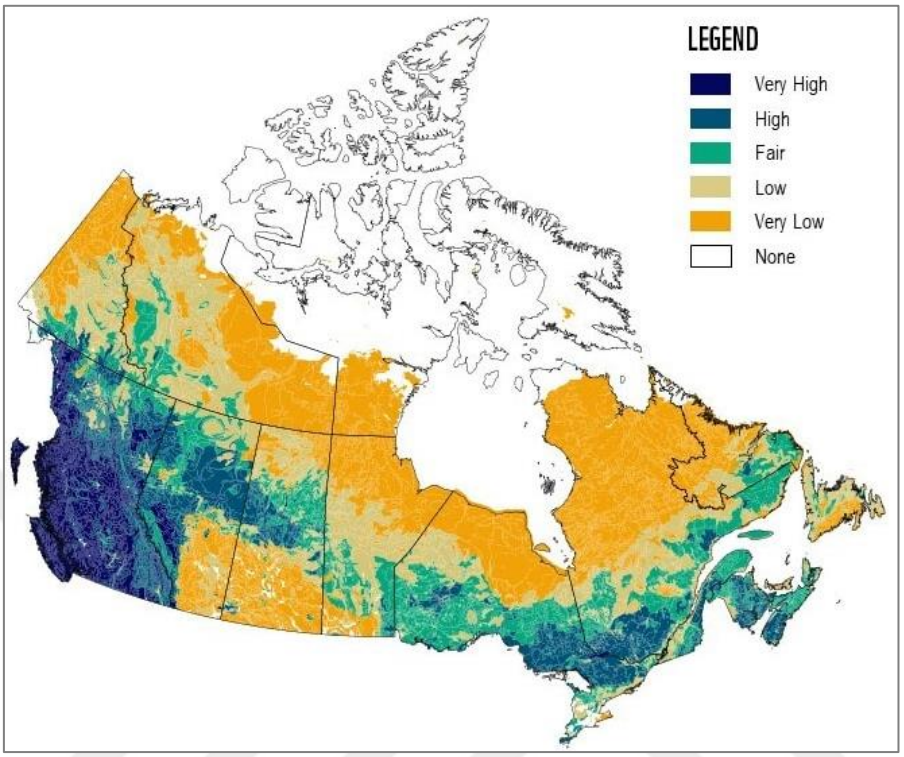


Figure 3.7 Biomass and forest density of Canada [108]

3.6 Utilization of Nuclear Energy

It is possible to produce hydrogen from nuclear energy by means of the decomposition of water by the use of the following five general processes: (1) radiolysis, (2) electrolysis, (3) high-temperature steam electrolysis, and (4) hybrid thermochemical water splitting. The first method, method (1), uses nuclear radiation to directly split the water molecule into hydrogen and oxygen. The second method, method (2), uses electricity derived from nuclear energy to electrolyze water. Methods (3) and (4) are known as hybrid methods because they use both electricity and high-temperature heat to split water. In the current system, only currently active nuclear reactors considered in the calculations. CANDU reactors Bruce, Darlington, Pickering, and Point Lepreau and their electric capacities (MW_e) considered. 100% of the generated electricity is used for clean hydrogen production. Main reason is Canada is changing conventional nuclear power plants with new small modular reactors (SMR). Even if a road map and action plan is available, near

future of the SMR is still uncertain. Therefore, this technology is not considered in the calculations. Figure 3.8 illustrates active uranium mining&milling, uranium processing-refining, conversion, nuclear power generation, R&D, waste management, shutdown power sites, and active nuclear power facilities based on the Canada small modular reactor (SMR) Plan [109]. Small modular reactors are cheaper to compete with alternatives, enabling new applications such as hybrid nuclear-renewable energy systems, with SMRs serving as a load-following, dynamic energy source, paired with variable renewables on a decentralized grid. The Canadian province of Ontario is investing $26 billion to refurbish its nuclear reactor [109]. The federal government is investing $1.2 billion to revitalize Chalk River Laboratories, the origin of Canada's nuclear industry and the center of Canadian leadership in nuclear science and technology for the past six decades [109]. In Atlantic Canada, New Brunswick has invested $10 million to establish an SMR nuclear research community in the province, with an additional $10 million from industry [109].



Figure 3.8 Nuclear energy usage and power plants in Canada following small modular reactor (SMR) Roadmap [109]

4

RESULTS AND DISCUSSION

The potential for the production of clean hydrogen in a Canadian province is estimated by taking into account a variety of different resources. These include onshore solar and wind resources, offshore solar and wind resources (depending on location), geothermal, wave, and underwater current resources, as well as hydroelectric, nuclear, and biomass resources. It is assumed that the region's whole need for electricity is satisfied by power that is generated from renewable energy sources. After that, the electricity is fed through electrolyzers, which separate impurities from the hydrogen and produce pure hydrogen. This action is taken in order to meet the demand for electricity in the region.

The official Canadian government resource [91] can be used to determine the total energy consumption of each Canadian province. Although megawatt-hours (MWh) are used to measure electricity consumption, equivalent hydrogen energies (EHE) are what are used to describe the amount of energy contained in renewable energy sources. In the year 2019, the total amount of energy consumed in Canada is 3,418.05 TWh [91], which is equivalent to 69.13 Mt of hydrogen. Table 4.1 provides an overview of the overall potential for the production of hydrogen in each country, state, and province. Estimates suggest that Canada is capable of producing 693.11 Mt of green hydrogen annually from sources of energy that are both renewable and sustainable. This number is the result of the calculations that were done.

After taking into account the need for energy, this quantity comes to a grand total of 623.83 Mt. Among 13 provinces, potential can be listed as 125.71 Mt, 99.66 Mt, 89.08 Mt, 81.96 Mt, 59.09 Mt, 58.85 Mt, 50.95 Mt, 44.94 Mt, 33.70 Mt, 32.05 Mt, 8.14 Mt, 6.88 Mt, and 2.10 Mt, for Québec, British Columbia, Alberta, Ontario, Manitoba, Saskatchewan, Nunavut, Yukon, Newfoundland and Labrador, Northwest Territories, New Brunswick, Nova Scotia, and Prince Edward Island, respectively. On the other hand, these figures reflect the province's absolute maximum capability for producing hydrogen. Clean hydrogen production

potentials from excess electricity generated by renewable energy resources are listed as 114.49 Mt, 91.48 Mt, 65.71 Mt, 64.08 Mt, 57.09 Mt, 55.87 Mt, 50.51 Mt, 45.20 Mt, 32.11 Mt, 31.45 Mt, 6.56 Mt, 5.47 Mt, and 1.81 Mt for Quebec, British Columbia, Alberta, Ontario, Manitoba, Saskatchewan, Nunavut, Yukon, Newfoundland and Labrador, Northwest Territories, New Brunswick, Nova Scotia, and Prince Edward Island, respectively. With the exception of Manitoba and Saskatchewan, the order is almost exactly the same as the one that was established by the previous values. As a result of successfully meeting the demand for electricity, Manitoba has surpassed Saskatchewan.

Out of the thirteen provinces that make up Canada, the provinces of Québec, Ontario, British Columbia, and Alberta are the four that have the most potential to create hydrogen out of all of the country's provinces. There are three provinces that are considered to be "minor" ones: Prince Edward Island, Nova Scotia, and New Brunswick. Because of this, the limited availability of land in these areas that is appropriate for human habitation has a direct bearing on the amount of hydrogen that could potentially be produced there. At the moment, renewable energy sources account for approximately 18.9% of Canada's total primary energy supply [110]. Moving water is by far the most significant source of renewable energy in Canada, generating 59.3% of the country's total electricity generation [110]. Wind energy is the second most important kind of renewable energy in Canada. It is responsible for 3.5% of the entire electricity output in the country. According to the data presented in [110], biomass is the third most important renewable source for the production of energy in Canada. It contributes 1.4% of the total.

The results of the calculations show that Canada has a capacity of 623.83 Mt to manufacture green hydrogen through the utilization of an excess of renewable and clean energy sources. The production potential of green hydrogen from renewable sources is as follows: solar energy has 205.69 Mt, wind energy has 439.92 Mt, geothermal energy has 29.24 Mt, biomass energy has 2.65 Mt, hydroelectric-wave-undersea current energies have 13.94 Mt, and nuclear energy has 1.66 Mt. Solar and wind power are the only sources of energy that are capable of meeting the need for power and producing clean hydrogen on their own. Other resources are insufficient to accomplish both by themselves.

Table 4.1 Hydrogen production potential of each province from various renewable and clean resources

Province	Hydrogen from onshore solar energy (Mt)	Hydrogen from offshore solar energy (Mt)	Hydrogen from onshore wind energy (Mt)	Hydrogen from Offshore wind energy (Mt)	Hydrogen from geothermal energy (kt)	Hydrogen from Biomass energy (kt)	Hydrogen from hydro-wave-undersea current energies (Mt)	Hydrogen from nuclear energy (kt)	Total (Mt)
Alberta	19.75	0	42.68	0	26,090.91	518.46	0.041	0	89.08
British Columbia	24.35	1.27	61.47	7.99	1,875.38	449.33	2.251	0	99.66
Manitoba	17.22	0.59	36.78	3.18	0.49	242.62	1.071	0	59.09
New Brunswick	2.00	0.13	4.75	0.78	3.00	53.87	0.325	96.59	8.14
Newfoundland and Labrador	8.74	0.42	19.87	2.95	0	50.87	1.662	0	33.70
Northwest Territories	12.14	0.47	15.72	3.07	0	0	0.651	0	32.05
Nova Scotia	1.41	0.19	3.54	1.17	0.64	51.50	0.516	0	6.88
Nunavut	19.40	0.71	25.73	4.71	0	0	0.410	0	50.95
Ontario	26.40	0.54	48.78	3.10	4.50	363.20	1.206	1,564.27	81.96
Prince Edward Island	0.15	0.19	0.38	1.18	0.02	50.88	0.144	0	2.10
Québec	38.15	1.39	72.09	8.22	6.92	428.11	5.430	0	125.71
Saskatchewan	19.01	0	39.31	0	0.65	447.57	0.077	0	58.85
Yukon	10.93	0.14	31.52	0.94	1,258.65	0	0.151	0	44.94
Total	199.65	6.04	402.63	37.29	29,241.15	2,656.41	13.94	1,660.86	693.11

Among 13 provinces, clean hydrogen production potentials from excess electricity generated by renewable energy resources are listed as 114.49 Mt, 91.48 Mt, 65.71 Mt, 64.08 Mt, 57.09 Mt, 55.87 Mt, 50.51 Mt, 45.20 Mt, 32.11 Mt, 31.45 Mt, 6.56 Mt, 5.47 Mt, and 1.81 Mt for Quebec, British Columbia, Alberta, Ontario, Manitoba, Saskatchewan, Nunavut, Yukon, Newfoundland and Labrador, Northwest Territories, New Brunswick, Nova Scotia, and Prince Edward Island, respectively. Figure 4.1 shows the total excess clean hydrogen production potential of provinces in Canada. Potential increases from grey color to red.

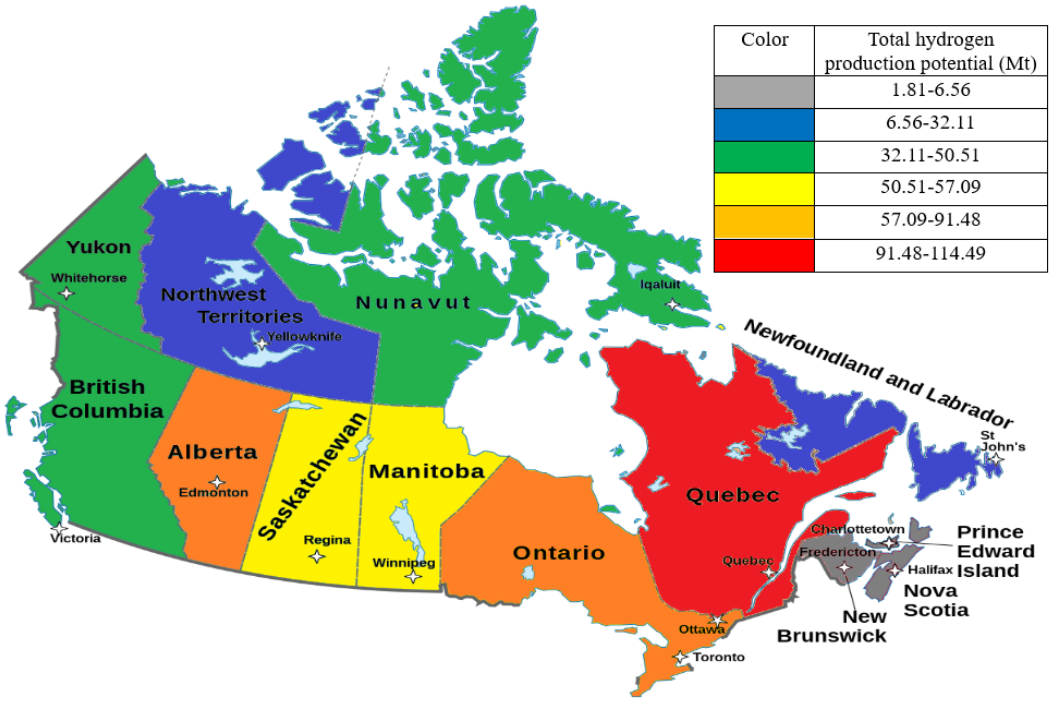
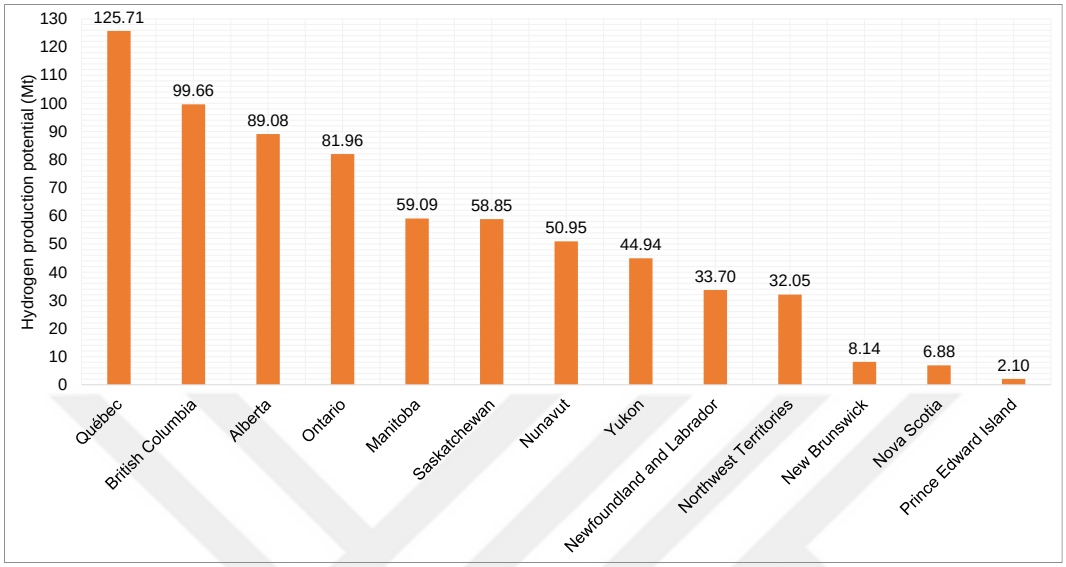


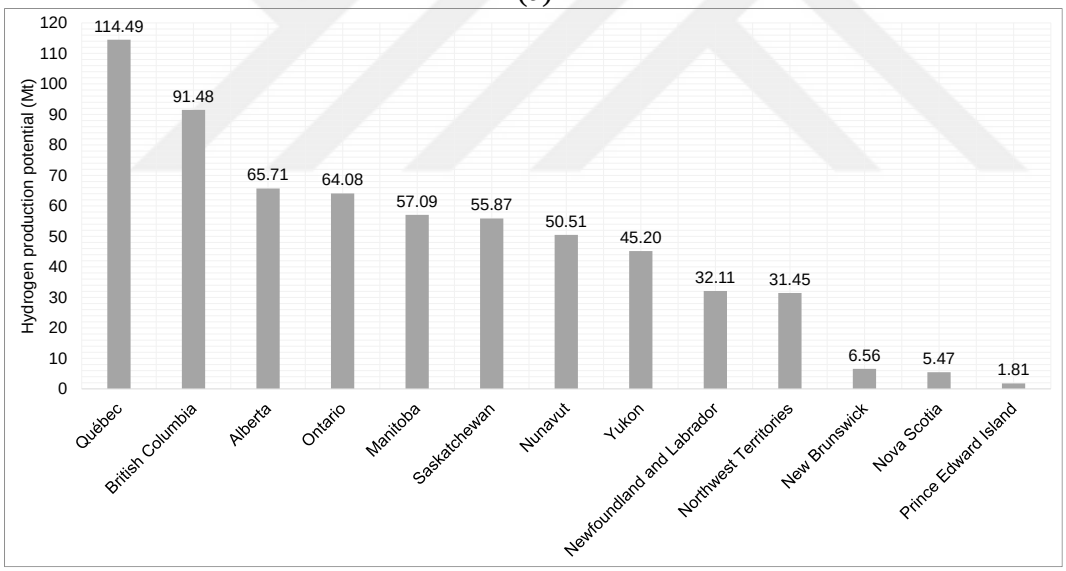
Figure 4.1 Clean hydrogen production potential of Canada from various resources using excess electricity.

Among all 13 provinces in Canada, Québec, Ontario, British Columbia, and Alberta can be listed as the top four provinces with the most hydrogen production potential. Figure 4.2 shows (a) all provinces' clean hydrogen production potential from most to least and (b) all provinces' clean hydrogen production potential from most to least after providing power demand. Prince Edward, Nova Scotia, and New Brunswick can be considered smaller than other provinces. Therefore, the lack of usable land in these parts affects hydrogen production potential directly. On the other hand, provinces like Yukon, Nunavut, and Northwest Territories can be considered the largest among all the other 13. However, extreme weather, harsh conditions, low

population, and lack of renewable resources prevent these provinces from being listed as the top three. The highest-listed province for green hydrogen production potential is Québec with 125.71 Mt. This value drops to 114.49 Mt after supplying power demand.



(a)



(b)

Figure 4.2 (a) Total hydrogen production potential of each province in Canada and (b) total hydrogen production potential of each province in Canada after supplying power demand.

4.1 Results of Solar Energy Utilization

Although there is solar photovoltaic potential in every province in Canada, the level of that potential varies greatly from location to location. Climate, latitude, and elevation are the primary factors that determine an individual's level of sun

exposure. Excess clean hydrogen production from onshore and offshore solar energy after supplying power demand is illustrated in Figure 4.3. The color of hydrogen production potential increases from black to red as the potential for production grows. In comparison to the other provinces, Quebec possesses the most untapped potential. Alberta is listed as zero because it doesn't have the capacity to provide power for demand then produce hydrogen. Main reason for this situation is there is no offshore applications in Alberta and energy consumption is higher compared to other regions.

