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Green Hydrogen Integration for Sustainable Low-Carbon Buildings: Establishing New Zealand's Clean Energy Future

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Abstract: **With environmental degradation intensifying due to energy demand escalation and population growth, achieving global decarbonization has become critically urgent. As a major contributor, transforming how buildings offers immense potential. This paper examines possibilities for deploying green hydrogen systems in buildings to align New Zealand with wider climate targets. The paper addresses hydrogen produced from renewable-powered electrolysis for sustainable low-emission heating and power, as well as decentralized hydrogen solutions for localized energy resilience. Analysis of the literature indicates research focused on integrating hydrogen technologies within buildings is scarce. This is constituting a key research gap.**

By extensively analysing scholarly literature, this paper offers significant elucidation around the complex interlinkages driving energy usage and emissions, and hydrogen's role in sustainable transitions. It also defines key future research needs, questions, aims and objectives for future research in green hydrogen-based technologies across New Zealand's built environment. Specifically, it evaluates economic feasibility, safety perceptions, policy levers, environmental impacts and technology maturity. This review informs practical roadmaps and decisions amongst multiple stakeholders, equipping them to leverage hydrogen's versatility for accelerating building decarbonization. Thereby it contributes robust perspectives toward attaining low-carbon, resilient built environments to contribute to New Zealand's legal and moral responsibilities under the terms of the Paris Climate Accord.

Keywords: **Green Hydrogen, Decarbonization, Sustainable Energy Transition, New Zealand Energy Landscape.**

1. INTRODUCTION

The urgent need for decarbonization to achieve zero net greenhouse gas emissions globally by 2050, as outlined in the Climate Change Response (Zero Carbon) Amendment Act 2019, underscore the significance of transitioning towards renewable energy sources [1], [2], [3], [4]. This paper focuses on green hydrogen production as a transformative energy vector, aligning with New Zealand's strategic priorities. It aims to describe the key role green hydrogen technologies are anticipated to play in fostering a sustainable, low-carbon built environment.

The necessity of exploring green hydrogen's potential within the larger discourse of achieving decarbonization serves as the cornerstone of this study. It is instrumental in both providing a structured investigation into green hydrogen technologies and identifying research gaps that necessitate further exploration.

The study's overarching objective is to bridge existing knowledge gaps surrounding green hydrogen systems, in the New Zealand context. This comprehensive literature review forms the initial step in delineating pathways for successful deployment and strategic implementation. It also sets the stage for subsequent research efforts towards facilitating sustainable, low-carbon built environments.

2. LITERATURE REVIEW METHODOLOGY

Literature analysis is central to fundamental research providing researchers with a repository of scholarly works and industry expertise for critical evaluation, analysis, and interpretation [5]. Its overarching objective is to amass an empirical body of knowledge pertinent to the research topic [6], [7], [8]. Literature review meticulously scrutinizes antecedent literature, affording a holistic comprehension of existing scholarship. Beyond identifying gaps, it significantly informs the research problem, shapes relevant questions, and delineates clear aims and objectives [9], [10].

This comprehensive review employs a mixed-method approach, amalgamating quantitative and qualitative data collection strategies. Onwuegbuzie's seven-step technique guides the exploration, initiation, storage and organization of data, selection/deselection, expansion and critical evaluation of data, analysis/synthesis and presentation of information. Each step demands systematic scrutiny, reflection, and organization to enrich the academic discourse [6].

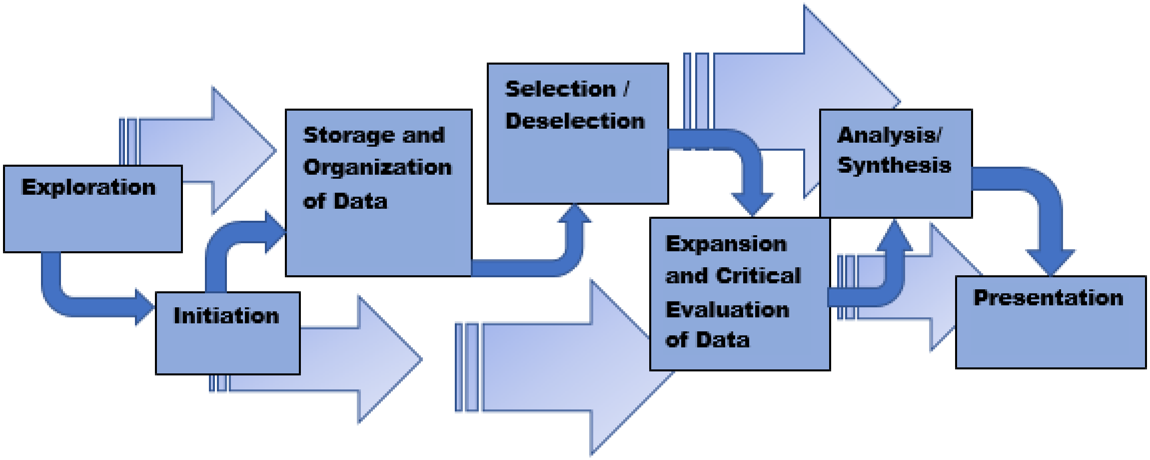

Diagram 1: Seven Step Technique of Literature Review based on Onwuegbuzie's Model [6]

Moreover, the absence of literature presents an opportunity for novel exploration and discovery within the research domain [11]. Throughout this process, researchers engage in iterative phases of data collection, interpretation, synthesis, and evaluation, ultimately shaping the foundation of their reports [11], [6], [12].

