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From hydro nation to solar giant: New Zealand's renewable build-out and hydrogen export scenarios

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Abstract

The transition to a decarbonised energy system presents a significant challenge for New Zealand, particularly as it strives to meet its net-zero emissions target by 2050. Existing peer-reviewed studies on New Zealand's energy transition are scarce and lack the necessary spatial and temporal resolution to accurately model the integration of renewable energy, green hydrogen production, and storage needs. To address these gaps, this study introduces REMix-NZ, a high-resolution energy system optimisation model tailored to New Zealand. REMix-NZ captures hourly time steps, geographic specificity, and diverse energy technologies to analyse the country's future energy pathways, including power system expansion and green hydrogen export scenarios. Through the use of REMix-NZ and scenario analysis, it is possible to evaluate future energy capacities, storage requirements, and the impact of hydrogen exports for the milestone years 2030 and 2050. Results show that New Zealand needs to increase its installed power generation capacity by up to 13 times by 2050, with solar photovoltaics providing over 65% of electricity. Additionally, approximately 650 GWh of new storage capacity, mostly batteries and hydrogen storage, will be required. Hydrogen exports to the Pacific Islands in the form of e-fuels are feasible with an additional capacity of around 11%, demonstrating an opportunity for international energy trade.

1. Introduction

The shift to a decarbonised energy system is pushed by several drivers, in particular, to reach ambitious climate targets (IPCC 2023), to avoid the negative impacts of air pollution (Jacobson *et al* 2019, Galimova *et al* 2022), and to reduce energy system costs using low-cost renewable energy, including wind and solar (Aghahosseini *et al* 2023). The energy transition presents an enormous challenge, requiring both substantial investment and rapid infrastructure deployment, as well as societal coherence. As energy systems grow more complex, sophisticated optimisation models become essential in guiding effective energy system planning and decision-making (Haas *et al* 2017). These models can address challenges like, increasing electrification, evolving energy demands, sector coupling, flexibility opportunities, and the integration of clean hydrogen production (Sasanpour *et al* 2021, Wetzel *et al* 2023). In the case of Aotearoa (New Zealand), this transition is urgent due to its net-zero emissions target by 2050 (Ministry for the Environment (MfE) 2021) and the 100% renewable electricity target by 2030 (IEA 2023).

Green hydrogen, and particularly its derivatives, have emerged as a promising solution for defossilising hard-to-abate sectors due to its versatility as an energy carrier (Vatankhah Ghadim *et al* 2024). Hydrogen is likely to serve as a complementary intermediary in the Power-to-X framework, which refers to converting renewable electricity into fuels, chemicals, or thermal energy for use in other sectors. These include Power-to-Heat (e.g. heat pumps), Power-to-Mobility (e.g. electric vehicles), and Power-to-Fuels (synthetic fuels including methane and Fischer–Tropsch fuels) or Power-to-Chemicals (hydrogen-based ammonia and methanol) (Bogdanov *et al* 2021a). By extending the reach of renewable electricity beyond the power sector, hydrogen can support the defossilisation of the energy system indirectly through renewable electricity-based fuels for sectors that cannot be fully electrified, including long-distance shipping and aviation (Breyer *et al* 2024). However, the precise role it will play in New Zealand's future energy landscape remains largely unquantified. Although some estimates of future demand are available (Ministry of Business Innovation and Employment (Te Manatū Ōhanga) 2023, Vatankhah Ghadim *et al* 2024), there is still a lack of clarity about the exact demand levels for New Zealand and the corresponding energy mix necessary to meet it.

New Zealand's potential for green hydrogen production is promising because of its abundant land, outstanding renewable energy resources, and high share of renewable electricity generation (IEA 2023, Ministry of Business Innovation and Employment (Te Manatū Ōhanga) 2025). Specifically, the country benefits from significant hydro power availability, which can provide valuable flexibility for integrating variable renewables (Beckitt *et al* 2021). New Zealand is also politically stable, important for a low cost of capital. Nevertheless, potentially transitioning towards a 'green hydrogen economy'—which, as studies suggest (Breyer *et al* 2024), would more accurately serve as a subset within a broader Power-to-X economy—would involve considerable hurdles, including the need for extensive infrastructure development and addressing the limitations of a relatively small existing electricity system. The country's significant reliance on fossil fuels, especially in the transportation and industrial sectors, highlights the need for a well-defined and comprehensive transition strategy.

In addition to domestic defossilisation, New Zealand's strong renewable energy base has been identified as a strategic advantage for large-scale green hydrogen production and export. Recent studies suggest that hydrogen exports could offer both economic and energy system benefits. Boston Consulting Group (2022) highlights hydrogen's role as a flexible demand resource that could enhance dry-year security while generating export revenues. A single hydrogen production facility could contribute up to NZD 450 million in annual GDP and support thousands of jobs (Boston Consulting Group 2022). Gulagi *et al* (2025) model a scenario in which New Zealand supplies e-fuels to Pacific Island nations, citing geographic proximity and a modest system cost increase relative to export potential. While not currently part of government policy, the export pathway in Gulagi *et al* (2025) has been explored as a strategic option to support regional decarbonisation and create value from renewable energy potentials. Although effective utilisation of renewable energy resources can increase energy independence in islands (Gao *et al* 2025), Pacific nations often face constraints in renewable production capabilities (Lal and Kumar 2022, Handique *et al* 2024) and thus rely on energy imports for sectors like transportation. Modelling a scenario in which New Zealand exports e-fuels (including hydrogen-based options such as e-ammonia and e-methanol) demonstrates the feasibility of meeting Pacific demand cost-effectively by 2050. Not only does this strategy align with New Zealand's commitment to a net-zero energy future, but it also positions the nation as a key player in regional energy transformation through the supply of green e-fuels.

1.1. Literature review

Current research on energy transitions often resorts to large-scale modelling frameworks to explore optimal defossilisation pathways. Models such as REMix (Scholz 2012), developed by the German Aerospace Center (DLR), have proven effective in evaluating infrastructure needs, technology integration, and cost-efficiency for European study cases (Gils *et al* 2017a, 2019, Cao *et al* 2021, Sasanpour *et al* 2021, Wetzel *et al* 2023) and for other regions (Gils and Simon 2017, Gils *et al* 2017b). The models EnergyPLAN (Østergaard *et al* 2022) and LUT Energy System Transition Model (Bogdanov *et al* 2021a, 2021b) are the two most widely used tools for highly renewable energy system analyses, especially for studying multiple energy sectors and their interactions as part of overall energy system transition considerations (Khalili and Breyer 2022). EnergyPLAN is used for model variations with broadened features such as optimisation and structured sensitivities as applied in the open-source EP-ALISON-LUT tool (Keiner *et al* 2024). Another widely used open-source tool is PyPSA, with PyPSA-Eur used specifically to perform sector-coupled optimisation of the European Energy System (Zeyen *et al* 2021, 2023, Millinger *et al* 2022, Victoria *et al* 2022, Hofmann *et al* 2025) and PyPSA-earth-sec being a sector-coupled model with global coverage (Abdel-Khalek *et al* 2025, Schumm *et al* 2025).

In recent years, several comprehensive reviews have been conducted to assess key aspects of the global energy transition, examining thousands of studies across diverse regions and topics. For instance, studies have synthesised research on energy storage (Haas *et al* 2017, Cebulla *et al* 2018), renewable energy adoption (Hansen *et al* 2019, Breyer *et al* 2022, Khalili and Breyer 2022, Meschede *et al* 2022), e-fuels trade (Galimova *et al* 2023), and critical material needs for the energy transition (Lundaev *et al*

2023). Collectively, these reviews have analysed over 1000 studies, primarily concentrated on regions like Europe, the U.S., and Australia, as the most investigated regions in the world (Khalili and Breyer 2022). However, New Zealand has received minimal coverage in existing reviews, with only two studies cited (Mason *et al* 2010, 2013) and some comparisons to other larger island countries (Meschede *et al* 2022). This reveals a significant gap in understanding how New Zealand's energy system will need to adapt in the future, especially concerning its renewable energy goals, energy storage challenges, and assessment of green hydrogen production and export scenarios.

