The role of Adaptive Energy Digital Twin technology in decarbonising emissions in the New Zealand process heat sector

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ABSTRACT

New Zealand (NZ) is uniquely placed to meet the goal of net zero emissions in the industry sector by 2050, but only with an 80% expansion of renewable electricity generation (TWh) combined with energy efficiency improvements through advanced process heat integration, improved energy system design and control, future deployment of high temperature heat pumps (HTHP) for process heat up to 200°C and biomass for heat above 200°C, and smart integration of renewable electricity via microgrid connected factories and communities. The development of Adaptive Energy Digital Twin (AEDT) technology applied widely by energy consultants, equipment providers and factory owners, is considered a key development to aid industry decarbonisation. A seven-year research programme is underway in NZ to develop an open source AEDT technology platform and to demonstrate its usefulness for decarbonising a wide variety of industry sectors, such as dairy, meat, food, wood, paper, metals and chemical processing industries of NZ. Electricity supply and demand differences across the regions of NZ for 2020 and predicted for 2050 are also presented.

KEYWORDS

Process heat decarbonisation, Adaptive energy digital twin, Sustainable process industry, Renewable energy integration, Industry 4.0

INTRODUCTION

The process heat sector in New Zealand (NZ) contributes 28% of energy-emissions but represents arguably the most complex and challenging energy sector to decarbonise economically (1). Research over many decades has shown that process heat decarbonisation cannot be simply resolved by a single technology or by switching to a low-carbon fuel; but rather, must be addressed through a highly integrated and energy efficient system that encompasses both the industrial site and the opportunities for local renewable energy integration at its edge (2). Traditionally, heat for running industrial processes has been supplied by combustion of fossil fuels, either via hot combustion gases or steam production. In order to replace fossil fuels, straightforward replacements include biomass and renewable electricity either directly or via green Hydrogen. Both energy sources are feasible options provided the processing site is located near sustainable supplies of biomass or renewable electricity, and biomass transport or electrical transmission and storage costs are not too high. Unfortunately, access to plentiful supplies of cheap biomass and renewable electricity are rarely available near factories, except for wood processing factories, and therefore decarbonising process heat in factories requires a more detailed and thoughtful approach than energy efficiency improvements combined with simple fuel switching.

The use of Energy Digital Twin (EDT) technology to help design, operate and manage highly integrated low-carbon factories is at an early stage of adoption (3) and it is anticipated that further development of smart factories under industry 4.0 will see further growth of EDT use.

Industrial sites, however, do comprise complex systems, whose behaviour is intrinsically difficult to model and control to a high degree of accuracy because they have distinct properties that arise from dynamic, nonlinear and non-continuous characteristics. To make the transition economically to net-zero-energy factories (NetZEF), even with the help of EDT technology will be difficult, and as the energy systems of these sites become more integrated, by consequence, they will become even more complex to model, control and optimise (4). Next generation ultra efficient industrial sites will also need to harness a range of emerging and market-available energy-technologies and EDT technology has the potential to help identify when, where and how to apply and operate these new technologies to maximise company objectives. across multiple time-horizons.

Ahuora researchers have identified eight key areas where Energy Digital Twin (EDT) technology needs further development (5) to enable more widespread adoption of the technology. These areas include:

1. Enhancement of EDT applications in service
2. Expansion of EDT to multiple application scales and the full life cycle
3. Development of adaptive EDT technology
4. Enhancement of EDT platform security
5. Frameworks for EDT data ownership and sovereignty
6. Specification of EDT software requirements
7. Engineering of AI-driven EDT
8. EDT computational requirements including benefit-to-power-use analysis

Six of the eight areas (points 3 – 8) are associated with applying developments in computer science and software engineering to create more advanced EDT technology that incorporates machine learning and artificial intelligence capabilities to continuously learn, adapt, and optimise industrial processes. These digital twins, called Adaptive Energy Digital Twins (AEDTs), utilise real-time data from sensors, automation systems, and outside sources to dynamically adjust and improve their simulation models. Such technology has the potential to provide real-time optimisation of operating plants, predictive insights into future trends, patterns and issues, improved process simulation and design capability for optimal decarbonisation, improve fault detection and maintenance of equipment, and aid collaborative decision making within factories and across entire industrial ecosystems of a region or country.

In this paper the development of an open-source Adaptive Energy Digital Twin (AEDT) technology platform underpinned by process integration and energy system science advancements is presented. The development is part of a seven-year research programme on process heat decarbonisation commissioned by the NZ government in October 2020. The research programme, called the "Ahuora project", is a multi-university collaboration between three NZ universities (Waikato, Auckland and Massey), led by the University of Waikato. "Ahuora" is a Māori word with the coupled meaning of "ahu" to fashion and "ora" state of living, combined to represent "creating sustainable industry". The Ahuora project aims to develop a digital twin technology platform that can assist NZ industry to re-engineer the way they use, convert, provision and store energy for process heat on the path to delivering Net Zero Energy Factories (NetZEF) across the country by 2050. The highlights of a top-down study of 2020 process heat demand, temperature levels and future 2050 electricity supply and demand of all NZ factories, buildings, residential homes and electrified transport sector is also presented across the regions of NZ to give context to the strategies being employed in the project. Options for new technology deployment such as Medium Temperature Heat Pumps (MTHPs) for hot water production up to 100°C and High Temperature Heat Pumps (HTHPs) for steam production up to 200°C, and integration of renewable energy to factories, with the assistance of AEDT technology is also discussed with reference to the NZ industry decarbonisation challenge.

INDUSTRY DECARBONISATION IN THE DIGITAL AGE

Digitalisation, digital twin (DT) technology, smart microgrids and Industry 4.0 are all important developments in the digital age on the way to achieving net-zero industry decarbonisation. Digitalisation is the process of leveraging digital technologies, and the ever-increasing amounts of data, to improve business efficiency, create value and increase profitability in the widest sense. This includes businesses, processing factories, manufacturing facilities, transportation networks, communication systems and more. Digitalisation, however, is not to be confused with a similar term “digitisation”. These two terms describe very different concepts. Digitisation simply involves converting information from a physical form to a digital one. Examples include scanning piping and instrument diagrams to create a digital copy or conducting 3D laser scanning of existing sites to develop a Building Information Model (BIM). While DTs may require some digitisation in their development, only when combined with high-fidelity computer simulation to enhance the performance of the physical asset, should the digital simulation be considered a DT. DT technology is therefore an enabler of digitalisation.