Further enhancing the study's integrity, systematic literature review methods are employed, systematically identifying and integrating relevant evidence from diverse sources [12].

The preliminary stages of this research commence with a conceptual model to introduce the topic, leading into an in-depth literature review. Employing a mixed-use method approach, diverse data from the online library catalogues, databases, Google Scholar [13], and grey literature are meticulously curated to align with the research goals [14].

Critical evaluation and selection of pertinent literature refine the dataset, ensuring its relevance and applicability to the research. Organized databases and annotated bibliographies contribute to the synthesis of findings and facilitate future research utilization [15].

Additionally, empirical sources corroborate the validity of information and substantiate the development of hypotheses. The synthesis of collected data informs the creation of structured interview questions [16], underscoring the research's empirical underpinnings.

In sum, this comprehensive literature review, aligned with theoretical frameworks, methodological tenets, and research objectives, underpins this research. The intention is to identify and describe the pathways of empirical validation and hypothesis formulation.

3. LITERATURE REVIEW

3.1 Population Growth and Energy Demand Growth

Energy demand increase is influenced by many factors. These include energy price fluctuation, economic growth, gross domestic product growth, social development, and population growth [17]. Global population growth caused by high fertility rate, increased world life expectancy and human longevity [18], [19]. Population growth in turn creates the energy demand increase per capita especially in the developed and transitional countries where the gross domestic product per capita is high, and it is expected that this trend will continue to grow [20]. Global population increased from 2.5 billion in 1950 to 7.9 billion in 2020 and it is projected that the number of people will reach approximately 10.0 billion in 2050 [21], [22].

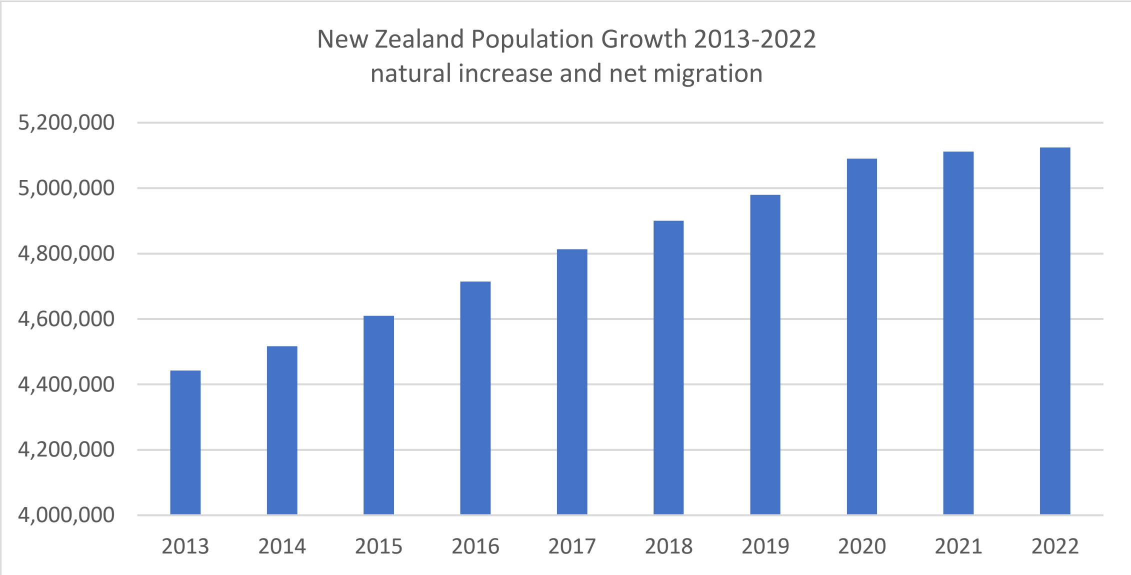

Figure 1: NZ population growth 2013 - 2022 (Source: Chart prepared based on national population statistics published by Stats NZ on 16th August 2022 www.stats.govt.nz)

New Zealand does not have a high population globally, rankings 126th or only 0.06% world population [23]. However, NZ population continues to grow steadily as it shown in Figure 1. The latest population estimate for New Zealand is circa 5.27 million residents [24]. This is a significant increase from the 1.9 million population in 1950.