In New Zealand, most energy system modelling to date has been led by government agencies, consultants, and the electricity sector. The TIMES-NZ 2.0 model (Pugliese *et al* 2021a, 2021b) is one of the few openly available models and considers multiple energy sectors but operates with low spatial (aggregated to two main regions) and temporal (24 annual time slices) resolution, limiting its ability to capture grid-level operational constraints or hourly flexibility requirements. LPCon is a power system model owned by Meridian Energy that simulates supply and demand at grid exit point level and includes detailed hydro inflows and stochastic treatment of dry years. It has been used for a range of applications including modelling climate change impacts on the power system (Purdie 2022). However, LPCon applies weekly resolution with stylised dispatch blocks and treats investment decisions exogenously. Studies by Energy Link using EMarket (a market dispatch and price simulator) and I-Gen (a generation investment module), provide high-resolution sub-hourly simulations for 220 nodes and have been used to study hydrogen as a dry-year firming resource (Energy Link Ltd 2022). These studies simulate predefined hydrogen storage and electrolyser capacities, but do not co-optimise hydrogen infrastructure with other energy system components and focus on the electricity sector. Concept Consulting (2021) evaluated flexible electrolyser operation at a single site to reduce curtailment and manage peaking needs but did not address national-scale hydrogen infrastructure deployment or export scenarios. Further strategic studies also contribute insights but have similar limitations. Boston Consulting Group (2022) uses two proprietary Concept Consulting models with simplified island-level transmission and exogenous hydrogen scenarios. The Market Development Advisory Group (MDAG) (2022) applies a two-node hourly framework within stylised weekly blocks to analyse price formation under 100% renewable electricity but does not model hydrogen endogenously. Transpower's Whakamana i Te Mauri Hiko reports (2020, 2024a) and the Electricity Demand and Generation Scenarios (EDGS) (Ministry of Business Innovation and Employment (Te Manatū Ōhanga) 2024, 2019) provide national-level projections but operate at annual resolution and do not include Power-to-X or hydrogen export modelling. Together, this literature offers valuable insights into New Zealand's electricity transition but does not provide an open, regionally resolved capacity-expansion framework that jointly optimises renewable generation, electricity storage, and large-scale hydrogen production.

Existing peer-reviewed studies on New Zealand's energy system are scarce (Breyer *et al* 2022). The few that exist highlight both the opportunities and obstacles associated with integrating renewables on a large scale. A review (Meschede *et al* 2022) on several scenarios for 100% renewable energy on islands includes New Zealand and emphasises the importance of considerable energy storage and system flexibility. A potential interconnection between Australia and New Zealand has been studied (Gulagi *et al* 2017), but no benefits have been found from it due to New Zealand's abundant renewable resources and the large distance between both countries. Over a decade ago, two studies (Mason *et al* 2010, 2013) suggested that a mix of hydropower, wind power, geothermal, and bioenergy can achieve the goal of 100% renewable energy, but they also highlight challenges such as wind spillage and the need for effective peaking strategies. A study from 2009 discussed the technical feasibility and potential advantages of transitioning to a fully renewable energy system, pointing out challenges such as decentralisation and increased reliance on fossil fuels (Sovacool and Watts 2009). In 2021, a case study of Rakiura–Stewart Island (New Zealand's third-largest island) presented a cost-effective, sustainable, off-grid micro-grid solution compared to diesel (Mohseni *et al* 2021). A 2023 study on geological energy storage in Taranaki examines its potential for addressing renewable energy variability, focusing on technical, geological, and social aspects but with limited attention on its role within the broader national energy system (Rendel *et al* 2023). Two studies from 2021 examined the roles of wind, solar power and geothermal energy in achieving high levels of renewables integration for New Zealand, highlighting the need for additional capacity and grid enhancements to support the shift to a fully renewable energy system (Gholami *et al* 2021, Poletti and Staffell 2021). Regarding hydrogen integration, recent studies have begun to explore the role of green hydrogen within New Zealand's energy system. Alé *et al* (2026) analyse hydrogen distribution infrastructure under earthquake risk and show that decentralised hydrogen hubs can enhance resilience and reduce system costs. Gulagi *et al* (2025) model different 100% renewable energy scenarios, including wave power assessment, but lacks spatial resolution, modelling New Zealand as a single node.

Together, these studies underscore the potential role hydrogen can play in New Zealand's transition but also highlight the absence of a multi-regional, hourly, co-optimised electricity-and-hydrogen model.

While global research on renewable energy transitions is advancing (and studies for Europe, the U.S., and Australia are abundant), a notable gap in multi-energy systems analysis specifically tailored to New Zealand remains. There are only a handful of publications for New Zealand, and these studies have clear limitations in terms of their underlying models and data assumptions. Existing studies often fall short in providing highly detailed spatial and temporal resolution, rely on outdated assumptions regarding electricity and energy demand, or fail to account for the potential of emerging technologies and hydrogen and its derivatives for domestic use and export. Given New Zealand's unique landscape (characterised by abundant renewable energy resources, geographic isolation, and regional variations in energy demand and resource availability), there is a need for high-resolution models that can accurately assess its energy transition potential.

1.2. Research questions and relevance

In this paper, REMix-NZ is presented, an advanced energy system model developed specifically for New Zealand's context. REMix-NZ considers hourly time steps, multiple geographic model regions, milestone years, and a broad range of energy technologies. It optimises capacity expansion and hourly operation.

The objectives of the present work include:

1. **Assess future electricity generation capacities**: assessing the future energy generation and installed capacities required to meet New Zealand's demand for electricity and green hydrogen by 2050. This includes the power sector, as well as electrification from the heat and transport sectors. Model outputs are validated against the results of EP-ALISON-LUT (Gulagi *et al* 2025).
2. **Determine requirements for storage and hydrogen production**: quantifying how much storage capacity is needed for New Zealand, which already has a large hydropower reservoir storage component, as well as the infrastructure for hydrogen production and storage.
3. **Evaluate export potential of hydrogen**: investigating the energy implications and requirements for hydrogen production to support the production and export of e-fuels to the Pacific Islands.

By incorporating multiple model regions and specific assumptions, REMix-NZ aims to offer a detailed understanding of New Zealand's energy transition and the potential impacts of hydrogen-based e-fuel export ambitions.

This study provides insights for policymakers, industry leaders, and researchers involved in energy transition planning. More specifically, this work offers crucial insights into the scale and configuration of energy infrastructure required to meet New Zealand's climate goals. By exploring both domestic energy needs and export opportunities, this research contributes valuable knowledge to the broader discussion on transforming energy systems to achieve sustainability.

The next section will detail the methods, which are based on a new optimisation tool developed for New Zealand (REMix-NZ). The results are shown and discussed in section 3, focusing on future generation capacities, storage and hydrogen requirements and exports. Section 4 presents the conclusions.

2. Methods

In this study, REMix-NZ, an advanced energy system optimisation model, is developed for New Zealand using the open-source framework REMix ('Renewable Energy Mix') developed by DLR (Wetzel *et al* 2024). It optimises the energy system configurations based on cost minimisation, operating over a full year with hourly time steps. REMix provides outputs on investment strategies and energy dispatch time series. The model uses a linear programming approach to identify the least-cost system configuration. The cost structure includes annualised investment costs, fixed and variable operational costs, and fuel import expenses into the modelled regions. Details about the original model and its primary components are described in Scholz (2012) and Gils *et al* (2017a), which has been under continuous development.

The flowchart of the methods along with its associated section, is presented in figure 1. Next, the new model (REMix-NZ) will be described (section 2.1), followed by the inputs (section 2.2) and scenarios explored in this work (section 2.3).

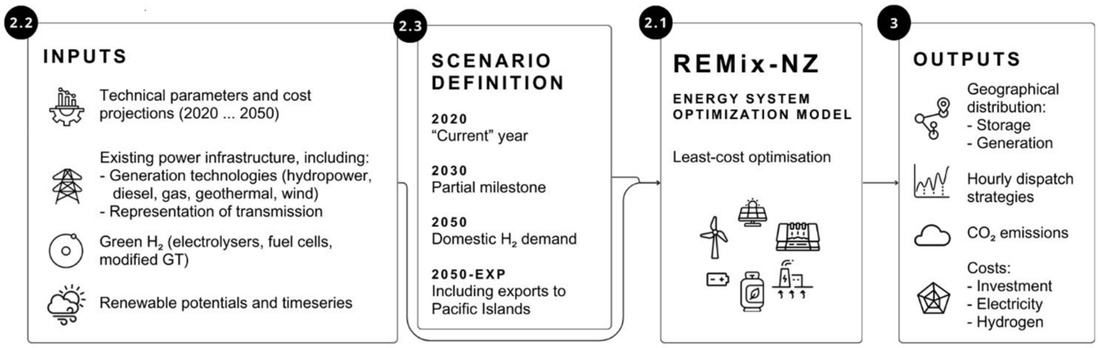

Figure 1. REMix-NZ modelling workflow. Overview of data inputs, optimisation, and outputs.