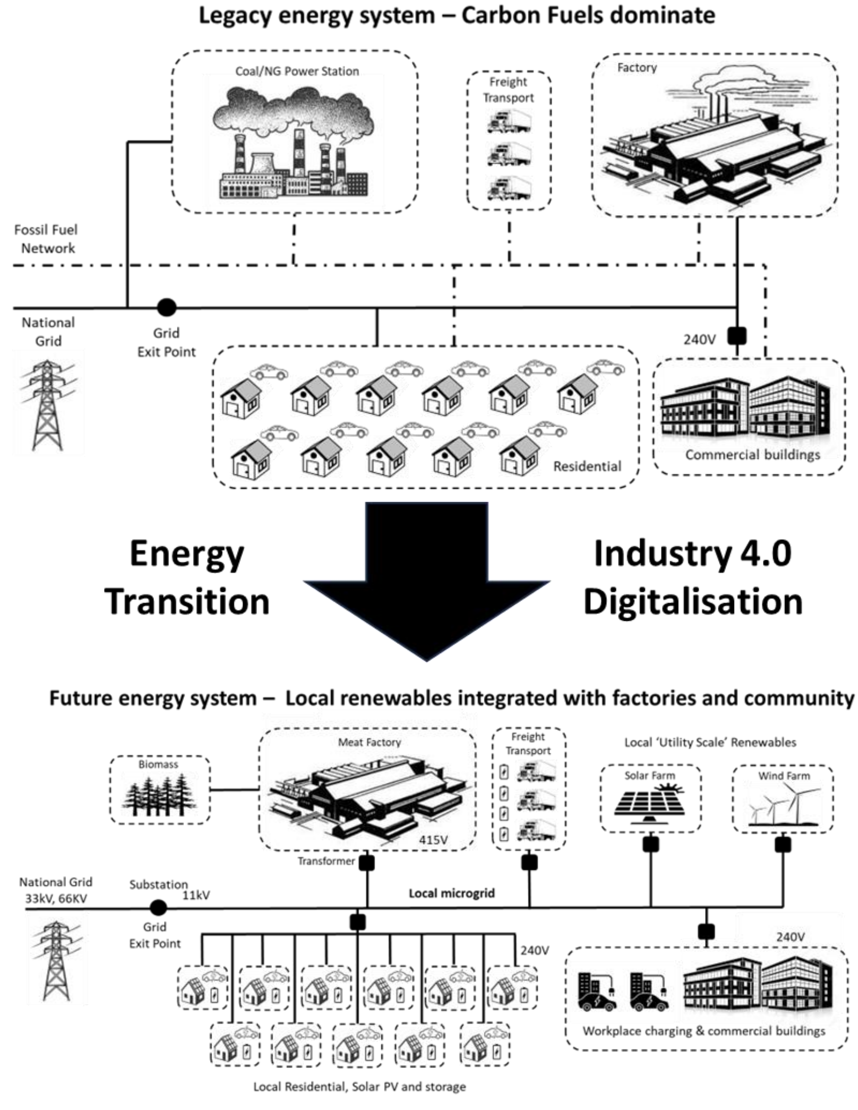


Figure 1. Energy transition from centralised energy networks to decentralised smart microgrids with renewables integrated with factories and the community.

The legacy energy system, illustrated in Figure 1, needs to transition from a carbon fuel dominated system to a renewable electricity dominated energy system based on local renewables and a smart microgrid. A smart microgrid is an integrated system of local distributed energy resources, such as solar panels, wind turbines and energy storage devices, connected to local power loads, including buildings, homes and factories. Microgrids can operate autonomously at the grid edge or connected to the main grid and function to efficiently manage the generation, distribution, and consumption of electricity locally. By integrating renewable energy sources and storage technologies with factories, smart factory centred microgrids can reduce reliance on fossil fuel-based power and enable the effective utilisation of renewable zero-carbon electricity in industry. Microgrids can also help to balance local supply and demand at the grid edge, thus reducing transmission losses, and enhancing grid resilience (6).

Industry 4.0 is a related term to digitisation that refers to the integration of digital technologies, including DTs, into industrial processes to enhance efficiency, productivity and sustainability. The term is in fact a subset of the wider term of digitalisation. By adopting Industry 4.0 principles, industries can optimise their operations, minimise waste, and reduce energy consumption.

ENERGY DIGITAL TWIN TECHNOLOGY

It is envisaged that Energy Digital Twins (EDT) can help manage smart microgrids in addition to factories and other community loads like buildings, homes and transport. A family of EDTs can potentially work together to form a community wide or regional DT that can be used for designing and achieving overall optimal energy system performance. EDT technology aims to capture the likeness and behaviour of physical energy systems using digital models while also data linking the physical and digital assets as shown in Figure 2. Digital twinning of physical assets is a complex task that requires considerable computing resources and detailed understanding of the process, starting materials, controls and states of the plant being simulated. Factories often encompass large amounts of infrastructure with physical limitations and this consideration needs to be accounted for in the DT across multiple time horizons from a few seconds to months, years and even decades.