Since 1990, NZ population has steady growth at 1.2% per annum and it is projected that the population will continue to increase from 2023 to 2073 as can be seen in Figure 2 [25], [26]. Generally, two main streams contribute to NZ population growth - natural increase and net migration. The birth rate is higher than the death rate and the immigrant stream is higher than the number of people leaving the country. However, during the COVID-19 borders closure, migrant arrivals decreased by 40% while migrant departure increased by 3% [24]. Nevertheless, the index shows that overall NZ population growth has an increasing trend.

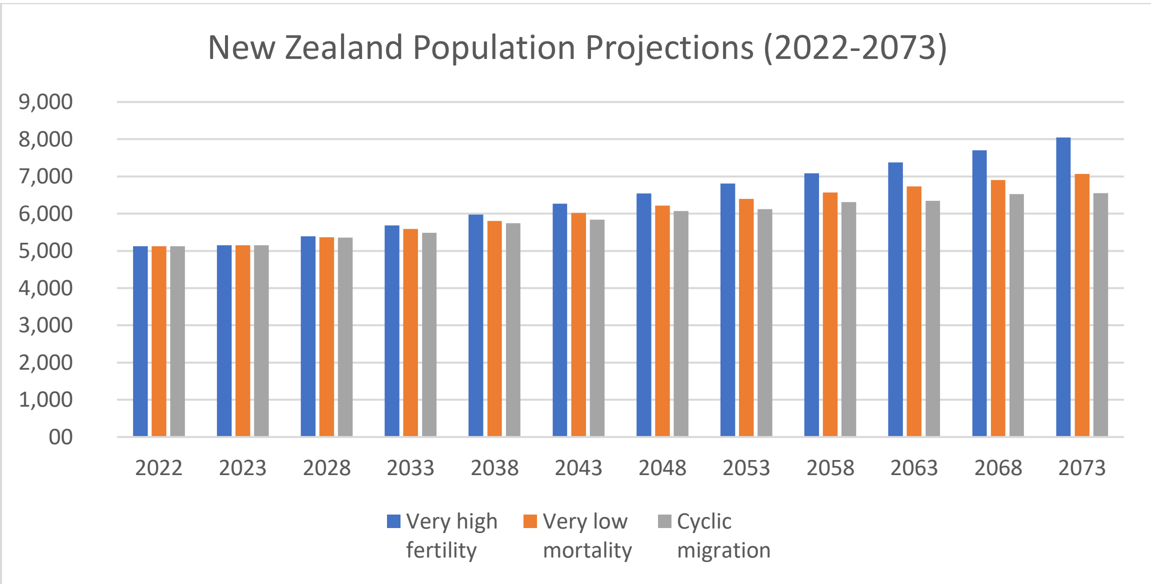

Figure 2: NZ population projection (Chart prepared based on national population projections statistics published by Stats NZ on 27th July 2022 www.stats.govt.nz)

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Population growth is central to residential energy consumption, the steady trend can indicate that energy demand will increase proportionally to population growth [26]. Figure 3 identifies a strong corelation between the population growth and domestic electricity consumption growth. Based on NZ population projections where population variables correlated to electricity consumption, a linear energy consumption model may forecast the increase in energy demand in the long term [27].

Growing populations require increased energy generation [28]. The interdependence between population, energy and economic growth contributes to environmental degradation, increased fossil fuel consumption and carbon dioxide emissions [29]. The emissions contributed by the energy sector increased from 23.9 million tonnes in 1990 to 31.5 million tonnes of carbon dioxide equivalent in 2020 [30]. Thus, the overall uptrend can be drawn as the following: the environmental degradation is caused by population and economy growth, increased energy consumption, fossil fuels and CO2 emission.