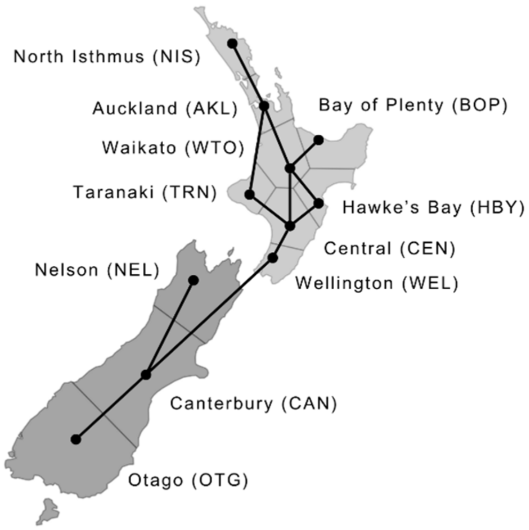

Figure 2. Map of New Zealand and corresponding REMix-NZ model regions and electrical interconnections.

2.1. REMix-NZ

The REMix-NZ model represents New Zealand's energy system using eleven model regions with eleven power generation technologies: run-of-river hydropower, geothermal, coal, gas (three alternatives), diesel engines, onshore wind power, offshore wind power, and solar photovoltaic (PV) (centralised and decentralised). The model also considers three hydrogen technologies (electrolysers for hydrogen production, fuel cells, and modified gas turbines (GTs) for hydrogen re-electrification) and three energy storage technologies (hydropower reservoirs, lithium-ion batteries, and hydrogen gas tanks). Using a myopic approach, the REMix optimisation treats each year independently, passing capacities forward while decommissioning components which are past their lifetime. Each year (2020, 2030 and 2050) is modelled at an hourly resolution of 8760 consecutive time steps (representing every hour of a year).

Geographically, the North Island (figure 2, light grey) is divided in eight nodes (North Isthmus, Auckland, Bay of Plenty, Waikato, Taranaki, Hawke's Bay, Central and Wellington) and the South Island (figure 2, dark grey) in three nodes (Nelson, Canterbury and Otago) for a total of 11 model regions (a three-letter code is used for each model region, as shown figure 2). Both island's power systems are connected via an existing inter-island high-voltage direct current link. This model region division was based on identified electricity transmission bottlenecks, and there are 12 transmission links considered (figure 2, black lines). Electricity networks within these regions are not considered.

Each power-generating technology is characterised by operational constraints (such as efficiency, fuel consumption, and emissions), and availability (more details on intermittent renewable energy resources can be found in section 2.2.2). The renewable electricity generation technologies considered are run-of-the-river hydropower, both centralised and decentralised solar PVs, onshore and offshore wind power, and geothermal. Hourly solar irradiance and wind speed data generated with the EnDAT tool (Stetter

2014) were used for the analysis of solar PV and wind electricity generation potentials. The fossil-fuel-based generation technologies: gas (including GT), open cycle GTs, and combined cycle GTs (CCGT)), coal, and diesel, are included to reflect current generation assets and potential transition scenarios where renewable energy penetration is lower. There are no emissions constraints or phase-out enforcement.

Every activity using fossil fuels has associated equivalent emissions, which are represented as indicators. This study does not consider carbon prices, budgets, or limits, so any adoption of renewable energy technologies is driven by technology and fuel costs.

The hydrogen conversion technologies included in the model are electrolysers (which produce hydrogen from electricity), fuel cells that convert hydrogen back into electricity, and modified GT designed to operate with renewable hydrogen. Enabling the reconversion of stored hydrogen into electricity, allows hydrogen to play a role in the system's flexibility and in scenarios with high renewable energy penetration where balancing intermittent resources like wind and solar energy may become necessary.

Three storage technologies are incorporated into the model: (1) hydropower reservoirs, which play a dual role as both generation and storage, providing flexibility to meet peak demand, (2) lithium-ion batteries, which typically provide short-term storage, for balancing hourly fluctuations in solar and wind electricity generation, and (3) hydrogen gas tanks, which store hydrogen that potentially can later be converted back to electricity.

The transmission system is modelled in REMix-NZ using a transfer model that reflects the physical flow of a commodity between regions (in this case electricity, without including hydrogen transfer), subject to constraints such as transmission capacity and losses. Electricity can be exchanged between nodes, and losses are proportional to transmitted power. The model allows for unserved energy and curtailed energy to address energy shortages and surpluses, respectively, both penalised in the objective function (Scholz 2012).

The main equations driving the REMix-NZ model are the energy balance equation and capacity constraints:

- Energy balance equation: This ensures that at each time step, and in each model region, the sum of power generation equals or exceeds the sum of demand, exports, storage consumption, and any energy surplus.
- Capacity constraints: These restrict generation and storage technologies to their maximum installable capacities. The model is supplied with parameters for maximum installable capacities and maximum hourly power generation for each of the 11 model regions.

The REMix-NZ model minimises the total annual system cost C_{total} which is the sum of investment, fixed and variable operation and maintenance, fuel, emission (optional), and unserved load penalty costs,

$$\min C_{\text{total}} = \sum_{r,p,c} C_{\text{inv},r,p} + C_{\text{OMfix},r,p} + C_{\text{OMvar},r,p} + C_{\text{fuel},r,c} + C_{\text{emission}} + C_{\text{unsuppLoad}}$$

where r indexes regions, p generation and storage technologies, and c energy carriers.

The primary constraint is that demand (load) must always be met, at each time step and in each region. This means that generation, imports, and storage discharges must be equal to or exceed the total demand, exports, storage charges, and surplus power in each region. Additionally, other constraints include:

- Capacity limits on generation and storage technologies.
- Power generation limits to reflect technology-specific constraints.
- Transfer capacities, dictating the amount of electricity that can be exchanged between regions.

In summary, the REMix-NZ model provides a detailed representation of New Zealand's electricity system, incorporating a broad spectrum of generation, storage, and transmission technologies. Through a linear optimisation process, the model balances the cost-effectiveness of deploying renewable and conventional resources with the need for reliability, flexibility, and efficiency in meeting future energy demands. The model's high-resolution hourly time steps and regional granularity allow it to capture both short-term operational challenges and long-term investment strategies.

2.2. Inputs

The REMix-NZ model focuses on the milestone years of 2030 and 2050 to analyse the evolution of New Zealand's energy system. Each milestone year is simulated with an hourly resolution, capturing 8760 consecutive time steps to ensure a highly detailed understanding of hourly demand fluctuations, generation patterns, and storage usage. Here, the main assumptions will be explained, starting with the technical parameters.

2.2.1. Technical parameters, cost projections and infrastructure

Cost projections and technical parameters are obtained from the Danish Energy Agency (DAE 2024). Current installed electricity generation and transmission capacities are based on historical data from New Zealand's Electricity Authority and Transpower (Transpower 2024b, Electricity Authority (EA) 2015). New power plant types permitted in the energy systems optimisation model include solar PV, onshore and offshore wind power, gas, diesel and coal power plants. New hydropower and geothermal plants are excluded in this study. The end-of-lifetime of current hydropower plants was considered to be outside of the modelling period as done in other national studies (BusinessNZ Energy Council 2015).

2.2.2. Renewable energy potentials and generation timeseries

An inventory from REMix is used to provide detailed data on the maximum installable capacity, and hourly power generation potential, for wind power and solar PV, which are renewable energy resources with intermittent availability. This inventory includes area-wide data on the capacity that can be installed and the electricity generated under sustainable conditions for specific technologies. To assess these potentials, three key steps were performed: (1) gathering spatial and temporal resource data, (2) analysing land areas for technology use, and (3) accounting for competing land uses. A power plant model was applied to estimate the technical potential of each technology, with adjustments for factors such as noise emissions and competing land uses. More details can be found in (Scholz 2012). The hourly generation time series are derived from historical meteorological data using the EnDAT tool (Stetter 2014). These time series reflect diurnal and seasonal variation in solar irradiance and wind speeds and are used to simulate hourly resource availability across all model regions and technologies.