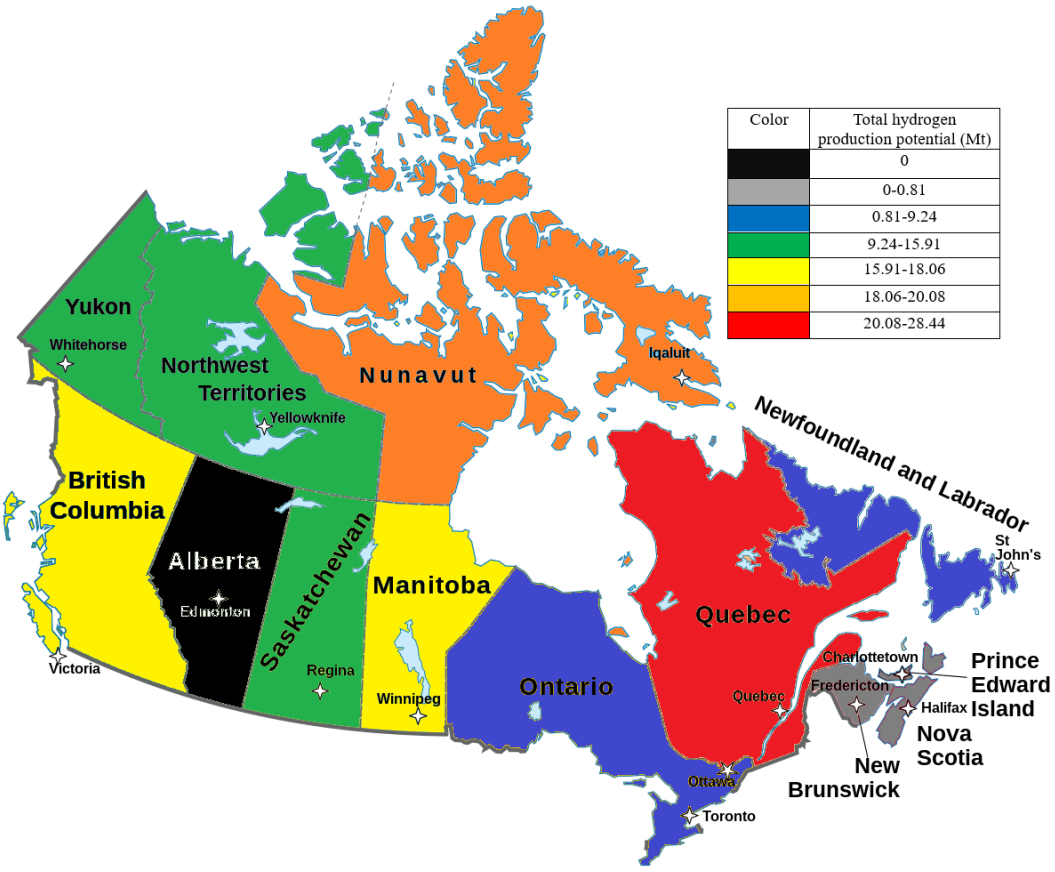


Figure 4.3 Green hydrogen production potential of Canada from onshore and offshore solar energy using excess electricity.

The government of Canada has committed to achieving an all-clean electricity supply by the year 2035[80]. It is anticipated that solar energy will play a significant part in the achievement of this goal. Solar Rooftop Incentive Program (SRFIP) [111] and the Net Metering Program [111] are only two of the many schemes that the federal government offers in order to encourage the growth of solar power. The solar energy business in Canada is expanding at an impressive rate. The nation

added 1.1 GW of solar capacity in 2022, which was a 50% increase from the previous year [10]. The high initial cost of installing photovoltaic panels is the primary barrier to entry for creating clean hydrogen from solar energy. Other obstacles include the limited sunshine hours during winter, which have a detrimental influence on the production potential, and maintenance.

Based on the current production capacity and additional onshore and offshore PV panels, green hydrogen potential from solar energy was found. The entire amount of land that is usable offshore was estimated by choosing all of the provinces that had access to the coastline and omitting from the calculation any transit routes, private areas, public beaches, marinas, or harbors. This allowed the total amount of land that is usable offshore to be expressed as the amount of land that is usable offshore. After that, in accordance with the official standards and policies of the provinces that were chosen, floating photovoltaic panels with bifacial surfaces are then put on the surface of the water. 40.13 Mt is the total amount of hydrogen that is produced by the use of environmentally friendly offshore solar energy. Figure 4.4 illustrates the possibility for Canada to produce environmentally friendly hydrogen by utilizing solar energy generated from offshore sources.

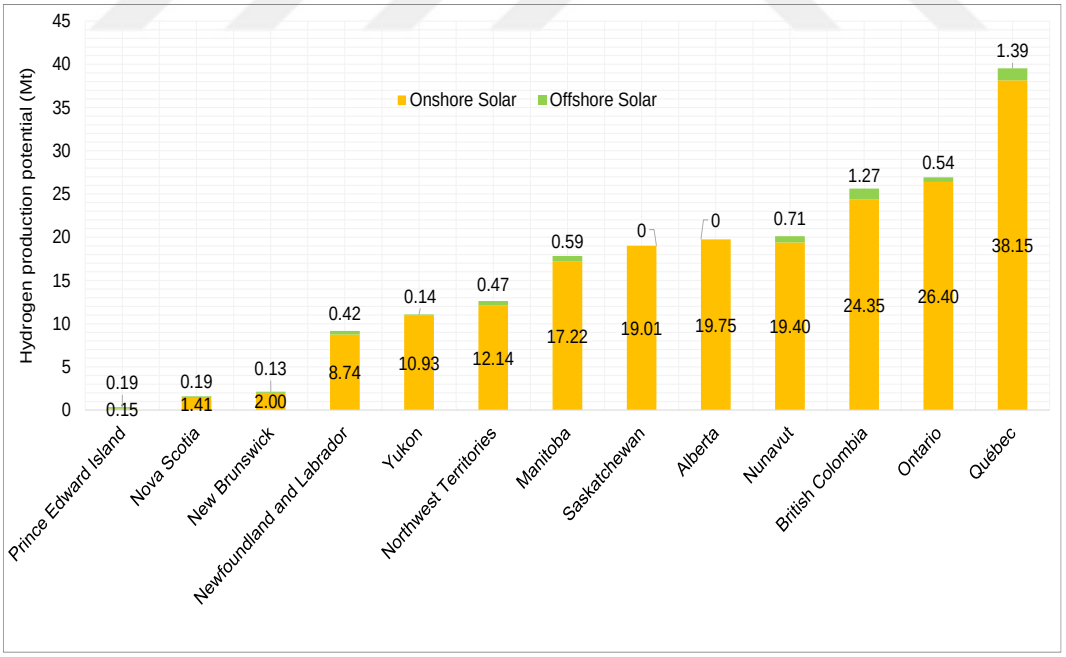


Figure 4.4 Green hydrogen production potential of each province in Canada from onshore and offshore solar energy

Figure 4.5 shows the clean hydrogen production potential of each province in Canada using onshore and offshore energy after supplying the power demand. There are some differences between Figure 4.4 and Figure 4.5. Some of the provinces with high energy consumptions moved backward on this list. For example, Alberta, Ontario, and British Columbia lost some of their potential. Alberta's generated electricity from solar energy is not enough to compensate the power demand. Therefore, it is shown as zero in the Figure 4.5.

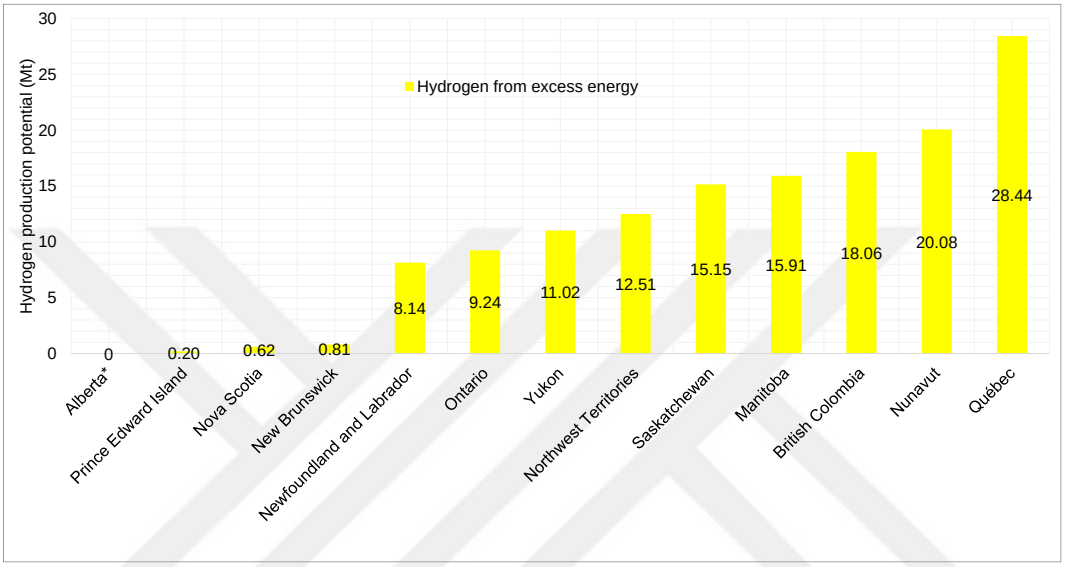


Figure 4.5 The clean hydrogen production potential of each province in Canada using onshore and offshore energy after supplying the power demand.

Six different PV array orientations were used in the calculations. These photovoltaic panels have a horizontal orientation with a latitude tilt, a southward orientation with a latitude tilt of -15 °, a southward orientation with a latitude tilt of +15 °, a southward orientation with a vertical tilt, and two-axis tracking. PV panels are evaluated against one another using this selection, which is positioned to face south at a latitude of 15 ° as the starting point. When compared to south facing with a latitude of 15 °, power generation is reduced by 5%, 23%, and 25% when using south-facing vertical tilt, horizontal PV panels, and south-facing PV panels with a south-facing latitude tilt, respectively. On the other hand, power generation is increased by 0.01% and 43% when using south-facing latitude tilt and 2-axis tracking PV panels. Figure 4.6 illustrates Canada's potential for producing environmentally friendly hydrogen based on the PV panel selection made for the country's total and excess hydrogen production potential from solar energy.

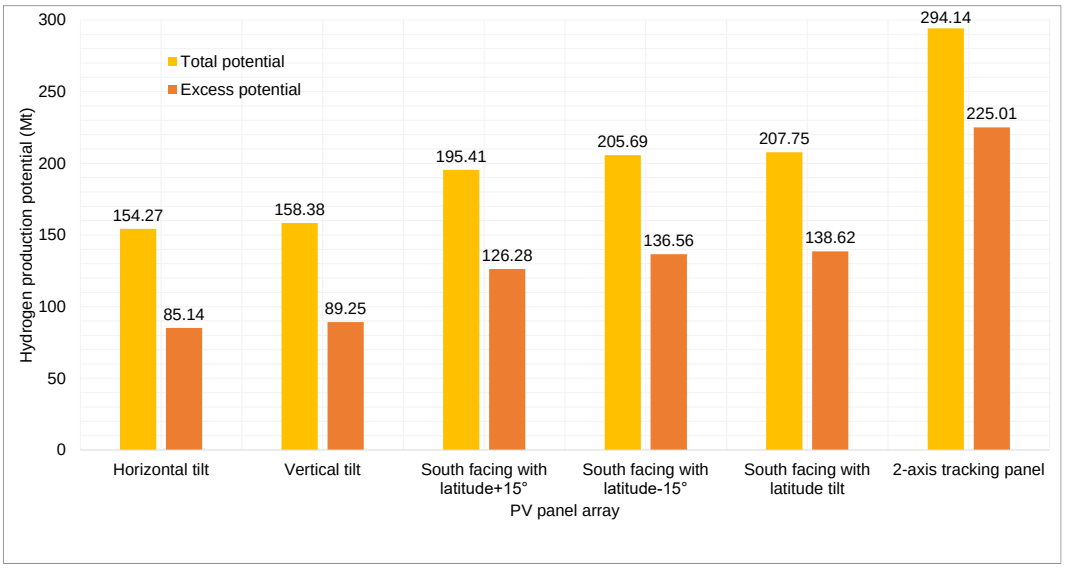


Figure 4.6 Green hydrogen production potential of Canada using six different PV panel array orientations.

4.2 Results of Wind Energy Utilization

The wind industry in Canada is growing rapidly. In 2022, the country installed 2.7 GW of wind capacity, a 50% increase from the previous year [17]. The Canadian government has set a target of 30% renewable energy by 2030 [17]. Wind energy is expected to play a major role in meeting this target. However, like any other power generation system, wind energy has its own limitations and challenges. The cost of the wind plants, storing and transporting the hydrogen from the wind farms in remote areas, and the impact on the wildlife can be listed as challenges for producing clean hydrogen from wind energy in Canada. When it comes to wind energy, all of the data come from the Canada Energy Regulator (CER) [17], and the wind speed readings come from 60 m above the ground. The onshore wind speed in Canada ranges anywhere from 3.5 to 14.8 m/s. The speed offshore is increasingly higher than the speed onshore. This figure falls somewhere in the range of 5.10 to 16.26 m/s. The government of Based on this disclosed information, the potential was increased by the installed power and electricity generated at the moment. Figure 4.7 depicts the possibility that onshore wind energy could be used to produce hydrogen that is free of harmful impurities. As the color transitions from gray to red, one can observe an increase in the hydrogen generating potential of the system. In terms of the production of hydrogen from wind energy, British Columbia and Quebec both have the potential to be listed among the top jurisdictions in the world.

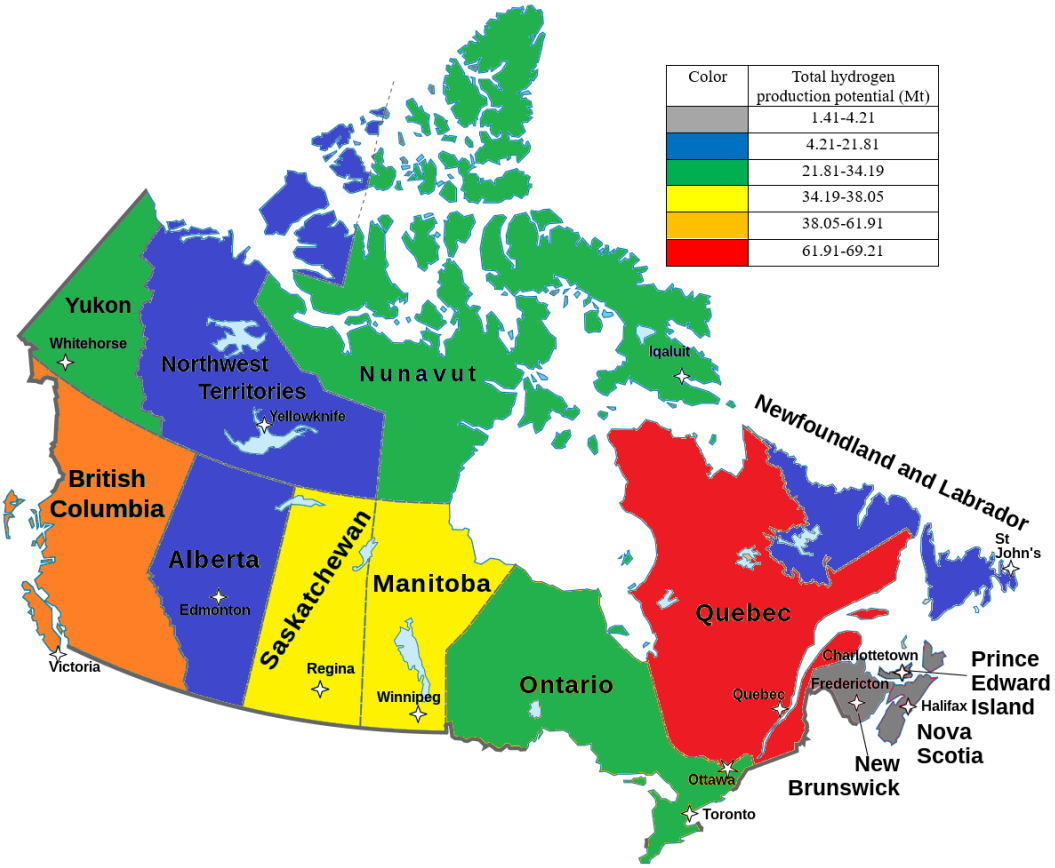


Figure 4.7 The clean hydrogen production potential of Canada from wind energy using excess electricity.

The Canadian province of Alberta is home to a number of operational wind energy projects, the most notable of which being the Blackspring Ridge Wind Farm [112], which is the biggest wind farm in the entire province. In the province of Ontario, there is a substantial amount of unused potential for wind energy; at the moment, the province is home to numerous active wind energy projects, one of which is the Henvey Inlet Farm [113]. The Canadian province of Quebec is home to a variety of current wind energy projects. These projects include the Seigneurie de Beaupré Farm [114], which holds the title of being the largest wind farm in Canada, as well as the Rivière-du-Moulin Wind Farm [115]. After removing transit routes, private areas, public beaches, marinas, and ports from the computation of the relevant offshore area, the total amount of land that is usable offshore was established. It was decided which provinces should be included in the eligible offshore area by looking at which ones have access to the coastline. Following this step, wind turbines that are suitable for a certain location are positioned within the confines of the government's regulations and policies. When performing the calculations, the

values of wind speed, power, and frequency are all taken into account. The overall potential for producing environmentally friendly hydrogen from offshore wind energy is estimated to be 44.36 Mt. Figure 4.8 illustrates how each of Canada's provinces stacks up against one another in terms of their capacity to generate environmentally friendly hydrogen from offshore wind energy.