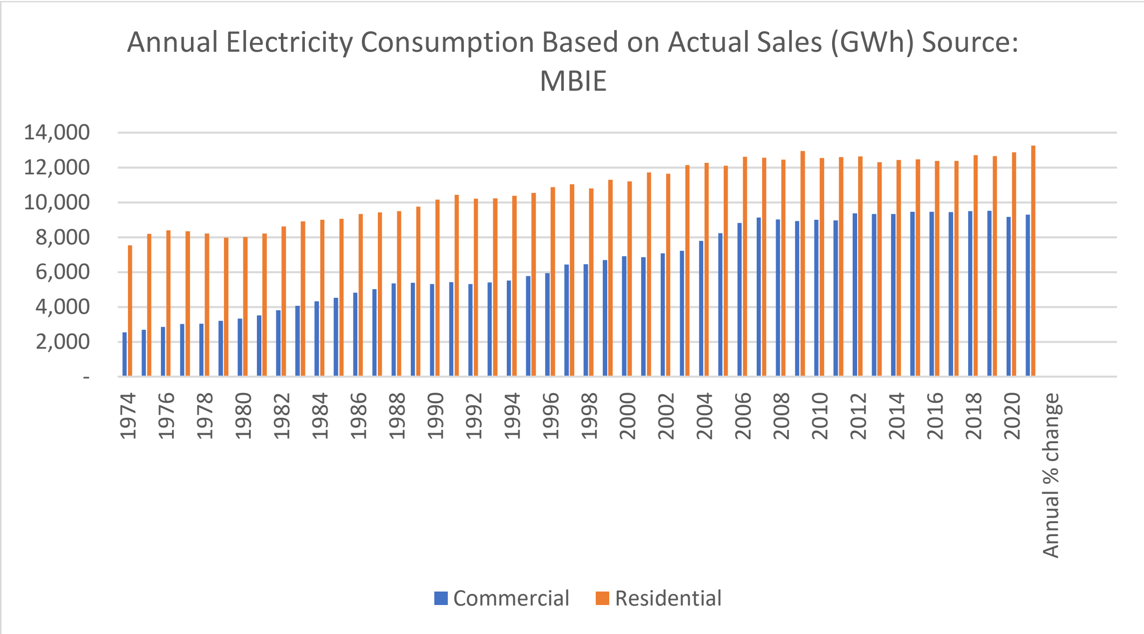

Figure 3: Annual electricity consumption in GWh from 1974 to 2020 (Source: MBIE Energy Statistics Energy in New Zealand | Ministry of Business, Innovation & Employment (mbie.govt.nz))

The symbolic growth of population and energy increases carbon footprint and contributes to GHG emissions. Managing the ecological footprint can be achieved through the implementation of effective government policies, transitioning to renewable energy, and enhancing energy efficiency in the short term, ultimately contributing to improved environmental sustainability and quality of life in the long term [31].

On the other hand, Yunez-Cano suggests that transition to renewable energy and hydrogen in particular can contribute to reduction of fossil fuel dependency and pollution emissions. It can change the uptrend direction. In other words, the interdependence between population, energy and economic growth will continue go up, while consumption of fossil fuels and pollution emissions will go down [32].

However, if fossil fuels will be replaced by green hydrogen, the overall trend will be reversed and the temperature will be stabilised [33].

Sheffield measured the energy value per capita and analysed the interconnection between population growth due to high fertility rates and energy demand growth [20]. He projected that fossil resources will meet energy demand; however, due to global-warming concerns, Sheffield recommended a policy of restricting fossil fuel use, carbon sequestration, using sustainable renewable energy sources and increase energy efficiency *"to minimise energy demand"*. According to Sheffield, one of the possible solutions to meet energy demand is to introduce hydrogen energy via hydrogen fuel cells for *"static and mobile applications"* [20].

Consequently, a strong interrelation between population growth, energy demand growth and environmental degradation has been identified. It is essential to assess if all energy sources contribute to global greenhouse gases and carbon dioxide emissions. Identifying an energy source that could potentially resolve this urgent issue is crucial.

3.2 Energy Sources

Energy sourcing globally involves a triad of fossil, renewable, and nuclear fuels, each contributing distinctively to the energy matrix [34]. Fossil fuels, encompassing oil, coal, and natural gas, reign as the primary energy sources, accounting for a staggering 84.3% of the world's energy consumption. In contrast, renewable and nuclear energy, from sources like solar, wind, biofuels, and hydropower, collectively represent a mere 16% of the global energy output [35].

Fossil fuels account for three-quarters of global greenhouse gas emissions [36]. Such emissions, predominantly from the combustion of fossil fuels, have accelerated environmental degradation and heightened CO2 levels in the atmosphere. Mitigating these effects requires bolstering energy efficiency and transitioning toward sustainable energy strategies, such as hydrogen, a potential solution yet to be explored.

In New Zealand's energy landscape, a departure from the global trend is evident. While fossil fuels still command a significant presence, including oil and gas, the nation embraces hydropower as the second major energy source, followed by coal, renewables, and wind. Despite solar's growing prominence globally, it currently represents 3% of global energy generation and just 1% in New Zealand's energy mix [37].

New Zealand's energy history, marked by a historical reliance on green energy sources such as hydro and geothermal power, faced challenges due to a rapid population increase. This led to a transition towards increased dependence on fossil fuels, contributing to environmental concerns related to global warming and climate change [37].

3.3 Non-Renewable Sources of Energy

Approximately two-thirds of New Zealand's energy consumption is derived from non-renewable sources like oil, gas, and coal [38]. Despite their prevalence, these sources are significant contributors to greenhouse gas emissions, pollutants, and environmental harm. Extracting energy from fossil fuels releases sulfur dioxide and nitrogen oxides, contributing to climate change and health risks [39]. Coal extraction is linked to respiratory illnesses and pollutes surface and groundwater systems, elevating their toxic metal content [39], [40].

In response, the New Zealand government has implemented measures to restrict fossil fuel extraction [42], including prohibiting new extraction of gas, oil, and coal and halting the issuance of new exploration licenses. While some argue that this ban may have limited direct impact on emissions reduction, there are potential economic ramifications, with estimates suggesting a possible NZ$40 billion impact on the economy by the middle of this century. Additionally, exported fossil fuels burned overseas contribute to global pollution, albeit outside New Zealand's borders [43].

Despite economic and global factors, the ban sets the stage for the advancement of renewable energy sources and cutting-edge technologies in electricity production. Embracing alternatives such as hydrogen and related technologies emerges as a viable strategy to transform the fossil fuel-driven economy [43].