Run-of-river hydropower generation is also limited by installed capacity and available natural resources. In terms of hydropower, inflows are sourced from historical data (Electric Power Optimization Centre (EPOC) 2023) and hydropower plants are modelled on one simplified equivalent plant per model region without cascades. The conversion from water to power is summarised in a yield parameter, which is assumed to be constant for each reservoir. Geothermal is considered to operate on a base load.

2.2.3. Electricity demand

Current-year demand for electricity is sourced from the Electricity Authority's year 2019 information to avoid COVID-19 impacts on electricity consumption. The demand per node obtained from the Electricity Authority (EA) (2020) is aggregated hourly to fit REMix-NZ model regions. The projected hourly profile of the electricity demand is scaled in magnitude based on a global study (Toktarova *et al* 2019) considering hourly variation.

The annual magnitude of projected demand is aligned with the full sector coupling scenario from EP-ALISON-LUT (Gulagi *et al* 2025). In this framework, total electricity demand represents final-energy uses (power, heating, transport, and industry) that are electrified through direct electricity use, heat pumps, or Power-to-X conversion (e.g. hydrogen and synthetic fuels). This integration reflects an energy system where fossil-fuel consumption in end-use sectors is progressively substituted by renewable electricity and electricity-based fuels. The resulting projection used for REMix-NZ shows a growing electricity demand from around 40 TWh in 2020 to 96 TWh by 2050. While electricity demand is expected to increase significantly over this period, the rise mainly reflects the electrification of existing fossil fuel uses in transport, heating, and parts of industry, as well as the introduction of new electricity-based processes (e.g. hydrogen and synthetic-fuel production). In this context, the increase in electricity demand represents a shift of energy carriers rather than a substantial net increase in total final energy consumption: energy that is currently supplied by fossil fuels is progressively replaced by renewable electricity or hydrogen and its derivatives. Many of the technologies assumed (e.g. electric vehicles and heat pumps) are also more energy-efficient, leading to lower overall energy input requirements in several sectors. Figure 3 illustrates this transition, showing both the 2020 reference (where electricity demand appears accompanied by approximately 200 TWh of 'other energy' from fossil and non-electric sources) and the projected electrified demand used in REMix-NZ, based on Gulagi *et al* (2025).

2.2.4. Hydrogen generation and demand

In this study, electrolysers are the only technology considered for (green) hydrogen production. This hydrogen is stored in gas tanks, and no transport is currently considered. Hydrogen imports are excluded from this study. Fuel cells and modified GT can be used to re-electrify hydrogen.

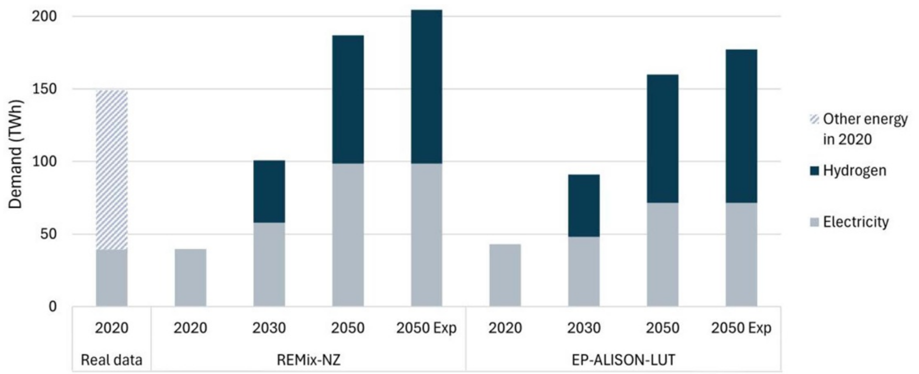

Figure 3. Electricity and hydrogen national demand (in TWh) used for years 2020, 2030, 2050. Column 2050-exp includes the demand required to supply e-fuels exports to the Pacific Islands, on top of domestic demand. The 2020 reference column shows total final energy consumption from all fuels for context. For 2030 and 2050, REMix-NZ models only electricity and hydrogen demand. The 2050 scenarios reflect full electrification of most end-use sectors, whereas the 2030 values represent electricity and hydrogen consumption only and therefore do not show total final energy demand.

In this analysis, REMix-NZ adopts the hydrogen demand projections from the EP-ALISON-LUT scenarios (Gulagi *et al* 2025), enabling more consistent comparisons with said study. These scenarios project hydrogen demand to reach about 43 TWh (1.3 Mt) by 2030, 88 TWh (2.7 Mt) by 2050, and 106 TWh (3.2 Mt) by 2050 when accounting for e-fuels exports to the Pacific Islands (requiring an extra 17 TWh (0.5 Mt) of hydrogen). Projected hydrogen demand in TWh equivalent is shown in figure 3.

2.3. Scenarios

In this study, four distinct scenarios are examined: a reference year (2020), a milestone year (2030), and two scenarios for 2050, one without hydrogen exports and another with hydrogen exports. Both 2050 scenarios are compared to evaluate the potential impacts of a hydrogen export strategy on New Zealand's electricity infrastructure.

Figure 3 shows the electricity and hydrogen demand used to model REMix-NZ, as well as the values used for the EP-ALISON-LUT study (Gulagi *et al* 2025) used to validate the model, as detailed in section 2.3.4. In 2020, figure 3 shows both electricity use and the remaining final energy from non-electric fuels (Energy Efficiency and Conservation Authority (Te Tari Tiaki Pūngao) 2025). For 2030 and 2050, the model includes only electricity and hydrogen demand, with total final energy converging toward electricity and hydrogen in 2050 under full electrification assumptions.

2.3.1. Reference year

The year 2020 is used as a reference, where the actual performance data of New Zealand's energy system is compared against the outputs of the model.

2.3.2. No exports

For the years 2030 and 2050, the model runs a free cost optimisation (FCO), which minimises overall system costs without imposing any constraints on emissions. This scenario explores the potential outcomes of technology deployment and energy system changes without considering specific emissions reduction targets. The results are compared to Gulagi *et al* (2025) which modelled a complete phase-out of fossil fuels across all sectors to achieve a net-zero emissions system.

2.3.3. Export scenario

In addition to the domestic energy demand modelled in the 2050 scenario, an export scenario (2050-Exp) examines New Zealand's potential to export synthetic e-fuels (e-diesel, e-kerosene, e-ammonia, e-methanol), to the Pacific Islands. This scenario assumes New Zealand meets the full e-fuel demand of the Pacific Islands by 2050, estimated at over 12 TWh (Gulagi *et al* 2025). The scenario explores how such export opportunities could impact New Zealand's energy infrastructure and generation capacity, and its overall economic viability.

2.3.4. Comparison to EP-ALISON-LUT

In this paper, results for REMix-NZ are compared to the most recent study of energy transition in New Zealand including green hydrogen (Gulagi *et al* 2025), where the EnergyPLAN Add-on for linear system optimisation by LUT (EP-ALISON-LUT) was used to model New Zealand in a single-node spatial resolution. The authors examined five different scenarios: a reference scenario year 2020, milestone year 2030—power sector decarbonisation (MY-2030), a net-zero renewable energy-based system in 2050 (RE-2050), and a net-zero renewable energy-based system in 2050 with e-fuel exports to Pacific Islands (RE-2050-eFe). Results from REMix-NZ are compared to FCO results from Gulagi *et al* (2025) with all available technologies (no constraints on emissions), showing the years 2020, 2030, 2050 and 2050-Exports (considering e-fuels exports to the Pacific Islands).

3. Results and discussion

This section presents key findings from the REMix-NZ model, including required generation capacities and the energy balance (section 3.1), storage and hydrogen requirements (section 3.2), costs and the potential for e-fuel exports to the Pacific Islands (section 3.3). Some results are compared with results from the EP-ALISON-LUT model for New Zealand (Gulagi *et al* 2025), as they currently serve as the most comparable model for New Zealand and provide a useful benchmark. Additionally, these findings will be contextualised against previous projections to highlight advancements in modelling and the upcoming challenges for New Zealand's energy transition.

3.1. Future energy mix

3.1.1. Required generation capacities

Figure 4 shows the optimal expansion pathway for New Zealand. The first column ('Real data') refers to the reference case representing New Zealand in 2020, the second group displays the results from the model REMix-NZ, and the third group shows the model outputs from EP-ALISON-LUT (Gulagi *et al* 2025).