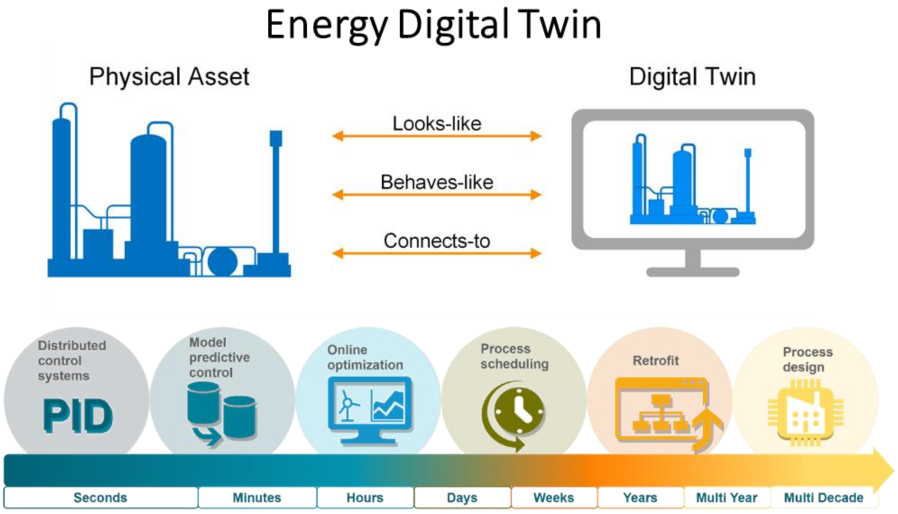


Figure 2. Energy digital twin characteristics helping decision-making across all time horizons.

There are two improvement cycles that can be exploited with EDTs. These cycles are illustrated in Figure 3. At the operational level an “Operational DT” can communicated with the plant to take in data at the site edge and from within the site. The data is used to create digital and hybrid models, which then can be used to shadow, control, optimise or make decisions on product scheduling, energy use, carbon emissions, cost minimisation, process improvements and safety. At the design level a second cycle called the "Engineering Design DT" can operate to assist with longer term decision making involving improvements to existing plants due to redesign, retrofit and retiring of assets (R^3 analysis). With this cycle again data from the factory edge and from within the factory is used to create reliable simulations of either an existing process or a future new or greenfield process. Hybrid models made from first principles and plant data can be created and/or refined such that specific cases can be analysed for adoption of new and emerging technology using automated R3 analysis methods. Discrete redesign and retrofit cases can be simulated, evaluated and optimised using a redeveloped EDT, operating in a digital shadow manner. Using historical data over a full year of typical operation, the proposed modified plant or a proposed new ultra-energy-efficient plant can be more thoroughly evaluated both from a business risk and process performance perspective.

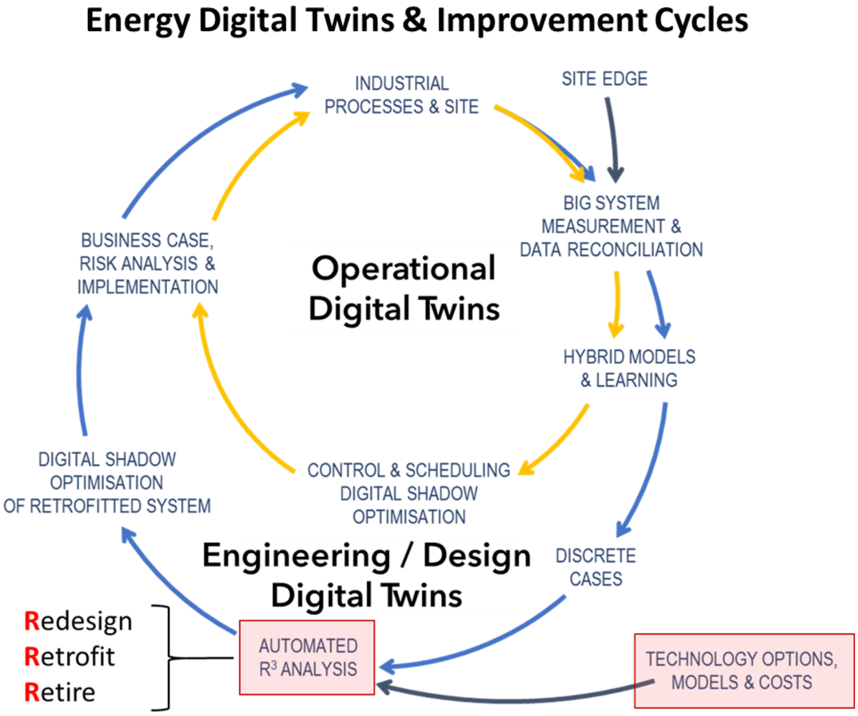


Figure 3. Energy digital twin operational and engineering design improvement cycles.

ADAPTIVE ENERGY DIGITAL TWIN CONCEPT

One of the weaknesses of EDT technologies is the lack of real-time adaptability of the digital models to changes occurring within and around the plant. The Ahuora project is working to address this gap by incorporating adaption functionality within a new type of DT called an Adaptive Energy Digital Twin (AEDT). The goal is to improve the accuracy of the DT over the lifetime of the asset. Developing effective AEDT solutions for industry and neighbouring residential homes, however, requires pragmatic collaboration between domain experts to manage the balancing of capability and complexity of the DT models with the actual gains to be achieved. The law of diminishing returns is always present when investing in human and computing resources, to gain model accuracy, fast solving times, useful outputs, and maximum financial benefit. This trade-off between resource inputs and useful outputs needs to be understood and respected.

The additional dimension of adaptivity aims to create an EDT that will be able to imagine future developments and respond to changes in process behaviour, external conditions and strategic goals. Five distinct adaptability attributes are envisaged in the Ahuora AEDT technology platform:

1. Self-learning: This entails real-time process performance analysis that uses thermodynamics and first principles relations to partially decompose data, from which artificial intelligence (AI) and machine learning (ML) methods can be applied to automatically build and update models for use in virtual twins.
2. Self-optimising: This checks operational set-points and site decisions using virtual twins to optimise physical-domain decision-variables including process control, planning and scheduling, and energy trading.
3. Self-evolving: This emphasises the need to optimally decide how best to retrofit, revamp and retire process and utility system assets. These decisions, unlike the self-optimising attribute, tend to be discrete modifications to the industrial site, which are essential to achieving the strategic NetZEF goals.
4. Self-healing: This includes an asset-monitoring system using advanced methods, such as AI and ML, to detect and predict failures and problems with physical equipment. These predictions can then form the basis of a proactive maintenance plan to prevent component failures and avoid unplanned shutdowns.
5. Self-protecting: This recognises the increased vulnerability of digital systems to cyber-attacks due to cloud-based computing and the proliferation of IoT and smart assets. Methods are being developed to block and counteract malicious attacks.