3.4 Nuclear Power

Nuclear power, often considered non-renewable yet recyclable and sustainable, has gained attention for its potential as a low-emission electricity source. However, concerns persist due to historical disasters like Chernobyl in 1986 and Fukushima Daiichi in 2011 [44]. The Chernobyl Panel report notes 59 total deaths to date from the Chernobyl incident, comparing it to the oil industry's 10,273 deaths in a shorter period from 1970 to 1992 [45].

Despite New Zealand's ban on nuclear power under the Nuclear Free Zone Act of 1987, Smith advocates for its consideration, emphasizing its safety and environmental attributes. He points to the presence of radioactive elements in NZ rocks and soil used in industry and medical institutions. Smith questions NZ's *"nuclear-free"* stance, highlighting the storage of nuclear waste in the Christchurch nuclear waste dump. He also notes Australia, part of the 1985 South Pacific Nuclear Free Zone Treaty like NZ, produces medical isotopes used by NZ's medical facilities. Smith contends NZ's ban on nuclear ships entering territorial waters is an error and urges the adoption of energy technologies with economic and environmental reliability [45].

However, despite Smith's advocacy, nuclear power remains unsuitable for NZ. While offering cleaner energy with higher efficiency and lower carbon output compared to fossil fuels, the capital expenditure for nuclear plants is exorbitant. Safety concerns, including the risk of explosions and high-level nuclear waste, pose significant risks to both people and the environment [46], [47].

In light of Smith's proposition regarding the adoption of economically and environmentally reliable energy sources, hydrogen emerges as a viable contender.

3.5 Renewable Sources of Energy

3.5.1 Hydropower

Hydropower, a longstanding renewable energy source in NZ, faces challenges due to unpredictable dry seasons, potentially leading to energy shortages and constraints in small-scale hydro plants with limited reservoirs [48]. During such dry spells, the country might temporarily resort to oil and gas, conflicting with the objectives of the net-zero emissions strategy. Continued reliance on local gas may not meet energy demands, leading to potential imports of oil, gas, and coal during prolonged dry spells, compromising environmental goals and affordable electricity tariffs. Past power crises in 1992 and 2021 could recur, resulting in power restrictions without the introduction of reliable renewable energy sources [49].

Beyond weather-related challenges, hydropower encounters obstacles in broader development, including the remote locations of hydro stations compared to consumers. For example, Manapōuri, the largest hydroelectric plant, is situated in the South Island, distant from primary electricity consumers in the North Island. Delivering generated electricity requires undersea high-voltage DC cables, demanding significant investment in the development, operation, and maintenance of horizontal hydropower infrastructure. Ensuring hydroelectricity availability during dry seasons remains the primary challenge for hydropower [50].

3.5.2 Geothermal Energy

Geothermal power, a distinct renewable energy source in NZ, harnesses the earth's heat, hot water, and steam, offering reliable electricity generation and heat for residential and industrial applications, unaffected by weather conditions. Wairakei, NZ's first geothermal plant established in 1958, marked a global milestone as the second of its kind. Despite subsequent plant constructions, geothermal energy contributes only 17% to NZ's overall energy market [50].

Uncontrolled geothermal energy extraction in the mid-80s prompted stringent government regulations due to adverse consequences. Over-extraction depleted geysers and hot springs, once major tourist attractions. Geothermal sites, like Orakeikorako, faced challenges from nearby hydroelectric developments, causing thermal quenching in geysers, hot spring flooding, and land subsidence due to groundwater withdrawal. These environmental impacts resulted in nearly a threefold reduction in geothermal energy extraction [50].

Recognizing the importance of this issue, any future geothermal energy development is deemed a matter of national importance, requiring consultation with Māori communities to honour their natural resource management rights and preserve the *"cultural and spiritual values"* associated with water and land, avoiding potential conflicts [51].

3.5.3 Wind Energy

In contrast to nuclear power, public reception toward wind power in NZ appears more positive; however, widespread support for wind turbine installations is lacking within communities. While the NZ public generally views wind power favourably as an alternative energy source, specific wind farm developments face opposition [52].

NZ's geographic location and exposure to ocean winds provide ideal conditions for wind power generation, boasting one of the highest capacity factors globally. Despite this potential, the growth of wind power remains sluggish, attributed to various factors including landscape preservation, cultural heritage protection, and Māori interests. Concerns abound regarding adverse ecological impacts, with many expressing fears that large-scale wind turbine construction could detrimentally affect landscapes, agricultural areas, and ecosystems. Consequently, while wind energy from these farms could meet energy demands and align with zero-emission objectives, widespread public resistance may impede large-scale wind turbine projects in NZ [52].

Conversely, while large- and small-scale wind turbine projects have faced local opposition, micro-generation, specifically for hydrogen production, has garnered more positive responses and holds potential [53].