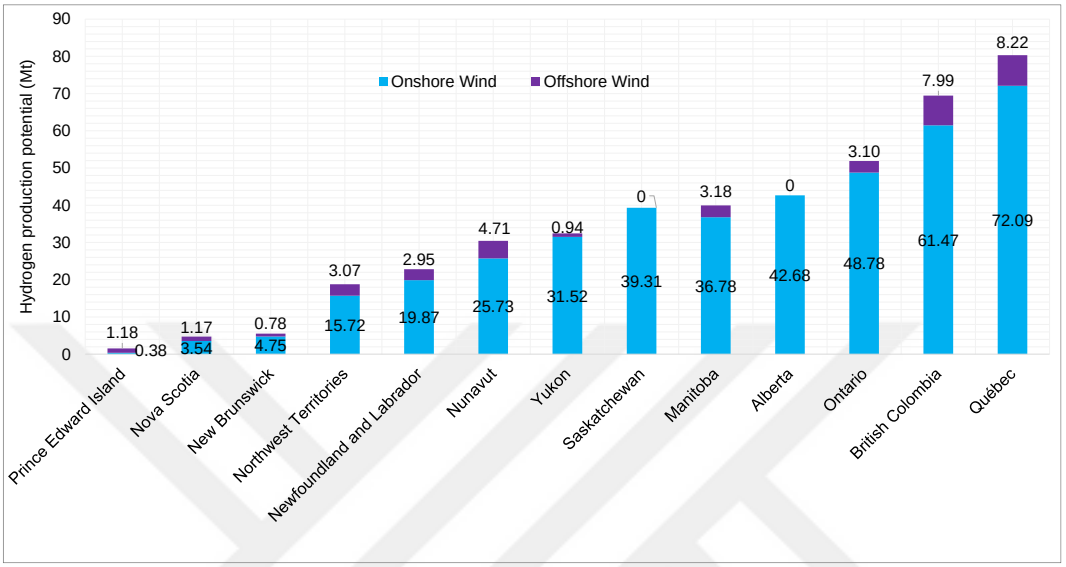


Figure 4.8 Green hydrogen production potential of each province in Canada from onshore and offshore wind energy

After meeting the demand for electrical power, the quantity of clean hydrogen that may be produced in each of Canada's provinces utilizing onshore and offshore wind energy is represented in Figure 4.9. This information is presented after the requirement for electrical power has been satisfied. After the requirement for the availability of electrical power has been satisfied, this information is then given. In a few of the provinces, the amount of power generated from renewable sources is either not enough to satisfy the demand or only just about enough to make up for it. This is because these provinces have high energy consumption. Both Ontario and Alberta have huge populations and high energy consumption due to their large populations. These two provinces held the third and fourth spots on the list before to the extraction of the power need; however, Figure 4.9 demonstrates that after the power demand was met, these two provinces dropped to the fifth and ninth spots, respectively..

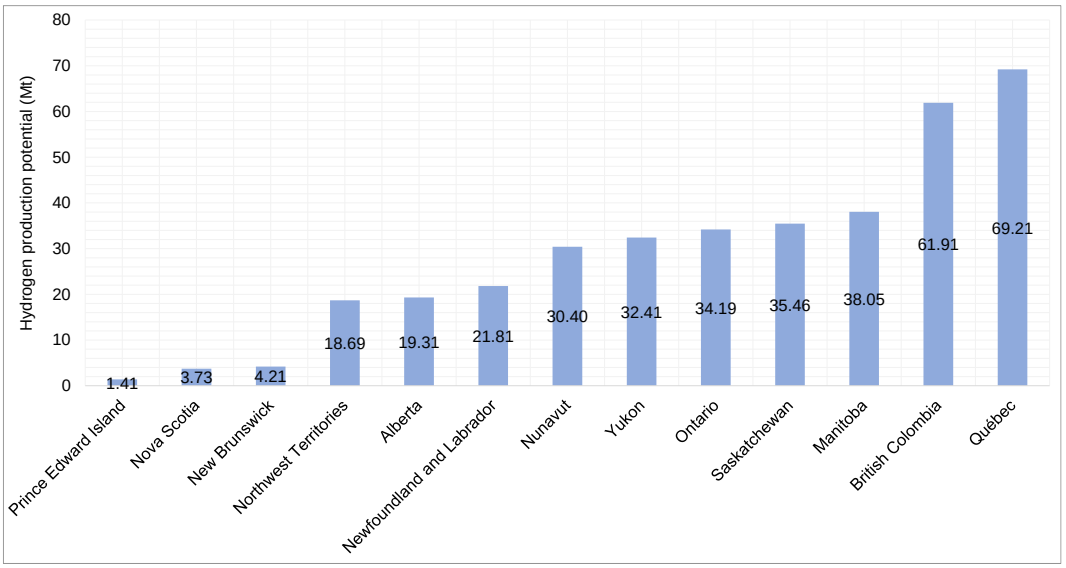


Figure 4.9 The clean hydrogen production potential of each province in Canada using onshore and offshore wind energy using excess electricity.

4.3 Results of Geothermal Energy Utilization

Despite the significant geothermal potential of the country, Canada does not yet have any geothermal power plants that generate electricity. In descending order of their geothermal energy potential, the provinces of Alberta, British Columbia, and Yukon are the three with the largest combined total. There is some untapped geothermal energy potential in the province of Alberta. Resources with higher temperatures can be discovered in the Rocky Mountains, while resources with lower temperatures can be found in the foothills. There is geothermal energy potential in British Columbia, with higher-temperature resources found in the Cascade Mountains and lower-temperature resources found in the Okanagan Valley. Both regions are located in the province. These three provinces have had extensive research conducted on them to determine their geothermal potential at a variety of depths, temperatures, and preferred research approaches. The Frontenac Arch contains low-temperature geothermal resources, which means that Ontario has a limited potential for geothermal energy. The Laurentian Mountains have resources with higher temperatures, but the St. Lawrence Lowlands are home to resources with lower temperatures. As a result, Québec possesses some geothermal energy potential. The possibility for the production of green hydrogen in Canada using geothermal energy is illustrated in Figure 4.10. The hue grey denotes an

absence of potential, while the progression from blue to red indicates an increase in potential.

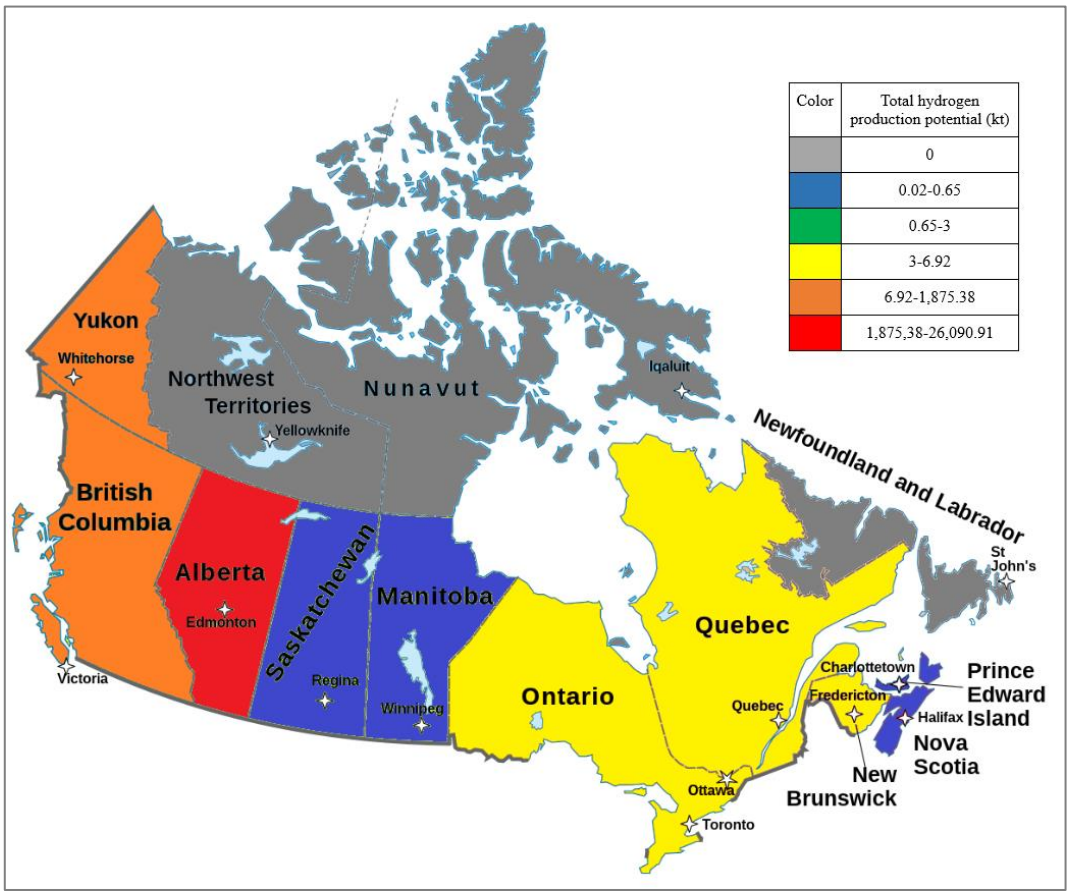


Figure 4.10 Green hydrogen production potential of Canada from geothermal energy

Only three of Canada's provinces-Alberta, British Columbia, and the Yukon-have the capacity to generate a considerable amount of hydrogen using geothermal energy. These provinces are Alberta, British Columbia, and the Yukon. Unfortunately, there are not enough geothermal wells and the temperature beneath is too low, which has a significant impact on the potential. The production of clean hydrogen using geothermal energy in Canada has a number of significant problems, the most significant of which include a shortage of high-temperature underground wells, high costs, and a limited number of potential locations. The generation of geothermal green hydrogen in each of Canada's provinces and territories is depicted in Figure 4.11. In some provinces, geothermal energy cannot be harvested because there are insufficient subsurface wells with high temperatures that are located at depths that are accessible. These areas may continue to make use of the current

wells as well as any potential wells for the purpose of heating, providing hot water, and establishing tourist attractions. There have been several recent advances for new geothermal energy efforts in the territories of Alberta, British Columbia, Saskatchewan, and the Yukon. Among 13 provinces, only Alberta is self-sufficient for excess hydrogen production from geothermal energy. Other provinces don't have enough geothermal potential to supply the power demand and produce clean hydrogen.

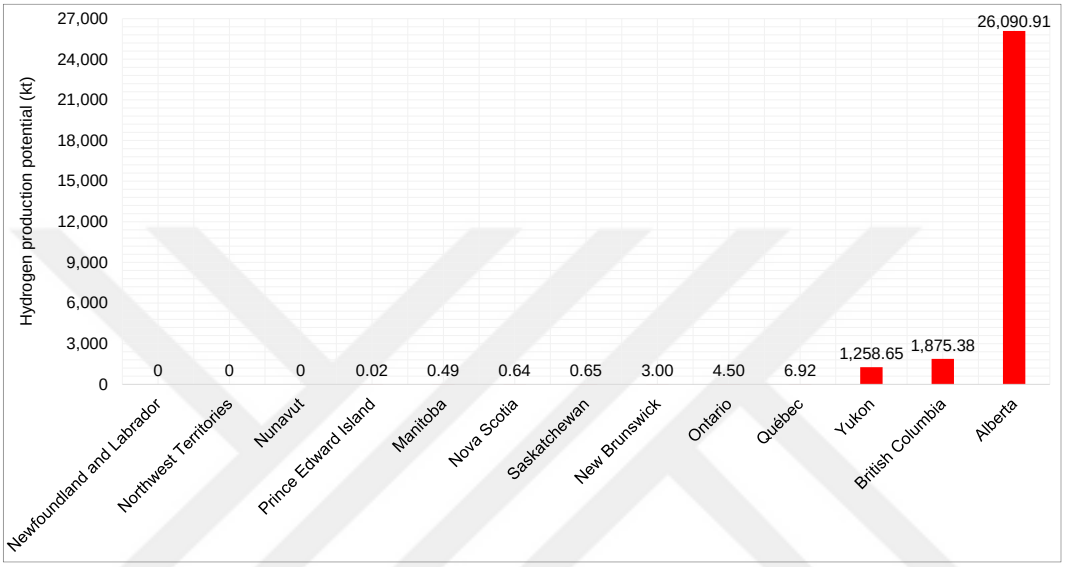


Figure 4.11 Green hydrogen production of each province in Canada from geothermal energy

4.4 Results of Hydro and Marine Energies Utilization

The best hydropower resources in Canada are found in the mountainous regions of the west and the north. The Rocky Mountains, the Canadian Shield, and the Laurentian Mountains all have significant hydropower potential. Canada has a number of large hydroelectric dams in operation, including the James Bay Project [116] in Québec, the Churchill Falls Generating Station [117] in Newfoundland and Labrador, and the Robert-Bourassa Generating Station [118] in Québec. These dams provide a reliable and affordable source of electricity for millions of Canadians. Hydropower accounts for about 60% of Canada's electricity generation [22]. Figure 4.12 shows the green hydrogen production potential of Canada from hydroelectric, tidal, and wave energies. For every province in Canada, already installed large, small, and micro-hydroelectric power plants, run-of-river systems, and the new hydroelectric power plants that are constructed are calculated and

estimated generated power is created. For undersea current and wave energy potential, official shared information from the government database is used [33].

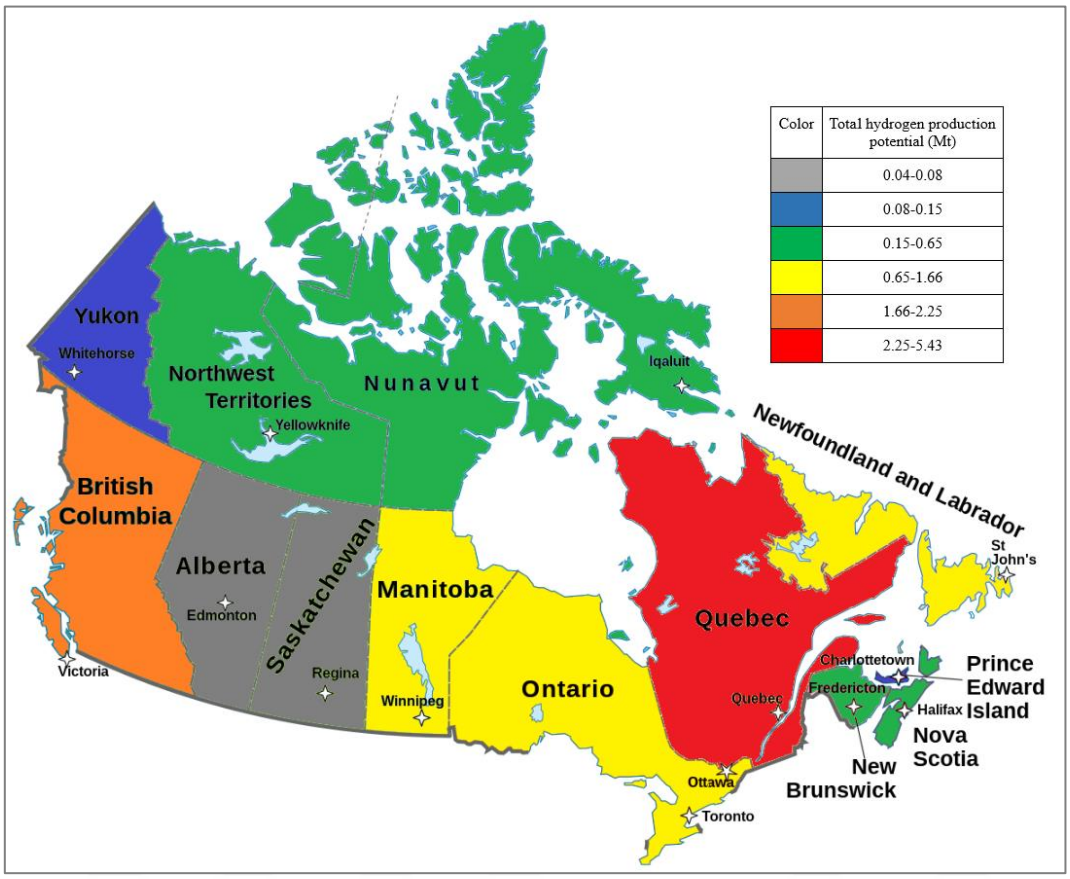
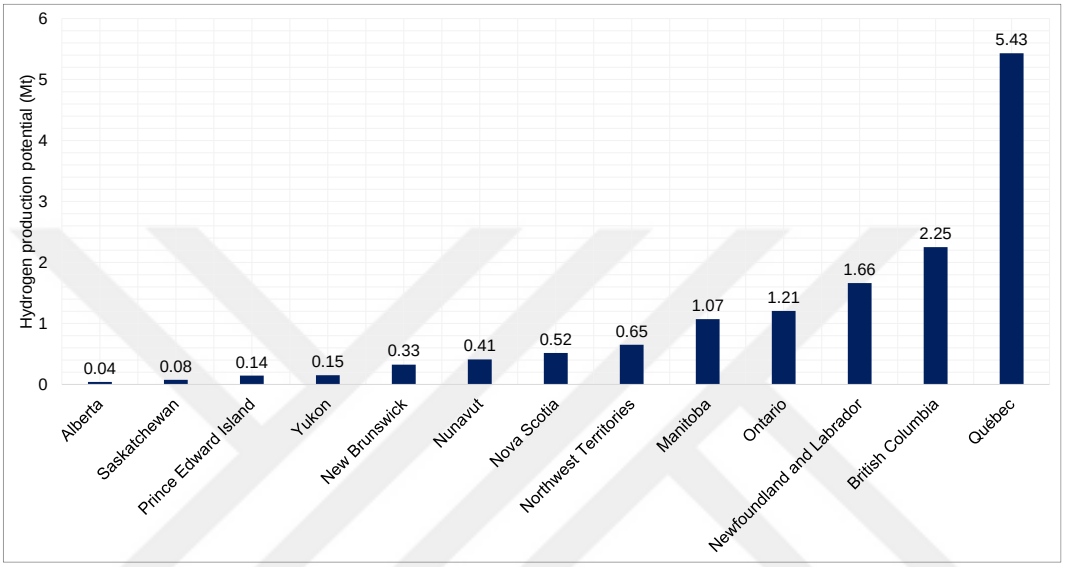


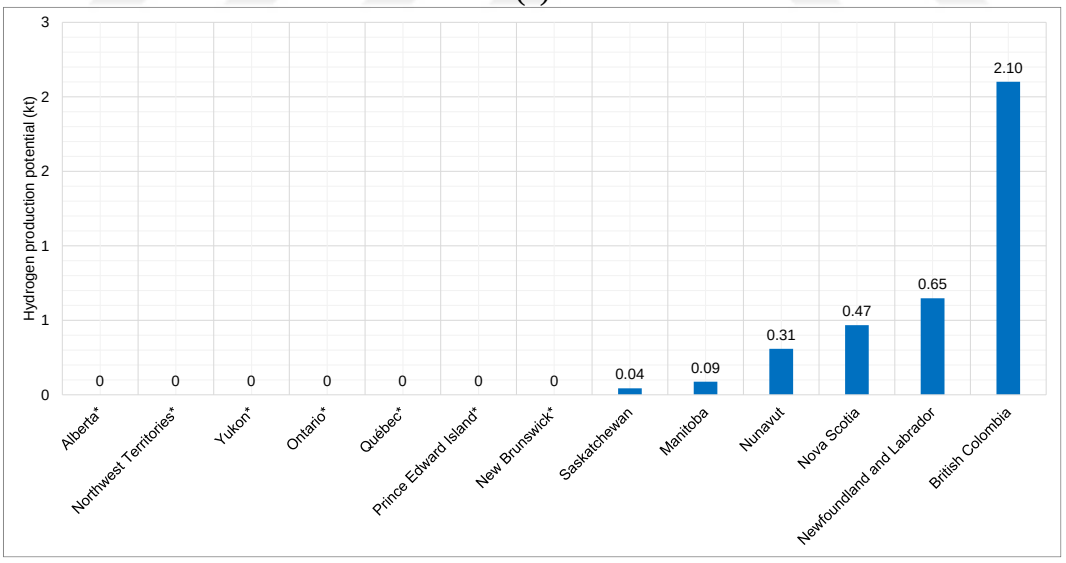
Figure 4.12 Green hydrogen production potential of Canada from hydroelectric, tidal, and wave energies

Alberta has limited hydropower potential, with a few small hydroelectric dams in operation. The province's best hydropower resources are found in the Rocky Mountains, but these resources are not yet developed. British Columbia has a significant amount of hydropower potential, with over 100 hydroelectric dams in operation [22]. The province's best hydropower resources are found in the coastal mountains and the interior plateau. Québec has the most hydropower potential in Canada, with over 600 hydroelectric dams in operation [23]. The province's best hydropower resources are found in the Laurentian Mountains and the Saint Lawrence River system. Newfoundland and Labrador have a significant amount of hydropower potential, with over 50 hydroelectric dams in operation [23]. The province's best hydropower resources are found in the Churchill River system and the Great Northern Peninsula. Figure 4.13 shows (a) total the green hydrogen

production potential from hydroelectric, wave, and undersea current energies and (b) excess green hydrogen production potential from hydroelectric, wave, and undersea current energies. Combination of hydropower, wave, and undersea current marine applications are very important for clean hydrogen production. In the excess hydrogen scenario, six provinces have potential to supply power demand and produce clean hydrogen. These are, British Columbia, Newfoundland and Labrador, Nova Scotia, Nunavut, Manitoba, and Saskatchewan, respectively.