The interrelationship of the five adaptive features of the Ahuora DT and the three research aims (RA1, RA2, RA3) for creating NetZEF are illustrated in Figure 4. The EDT is envisaged as a key component to developing and managing decarbonisation solutions that span both within the factory and the renewable energy options at the factory edge.

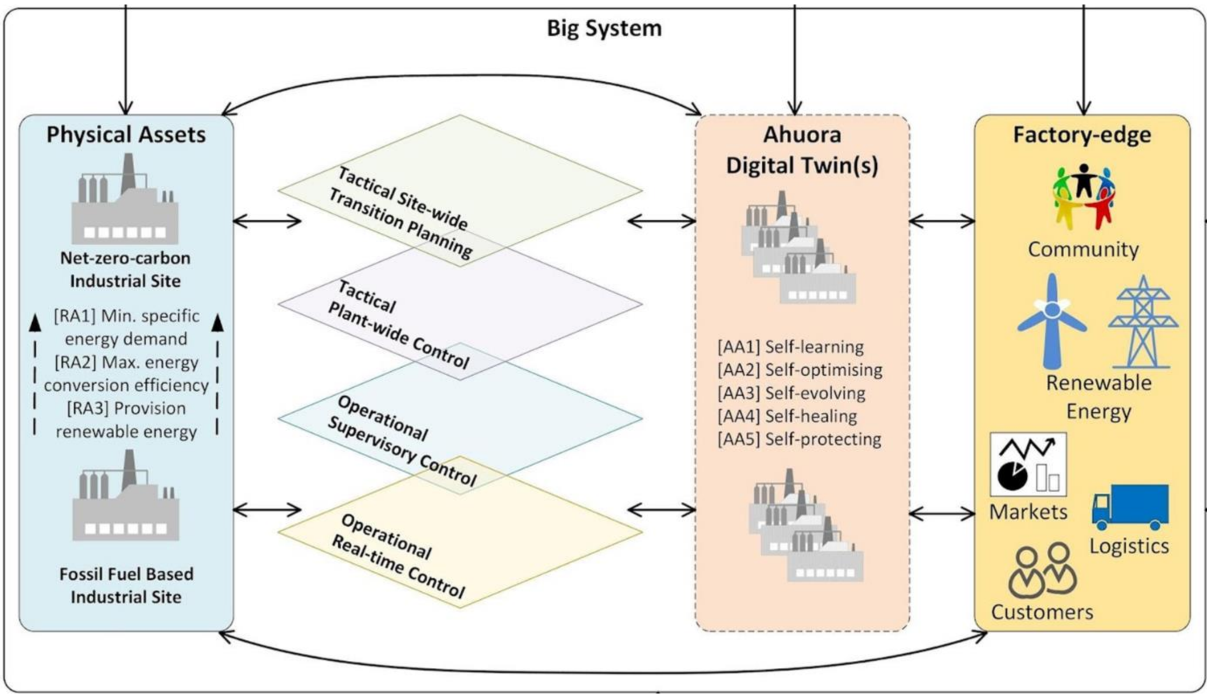


Figure 4. Overview of the Ahuora Adaptive Energy Digital Twin platform research project

While EDTs and AEDTs in general will be able to assist in design, debottlenecking, operational control and optimisation of energy systems, they alone cannot fully decarbonise an industrial site. A key to achieving decarbonisation lies in a combination of infrastructure changes and control optimisations. Infrastructure changes, including the deployment of net-zero-carbon energy sources and technologies. However, these changes often require massive capital investment, which is risky. Accurate forecasting of what new infrastructure is needed to reduce carbon emissions, and how it would integrate and operate along-side existing processes over the complete lifetime of the plant is therefore an important use for the AEDT development.

AEDT technology platform features

Chemical, food, energy and utility process simulation using the open-source DWSIM platform as a starting point for the web based Ahuora AEDT technology being develop. DWSIM is an open-source CAPE-OPEN compliant chemical process simulator built on top of the Microsoft .NET and Mono Platforms. It features a Graphical User Interface (GUI), advanced thermodynamics calculations, reactions support, petroleum characterization and hypothetical component generation tools. The CAPE-OPEN Interface Standard consists of a series of specifications that define a set of software interfaces that allow plug and play inter-operability between a given Process Modelling Environment and a third-party Process Modelling Component.

Additional process simulation and thermodynamic property features that relate to the three Research Aims (RA1, RA2, RA3) of the Ahuora project and the main processing industries of NZ are also being added to DWSIM. The chemical process simulator (DWSIM) is being expanded to include electrical modelling capability both within the factory and with neighbouring loads, and renewable electricity generation sources, such as wind and solar. A key feature of the platform is the inclusion of advanced process integration, modelling and data analytic tools that incorporate AI and ML capability within the platform. Proposed tools and features of the AEDT technology platform are presented in Figure 5.