3.5.4 Solar Energy

Some countries incentivize solar energy usage by compensating consumers for excess electricity generated by their private PV cells and fed back into the grid. However, off-grid consumers reliant on seasonal solar energy may experience shortages during periods of insufficient sunlight. Sheffield, referencing Johansson and Socolow, posits that harnessing seasonal solar excess could aid in hydrogen production, potentially catering to fluctuating seasonal patterns [20].

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In New Zealand, solar energy finds application in residential and commercial sectors for water heating and photovoltaic technologies, converting sunlight into electricity. Despite being environmentally friendly, PV cells carry drawbacks, notably high capital costs and unreliability due to their weather dependency [54]. Solar generation peaks in summer and dwindles significantly in winter. On average, NZ households consume about 22 kWh per day, with PV panels converting only around 15% of available 4 kWh of raw solar energy per m2 per day. While sufficient under certain weather conditions, this energy meets daily electricity demand during spring and autumn. However, there is an ongoing need for more energy during winter. Meeting this demand might require enlarging PV cells or their numbers, yet many buildings lack the roof space for additional cells [55], [56].

This challenge prompts consideration of hybrid systems - combinations of PV cells, electrolysers, hydrogen fuel cells, and storage - to satisfy energy demands while respecting the environment and enhancing energy efficiency in residential and commercial buildings. This aligns with the Government's vision for an *"affordable, secure, and sustainable energy system"* that promotes the wellbeing of New Zealanders in a low-emission world [57].

3.5.5 Hydrogen

Hydrogen, not naturally available in elemental form, can be produced using various methods derived from both fossil and renewable sources [58], [59], [60]. To date, 24 sustainable hydrogen production methods have been identified [61], [62]. Green hydrogen, considered environmentally friendly, can be derived from water (through electrolysis, thermolysis, and photolysis) or biomass (via gasification and pyrolysis) [61], [63], [64], [65], while black, grey, and brown hydrogen are fossil fuel-derived [61], [66], [67], [68].

A widely used method for hydrogen production from natural gas is steam methane reforming, accounting for over 95% of current hydrogen production [69], [70]. This process involves high-temperature treatment of methane (natural gas), yielding hydrogen and either carbon dioxide, which can be sequestered into saline aquifers below the ocean bed, or solid black carbon applicable in various industries [71], [72]. This method transforms natural gas into clean energy, minimizing CO_2 emissions through carbon capture, leading to the term *"blue hydrogen"* [73], [74]. However, the methane sequestration involved may pose environmental concerns [75]. Hydrogen produced from fuels, while cleaner, is not deemed *"green"* and is not recommended for adoption in NZ [76].

Another eco-friendly method to produce hydrogen involves electrolysis of both fresh and seawater using renewable energy, such as solar or wind [77]. Hydrogen generated through methane decomposition and water electrolysis can power hydrogen fuel cells. Green hydrogen from water does not emit CO_2, complements the water cycle, and stands as the most environmentally sound choice for hydrogen fuel cells. Additionally, the use of seawater aligns with the vision of three waters reform. In-situ production and storage of hydrogen offer a means to meet seasonal electricity demand, decentralize energy systems, and supply remote areas.

The primary hydrogen classifications, based on the energy source required for production, are outlined in the table below.

Table 1. Hydrogen classifications based on production and sources of energy.

Hydrogen classifications based on production and sources of energy		
Hydrogen Classification based on source of energy required to produce Hydrogen	**Source of Energy Required for Hydrogen Production**	**Hydrogen classification based on carbon intensity**
Black Hydrogen	Bituminous Coal	High Carbon Hydrogen
Grey Hydrogen	Natural Gas or Methane	
Brown Hydrogen	Brown Coal (Lignite)	
Blue Hydrogen	Natural Gas or Methane with Carbon Capture and Storage	Low Carbon Hydrogen
Green Hydrogen	Electrolysis powered by renewable energy	
Pink Hydrogen	Electrolysis powered by nuclear energy	

Source: Greening the grid https://www.nrel.gov/docs/fy22osti/82554.pdf (www.greeningthegrid.org)

Thus, this paper will focus on energy produced from green hydrogen since this energy starts and finishes with water, environmentally friendly, sustainable and aligns with water reform. However, safety concern is a main challenge associated with hydrogen production, storage and utilization.

3.6 Safety Concerns

Safety concerns related to hydrogen, acknowledged in various studies [78], stem from historical events such as the Hindenburg airship catastrophe in 1937 [79], emphasizing combustibility and flammability issues.

Hydrogen's unique characteristics, including odourless, colourless, and *"low explosive limits"*, pose challenges due to explosion hazards [80]. Higher flame velocity and a broader flammability range compared to other gases contribute to complexities in applying, optimizing, and accommodating hydrogen in the built environment [81].

Ng & Lee suggest resolving safety issues before achieving public acceptance, emphasizing proper ventilation and contamination avoidance in hydrogen storage [82]. Maclntyre and Najjar advocate for risk analysis, design optimization, and sensor detectors to prevent hazardous events and address potential leakage [83].