(a)



(b)

Figure 4.13 (a) Total the green hydrogen production potential from hydroelectric, wave, and undersea current energies and (b) excess green hydrogen production potential from hydroelectric, wave, and undersea current energies.

Canada has a significant potential for wave energy, with the National Round Table on the Environment and the Economy estimating the extractable potential for wave power at up to 16,000 MW [22]. The west coast of Canada is particularly well-suited for wave energy development, due to the strong and consistent waves that occur in this region. The Strait of Georgia and Johnstone Strait in British Columbia, and the Bay of Fundy in Nova Scotia, are particularly well-suited for underwater current energy development, due to the strong and consistent currents that occur in these regions. Figure 4.14 shows each province's hydrogen production potential from hydropower, wave, and undersea current energies. Three different colors represent each of these subtypes, their value, and their percentage. Most of the potential comes from hydropower, then wave energy and undersea current.

Alberta (a) has an estimated 20,000 MW of untapped hydropower potential [22]. Using the current installed and under construction hydroelectric power plants, clean hydrogen production comes to 7.69 kt.

British Columbia (b) is the second-largest province in terms of hydropower potential, with an estimated 100,000 MW of untapped resources [22]. The province currently generates about 60% of its electricity from hydroelectricity, and there is potential to develop more projects in the future. Each of the marine applications can be used in this province. However, the main source is hydropower with 72.01% of all. Clean hydrogen from hydropower, wave energy, and undersea current is 1,627.28 kt, 622.42 kt, and 1.32 kt, respectively.

Manitoba (c) has the third-largest province in terms of hydropower potential, with an estimated 50,000 MW of untapped resources [22]. The province has a number of large hydroelectric dams, including the Winnipeg River Generating Station [119] and the Nelson River Generating Station [119]. The province currently generates about 90% of its electricity from hydroelectricity, and there is potential to develop more projects in the future. 62.52% of the total clean hydrogen from marine applications comes from hydropower.

New Brunswick (d) is the twelfth-largest producer of hydroelectricity in Canada, with 63% of its electricity generated from this source [22]. Province has access to every marine application. However due to being a small province, hydropower

potential is less than wave energy. Wave energy provides 80.27% of the total clean hydrogen from marine applications.

Newfoundland and Labrador (e) has the fifth-most hydropower potential in Canada, with an estimated 20,000 MW of undeveloped capacity [22]. The province already generates about 54% of its electricity from hydroelectricity, and there is potential to develop more projects in the future [23]. Undersea current potential is less than 1% but wave and hydroelectric potentials are close to each other with 4304% and 56.87%.

Northwest Territories (f) is the ninth-largest producer of hydroelectricity in Canada, with 10% of its electricity generated from this source [22]. The province has a number of small hydroelectric dams, including the Snare River Generating Station and the Taltson River Generating Station [120]. Hydropower potential is very low in this province. Extreme weathers and harsh conditions prevent the population from taking advantage of renewable resources. Wave energy provides 98.66% of all marine applications.

Nova Scotia (g) is the eleventh-largest producer of hydroelectricity in Canada, with 60% of its electricity generated from this source [22]. The province has a number of small hydroelectric dams, including the Shubenacadie Falls Generating Station and the Grand Narrows Generating Station [121]. Nova Scotia is one of the smallest provinces in Canada and wave and undersea current energies are more suitable for green hydrogen production instead of hydropower. There are multiple projects on tidal energy as well. 95.30% of the clean hydrogen from marine applications comes from wave energy.

Nunavut (h), the largest and northernmost territory of Canada, has a vast hydropower potential. The territory's rivers and streams have an estimated potential of 10,000 megawatts of hydroelectricity, which is enough to power over 1 million homes [23]. However, the development of hydropower in Nunavut faces some challenges. The territory's remote location and harsh climate make it expensive to build and operate hydroelectric projects. Additionally, the environmental impact of hydropower development is a concern for some communities in Nunavut. Despite these challenges, there is growing interest in developing hydropower in Nunavut.

The territory's government has set a goal of increasing the share of renewable energy in its electricity mix to 50% by 2030 [22]. Hydropower could play a significant role in achieving this goal. The Iqaluit Hydroelectric Project [122], which is currently on hold, has the potential to generate 23 megawatts of electricity.

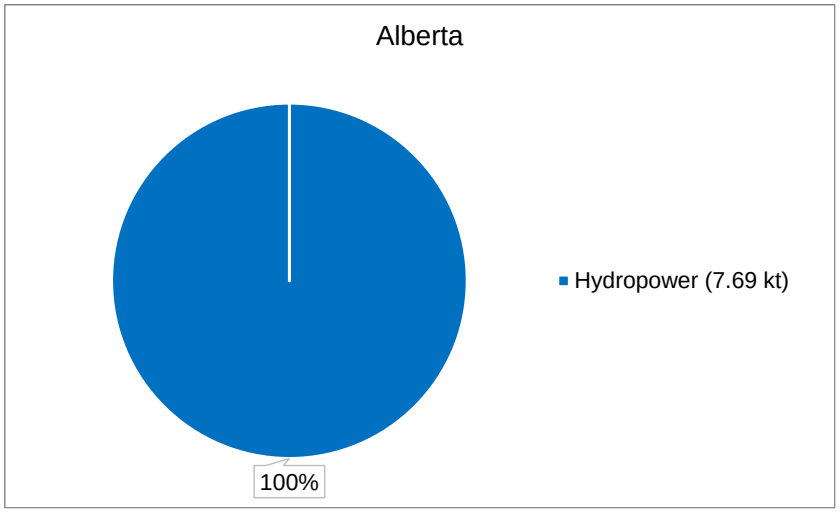
The province of Ontario (i) has an estimated 30,000 MW of undeveloped capacity [22], making it the province with the fourth-most hydropower potential in Canada. There is potential for the province to construct additional hydroelectric projects in the future, and the province now generates around 20% of its electricity from hydroelectricity. Large hydroelectric dams, such as the Sir Adam Beck Generating Station and the Niagara Falls Generating Station, can be found throughout the province [123]. Hydroelectric power is the source of 60.55 percent of the pure hydrogen used in maritime applications. Wave energy accounts for 39.04% of the total, whereas underwater current accounts for 0.41% of the total.

The province of Prince Edward Island (j) is responsible for the generation of 20% of the power that is used in the province, making it the tenth greatest generator of hydroelectricity in Canada [22]. The potential for the generation of hydropower in this province is very low indeed. Waves and underwater currents are Prince Edward Island's two most promising options for the generation of renewable energy. Wave energy is responsible for the production of 143.09 kt of clean hydrogen, while the production of 0.3 kt of clean hydrogen is attributable to undersea current.

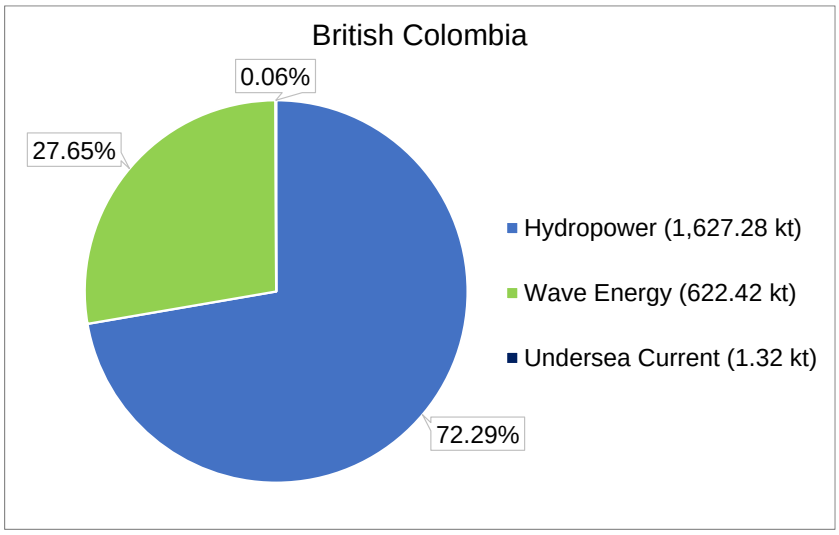
Hydroelectricity is the primary source of electricity generation in Quebec (k), which accounts for 53% of the province's total electrical output [22]. The province is home to a number of significant hydroelectric dams, the most notable of which is the Robert-Bourassa Generating Station, which holds the title of the country's largest hydroelectric dam [124]. The province has the highest amount of hydroelectricity is Quebec, followed by British Columbia, Manitoba, and Ontario in that order. These four provinces are responsible for more than 90 percent of the hydroelectricity generation in the country. The hydroelectric power plants in Quebec are responsible for the production of 75.92% of the clean energy that is generated from maritime applications.

The Canadian province of Saskatchewan is the seventh-largest generator of hydroelectricity, and this source is responsible for 10% of the overall energy production in the province [23]. The Gardiner Dam and the Shell Lake Generating Station [125] are two of the most prominent small hydroelectric dams that can be found in the Canadian province of British Columbia, which is home to a number of these dams. Wave energy and the utilization of underwater currents are not practical options in this section of the country because this region does not have access to the open sea. Clean hydrogen from hydropower is 76.64 kt.

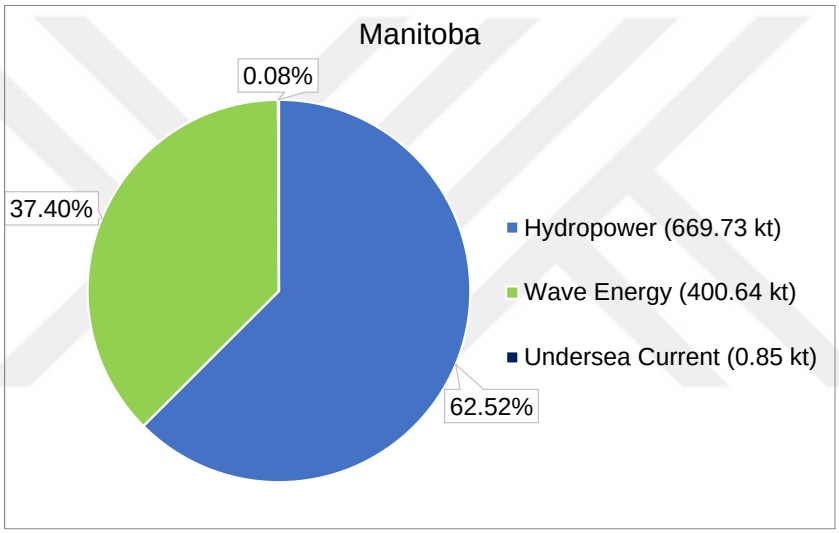
The hydroelectricity sector is responsible for 40% of the Yukon's total energy output [23], making it the Yukon the eighth-largest generator of hydroelectricity in Canada. The Whitehorse Rapids Generating Station and the Teslin Lake Generating Station [126] are just two examples of the numerous smaller hydroelectric dams that are spread out across the territory. However, the production of clean hydrogen is hindered when the harsh weather and extreme conditions happen often. Wave energy and the energy carried by underwater currents are, in contrast to other potential sources of energy, superior possibilities for the province of Yukon. The percentage of total clean hydrogen that is produced by marine applications that is attributable to wave energy is 94.27 %.



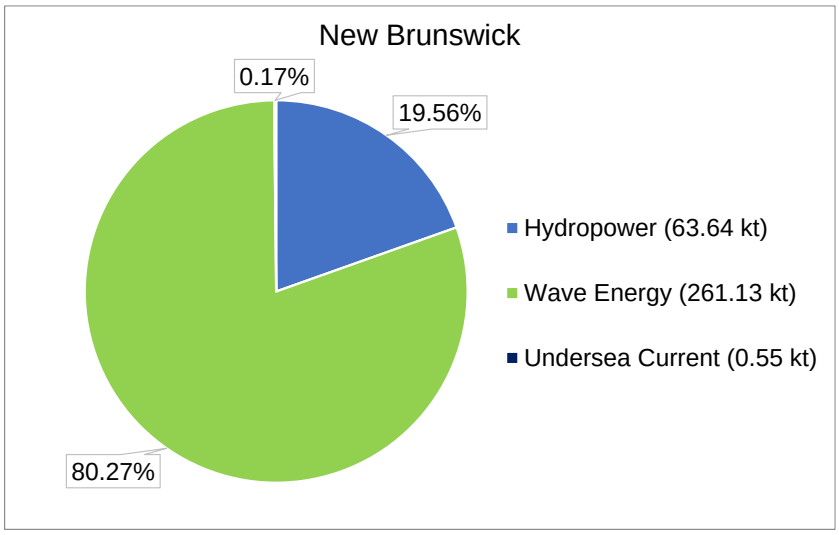
(a)


British Colombia
0.06%
27.65%
72.29%
Hydropower (1,627.28 kt)
Wave Energy (622.42 kt)
Undersea Current (1.32 kt)

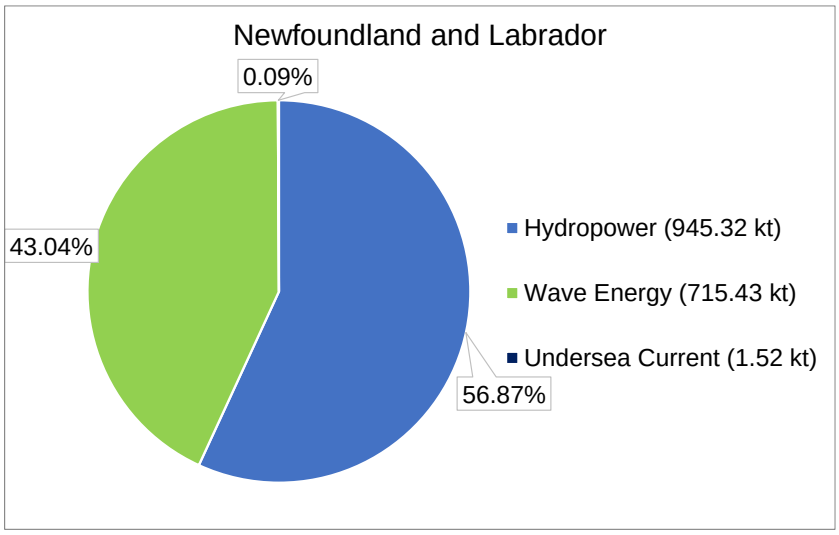
(b)


Manitoba
0.08%
37.40%
62.52%
Hydropower (669.73 kt)
Wave Energy (400.64 kt)
Undersea Current (0.85 kt)

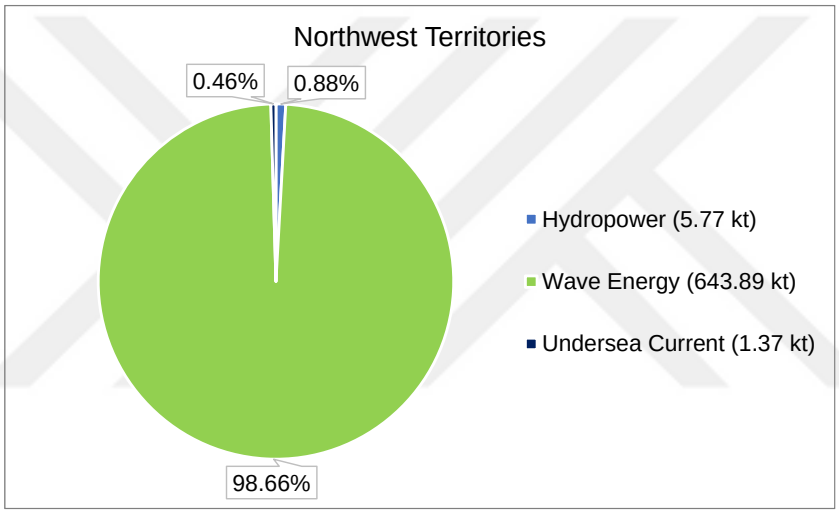
(c)


New Brunswick
0.17%
19.56%
80.27%
Hydropower (63.64 kt)
Wave Energy (261.13 kt)
Undersea Current (0.55 kt)

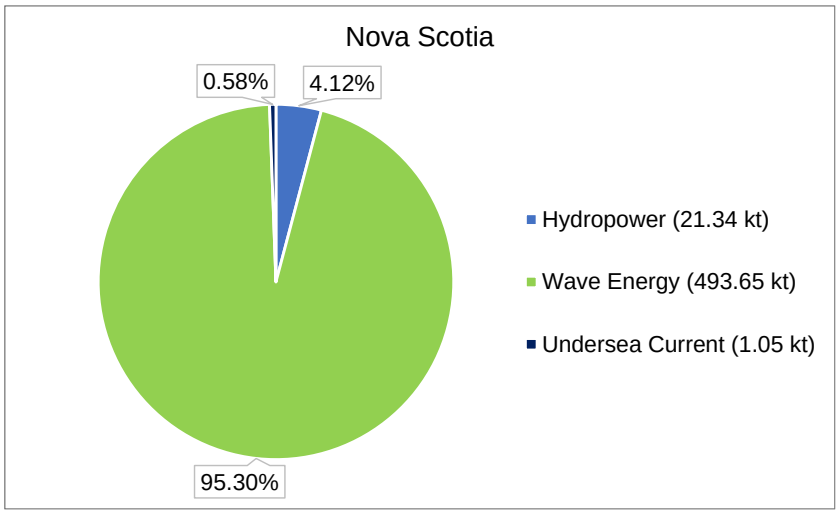
(d)