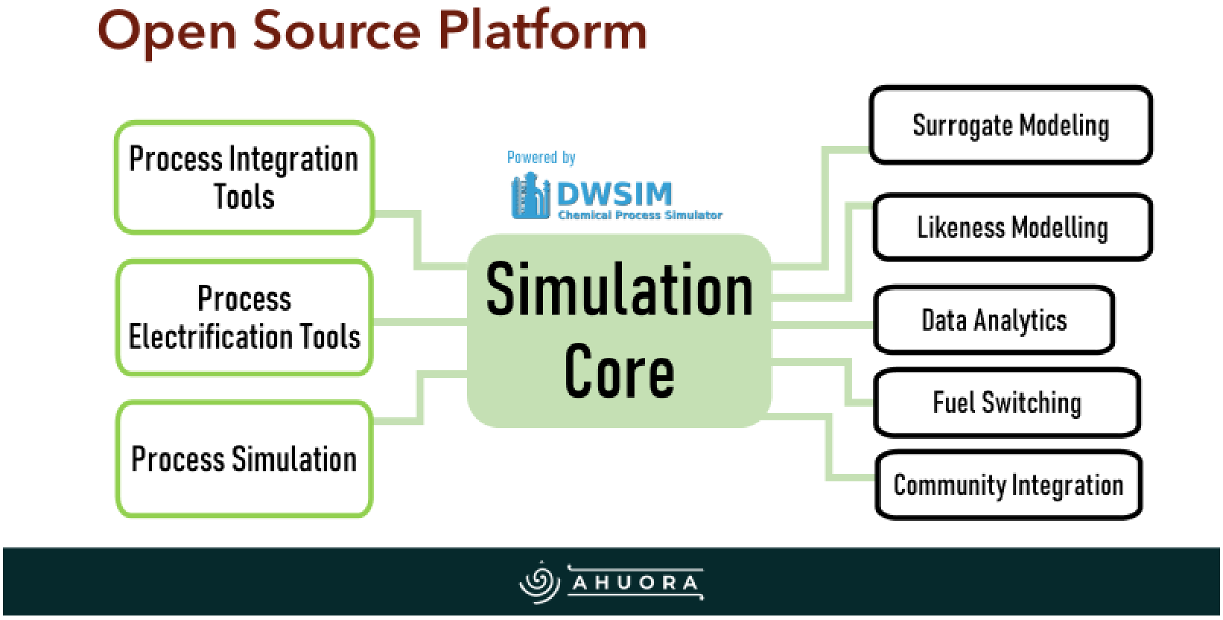


Figure 5. Ahuora Adaptive Energy Digital Twin platform features

The data analytics tool kit will include process performance analysis for constructing and updating models, asset monitoring system for smart maintenance, and methods for detecting and blocking outside interference. Advanced process integration and electrification tools will involve using automated algorithms for rapid (seconds) determination of optimal process, scheduling, planning and energy storage settings and retrofit, revamp and retire options of plant and utility assets. The fuel switching tool enables quick evaluation of options for local renewable electricity supply including storage versus local biomass availability, supply and costs. The community integration tool enables inclusion of other electricity loads in the modelling, for such areas as local transport for EV charging, residential, commercial buildings, schools, hospitals, other factories and local hydrogen production as a feedstock for making important domestic chemicals such as fertiliser, aviation fuel, dimethyl ether (DME) as an alternative to diesel, hydrogen peroxide, steel, methanol and potentially others in the future.

Chemical, Mechanical and Electrical Engineering Perspective

From a chemical, mechanical and electrical engineering domain perspective, AEDTs and the modelling and analytics involved need to span multiple spatial and time scales to capture critical interactions and information in terms of likeness and behaviour of the physical asset.

Scale describes the granularity of the modelled system. Modelling can range from the molecular level involving chemical or biochemical reactions within unit operations to much larger levels involving plants, sites and communities. Nano-scale modelling is required for tracking the behaviour of fluids in real processes involving flow maldistribution, fouling, hydraulic and thermal losses. A collection of unit operations tasked with specific production goals form a process, while an entire industrial site comprises a collection of processes with potentially one or more products. The site also includes utility services, such as boilers, heat pumps and refrigeration, located within a specific context where the site-edge includes neighbouring energy demands from factories, commercial buildings, residential homes and EV transport and renewable electricity generation sources, most likely from solar and wind.

Likeness captures the spatial layout of an industrial system and proximity to neighbouring demands and energy sources. A 1-D diagram is a linear representation of a process, showing primarily the order that certain unit operations or functions occur (e.g., a block diagram). A 2-D diagram captures the detailed layout of an industrial plant (e.g., process flow diagram, P&I diagram). Lastly, a 3-D representation enables more detailed modelling of where various pipes and other equipment are located (e.g., plant topology), which can be used to assess spatial constraints and transport distances within the plant and to neighbouring energy demands and renewable energy sources.

Behaviour describes how input and output process variables are related, and how they vary with time. Four types of behaviour models exist. Steady-state models assumes the plant is stable and operates at constant mean values. Unsteady state or time-varying models assume modelling includes transients and transitions between states and/or disturbances from a desired state. Feedback models measures system outputs and adjusts the input to achieve a target outputs. Predictive models envisage how physical changes and retrofits will impact operations and make changes in the process to counteract disturbances before a change in system output is detected.

Software Engineering perspective

From a software engineering perspective, AEDTs need to encompass methods that improve connectivity with operations and historical data while maintain cyber security of data, enable greater autonomy, and make allowance for human-in-the-loop interventions.

Connectivity and Cyber Security describes an AEDTs capability for information flow with other energy systems, and other EDTs. At the lowest level, the AEDT does not connect with the physical twin (or plant); but instead, is operated manually as a Digital Model. At the next level, the AEDT can be connected to receive information from the plant but not yet send a signal back to the plant; this is defined as a one-way communicating AEDT or a Digital Shadow. As the technology matures, and trust grows, the AEDT may have two-way communication to and from the plant and this defines the AEDTs as a Digital Manager. The highest level of connectivity is for various AEDTs to start exchanging information among themselves, essentially forming an Internet of EDTs.

Autonomy describes the ability of an AEDT to make independent and well-informed actions. This dimension might be one of the hardest to completely apply given the significant safety risks associated with many industrial sites. It is expected that a human-in-the-loop would still be part of the process, even for high levels of autonomy. Manual AEDTs would rely completely on human operators to effect any changes they recommend to the plant. Automated AEDTs would be able to actuate the plant on their own; however, they would have low sophistication, comprising mostly pre-scheduled or trigged tasks. Near autonomous AEDTs would make adaptive decisions to ensure the system maintains its stability in the presence of uncertainty and changing operator goals. Further, Intelligent AEDTs would leverage artificial intelligence (AI) and machine learning (ML), including large language models (LLM), to generate and validate data-driven models of the plant and control actions, facilitating self-adaptation for non-anticipated changes.