As shown in figure 4, the results from REMix-NZ project a massive growth in installed capacities from around 10 GW in 2020 to 60 GW in 2030, and 130 GW by 2050. When additionally considering exports, a further 15 GW of installed capacities are needed. These numbers are in line with EP-ALISON-LUT, which estimates a similar number, reaching over 40 GW in 2030, 116 GW for 2050, and an additional 17 GW when considering exports. The 10–13 times growth in capacity required according to both models is far larger than previous national projections. Much of this difference reflects fundamentally different demand assumptions. REMix-NZ (and EP-ALISON-LUT) adopt a full-sector electrification framework in which transport, heat, and parts of industry transition to electricity and Power-to-X fuels. This results in a considerably higher 2050 electricity demand than studies limited to the power sector alone or with partial electrification of transport and process heat.

There is significant uncertainty around electricity demand and generation projections, and much of the discrepancy between studies stems from differing assumptions, including those on electrification levels, future cost projections, the aggressiveness of electrification pathways, and the efficiency of technologies, among other variables. The first version of the EDGS (2019) projected a need for between 4 and 11 GW of new capacity by 2050, with less than 0.5 GW of utility solar (Ministry of Business Innovation and Employment (Te Manatū Ōhanga) 2019). The updated EDGS (2024) increases the new build to between 5 and 15 GW, including between 2.7 and 9.1 GW of solar PV, reflecting cheaper technology costs, updated modelling, and a rapidly growing solar pipeline (Ministry of Business Innovation and Employment (Te Manatū Ōhanga) 2024). The revised EDGS assumptions therefore move national projections closer to the broader international modelling consensus that solar will play a major role in future systems. However, the EDGS remain focused on the electricity sector with limited electrification of transport and heat, and therefore their projections are lower than those under full-sector electrification and hydrogen scenarios such as those modelled here.

In terms of technologies to be deployed, the technology development and projected reductions in costs result in a highly renewable energy system by 2050. The renewable energy capacity in REMix-NZ increases from 83% in 2020 to 97% by 2030 and 98% by 2050 (reaching 105 GW of solar PV by 2050, and 117 GW for 2050-Exp, as shown in figure 4). EP-ALISON-LUT sets carbon pricing, and projects a complete transition to 100% renewable energy by 2050 (with 109 and 126 GW of solar PV installed in 2050 and 2050-Exp, respectively). Unlike EP-ALISON-LUT, which applies a carbon limit, REMix-NZ excludes explicit CO_2 pricing or caps since its optimised pathways already reach near-complete renewable generation. This allows the analysis to demonstrate that renewables become least-cost on their own merits; applying a carbon price would only strengthen this conclusion. The higher spatial resolution of REMix-NZ better captures the potential for onshore wind power, foreseeing a deployment of 15 and

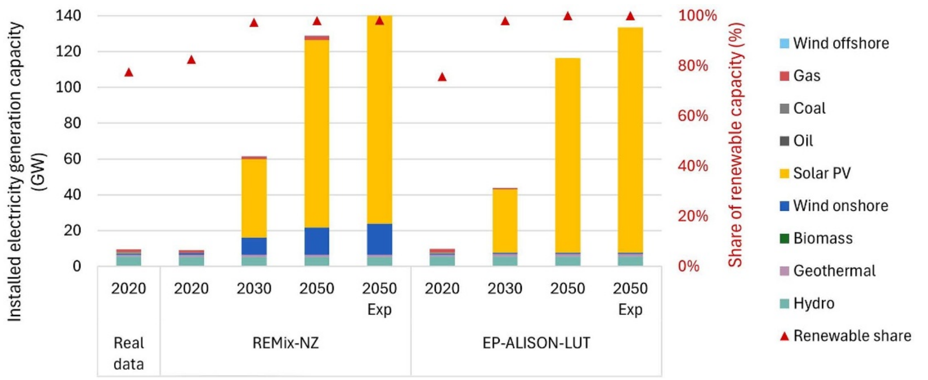

Figure 4. Installed generation capacities (GW) pathways (2020, 2030, 2050) with and without exports; comparison between real data and model results from REMix-NZ and EP-ALISON-LUT. Red triangles indicate percentage of renewable electricity capacity.

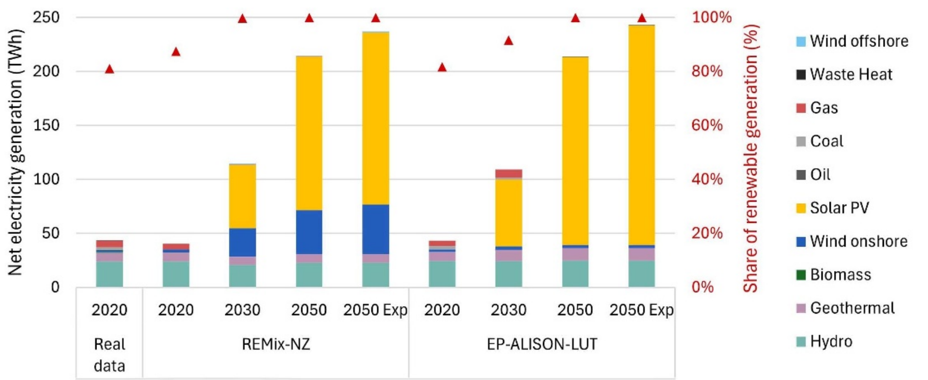

Figure 5. Net electricity generation (TWh) comparison between real 2020 data and model results from REMix-NZ and EP-ALISON-LUT. Red triangles indicate percentage of renewable electricity generation.

17 GW of installed capacity for 2050 and 2050-Exp, respectively. Compared with other national modelling efforts, the higher capacities in REMix-NZ stem primarily from more extensive electrification assumptions and the inclusion of hydrogen demand for exports.

In summary, REMix-NZ projects a significant need for expansion in New Zealand's power capacities: a 10–13-fold increase in installed capacity by 2050 (from 10 GW in 2020 to 130 GW in 2050), driven by a large increase in electricity demand. This is in line with earlier findings from EP-ALISON-LUT but far exceeds other national reports that do not account for full electrification. The optimal mix in REMix-NZ heavily relies on solar PV, similar to EP-ALISON-LUT. These projections suggest that the challenge of meeting our future electricity demand is even greater than previously thought, with solar playing a pivotal role.

3.1.2. Energy balance

In line with the large deployment of new solar PV, most (over 65%) of the electricity generation from 2030 onwards comes from solar PV, as shown in figure 5. The high share of solar PV by 2050 results from its strong cost reduction trajectory, its proximity to load centres that reduces transmission expansion needs, and its synergy with flexible hydrogen production, which improves utilisation of daytime generation. Although solar variability requires additional storage, this cost is included in the optimisation, and the resulting mix represents the least-cost configuration under the assumed conditions. After solar PV, the second largest contributor is onshore wind power (over 19%), followed by hydropower. With no growth in hydropower capacity, its influence, though still significant, takes on a secondary role as solar PV and wind power emerge as the leading contributors.

Total net generation is projected to increase from around 40 TWh in 2020 to 215 TWh by 2050 in the REMix-NZ model. EP-ALISON-LUT supports these numbers with a comparable generation projection of 214 TWh by 2050. The differences in total generation values across models can be attributed to variations in capacity factors and technology assumptions, as well as the spatial resolution. Solar PV emerges as a dominant generation source in both models by 2050, as shown in figure 5, with REMix-NZ projecting 143 TWh and EP-ALISON-LUT a higher 174 TWh annual generation.

Both models show a rapid phase-out of coal by 2050, with REMix-NZ eliminating it by 2030 and EP-ALISON-LUT by 2050. Natural gas use is almost entirely reduced, in REMix-NZ there is very minor use in 2050-Exp scenario (less than 0.1% of the total net generation), while due to carbon limits EP-ALISON-LUT phases out gas entirely by 2050.

Previous EDGS studies (Ministry of Business Innovation and Employment (Te Manatū Ōhanga) 2024, 2019) foresee a rise in renewable electricity generation share by 2050 but without reaching fully renewable electricity generation. Although the role of gas power plants is to operate in a peaking role, the average renewable electricity generation share reaches between 96 and 98% across the different modelled scenarios (Ministry of Business Innovation and Employment (Te Manatū Ōhanga) 2024, 2019). Another study estimated renewable generation to decrease from 90% in 2020 to 84% by 2050 with the introduction of gas and coal with carbon capture and sequestration (CCS) (BusinessNZ Energy Council 2015). In contrast, the results from REMix-NZ and EP-ALISON-LUT show that 100% renewable electricity generation is feasible for New Zealand.