Newfoundland and Labrador
0.09%
43.04%
56.87%
Hydropower (945.32 kt)
Wave Energy (715.43 kt)
Undersea Current (1.52 kt)

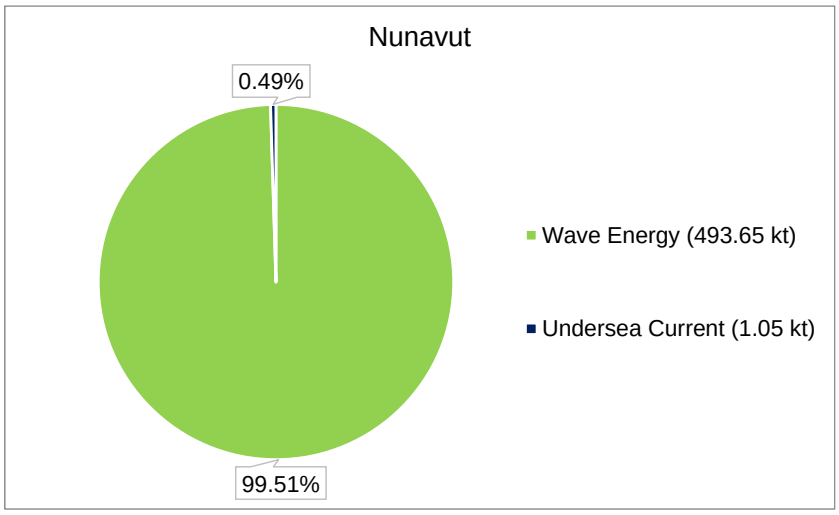
(e)


Northwest Territories
0.46%
0.88%
98.66%
Hydropower (5.77 kt)
Wave Energy (643.89 kt)
Undersea Current (1.37 kt)

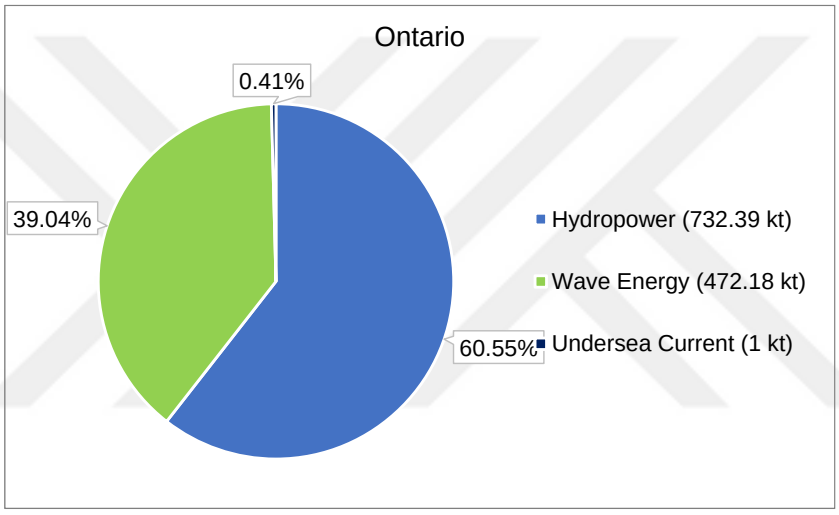
(f)


Nova Scotia
0.58%
4.12%
95.30%
Hydropower (21.34 kt)
Wave Energy (493.65 kt)
Undersea Current (1.05 kt)

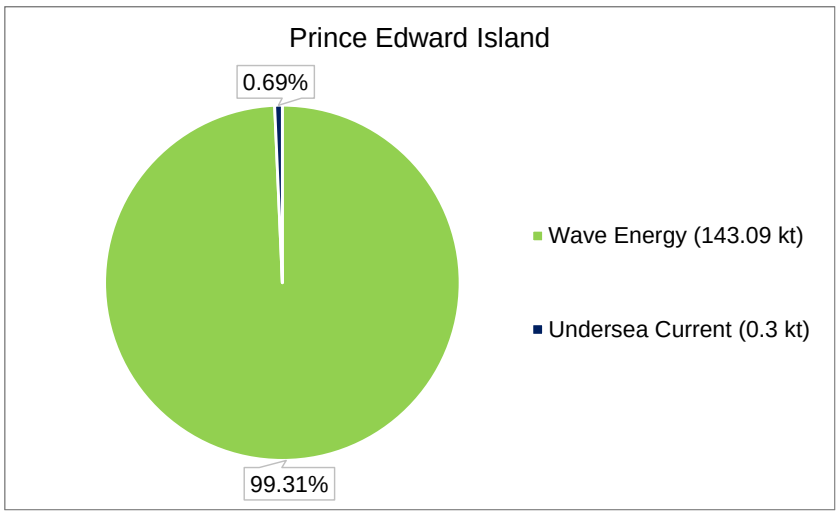
(g)


Nunavut
0.49%
99.51%
Wave Energy (493.65 kt)
Undersea Current (1.05 kt)

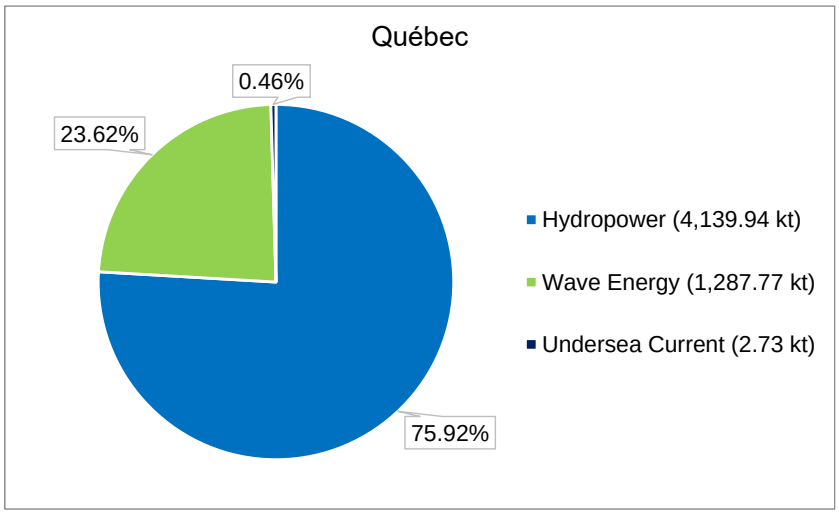
(h)


Ontario
0.41%
39.04%
60.55%
Hydropower (732.39 kt)
Wave Energy (472.18 kt)
Undersea Current (1 kt)

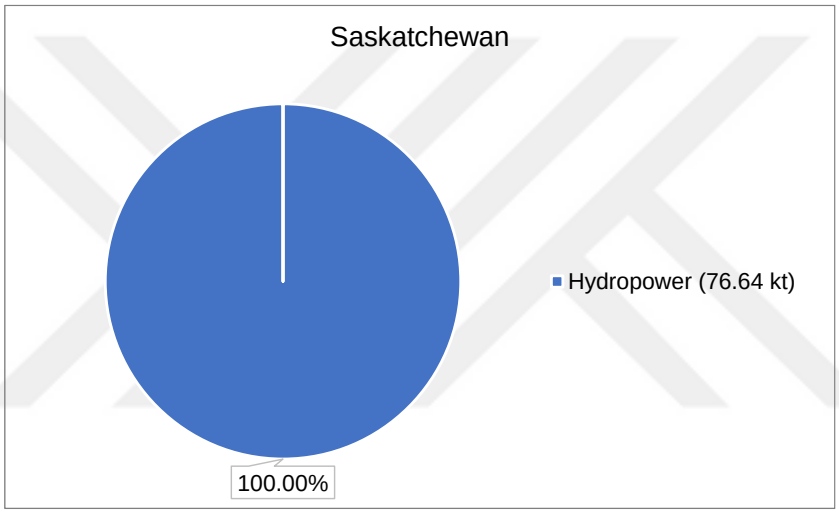
(i)


Prince Edward Island
0.69%
99.31%
Wave Energy (143.09 kt)
Undersea Current (0.3 kt)

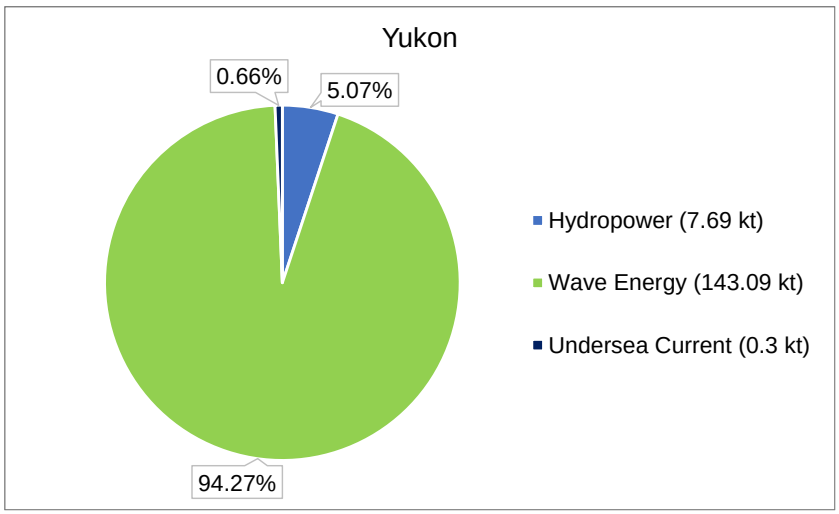
(j)



(k)



(l)



(m)

Figure 4.14 Green hydrogen production potential of each province in Canada (a-m) from hydroelectric, wave, and undersea current energies

4.5 Results of Biomass Energy Utilization

There is a large opportunity for the usage of biomass in the generation of energy in Canada; there is around 200 Mt of biomass that is available for consumption on a yearly basis. In Canada, building is now underway on a number of different biomass energy projects. These projects include power stations that are fueled by biomass, heating systems that are fueled by biomass, and facilities that convert biomass into liquids [28]. Because of issues such as high initial costs, the transportation of biomass from its source to the power plant, the likelihood of greenhouse gas emissions, and the inefficiency of the systems, there are restrictions placed on the generation of clean hydrogen from biomass energy in Canada. As examples of biomass resources, we can include things like urban garbage, livestock waste, forestry residue, forestry byproducts, crop residue, and energy crops specifically developed for that reason. The sectors of forest products, agriculture, and municipal garbage in Canada each have their own unique advantages when it comes to the availability of high-quality biomass supplies. The industry that deals in forest residue generates a significant amount of biomass every year. This biomass comes in the form of scrap wood, bark, and sawdust. The agricultural industry generates a significant amount of biomass every year in the form of crop residues, animal dung, and wood chippings. In the form of municipal solid waste, industrial waste, and agricultural waste, the waste industry is responsible for the production of a significant amount of biomass. In Canada, there are 111 operational power stations that run on biomass [29]. Figure 4.15 illustrates how each of Canada's provinces and territories fares in terms of its capacity to produce environmentally friendly hydrogen. Rich biomass resources and dense forest cover can be found in the region surrounding the southern border of the United States. Sadly, the Yukon, the Northwest Territories, and Nunavut all came up with zero for this research. The reason for this is neither a shortage of forest density or of materials that may be converted into biomass. It is not possible to use it because of the extremely cold weather, the difficult conditions, and the natural parks. Additionally, these provinces are recorded as having zero biomass in the government's resources inventory and data [28].

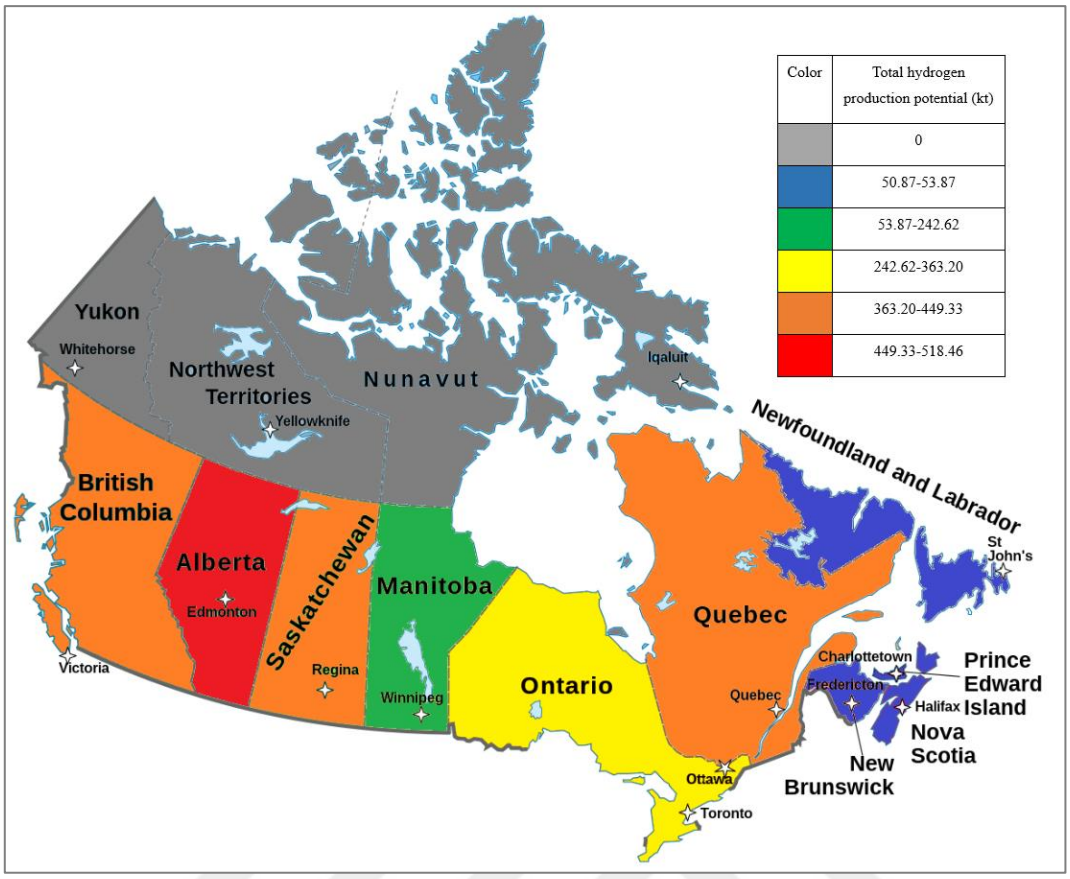


Figure 4.15 Green hydrogen production potential of Canada from biomass energy

Northwest Territories, Nunavut, and Yukon lack biomass potential for hydrogen production potential. Alberta can be listed as a tier-one province while Québec, Saskatchewan, and British Columbia are tier-two provinces. Biomass data from New Brunswick, Nova Scotia, Prince Edward Island, and Newfoundland and Labrador provinces are shared as a whole. Alberta has a significant amount of biomass potential. The province's best biomass resources are found in the forest products sector and the agricultural sector. British Columbia has a number of biomass energy projects in operation, including biomass-fired power plants, biomass-fired heating systems, and biomass-to-liquids facilities [28]. The main biomass sources for the province are forest products in the form of wood waste, bark, and sawdust, and the agricultural sector in the form of crop residues, manure, and wood chips. Figure 4.16 shows the green hydrogen production potential of each province in Canada from biomass energy. Unfortunately, none of the 13 provinces in Canada has capacity to supply the power demand then produce clean hydrogen solely from biomass resources.

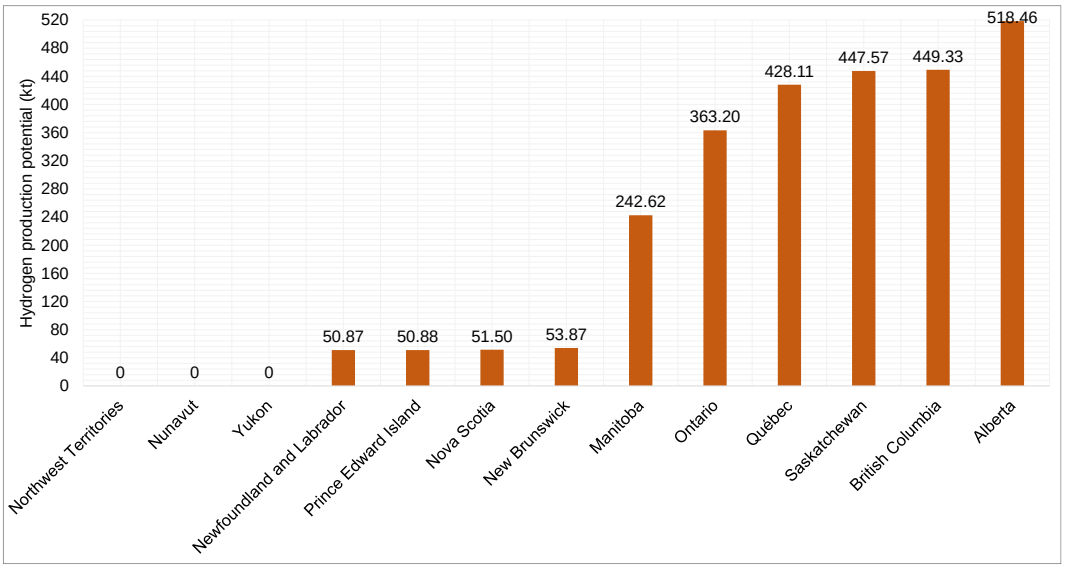


Figure 4.16 Green hydrogen production potential of each province in Canada from biomass energy

Biomass energy is a clean and renewable energy source that has the potential to play a major role in meeting Canada's future energy needs. In 2020, biomass accounted for 6.3% of Canada's total energy production. The Canadian government has set a target of increasing the share of biomass in Canada's energy mix to 10% by 2030 29. The Canadian government has a number of programs and initiatives that support biomass energy development, including the Bioenergy for Sustainable Heat and Power Program and the Biomass Energy Technology Transfer Program [28]. Figure 4.17 shows each province’s biomass waste usage percentage and value. Urban waste (municipal and industrial wastes), animal waste, forestry waste, agricultural waste, and purpose-grown energy crops are considered in the calculations for hydrogen production from biomass resources.

Alberta (a) is the fourth-largest producer of biomass energy in Canada, with about 0.3% of its total energy production coming from this source [28]. The province has a number of biomass power plants, as well as several landfill gas-to-energy projects. The province also has some biomass heating systems that are used to heat homes and businesses. Clean hydrogen produced from biomass is 7.84 kt, 79.69 kt, 124.58 kt, 141.69 kt, and 153.95 kt for urban waste, livestock, forestry residue, crop residue, and purpose-grown energy crops, respectively.