Human-in-the-Loop intervention is important, and incorporating ways to observe and provide human feedback is crucial to developing trust in AEDTs. In industrial digitisation operation of the physical domain (the plant) starts with a Human-Machine Interface (HMI), which facilitates exchange of information to and from the plant by operators or engineering teams. In plant design, Graphical User Interface (GUI) applications, such as Computer-Aided Design (CAD) software, can be used with assistance from the AEDT in design decision making. To facilitate more human lead use, a first step is to enable human input of instructions for what is required for the system to do. This could be followed by the development of a higher layer that can automatically implement execution plans based on human-specified goals. Under this development the AEDTs interfaces will switch from “how-to-do” instruction to “what-to-achieve” instructions, which is a much more user-friendly way to interact. The highest level of human-friendly interaction could be achieved when AEDTs move away from developer-oriented instructions to more intuitive observe and control instructions possible through technologies like Augmented Reality (AR) and Virtual Reality (VR), which allow humans to interact with the system in a fully immersive way that best fits their natural inclinations.

NEW ZEALAND CASE STUDY

A top-down study of future 2050 electricity supply and demand across the regions of NZ has been undertaken to determine the extent to which renewables can meet the regional demand growth anticipated. Changing populations are anticipated across the 14 regions of NZ and this will contribute to baseload electricity growth and regional differences in electricity demand for transport, commercial buildings and residential. The role that electrifying process heat in factories plays in driving up regional electricity demand is also investigated. Process heat data for 2019 (7,8), electricity data for 2020 (9), regional electricity data from 2015 (10) and projected electricity data for transport, process heat and base load demand are used as starting points for the study (11).

Process heat demand in New Zealand industry

Around 375 NZ factories contributed a little over 200 PJ (57.4 TWh) of process heat demand (including direct heat) and 9.1 Mt CO_2-e of GHG emissions in 2019 (1). Approximately 40 PJ of electrical energy is also used to power machinery giving a thermal to electrical energy split of 80:20 for NZ industry. The dairy, food, wood and meat processing sectors constitute 83 percent of factories confirming the importance of these industries to NZ (Figure 6). The chemicals sector is the largest consumer of process heat followed by dairy, pulp and paper, wood processing, basic metals, food and horticulture, meat processing and finally manufacturing. Net emissions follow a similar order except for pulp and paper and wood processing which show a large drop in percentage emissions compared to process heat. The six industry sectors with high percentage emissions predominantly use fossil fuels for process heating, while the pulp and paper, and wood processing sectors, with low net emissions predominantly burn forest residues and some natural gas, supplemented with geothermal steam for process heating. Electricity is a modest provider of process heat generally, except for the 14.5 PJ of electricity used directly in the Aluminium smelting process and approximately 4 PJ of electricity for a future steel recycling plant to replace the current steel plant which is heavily reliant on coal and natural gas (12).

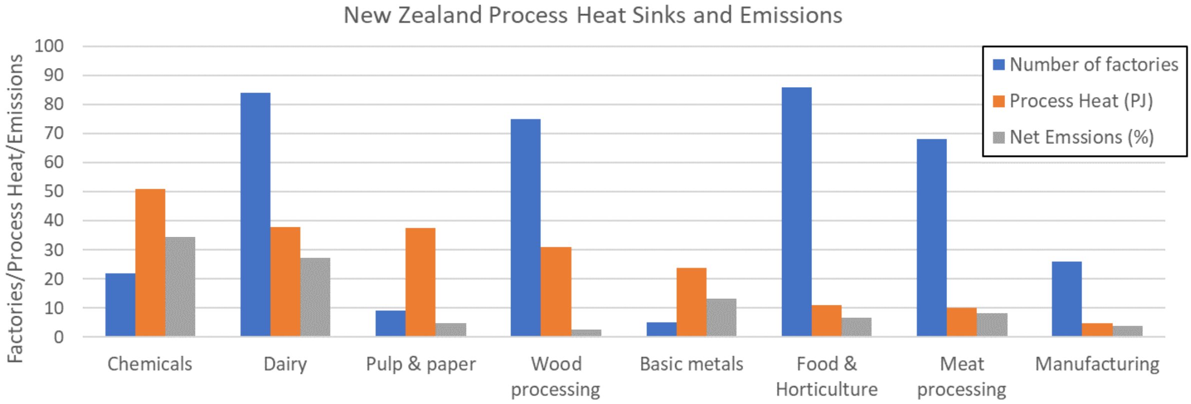


Figure 6. New Zealand industrial process heat demands and carbon emissions for each industry sector.

At a regional level across NZ process heat demand varies dramatically as shown in Figure 7. The Waikato region stands out as the largest consumer of process heat with pulp and paper and dairy sectors being the dominant users. Next is Southland, Auckland and Canterbury. In the Southland region process heat and direct use consumption is dominated by an Aluminium smelter, and in Auckland by the one steel mill in the country. Canterbury and Taranaki like Waikato are also strong in dairy. The one oil refinery has not been included in the study as it recently closed, and the two internationally owned methanol plants located in Taranaki have also been excluded as they are very likely to close within the next couple of years.