Despite its potential, and the global trends (Al-Shetwi *et al* 2024), solar PV has yet to see widespread adoption in New Zealand. A 2015 study by the BusinessNZ Energy Council projected solar PV to contribute only 3% of the country's total generation output (BusinessNZ Energy Council 2015). However, a NIWA report (Liley *et al* 2023) indicates that New Zealand enjoys a consistent global horizontal irradiance (GHI) ranging from 1200 to 1500 kWh m^{-2} annually, making the entire country well-suited for solar energy, and on a higher specific level as the per capita leading country in the world, the Netherlands, or the country with the third most installed capacities, Germany (de L'epine and Kaizuka 2024). The NIWA report highlights that New Zealand's annual average GHI surpasses that of Germany, which had around 40 GW of capacity just from rooftop solar at the time of the study (Liley *et al* 2023) Click or tap here to enter text. By the end of 2023, Germany's installed solar capacity totalled 81.7 GW (Bundesnetzagentur 2024). Results from REMix-NZ show solar PV representing over 65% of the total generated electricity by 2050; the value from EP-ALISON-LUT is even higher (over 82%).

Current data shows there is approximately 2600 GWh yr^{-1} of new renewable electricity generation expected to be online between 2023 and 2026. These are mostly solar PV farms, followed by wind turbines and geothermal plants (Electricity Authority (EA) 2023). Comparing 2020 and 2030 REMix-NZ results, new renewable generation exceeds 63 000 GWh. While New Zealand is progressing toward a renewable energy future, these findings suggest that the pace and scale of deployment need to be significantly greater than what is being done today (Cooney 2023, Electricity Authority (EA) 2024a, Energy Efficiency and Conservation Authority (Te Tari Tiaki Pūngao) 2025).

Hydropower has historically dominated New Zealand's electricity mix, but its relative share is expected to decline as wind and solar generation expand rapidly. Results from the EDGS (Ministry of Business Innovation and Employment (Te Manatū Ōhanga) 2024, 2019) and TIMES-NZ 2.0 (Pugliese *et al* 2021b) consistently show hydro remaining an important part of the system for flexibility and peak demand but playing a smaller role in baseload generation as the portfolio diversifies. In 2020, hydropower represented over 50% of New Zealand's installed capacity and generation. Results from REMix-NZ show that by 2050, hydropower would contribute around 10% of annual generation, in line with the results from EP-ALISON-LUT. This decline in share is not due to a reduction in hydropower output but rather reflects the rapid growth of other renewable energy sources (such as solar and wind) becoming increasingly significant in the country's electricity mix.

In short, to meet a quickly growing electricity demand (from 40 TWh in 2020 to 215 TWh in 2050), New Zealand's generation landscape will need a switch, moving from a negligible solar PV contribution to a system where solar PV accounts for over 65% of electricity generation by 2050. REMix-NZ projects total generation to rise, driven primarily by solar PV and supported by wind power, while hydropower's proportion declines to around 10%.

3.2. Storage and hydrogen production

This subsection shows results related to storage capacity requirements for their energy capacity (GWh), power capacity (GW) and yearly throughput (TWh). In this case, results from REMix-NZ are not compared to EP-ALISON-LUT, as hydropower reservoirs and their deployment, a critical element for storage in the energy system, are captured in higher resolution in REMix-NZ.

Figure 6 shows the optimal storage capacities and their operation for each modelled scenario. In terms of energy capacity, by 2050 more than 500 GWh of extra storage will be needed, with most of the storage energy capacity needs being met by existing hydropower reservoirs. Additional storage will

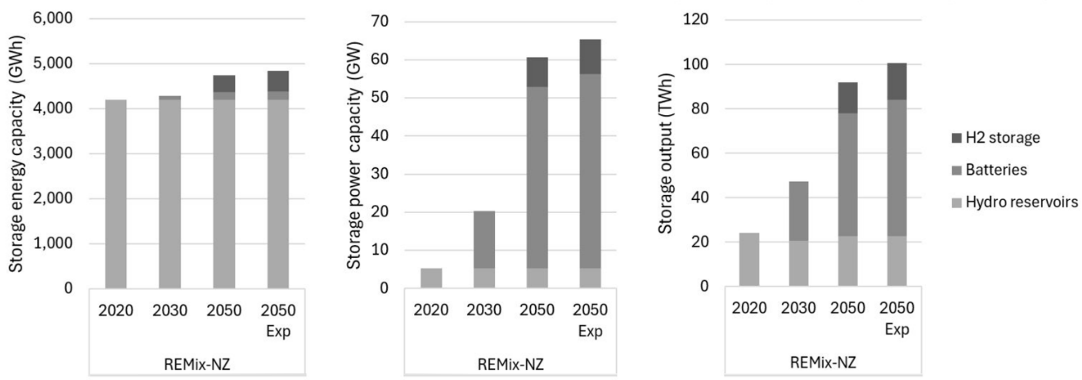

Figure 6. Storage capacity in GWh (left) and GW (centre), and annual throughput in TWh (right).

primarily be provided by batteries (170 GWh by 2050, 190 GWh if considering exports) and hydrogen storage (370 GWh by 2050, 460 GWh if considering exports).

The installed capacity of batteries increases rapidly to 48 GW in 2050 (51 GW in the export scenario, figure 6). Batteries have the highest power capacity of all storage technologies, 10 times the power capacity of the hydropower reservoirs.

New Zealand is currently expanding its storage capacity to address emerging flexibility needs. The 5 TWh Lake Onslow pumped-hydro project was previously explored as a long-duration, seasonal resource for mitigating dry-year risk, with potential system benefits including inter-year energy storage and stability services. However, its location in the South Island limits its ability to contribute to North Island peak demand, where most electricity consumption occurs and where future demand growth is concentrated (Boston Consulting Group 2022). Combined with uncertainties around cost and delivery timeframes, the project was discontinued in 2023 (Brown 2023). In contrast, the storage identified in our modelling serves a different purpose: batteries and hydrogen storage can provide short-term balancing that operates continuously in a high-renewable system. These technologies are modular and can be deployed near demand centres, complementing large hydro reservoirs. Consistent with this trend toward distributed, short-duration flexibility, the Electricity Authority reports plan to connect 0.7 GW of battery storage by 2030, and more than 8 GW of solar projects have applied for grid connection, including around 3 GW co-located with batteries (Electricity Authority (EA) 2024b). Despite this progress, both the REMix-NZ and EP-ALISON-LUT models indicate a significant increase in storage capacity and an extremely rapid deployment rate. While New Zealand is progressing toward a renewable energy future, these findings suggest that the pace and scale of deployment need to be significantly greater than what is being done today (Cooney 2023, Energy Efficiency and Conservation Authority (Te Tari Tiaki Pūngao) 2024, Electricity Authority (EA) 2024b).

To reach systems that are 100% renewable, high levels of flexibility are required to address temporal and spatial variability and uncertainty (Haas *et al* 2018). While the difference between achieving a system that is 97% renewable and one that is 100% renewable may seem minor, research has demonstrated that this small gap can significantly impact storage needs (Cebulla *et al* 2018). The existing hydropower reservoirs in New Zealand offer a substantial advantage in managing the integration of intermittent generation sources such as wind power and solar PV. This flexibility is critical for maintaining a stable and reliable energy supply as the country continues its transition towards greater reliance on renewable energy sources (Goran Strbac *et al* 2012).