British Columbia (b) is the third-largest producer of biomass energy in Canada, with about 0.5% of its total energy production coming from this source [28]. The

most common type of biomass used in British Columbia is wood. The province has a large forest industry, and wood residues from the forestry sector are a major source of biomass. Other sources of biomass in British Columbia include agricultural waste, municipal solid waste, and landfill gas. The province has several biomass power plants, including the Williams Lake Biomass Power Plant and the Prince George Biomass Power Plant [29]. The province also has a number of biomass heating systems that are used to heat homes and businesses. 86.96% of the clean hydrogen from biomass energy comes from forestry residue. British Columbia has the most forest products and forestry residue in the whole country.

Manitoba (c) is the fifth-largest producer of biomass energy in Canada, with about 0.2% of its total energy production coming from this source [28]. The province has some biomass power plants, as well as many wood pellet plants. Province has every type of biomass resource and 44.47% of the clean hydrogen from biomass comes from crop residue. Purpose-grown energy crops follow it with 32.70%.

New Brunswick (d) is a province in eastern Canada that has a long history of using biomass as a source of energy. In recent years, the province has been investing in new biomass projects, and biomass now accounts for about 10% of the province's total energy production [28]. The most common type of biomass used in New Brunswick is wood. The province has a large forest industry, and wood residues from the forestry sector are a major source of biomass. Other sources of biomass in New Brunswick include agricultural waste, municipal solid waste, and landfill gas. 36.76% of the clean hydrogen from biomass comes from forestry residue. Livestock and urban waste are the least used biomass resources.

Newfoundland and Labrador (e) is a province in eastern Canada that has a long history of using biomass as a source of energy. In recent years, the province has been investing in new biomass projects, and biomass now accounts for about 0.1% of the province's total energy production [28]. Biomass is used in Newfoundland and Labrador for a variety of purposes, including electricity generation, heat production, and transportation fuel. The province has a number of biomass power plants, as well as a number of biomass heating systems that are used to heat homes and businesses. Biomass is also used to produce biogas, which can be used as a transportation fuel or to generate electricity. The Corner Brook Biomass

Cogeneration Plant [126] is the largest biomass power plant in Newfoundland and Labrador. It has a capacity of 15 megawatts (MW) and generates electricity from wood residues from the forestry sector [126]. Urban waste, livestock, forestry residue, crop residue, and purpose-grown energy crops help to produce 1.53 kt, 6.61 kt, 25.44 kt, 15.26 kt, and 20.35 kt, respectively.

Nova Scotia (f) is a province in eastern Canada that has a long history of using biomass as a source of energy. In recent years, the province has been investing in new biomass projects, and biomass now accounts for about 0.05% of the province's total energy production [28]. The most common type of biomass used in Nova Scotia is wood. The province has a large forest industry, and wood residues from the forestry sector are a major source of biomass. Other sources of biomass in Nova Scotia include agricultural waste, municipal solid waste, and landfill gas. The Point Tupper Biomass Power Plant [127] is the largest biomass power plant in Nova Scotia. It has a capacity of 10 megawatts (MW) and generates electricity from wood residues from the forestry sector.

Ontario (g) is a province in central Canada that has a long history of using biomass as a source of energy. In recent years, the province has been investing in new biomass projects, and biomass now accounts for about 1% of the province's total energy production [29]. The most common type of biomass used in Ontario is wood. The province has a large forest industry, and wood residues from the forestry sector are a major source of biomass. Other sources of biomass in Ontario include agricultural waste, municipal solid waste, and landfill gas. Biomass is used in Ontario for a variety of purposes, including electricity generation, heat production, and transportation fuel. The province has several biomass power plants, as well as a number of biomass heating systems that are used to heat homes and businesses. Biomass is also used to produce biogas, which can be used as a transportation fuel or to generate electricity. The Kapuskasing Biomass Power Plant [128] is the largest biomass power plant in Ontario. It has a capacity of 38 megawatts (MW) and generates electricity from wood residues from the forestry sector. 42.80% of the clean hydrogen from biomass comes from forestry residue. Purpose-grown energy crops follow it with 30.52%.

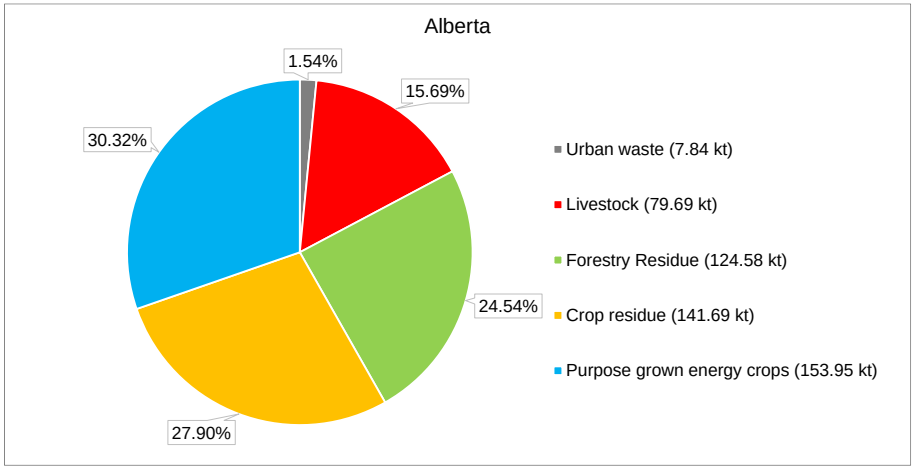
Prince Edward Island (h) is one of the smallest provinces in Canada. Unfortunately, biomass resources are scarce and few. Biomass now accounts for about 2% of the province's total energy production [28]. Available biomass resources are used in Prince Edward Island for a variety of purposes, including electricity generation, heat production, and transportation fuel. The Afton Biomass Power Plant [129] is the largest biomass power plant in Prince Edward Island. It has a capacity of 12.4 megawatts (MW) and generates electricity from wood residues from the forestry sector. Lack of population and livestock affects the biomass variety negatively. 36.76% of the clean hydrogen from biomass comes from forestry residue. While urban waste and livestock consist of 2.21%, and 9.56% respectively.

Quebec (i) has been investing in new biomass projects in recent years, and biomass now accounts for about 2% of the province's total energy production [28]. The most common type of biomass used in Quebec is wood. The province has a large forest industry, and wood residues from the forestry sector are a major source of biomass. Other sources of biomass in Quebec include agricultural waste, municipal solid waste, and landfill gas. Biomass is used in Quebec for a variety of purposes, including electricity generation, heat production, and transportation fuel. The province has several biomass power plants, as well as some biomass heating systems that are used to heat homes and businesses. Biomass is also used to produce biogas, which can be used as a transportation fuel or to generate electricity. The province has a number of biomass projects in development, and biomass is seen as a key part of the province's plan to reduce greenhouse gas emissions. Over 65% of the clean hydrogen from biomass is generated from forestry residue. Purpose-grown energy crops follow it with 15.18%, then livestock with 13.25%. Urban waste and crop residue are listed as the last two potions for biomass in Quebec with 3.54%, and 3.01%, respectively.

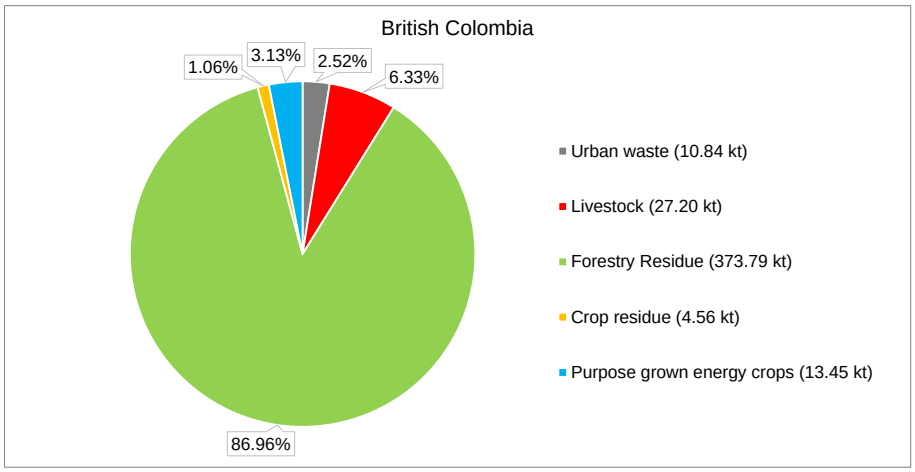
A lengthy tradition of utilizing biomass as a source of energy may be traced back to Saskatchewan (j), a province located in western Canada. The province has been making investments in new biomass projects over the past few years, and as a result, biomass now accounts for around 10% of the overall energy production in the province [28]. The Meadow Lake Tribal Council Biomass Power facility is the most significant biomass power facility in the Canadian province of Saskatchewan. It is

capable of producing 8.3 megawatts (MW) of power and uses the waste wood from the forestry industry as its primary fuel source [130]. With a capacity of 6.6 megawatts (MW), the Prairie Clean Energy Biomass Plant [130] is one of the more modest biomass power plants. It does this by burning wood pellets, which are made from the scraps of wood that are left over from the forestry industry. This creates energy. The majority of Saskatchewan's clean hydrogen from biomass resources comes from crop residue and purpose-grown energy crops, respectively, accounting for 43.30% and 43.67% of the total. Because there are so few people living in the cities, there is almost little waste produced. In the calculations for the production of hydrogen from biomass energy, the territories of Nunavut and Yukon have been omitted.

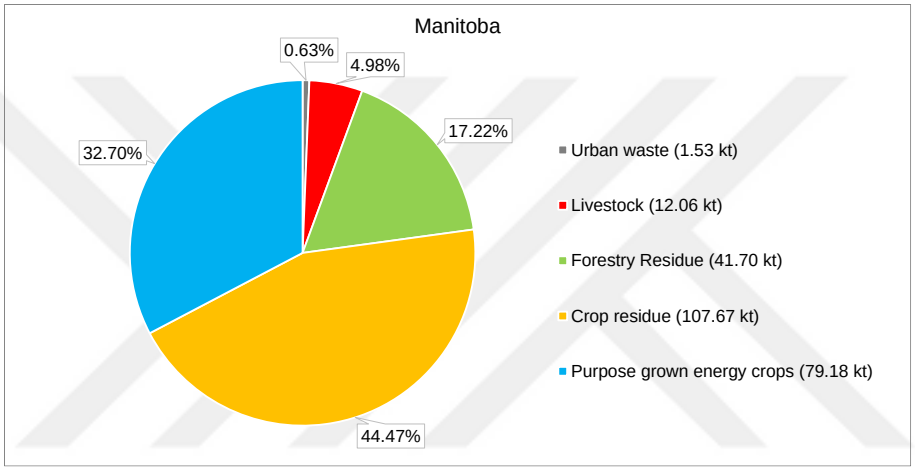
Because of its subarctic environment and lack of forestland, Nunavut has a low potential for producing biomass. However, there are some possible sources of biomass in the territory. These sources include fish waste, municipal trash, and wood waste from building and demolition, all of which might be used to make biomass pellets or heat. There are a few obstacles that stand in the way of the growth of biomass energy in Nunavut. Transporting and processing biomass in the area is difficult and expensive due to the region's isolated location and severe environment. In addition, the environmental impact of developing bioenergy sources in some Nunavut towns is a source of concern for those populations.



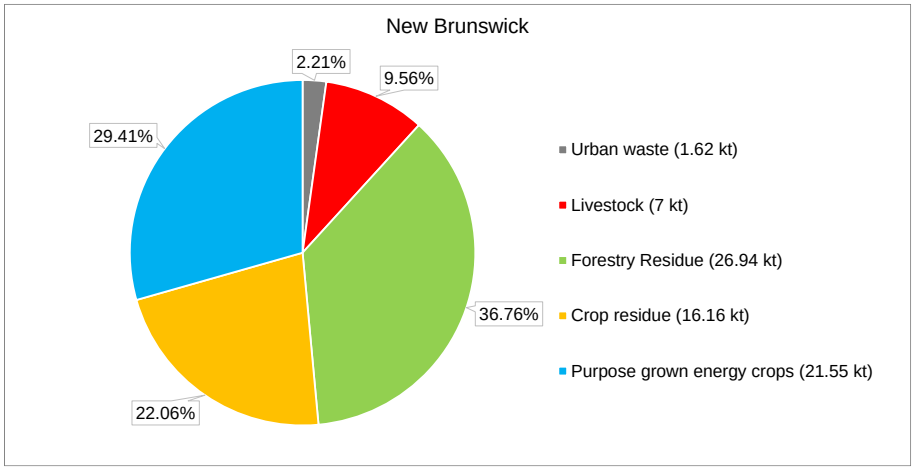
(a)


British Colombia
1.06%
3.13%
2.52%
6.33%
86.96%
Urban waste (10.84 kt)
Livestock (27.20 kt)
Forestry Residue (373.79 kt)
Crop residue (4.56 kt)
Purpose grown energy crops (13.45 kt)

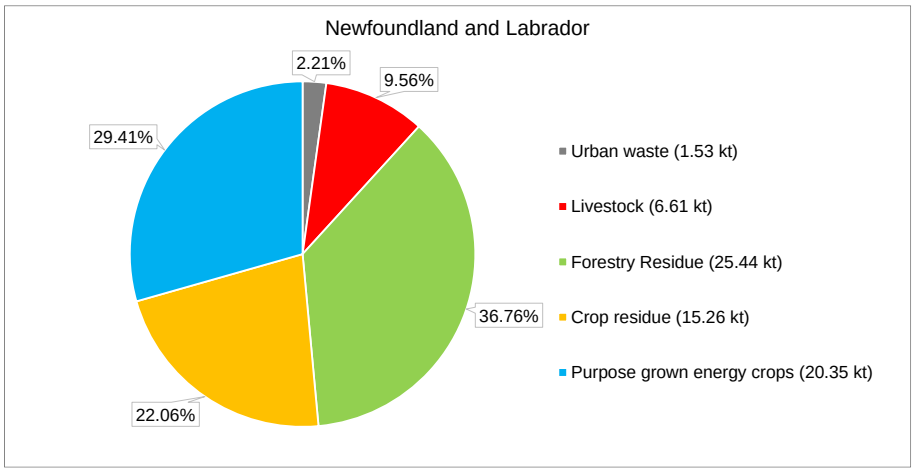
(b)


Manitoba
0.63%
4.98%
17.22%
32.70%
44.47%
Urban waste (1.53 kt)
Livestock (12.06 kt)
Forestry Residue (41.70 kt)
Crop residue (107.67 kt)
Purpose grown energy crops (79.18 kt)

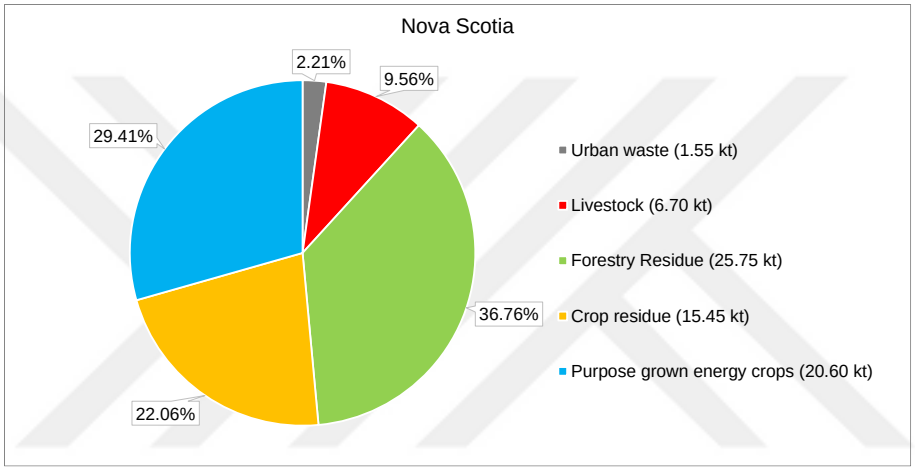
(c)


New Brunswick
2.21%
9.56%
29.41%
36.76%
22.06%
Urban waste (1.62 kt)
Livestock (7 kt)
Forestry Residue (26.94 kt)
Crop residue (16.16 kt)
Purpose grown energy crops (21.55 kt)

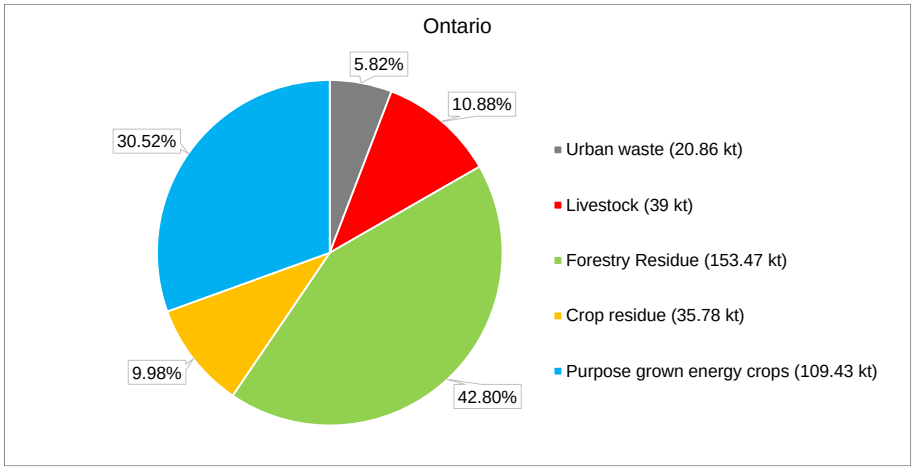
(d)


Newfoundland and Labrador
2.21%
9.56%
29.41%
36.76%
22.06%
Urban waste (1.53 kt)
Livestock (6.61 kt)
Forestry Residue (25.44 kt)
Crop residue (15.26 kt)
Purpose grown energy crops (20.35 kt)

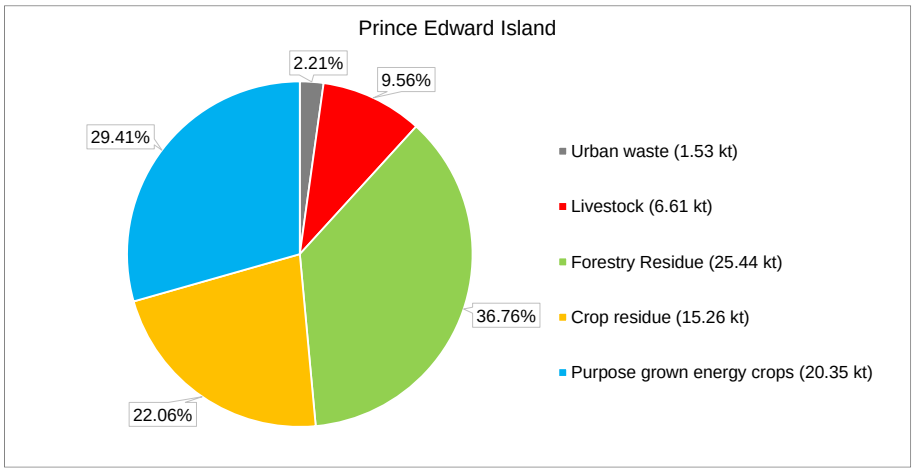
(e)