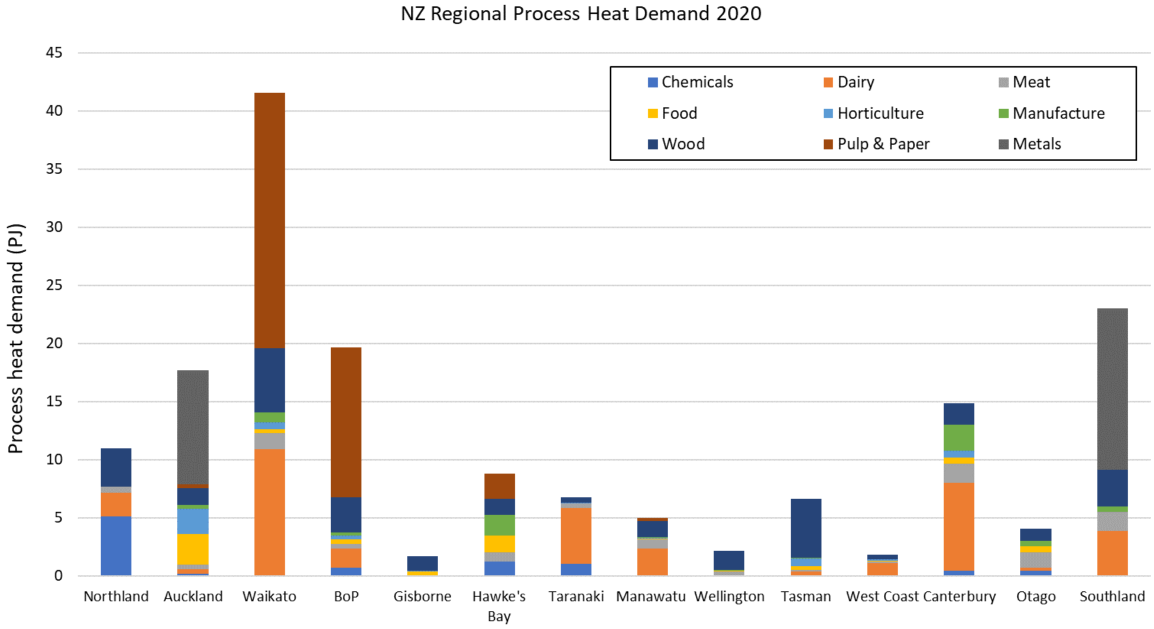


Figure 7: Process heat and direct use electricity by industry sector for 2019 data and for Future 1 scenario when the Refinery and two Methanol plants are closed.

Future process heat demand to 2050

Three factories in the chemical sector (Refinery and two Methanol plants) and two factories in the basic metals sector (steel and aluminium) previously constituted 32% of total process heat demand and 40% of total GHG emissions. These factories are over 30 years old and are nearing the 'end of life'. The oil refinery closed in April 2022 and is now only an import terminal for refined product. The two methanol plants are likely to close within the next few years as current gas reserves run out, and discovering new reserves is unlikely given the offshore oil and gas exploration ban. Closing the refinery and the two methanol plants (Future 1) reduces process heat demand by 41 PJ (20 %) and reduces carbon emissions by 2.45 Mt CO2-e (27 %).

The steel mill and aluminium smelter are similarly quite old, and their continued operation will depend on the domestic price of industrial energy and the price of carbon in the future. If cheap hydroelectricity continues to be available for the Aluminium smelter at the bottom of the South Island the plant could continue to run for some time. However, the uptake of more electric vehicles as part of the transport energy transition and installing a large pumped hydro scheme to balance fluctuations from large increases in wind and solar will reduce the likelihood of cheap electricity being available.

The one steel mill in the country is coming under increasing economic pressure to reduce emissions by adopt new technology or change completely to a recycle mill. Current steel making technology produces large amounts of carbon dioxide as coal is used for heat and as a reducing agent for converting iron oxide to iron metal. If domestic steel making is maintained as a strategic industry to enable a circular economy of automotive, construction and building materials the mill is best suited to become a recycle steel mill only which can be done with electricity (12). Cement production is also another large carbon dioxide emitting industry, along with urea for agricultural fertiliser (8). Both chemical industries were considered essential for the country and have remained in the industry mix in the two future scenarios presented. Natural gas for urea production will continue to be needed from domestic supplies and long-term urea will be produced from domestic hydrogen and biomass gasification.

Identifying further carbon emissions reduction possibilities, such as fuel switching to biofuels or retrofitting new technology like heat pumps, requires an understanding of the temperature levels of process heat demand for each industry sector. Estimates of temperature ranges and process heat enthalpy values for all NZ industry sectors and the common processes are presented and discussed in the next section.

Process heat temperature profiles

An estimated net composite heating curve for all NZ industries is presented in Figure 8. The curve was derived using information from the national boiler and fuels data base giving boiler sizes and annual fuels usage for each factory (7). Actual process heating demand will be larger than presented here especially in industry sectors, like the dairy sector, where significant levels of process heat recovery is practiced. Temperature levels have been determined from process understanding of the industry sectors and specific factories. Due to the high number of dairy, meat and food plants it is not surprising that in 2019 ~80 PJ (39 %) of the net heating load is below 100 degrees, ~50 PJ (24 %) is between 100 and 200 degrees and ~76 PJ (37 %) is above 200 degrees. Similar net composite heating curves are shown for the future scenarios, where the refinery and methanol plants have closed and all other plants remain the same with 2019 values (Future 1) and where the refinery, methanol, steel and aluminium plants have all closed and again the 2019 data applies to the rest of the plants (Future 2). For each of the three scenario the temperature profiles below 200 degrees remain very similar and above 200 degrees high temperature heat demand reduces dramatically from

76 PJ to 35 P to 11 PJ significantly. This in turn reduces the need for renewable fuels with a high flame temperature, like biomass and hydrogen.