While hydrogen is non-toxic and lacks the risk of CO poisoning, its introduction to residential and commercial sectors requires establishing safety regulations and standards [80].

Countries such as Canada and Australia have initiated hydrogen safety programs with policies, regulations, and guidelines [83]. New Zealand can adopt international standards, developing safety regulations as part of its decarbonization strategy.

Thus, the first objective of this thesis can be outlined as the following:

Objective 1:

In order to develop public acceptance, identify the safety standards, challenges and opportunities and discuss the projects accomplished worldwide.

The discussion around safety could help to formulate the first research question:

Question 1:

What specific hydrogen safety requirements need to be addressed to introduce hydrogen technologies to all New Zealand stakeholders?

3.7 Transition to Hydrogen Strategy

Decarbonisation, a long-term goal for a carbon-free era, positions hydrogen as a key player in the global economy across industrial, manufacturing, transportation, and building sectors. To achieve this, fossil fuels must undergo decarbonisation, separating energy from carbon content through transformation [71].

Asia, Japan, Korea, and the USA have taken initial steps toward a zero-carbon future, commercializing hydrogen and hydrogen fuel cells. Dodds criticizes Europe for neglecting hydrogen and fuel cells in favour of a limited range of technological options, urging policymakers to analyse these technologies for a zero-carbon future [84].

Socolow supports a hydrogen world economy, emphasizing its role in replacing fossil fuels and reducing carbon dioxide to combat the climate crisis. Johansson projects a 75 percent reduction in global carbon dioxide by 2050 through transitioning to hydrogen from fossil fuels [71], [85].

Yunez-Cano and others highlight the significance of transitioning to reliable, environmentally friendly, and affordable energy through a hydrogen strategy. They advocate for reconsidering the energy supply chain from production to consumption [32]. Najjar sees hydrogen as an ideal fuel, emphasizing its cleanliness, energy efficiency, and convenience, contributing to energy independence [80].

3.8 Hydrogen Fuel Cells and Hybrid Systems

Hydrogen fuel cells, utilized in critical facilities like hospitals and remote off-grid locations, offer constant, uninterrupted energy [86], [87], [88]. They operate as long as hydrogen is supplied, are noiseless, non-toxic, and highly energy-efficient, producing electricity through chemical processes with minimal environmental impact [89], [123]. Dincer emphasizes the importance of hydrogen and fuel cells for a better environment and sustainability [90].

Research on green hydrogen energy has focused on industrial and transportation sectors, with limited attention to its applications in the built environment [91]. Hybrid systems, combining photovoltaic and hydrogen fuel cells, show promise for off-grid households, remote locations, and commercial buildings [92], [93]. Pilot projects like Phi Suea House in Thailand demonstrate successful implementation, utilizing solar panels, electrolysis, and hydrogen energy storage [94], [95].

Studies by Srisiriwat and Pirom support hybrid systems, asserting that solar energy, when combined with hydrogen fuel cells, ensures reliability in remote areas with varied weather conditions [78]. Bidi further supports integrating hydrogen energy into micro-grids, remote locations, and islands for efficient energy systems [96]. Avril's study on La Nouvelle island shows higher efficiency and environmental benefits of hybrid systems over standalone photovoltaic cells [97].

While hydrogen energy offers environmental benefits, economic challenges persist due to production and storage costs [98]. However, advancements in technology, combining electrolysers and fuel cells into a single unit, enhance efficiency and commercial viability [92].

Hydrogen's role in heating applications, especially during winter, where waste heat can be utilized, contributes to the thermal to electric ratio in buildings [92]. Knosala's analysis suggests that hybrid systems for homes achieve energy autonomy and cost reduction, aligning with the NZ Government's affordability goals [92]. Despite being in a nascent stage, hydrogen's implication in the built environment is gaining attention, emphasizing the need for a strategic framework and a systems approach [99]. The New Zealand Government's Green Paper seeks feedback on hydrogen production and utilization, addressing gaps in safety and regulatory policies [101].

Since the gap has been identified, the second research objective and the second research question can be formulated as the following:

Objective 2:

Identify and analyse the techno-economic performance of hydrogen technologies for the built environment to maximise energy outcomes.

Question 2

How can hydrogen technologies contribute into decarbonisation of the built environment and how can this be measured?

3.9 Energy Efficiency, Economic Growth and Environmental Protection

The NZ Energy Efficiency and Conservation Strategy, aiming for net-zero carbon emissions by 2050, emphasizes renewable energy generation and implementation across sectors [102], [103]. Energy efficiency brings financial savings, increased productivity, and environmental security, reducing dependence on imported fuels and emissions [103], [105]. The hydrogen strategy aligns with energy efficiency, offering sustainable, long-term energy production [98]. Unlike solar and wind, hydrogen can be stored for extended periods, ensuring reliability [92], [106].