Nova Scotia
2.21%
9.56%
29.41%
36.76%
22.06%
Urban waste (1.55 kt)
Livestock (6.70 kt)
Forestry Residue (25.75 kt)
Crop residue (15.45 kt)
Purpose grown energy crops (20.60 kt)

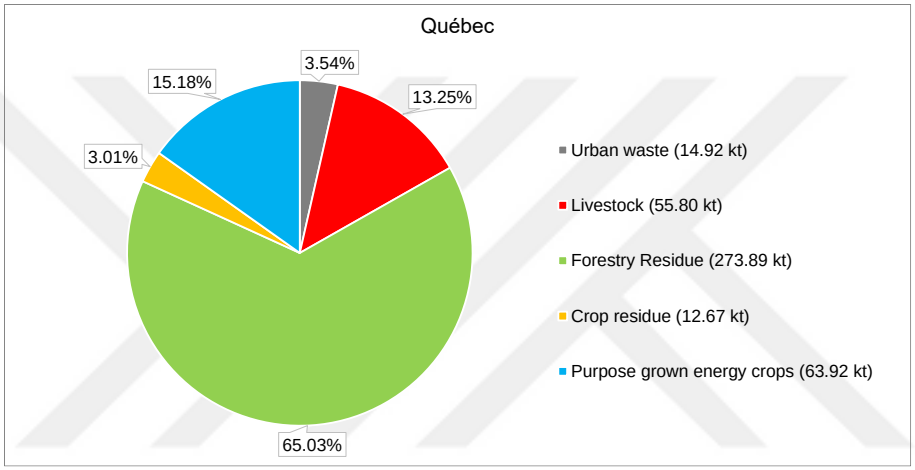
(f)


Ontario
5.82%
10.88%
30.52%
9.98%
42.80%
Urban waste (20.86 kt)
Livestock (39 kt)
Forestry Residue (153.47 kt)
Crop residue (35.78 kt)
Purpose grown energy crops (109.43 kt)

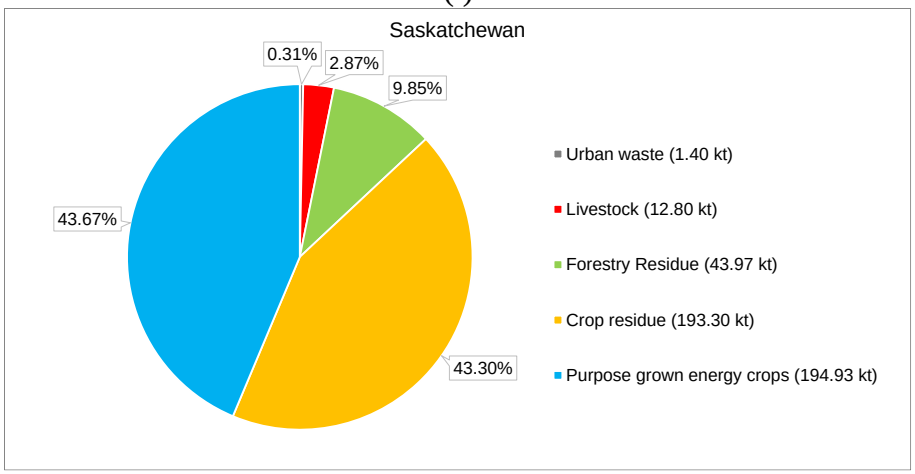
(g)



(h)



(i)



(j)

Figure 4.17 Green hydrogen production potential of each province in Canada (a-j) from biomass energy

4.6 Results of Nuclear Energy Utilization

Canadian nuclear power facilities have been commercially producing electricity since the early 1960s. Currently, five facilities in three provinces contain twenty-two nuclear power reactors. About 15% of Canada's electricity is generated by nuclear power. To protect the public and the environment, the CNSC employs a team of technical specialists and on-site inspectors to ensure that strict oversight of plant operations is maintained. Active nuclear facilities included in the calculations are Bruce Nuclear Generating Station [131], Pickering Nuclear Generating Station [132], and Darlington Nuclear Generating Station [133], all located in Ontario, and Point Lepreau Generating Station [134], located in New Brunswick. Recently, the Gentilly-2 [135] Nuclear Facility in Quebec was shut down. Therefore, Gentilly-2 is disregarded. In Canada, every nuclear power reactor is a CANDU (Canadian Deuterium-Uranium) reactor [38]. This heavy water pressurized reactors use natural uranium as their fuel and heavy water as their coolant and moderator. Figure 4.18 shows, the clean hydrogen production potential of Canada from nuclear energy. Unfortunately, none of the 13 provinces in Canada has capacity to supply the power demand then produce clean hydrogen solely from nuclear energy.

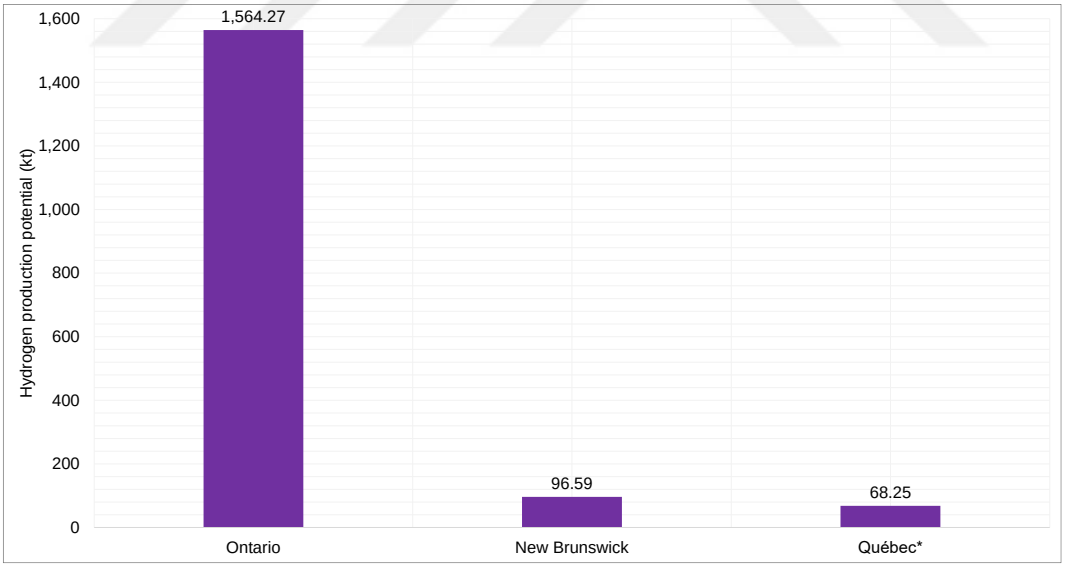


Figure 4.18 Clean hydrogen production potential of Canada from nuclear energy *Québec* Gentilly Power Plat shut down recently.

4.7 Results of Hydrogen Production of Each Province

Alberta has a significant amount of renewable energy potential, with about 30% of the province's electricity coming from renewable sources in 2021 [80].. Alberta

doesn't have access to offshore applications. However, unlike other provinces geothermal energy potential is very high and consists of 29.29% of all potential of the province. Most hydrogen production potential comes from wind energy and geothermal energy. Hydropower can be listed as the last resource among others. The total hydrogen production potential of Alberta is 89.08 Mt. Figure 4.19 shows the clean hydrogen production potential of Alberta.

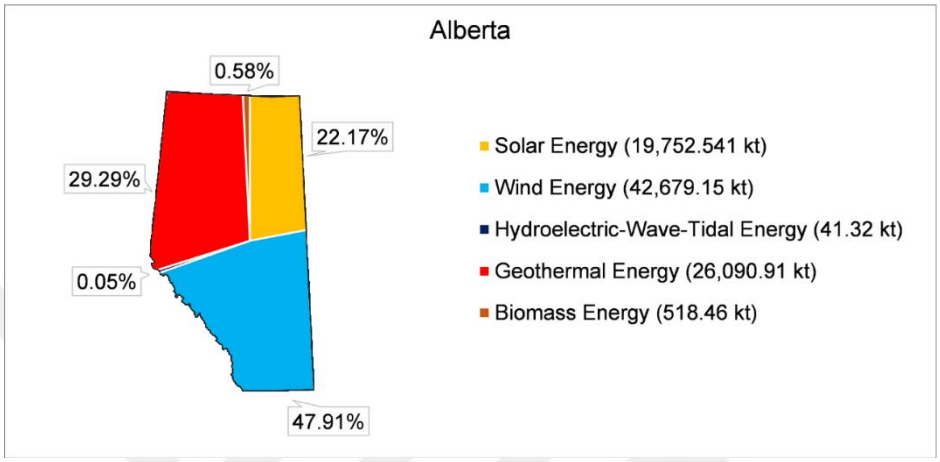


Figure 4.19 Clean hydrogen production potential of Alberta

British Columbia has a significant amount of renewable energy potential, with about 90% of the province's electricity coming from renewable sources in 2021 [80]. The province's best renewable energy resources are found in the hydroelectric, wind, and solar sectors. British Columbia has a good wind energy potential with responsible for over 70% of the whole province. The total clean hydrogen production potential of British Columbia is 99.04 Mt. Figure 4.20 shows the clean hydrogen production potential of British Columbia.

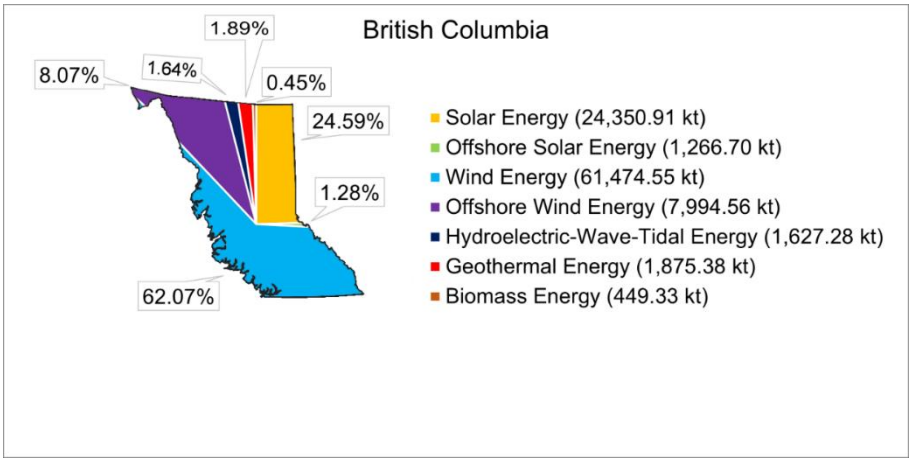


Figure 4.20 Clean hydrogen production potential of British Columbia

There is a substantial amount of potential for renewable energy in the province of Manitoba, with approximately 25% of the electricity in the province coming from renewable sources in 2021 [80]. The fields of solar power, wind power, hydroelectric power, and biomass supply the province with the most valuable renewable energy resources. Wind energy, both onshore and offshore, is Manitoba's most important resource for the potential production of hydrogen. It accounts for 68.21% of all of the available resources. The entire generation potential for hydrogen that is not polluting in Manitoba is 59 Mt. The potential for the production of clean hydrogen in Manitoba is depicted in Figure 4.21.

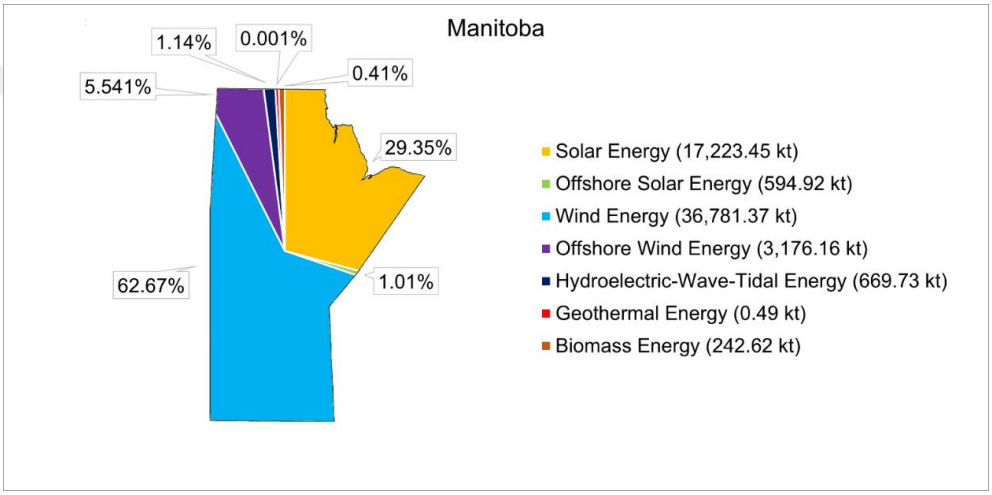


Figure 4.21 Clean hydrogen production potential of Manitoba

The quantity of potential renewable energy that New Brunswick possesses is rather low, and it is projected that just around 10% of the province's electricity will come from renewable sources in 2021 [80]. The analysis took into account all of the renewable and clean resources that are available to the province. Seventy one point one nine percent of the green hydrogen produced in the provinces comes from onshore and offshore wind and solar energy. The quantity of hydroelectric potential in New Brunswick is rather low, and the province only has a handful of minor hydroelectric dams in operation. The Miramichi River system is home to some of the most productive hydropower resources in the province. The overall production potential of New Brunswick for hydrogen that is not polluting is 7.88 Mt. Figure 4.22 illustrates the possibility for New Brunswick to produce hydrogen from clean sources.

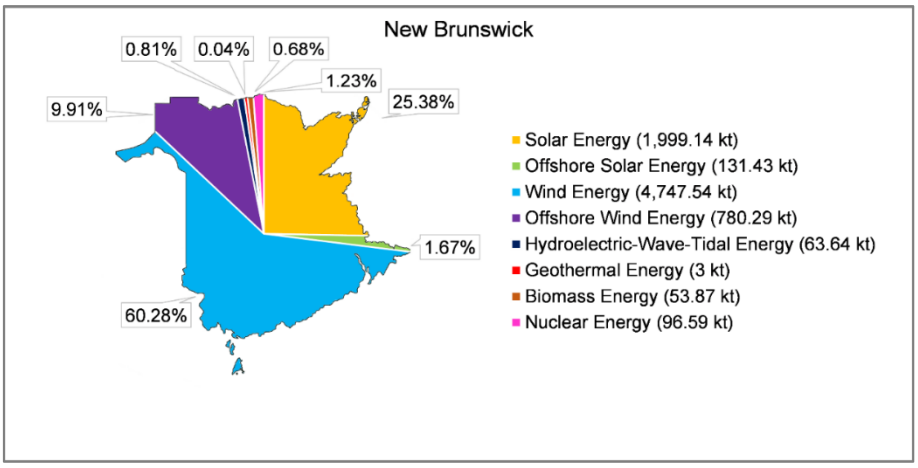


Figure 4.22 Clean hydrogen production potential of New Brunswick

Newfoundland and Labrador has a significant amount of renewable energy potential, with about 40% of the province's electricity coming from renewable sources in 2021 [81]. The province's best renewable energy resources are found in the hydroelectric, wind, and tidal sectors. Province has a significant amount of hydroelectric potential, with over 50 hydroelectric dams in operation. The province's best hydroelectric resources are found in the Churchill River system and the Great Northern Peninsula. Newfoundland and Labrador's municipality is committed to increasing the use of renewable energy in the province. Newfoundland and Labrador's total clean hydrogen production potential is 33.13 Mt. There are offshore applications, however, the sea surface and the applicable area are not high. Due to this, offshore solar and offshore wind energy contributes only 10.21%. Figure 4.23 shows the total clean hydrogen production potential of Newfoundland and Labrador province.

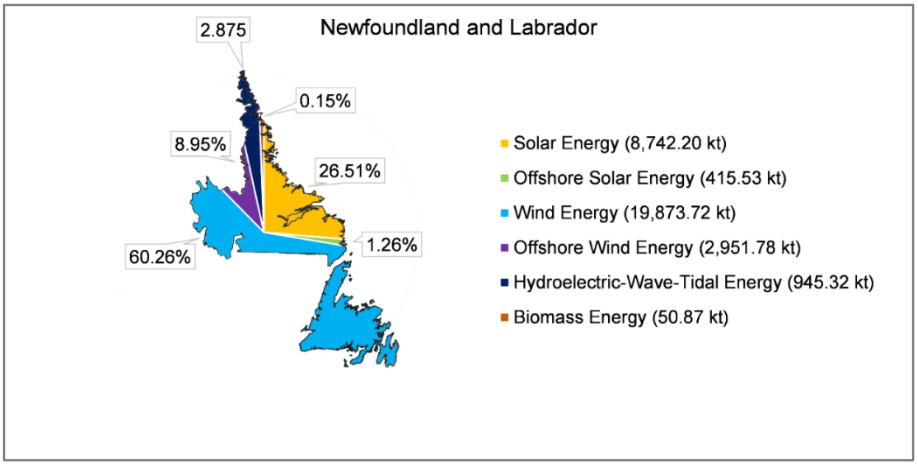


Figure 4.23 Clean hydrogen production potential of Newfoundland and Labrador

Northwest Territories is located in the northwest of the country. Lack of resources, and harsh weather effects green hydrogen production negatively. Biomass, geothermal, and nuclear energies are not available in this region however, wind and solar energies make up for the lack of other sources. The Northwest Territories has a significant amount of hydroelectric potential, with over 20 hydroelectric dams in operation [23]. The territory's best hydroelectric resources are found in the Mackenzie River system. The total clean hydrogen production of the Northwest Territories is 31.55 Mt. Figure 4.24 shows the clean hydrogen production potential of the Northwest Territories from renewable resources.

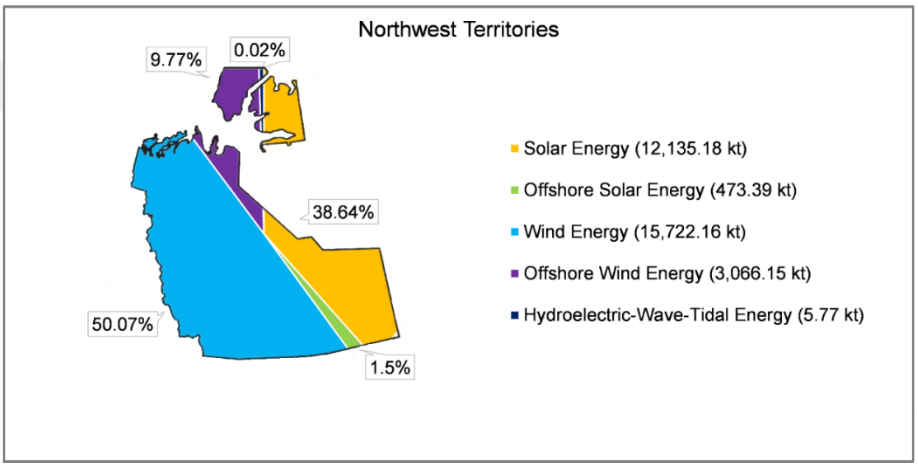


Figure 4.24 Clean hydrogen production potential of Northwest Territories

Nova Scotia has access to almost every renewable resource. Especially marine applications, tidal energy, and wave-catching power stations show promising potential for the future. However, the lack of available empty land forces provinces to offshore applications. Nova Scotia has a limited amount of renewable energy potential, with about 15% of the province's electricity coming from renewable sources in 2021 [81]. The province's best renewable energy resources are found in the wind, biomass, and tidal sectors. Nova Scotia has tidal-wave-current energy potential, with a relatively small tidal range found in the Bay of Fundy. The total clean hydrogen production potential of Nova Scotia is 6.45 Mt. Figure 4.25 shows its clean hydrogen potential of it.