Batteries move more energy than hydropower reservoirs. As shown in figure 6, batteries have double the throughput of hydropower reservoirs in 2050 (56 TWh vs 23 TWh) and almost triple the throughput of hydropower reservoirs when considering e-fuel exports in the 2050-exp scenario (62 TWh). Batteries have a high efficiency and can be rapidly charged and discharged making them ideal for balancing short-term fluctuations in supply and demand, especially with the expected growth in intermittent renewable energy sources like solar PV and wind power (Jafari *et al* 2022, Wetzel *et al* 2023). Unlike hydropower, which is limited to specific reservoir locations, batteries can be deployed anywhere across the grid, supporting distributed electricity generation, and enabling more localised management of energy flows. This would help ensure that different regions of New Zealand can maintain grid stability, even if they are far from hydropower resources. The deployment of batteries near urban and industrial areas would allow for

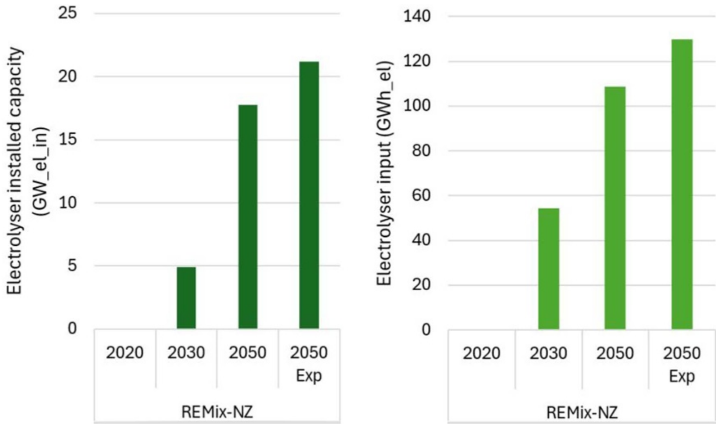

Figure 7. Electrolyser installed capacity (in GW) and electrolyser input (in GWh of electricity).

better integration of distributed renewable energy resources. Hydrogen storage could complement batteries by providing longer-term, seasonal, or even inter-annual storage, potentially in the form of methane, methanol, or ammonia storage (Brown and Hampp 2023).

The combined behaviour of hydropower and batteries illustrates a structural feature of New Zealand's future power system. Because hydro reservoirs already provide substantial long-duration energy storage (GWh), additional storage needs under high PV penetration are driven primarily by storage power capacity (GW) rather than large new energy volumes. Batteries provide high discharge power and cycle frequently to manage short, PV-driven evening peaks, while hydro reservoirs continue to supply seasonal and inter-annual balancing energy. This division of roles explains why the model requires large increases in storage power but comparatively modest additions to total stored energy.

Future hydrogen demand projections, both nationally and globally, are uncertain and differ significantly among studies. A recent New Zealand study estimates that approximately 0.9 Mt (30 TWh) of domestic hydrogen will be needed for the so-called 'unavoidable' applications (ammonia, methanol, green steel, e-kerosene, container shipping) (Vatankhah Ghadim *et al* 2024). In this context, it is noted that 1% of the anticipated global hydrogen market would equate to around 3 Mt (100 TWh) per year, based on a total global demand of 300 Mt (10 000 TWh) annually (Vatankhah Ghadim *et al* 2024). Furthermore, a global study (Breyer *et al* 2024) indicates that this same 3 Mt would represent only 0.17% of global demand, as it projects a total requirement of approximately 62 000 TWh, showing a considerable variation (about sixfold) in global projections.

Currently, the only hydrogen production method enabled in the model is via electrolysis (i.e. green hydrogen). Figure 7 shows that the optimal electrolyser installed capacity reaches around 18 GW by 2050 without considering exports and 21 GW for 2050-Exp. To meet the hydrogen demand, these electrolysers consume annually around 110 TWh of electricity in 2050 and 130 TWh in 2050-exp.

New Zealand would require about 4850 GWh of storage but existing hydropower already provides up to 4200 GWh. Still, 650 GWh is needed from other technologies. The model estimates an additional 650 GWh of battery and hydrogen storage capacity. These 650 GWh refer to the total energy that can be stored and discharged, not to the annual generation required to cover extreme hydrological events. In a highly solar-dominant future, seasonal hydro shortages are expected to be partly mitigated by surplus PV generation and flexible hydrogen operation. In terms of throughput, battery systems are expected to provide the highest energy throughput, reaching between 56 and 62 TWh by 2050, followed by hydropower reservoirs with around 22 TWh, while hydrogen storage contributes an additional 14–17 TWh. It is rather well understood that an efficient and economic seasonal storage option could be hydrogen, while the final storage vector for inter-annual storage is less certain and could, in principle, be hydrogen, methane, methanol, or ammonia (Brown and Hampp 2023). The combination of hydropower reservoirs, batteries, and potentially hydrogen, positions New Zealand to develop a highly resilient, renewable-dominant energy system. Pumped hydro energy storage (Stocks *et al* 2021, Haas *et al* 2022) including the conversion of traditional hydropower cascades to pumping schemes, has previously been considered and discarded as an option for New Zealand (Brown 2023). The remaining challenge is scaling up battery and hydrogen storage to fully close the 650 GWh storage gap. This will require not only investment in technology but also careful grid planning to ensure that storage resources are deployed where they can most effectively support renewable electricity generation and maintain grid stability.

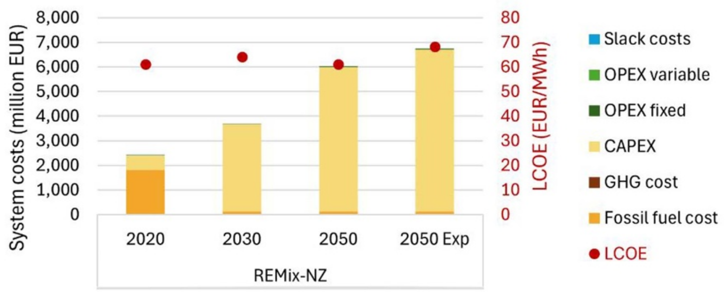

Figure 8. Total system costs (in millions of Euros) and LCOE (in Euro per MWh).

3.3. Green fuels trading assessment and system costs

Hydrogen export potential is a key driver in determining New Zealand's future energy infrastructure. With electricity demand set to rise due to electrification, the need for additional generation capacity will grow. Producing green hydrogen through electrolysis will further increase this demand and exporting hydrogen derivatives will require significant expansion of installed renewable energy capacity.

In REMix-NZ's 2050-Exp scenario, New Zealand would need around 106 TWh of hydrogen annually (equivalent to 3.2 Mt), with 17 TWh (0.5 Mt) allocated for e-fuels exports to the Pacific Islands. As shown in section 2.2.4, 3 Mt of hydrogen would account for about 1% of global hydrogen demand by 2050 (Vatankhah Ghadim *et al* 2024), or only 0.17% according to another study with significantly higher demand projections (Breyer *et al* 2024). To meet the additional 0.5 Mt for exports, REMix-NZ projects that 14 GW of new renewable electricity generation capacity will be required. This aligns with EP-ALISON-LUT's projection of 17 GW needed to supply the Pacific Islands with 0.5 Mt (Gulagi *et al* 2025). Similarly, a study (Vatankhah Ghadim *et al* 2024)estimates that 17 GW of new capacity would be needed for a demand of 0.9 Mt of hydrogen, while New Zealand's Interim Hydrogen Roadmap forecasts 13 GW for an export target of 0.6 Mt, representing 0.2% of the global market (Ministry of Business Innovation and Employment (Te Manatū Ōhanga) 2023).

From a cost perspective, the increased demand for electricity generation and storage to support export requirements would lead to an additional expense of €0.7 billion, representing a 12% cost increase. This excludes the cost of hydrogen transport, conversion or export infrastructure. The additional system cost reflects the model-optimised investment in new renewable capacity to supply hydrogen necessary to enable the export of 17 TWh of e-fuels equivalent, not current-market electricity purchases. At present wholesale prices this cost would be higher and that export feasibility depends on continued cost declines. However, reaching this potential will not only require this financial commitment but also the associated build-outs of renewable energy capacity, hydrogen production facilities, and storage infrastructure. Furthermore, establishing export-oriented policies and partnerships will be critical to enable the export of these e-fuels.

As shown in figure 7, REMix-NZ results show that achieving this export potential would require an increase in hydrogen production capacity, primarily through expanded electrolyser deployment from 18 GW in the 2050 scenario to 21 GW in the 2050-Exp scenario. This expansion is also associated with corresponding growth in renewable electricity generation. The 2050-Exp scenario indicates that more than 14 GW of additional solar PV and wind power capacity would be required compared to the domestic-only 2050 scenario, alongside a considerable expansion in hydrogen storage facilities, which would need to grow by approximately 90 GWh.

Total system costs are expected to rise in all scenarios, driven mainly by high investment costs required to reach future levels of generation, storage and transmission. The total systems costs see a rise from €2.5 billion in 2020 to €6 billion by 2050 and €7 billion in 2050-Exp (figure 8). Fuel expenditures are expected to decline significantly, given that most of the generation will be renewable. About 75% of the current total system cost comes from fossil fuels, this number is reduced to 2% by the year 2050 (in both scenarios, with and without exports). The levelised cost of electricity (LCOE) is projected to reach €61 MWh^{-1} by 2050, increasing to €68 MWh^{-1} when e-fuel exports to the Pacific Islands need to be considered.