Photovoltaic systems injecting excess energy into the grid find a solution in hydrogen production through water electrolysis, relieving pressure off the grid [107], [108]. Hydrogen technologies synergize with PV systems, creating a reliable hybrid energy system for the built environment and off-grid communities [69]. Hydrogen's ability to supply simultaneous energy and heat enhances security, with studies showing superior performance in meeting hot water demand [111]. Hydrogen fuel cells in the built environment contribute to high energy efficiency [112].

Green hydrogen, produced from solar energy, is environmentally friendly, sustainable, and a clean energy carrier, positively impacting the environment [110], [113]. Applications across industries contribute to environmental protection, displacing fossil fuels [80]. Despite policymakers accepting the hydrogen vision, public awareness, safety education, sustainability, and financial evaluations are yet to be addressed in the NZ market. Bezdek emphasizes the need for training programs to support hydrogen technologies, offering a broad spectrum of career opportunities [114]. Green hydrogen and hydrogen technologies offer social, economic, and environmental benefits for a low or zero-carbon future.

Thus, the third objective of this thesis can be outlined as the following:

Objective 3

Develop a framework to guide the introduction of new energy systems to NZ to guarantee social, economic and environmental security, public well-being.

3.10 NZ Fuel Poverty

Energy efficiency must be achieved without compromising security, affordability, and sustainability. Gas and electricity tariffs in NZ were relatively cheap at the end of the last century, ranging from c0.06 to c2.3 per kWh [115]. Many NZ households used electric appliances, unlike European counterparts relying on natural gas [116]. Presently, NZ electricity costs vary by region, averaging c30.22 per kWh. The North Island's majority faces high costs, covering both production and distribution via the electricity grid from the South Island. Despite lower bills in summer, winter bills strain low-income households.

Residential energy consumption surged during Covid quarantines, leading to increased bills. Financial difficulties prompted energy conservation, impacting energy efficiency and potentially causing health issues. In 2012, almost 25% of NZ households experienced *"fuel poverty"* due to inadequate heating, water systems, and insulation [117], [118]. With an average consumption of 7000kWh per year, families spent over 10% of their income on electricity, qualifying as *"fuel poverty"* [119].

Addressing *"fuel poverty",* New Zealanders adopted energy-saving practices, from basic steps like closing curtains to advanced measures like installing solar panels [120]. Government support through programs like *"The Warm Up New Zealand: Heat Smart"* aimed at insulating houses and installing clean heating appliances, not only improved health and reduced energy costs but also created new workplaces [117]. To continue support, the NZ Government developed an Aotearoa New Zealand Energy Strategy to achieve the energy trilemma of *"security, affordability, and sustainability"* [57].

This creates the third question of this thesis:

Question 3:

How to accelerate the hydrogen technologies acceptance by the public to bring the New Zealanders out of fuel poverty and to achieve the economic growth goals?

3.11 Regulatory Framework

Government agencies, like the Ministry of Business and Innovation (MBIE), are reviewing the regulatory framework for a green hydrogen economy. PwC, engaged by MBIE, suggests developing a clear strategy, legislative framework, and safety regulations for hydrogen applications in various sectors, including residential and commercial buildings. Despite the NZ Government's consideration of regulations and policies, no significant progress has been made due to existing systems primarily designed for traditional hydrogen applications. Seeking input from industry stakeholders, the government aims to create and implement hydrogen regulations aligned with international standards and NZ regulations [121].

Japan and Australia, with strong ties to NZ, have implemented hydrogen strategies, regulations, and begun production and export. Japan prioritizes safety, developing standards and regulations using a risk-based approach to manage safety risks [122]. New Zealand's regulatory agencies are exploring ways to meet legislative requirements for novel hydrogen technologies, as existing frameworks lack flexibility. While a clear national policy or regulatory framework is absent, incorporating hydrogen technologies into the NZ market requires improving regulatory flexibility and adapting international standards in the short term.

Objective 4:

Develop recommended hydrogen policies for Government describing safety regulations, codes and standards to assist with formulation of regulatory framework.

Question 4:

What factors may influence the Government's decision to accelerate development of new energy vector and how to provide the Government with a confidence to invest into advanced hydrogen technologies?

3.12 Conclusion

This literature review provides a solid foundation by addressing global challenges related to increasing energy demand, environmental degradation, and emissions. It emphasizes New Zealand's energy landscape, highlighting limitations in current renewable sources and the consequences of continued fossil fuel reliance.

The review positions green hydrogen, produced through renewable-electricity-driven electrolysis, as a promising avenue for sustainable energy transitions and urgent decarbonization. It discusses the potential benefits, applications, and integration capabilities of green hydrogen, while acknowledging barriers like economic viability and technological maturity.

Identifying knowledge gaps in deploying hydrogen-based technologies in buildings, the review sets the stage for future research. It informs specific research questions and objectives to explore feasibility, assess environmental merits, and propose a roadmap for scalable implementation in New Zealand's residential, commercial, and public infrastructure. The upcoming interdisciplinary study will delve into technical, economic, and policy dimensions, shaping the exploration of hydrogen's role in accelerating building decarbonization - a crucial aspect of achieving sustainable low-carbon built environments in New Zealand.

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