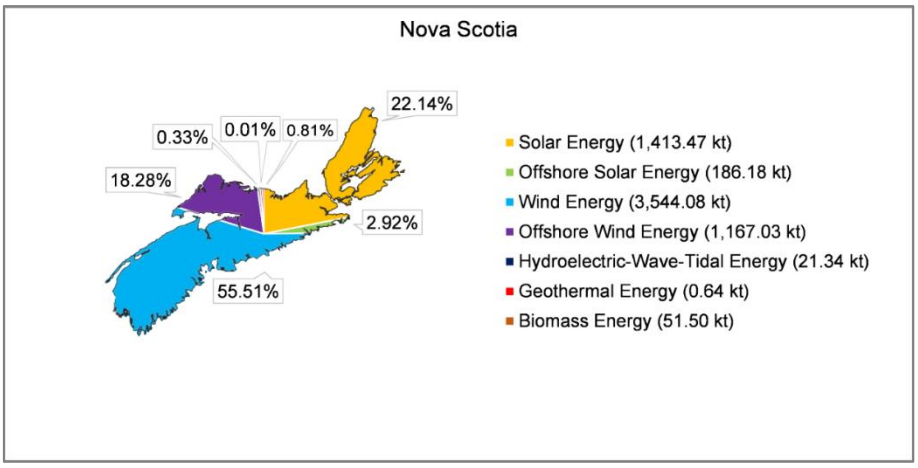


Figure 4.25 Clean hydrogen production potential of Nova Scotia

Nunavut is one of the coldest provinces in Canada. The north side of the region is full of ice islands, extreme weather, and harsh conditions. Due to this and low population density, the only available resources are solar and wind energy. The territory has a few solar and wind projects in operation, but these are still in the early stages of development. Figure 4.26 shows the clean hydrogen production potential of Nunavut. The total hydrogen production potential is 50.54 Mt.

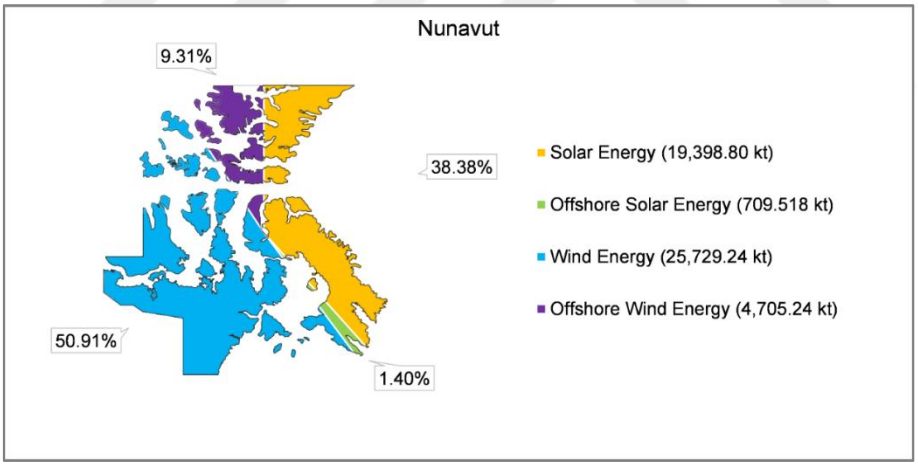


Figure 4.26 Clean hydrogen production potential of Nunavut

Ontario has a significant amount of renewable energy potential, with about 25% of the province's electricity coming from renewable sources in 2021 [81]. The province's best renewable energy resources are found in the hydroelectric, wind, solar, biomass, and geothermal sectors. Ontario is a well-developed province, and it has access to multiple renewable and clean energy resources. Ontario is one of the two provinces using nuclear energy for power generation. Wind energy supplies

63.67% of the produced clean hydrogen. Province has a vast amount of hydroelectric potential, with over 200 hydroelectric dams in operation. The province's best hydroelectric resources are found in the Great Lakes-St. Lawrence Lowlands and the Canadian Shield. Ontario is also the third highest-listed province for clean hydrogen production among others. The total clean hydrogen production of Ontario is 81.78 Mt. Figure 4.27 shows the clean hydrogen production potential of Ontario.

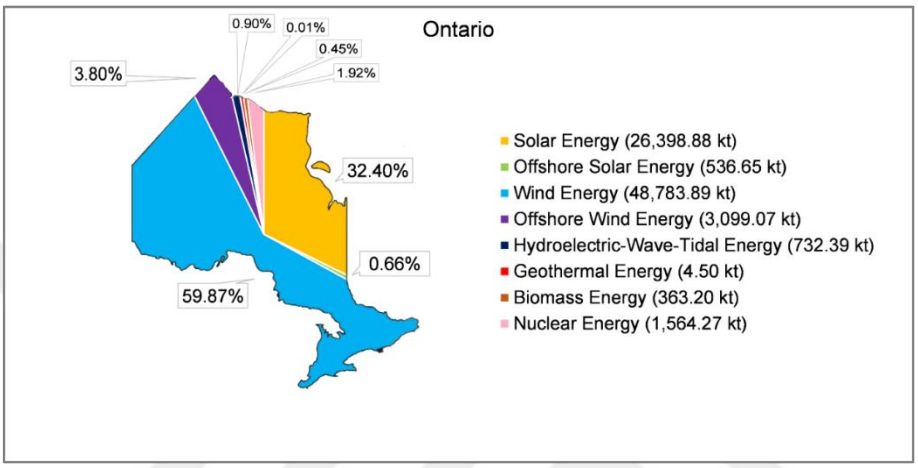


Figure 4.27 Clean hydrogen production potential of Ontario

Prince Edward Island is the smallest province in Canada. Due to this and the lack of usable empty lands, hydrogen production potential is very low. Province has access to multiple renewable sources however it is not enough. The total clean hydrogen production of Prince Edward Island is 1.96 Mt, and over 79% of it comes from offshore and onshore wind energy. Figure 4.28 shows the clean hydrogen production of Prince Edward Island.

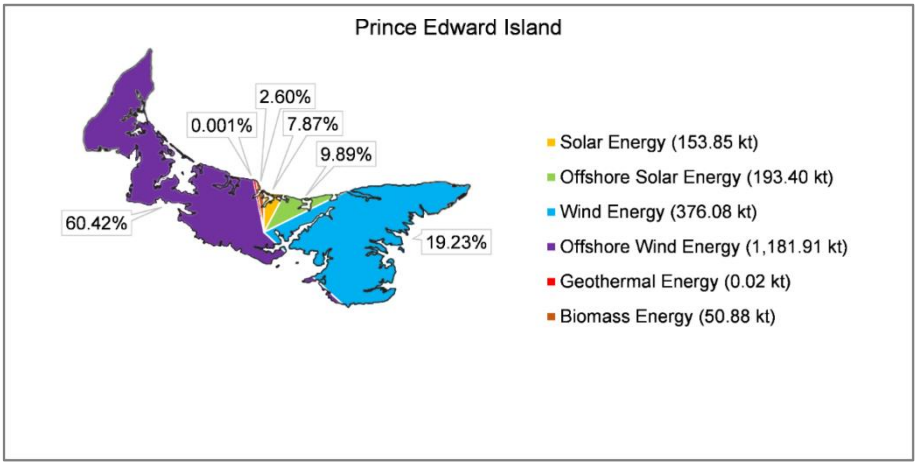


Figure 4.28 Clean Hydrogen Production Potential of Prince Edward Island

The province of Quebec ranks first among the states and provinces for the generation of hydrogen from eco-friendly and sustainable sources. It has access to all of the resources available, with the exception of nuclear energy. In addition, the province of Quebec is home to the most hydroelectric power stations in the world, with over 600 hydroelectric dams and marine applications [23]. The Laurentian Mountains and the Saint Lawrence River system are home to some of the most promising hydroelectric potential in the province. The agriculture and forest products sectors of the province are where some of the best biomass resources can be found in this province. The municipal government of Québec is dedicated to expanding the usage of renewable energy sources throughout the province. The province has committed to using only renewable sources of energy by the year 2035 [80]. Additionally, the government is spending money on research and development with the goal of making renewable energy technology more efficient and competitively priced. Figure 4.29 illustrates the overall capacity for the production of clean hydrogen in Quebec, which is 125.59 Mt.

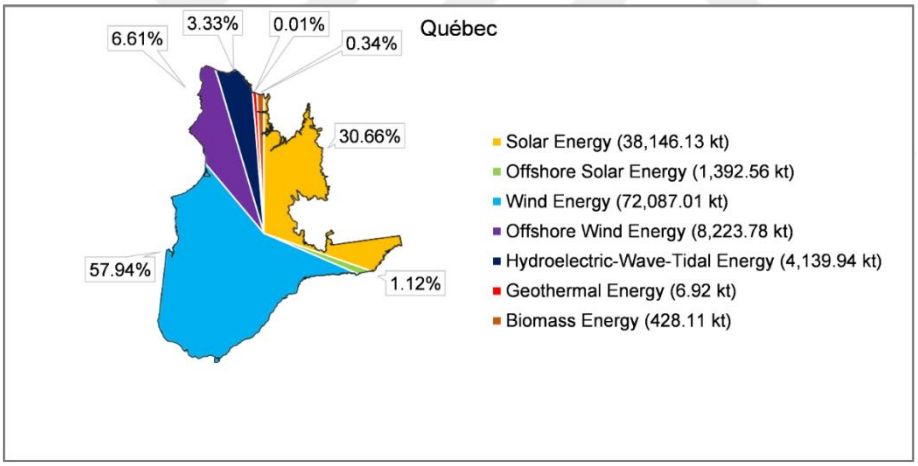


Figure 4.29 Clean hydrogen production potential of Québec

When compared to the potential of other jurisdictions for the production of clean hydrogen, Saskatchewan comes in at number six. It has access to a wide variety of renewable resources; however, the vast majority of the potential for hydrogen generation comes from solar and wind energy, accounting for 99.11% of the total. The potential for the production of hydrogen as a whole is 59.72 Mt. Figure 4.30 illustrates the province of Saskatchewan's potential for producing clean hydrogen.

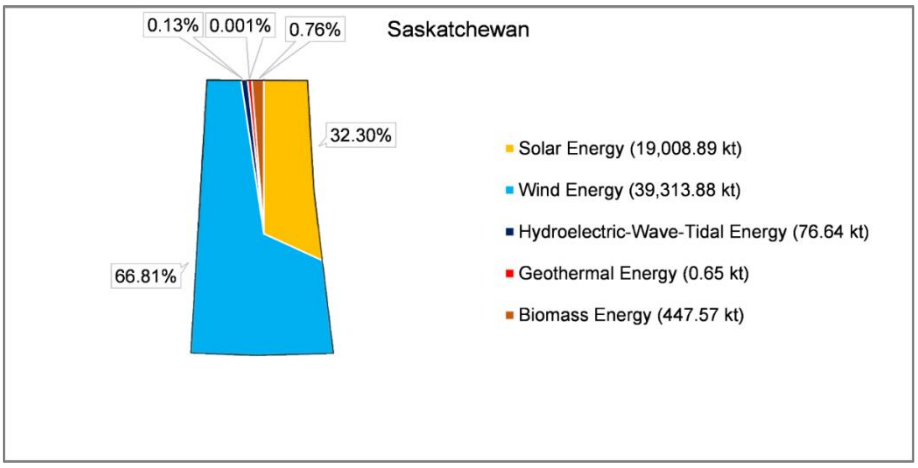


Figure 4.30 Clean hydrogen production potential of Saskatchewan

Geothermal power is only available in a select few Canadian provinces, with Yukon being one of those provinces. Geothermal energy accounts for 2.81 percent of the total potential for the production of hydrogen. Nevertheless, wind energy, just like in the other provinces, is the primary source of production here. The entire production potential of Yukon for hydrogen that is not polluting is 45.25 Mt. The percentage of Yukon's available renewable resources, as well as their potential values for hydrogen production, are displayed in Figure 4.31.

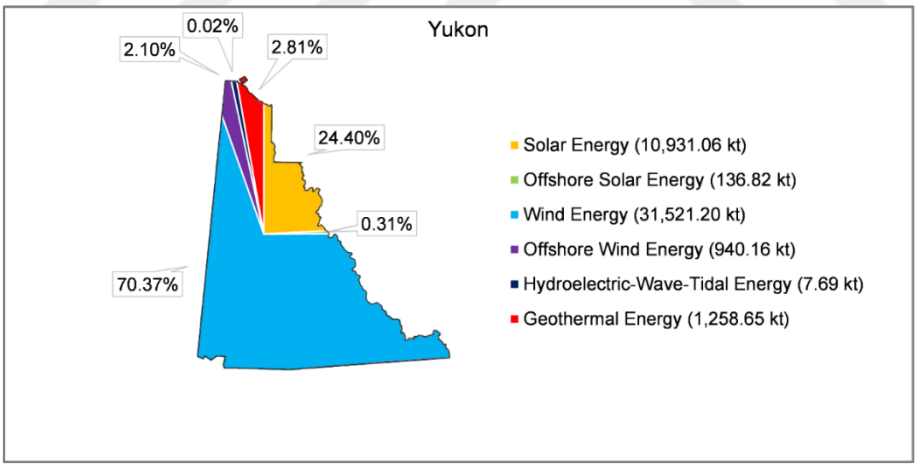


Figure 4.31 Clean hydrogen production potential of Yukon

5
CONCLUSIONS

5.1 Conclusions

Increasingly stringent policies to reduce greenhouse gas emissions through the use of renewable energy systems, on the one hand, and limited fossil fuel resources, on the other, convince policymakers and investors in energy sectors to establish a dependable energy base to address these issues. The concept of the hydrogen farm has the potential to be considered as a platform for the implementation of all renewable energies in multiple nations. Considered a viable candidate for this purpose in Canada. Investing in renewable energy sources at the opportune moment, in conjunction with the hydrogen hub concept to address storage issues, is among the deterministic steps for a sustainable future, particularly in developing nations. Consequently, Canada's high potential can be utilized to ignite the flames of establishing a solid platform for this transition, as predicted by the current study.

Creating a hydrogen center in Canada has the potential to offset the country's total energy consumption, according to the findings of this study. The feasibility study demonstrates that producing zero-carbon energy carrier hydrogen from renewable energy sources can support national objectives for sustainable energy policies and bring it to the attention of governments seeking to reduce their dependence on imported energy. This strengthens the country's political position and positions it as a leader in assimilating energy market investments. To achieve these objectives, a reasonable plan for the appraisal of hydrogen value chain risks and a safer production, storage, and distribution system for green hydrogen are required.

- Canada's capacity to produce clean hydrogen using renewable and clean energy sources is 693.11 million tons. After energy demand is met, this value comes to 623.83 Mt.
- Clean hydrogen production potential from renewable sources is 205.69 Mt, 439.92 Mt, 29.24 Mt, 2.65 Mt, 13.94 Mt, 1.66 Mt, for solar energy, wind energy, geothermal energy, biomass energy, hydroelectric-wave-undersea current energies, and nuclear energy, respectively. These values are

calculated before power demand. Only solar and wind energy applications have capacity to both supply the power demand and produce clean hydrogen from excess electricity.

- Among 13 provinces, potential can be listed as 125.71 Mt, 99.66 Mt, 89.08 Mt, 81.96 Mt, 59.09 Mt, 58.85 Mt, 50.95 Mt, 44.94 Mt, 33.70 Mt, 32.05 Mt, 8.14 Mt, 6.88 Mt, and 2.10 Mt, for Québec, British Columbia, Alberta, Ontario, Manitoba, Saskatchewan, Nunavut, Yukon, Newfoundland and Labrador, Northwest Territories, New Brunswick, Nova Scotia, and Prince Edward Island, respectively.
- Clean hydrogen production potentials from excess electricity generated by renewable energy resources are listed as 114.49 Mt, 91.48 Mt, 65.71 Mt, 64.08 Mt, 57.09 Mt, 55.87 Mt, 50.51 Mt, 45.20 Mt, 32.11 Mt, 31.45 Mt, 6.56 Mt, 5.47 Mt, and 1.81 Mt for Quebec, British Columbia, Alberta, Ontario, Manitoba, Saskatchewan, Nunavut, Yukon, Newfoundland and Labrador, Northwest Territories, New Brunswick, Nova Scotia, and Prince Edward Island, respectively.
- Hydrogen production potential from solar energy can be increased by using different PV panel array orientations. This potential increases by 90% from horizontal tilt array to 2-axis tracking panel use.
- Hydrogen production from solar energy is equal to 29.67% of all potential, while wind energy is responsible for producing 63.47% of it.
- Hydrogen production potential percentages of hydropower, wave, and undersea current are 59.78%, 40.12%, and 0.01% for marine applications.
- For biomass resources; forest waste, purpose-grown energy crops, agricultural waste, animal waste, and urban waste (municipal and industrial wastes) are responsible for 41.97%, 26.26%, 20.99%, 9.54%, and 2.39%, respectively.

5.2 Recommendations

In this thesis, eight distinct renewable energy resources have been examined. According to credible projections, solar, wind, geothermal, wave, undersea current, hydroelectric, biomass, and nuclear energies are promising by 2030 or 2040. Solar and wind energy systems are rapidly adopting contemporary technologies and

methods. In contrast to other resources, however, the implementation of modern hydrogen techniques and technologies is delayed due to its infrastructure requirements. Hydrogen as an environmentally friendly fuel will replace fossil fuels as the dominant energy source. Consequently, the transition procedure is significant. Implementation of renewable-based hydrogen production centers is a crucial step due to the positive outcomes described in this thesis. Recommendations are listed as follows:

- It is vital to conduct in-depth life cycle analyses of these renewable based systems in order to have a complete understanding of the emissions associated with each planned system.
- A cost assessment and analysis of the chosen electrolysers, fuel cells, and other technologies and infrastructures should be done to evaluate the possibility and the cost margins.
- Viable storage and transportation of the produced hydrogen should be investigated for each province with pros and cons. Hence, best option in terms of economic aspect or efficiency can be found and compared to each other as well.

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