A previous study (Ministry of Business Innovation and Employment (Te Manatū Ōhanga) 2019) estimated cumulative capital expenditures on new electricity generation to range between €4.4 b and €14.2 b by 2050, whereas our model reports point-in-time CAPEX of €5.9 b in 2050 (€6.6 b in the export scenario). These differences reflect scope and methodology: MBIE reports cumulative generation investment, while REMix optimises generation, storage, and transmission costs at specific milestones. However, they foresee a dominance of wind power, which is projected to comprise 55% of new capacity. In contrast, the REMix-NZ optimal mix mostly relies on solar PV (with 87% of the new installed capacity, and wind power representing 13% by the year 2050) which, due to declining technology costs and abundant resource availability, plays a central role in reducing overall system costs.

Besides exploring the possibility of supplying domestic demand and even evaluating export ambitions, another option has always been on the table: importing hydrogen or its derivatives. Although not explored in this work, a previous study (WSP 2022) evaluated the benefits of local and imported green ammonia for use in modified CCGTs to reliably supply energy during dry periods. The authors of said study suggest that an optimal pathway is to use domestic renewable energy to produce and store up to 1 TWh of green ammonia, supplementing an additional demand of up to 4 TWh (during very dry years) with imports. This conservative approach to local hydrogen production is seen to balance energy security concerns with the efficient use of local renewable energy resources. However, an import approach would make New Zealand reliant on international suppliers and transport networks, introducing potential vulnerabilities in securing this critical backup energy (WSP 2022).

In summary, the REMix-NZ model results show that New Zealand has the potential to become an exporter of hydrogen in the form of e-fuels by 2050, primarily driven by its abundant renewable energy resources. This additional hydrogen demand triggers the additional need for about 3 GW of electrolysers and 14 GW of renewables.

3.4. Limitations and outlook

REMix-NZ provides an open-source model for analysing New Zealand's long-term energy transition. While government and industry operate proprietary electricity-market models with great spatial and temporal detail the contribution of this study lies in establishing a transparent platform for multi-energy, capacity expansion and hourly operation optimisation that explicitly integrates hydrogen production and export within national energy planning. However, there are still notable limitations.

One key area for future improvement is enhancing the hydropower modelling to account for hydropower cascades and assessing the well-known 'dry year problem' through sensitivity analysis of different hydro years. Although, we note that with the large-scale deployment of solar PV, the critical challenge may shift from dry years to other weather conditions, potentially resembling the 'dark doldrums' experienced in Europe. Additionally, expanding the model to incorporate more technologies, such as different types of solar PV, wind turbines, pumped hydro storage, and hydrogen technologies and transport, would further refine its scope.

The current model also does not consider explicit demand response representation. Demand-side flexibility already plays an important role in New Zealand's electricity system, particularly through large industrial consumers like the Tiwai Point aluminium smelter, which can curtail load during dry periods, and through residential demand-management programmes (e.g. 'free power hour'), enabled by the hydro-dominated system. These mechanisms help to balance the grid and reduce the need for firm capacity and storage. REMix-NZ, however, uses fixed hourly demand profiles and therefore does not endogenously capture short-term load flexibility or user behaviour. Including such features would require dedicated behavioural and market modelling and is beyond the scope of this study. The results presented are therefore conservative upper-bound estimates of required storage and generation capacity, assuming inelastic demand.

Another limitation of the current model is the lack of representation of hydrogen transport infrastructure, which is critical for both the integration of hydrogen as a flexible energy carrier and the economics of large-scale hydrogen deployment. Without such infrastructure, hydrogen is constrained by location-specific production and storage, potentially driving up costs and limiting its role in the broader energy system. These infrastructure limitations could affect the feasibility and cost-effectiveness representation of hydrogen as a key defossilisation tool.

Currently, energy demands of all sectors are translated into electricity demand, which reflects an implicit approach to sector-integrated planning. However, this method falls short of capturing the full complexity of interdependencies and investment decisions between sectors such as transportation, industry, and heating. We are actively working on developing a fully sector-integrated planning framework, where investment decisions across all sectors are explicitly endogenised within the optimisation model. Agriculture, land use and CCS are not modelled.

Lastly, further exploration is needed to better understand the role of hydrogen as a final energy vector, particularly in its competition with e-ammonia, e-methanol, e-kerosene, and other e-fuels.

4. Conclusions and future work

In this study, we presented REMix-NZ, an advanced energy system model designed specifically for New Zealand, with 17 technologies, 8760 time steps, and 11 regions.

The key findings are:

1. Capacity expansion: REMix-NZ projects a 10- to 13-fold increase in New Zealand's installed power capacity by 2050 (from 10 GW in 2020 to approximately 130 GW in 2050). This growth is driven by a sharp increase in electricity demand, from 40 TWh in 2020 to around 215 TWh in 2050. Importantly, much of this increase reflects the electrification of transport, heating, and industrial processes, given that New Zealand's total final energy demand (beyond just electricity) was already nearly 150 TWh in 2020 (Energy Efficiency and Conservation Authority (Te Tari Tiaki Pūngao) 2025). The findings from REMix-NZ are consistent with earlier findings from EP-ALISON-LUT (Gulagi *et al* 2025) which uses the same full sector coupling demand assumptions but far exceed other national reports. The optimal mix in both models heavily relies on solar PVs, both in terms of installed capacities and energy generation, transitioning from a negligible contribution today to providing over 65% of the country's electricity by 2050. These projections suggest that the challenge of meeting the future electricity demand under full sector coupling and hydrogen deployment would require a substantially larger renewable build-out than previously thought, with solar PVs playing a pivotal role.
2. Storage requirements: New Zealand will require about 4850 GWh of electricity storage capacity by 2050. Fortunately, its existing hydropower infrastructure already provides 4200 GWh, offering a major advantage in integrating cheap solar PV. However, an additional 650 GWh of storage will still be necessary, primarily from batteries and hydrogen. Battery systems are projected to provide the highest energy throughput (56–62 TWh by 2050), cycling frequently despite smaller installed energy capacities. Hydrogen storage will also play a role, contributing between 14–17 TWh. Ensuring sufficient storage to meet this gap will require strategic investment in both battery and hydrogen technologies, alongside careful grid planning to optimise their deployment.
3. Hydrogen production and export potential: REMix-NZ results indicate that New Zealand has the potential to become a hydrogen exporter by 2050. Exporting e-fuels to the Pacific Islands, represented by 0.5 Mt of hydrogen equivalent, would require an additional 3 GW of electrolysers and 14 GW of renewable capacity, raising the LCOE from 61 to 68 €/MWh. We note that the final energy vector for hydrogen remains undecided and could, in principle, take e.g. the form of methane, methanol, or ammonia, and while the REMix-NZ model considers the energy contained in synthetic fuels (e.g. e-kerosene, e-diesel), it does not fully account for the entire production chain, which is a limitation in the export scenario analysis.

In conclusion, this work highlights the significant opportunities and challenges for New Zealand's energy future. The expansion of renewable capacity, strategic development of storage solutions, and potential for hydrogen export will play key roles in achieving a transition to a highly renewable energy system by 2050. This study aims to support long-term decision-making for policymakers and stakeholders in planning a sustainable future for New Zealand.

Beyond the national context, the results also highlight a system-level pattern that may be relevant for other hydro-rich or renewable-rich countries. Because New Zealand's hydro reservoirs already provide substantial long-duration energy storage, additional storage needs under high solar PV penetration are driven primarily by storage power capacity (GW) rather than large new energy volumes (GWh). Batteries supply fast high-power balancing to manage short PV-related evening peaks, while hydropower reservoirs continue to meet seasonal and inter-annual variability. Countries with similar hydropower characteristics like Norway, Switzerland, and Andean countries may therefore experience comparable storage requirements as they scale up electrification and deploy higher shares of solar and wind.

Data availability statement

The REMix framework is open-source and available for use (DLR, 2025).

The data that support the findings of this study are openly available at the following URL/DOI:. URL/DOI: http://doi.org/10.5281/zenodo.14100263.

Detailed Model Data available at http://doi.org/10.1088/2753-3751/ae2871/data1.

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The authors used AI-assisted tools for grammar, clarity, and consistency checks. The authors reviewed and edited all content and accept full responsibility for the manuscript.

Conflict of interest

The authors declare no competing financial or non-financial interests that could have influenced the work reported in this paper.

Ethics statement

This research did not involve human participants, animals, or social surveys requiring ethical approval.

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