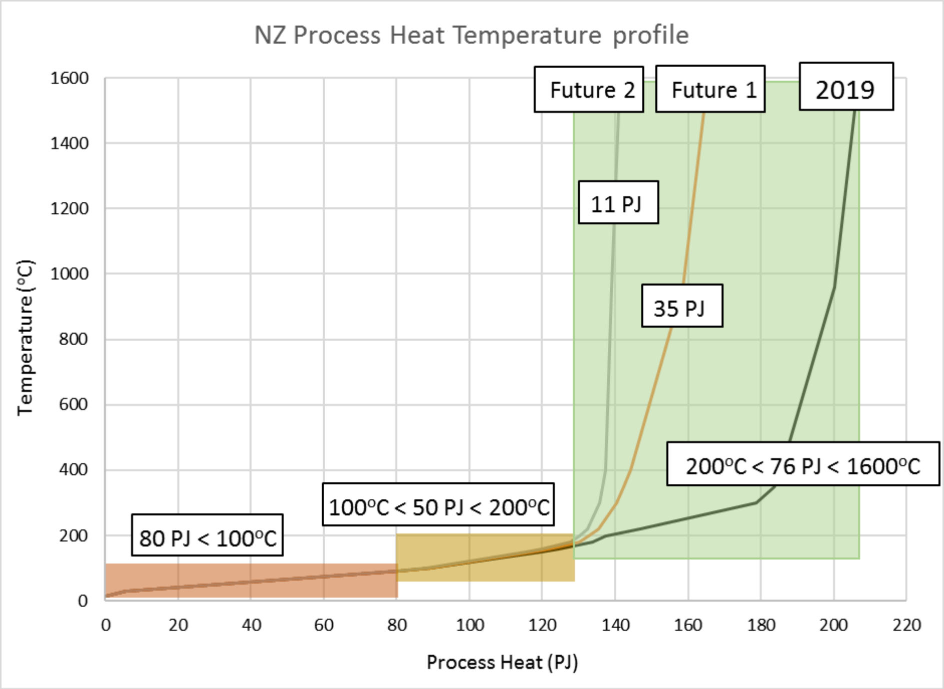


Figure 8: Comparison of process net heat demand temperature profile for 2019, Future 1 (no refinery and methanol plants) and Future 2 (no refinery, methanol, steel and aluminium plants) scenarios.

Looking more closely at the net heating demands for each industry sector gives a clearer picture of how much heat can be supplied by different technologies. A summary of the options is presented in Table 1. It is estimated that 37.6 PJ (26.3%) can be supplied by MTHPs, 15 PJ (10.5%) by HTHP, 12.7 PJ (8.9%) by E-boilers and 78 PJ (54.4%) by biomass or forest residues. Applying typical COPs for HP and E-boiler operation gives expected electricity demand of 8.02 TWh for supplying 65.3 PJ of heat. This contributes a 19.3% increase in electricity demand on 2020 values of 41.5 TWh. The 78 PJ of biomass for process heat is a non-trivial amount to source every year. Existing forest plantation forest have about 75 PJ of forest residues available per year at a cost up to NZ$16/GJ (13).

Table 1. Transition from fossil fuel to green fuel process heat

Heating technology	**Temperature limits (°C)**	**Process Heat (PJ)**	**Process Heat (%)**	**COP**	**Electrical (TWh)**
MTHP	< 100	37.6	26.3	2.5	4.18
HTHP	< 200	15.0	10.5	2.0	2.08
Electro-boiler	< 350	12.7	8.9	1.0	1.76
	Total	**65.3**			**8.02**
Biomass/wood residues		78.0	54.4		
Direct use electricity*		21.4			2.97
Grand Total		**164.7**	**100**		**11.0**

(*) Electricity supplied to aluminium smelter and recycle steel mill

The factories that need to decarbonise through electrification are scattered throughout the regional areas of NZ. Upgrading electricity supply will therefore be needed to facilitate large-scale adoption of medium and high temperature HPs, plus E-boilers. In addition, the growth in electrical transport and future population growth will also drive further electricity expansion. A key research aim of the Ahuora project is to identify the best way to integrate new renewable electricity at the grid edge and biomass into factories so nationwide upgrading of the grid and roads for biomass transport can be minimised.

Regional renewable electricity demand and supply growth to 2050

There are 16 regional areas of NZ, seven in the South Island (SI) and 9 in the North Island (NI). Results for the 16 regions are grouped into three zones, namely, the upper NI zone consisting of 54% of the population in 2020 including the largest city Auckland of 1.66 million, the central NI zone with 23% of the population including the capital city Wellington at the bottom of the NI, and the SI zone comprising 23% of the population, and the city of Christchurch, NZ's second largest city. The demarcation between the upper NI and the lower NI is shown in the map of regional NZ by red dashed lines presented in Figure 9. Electricity demand growth in each region through to 2050 was estimated by using a hybrid of two electricity growth scenarios, "Accelerated electrification" and "Mobilise to decarbonise" published by Transpower, the national gid company (11). Transport electrification over the entire country is estimated to increase by 15.9 TWh (38.3% increase), process heat by industry 8.0 TWh (19.3%) plus direct use for the steel mill 1.0 TWh (2.4%), heat for commercial and public buildings 1.5 TWh (3.6%) and base demand growth for population increase of 5.2 TWh (12.5%).

The regional electricity demand through to 2050 was determined using published data for 2020 combined with electricity growth data based on NZ government reports and industry process heat analysis. Published future electricity demand growth for transport, commercial and public buildings heating and base demand growth were distributed around the regions based on projected population growth from Statistics NZ (14). Process heat projections were based on the location of each of the 375 NZ factories. Since some factories can use the equivalent heat of several thousand homes, the presence of factories in a region were seen to have significant impact on regional electricity demand. Regional demands were presented within in their respective zones as presented in Figure 9.

Auckland has the highest predicted increase in electricity demand at 31.7%, mainly on the back of 31% population growth to 2050. Waikato and Canterbury regions come in second and third based on steady population growth, of 22 and 20% respectively, and significant industry electrification predicted with 20.4% of national total to Waikato and 15.4% to Canterbury (Figure 7). Other regions predicted to experience moderate growth are the Bay of Planty (BoP), Northland, Wellington, Hawkes Bay and Manawatu. Overall, the upper NI dominants demand growth with 57% of the 6.2 million population in 2050 predicted to be in that zone with significant industries located near Auckland to service the main population.

On the electricity supply side significant growth in electricity generation is expected to match the large increase in demand to 2050. Throughout the country a 165 percent increase in overall electricity capacity, from 9 GW to 24 GW will be required. Most of the capacity expansion will come from distributed solar PV 0.1 to 6.8 GW (+6.7 GW), wind 0.6 to 7.45 GW (+6.85 GW), geothermal 1.0 to 1.8 GW (+0.8 GW) and other, including waste, biomass, batteries and pumped hydro firming 0.0 to 2.4 GW (+2.4 GW). The extra capacity will be positioned near areas of high demand and in areas where there is high average wind speeds and good solar irradiance.

As illustrated in both Figures 9 and 10 the large increase in renewable electricity supply will arise in the Waikato and Manawatu regions because of significant investment in onshore and offshore wind and the doubling of geothermal in the Waikato. Significant solar growth also stands out in the Auckland and Canterbury regions where the two largest cities of Auckland and Christchurch are located.

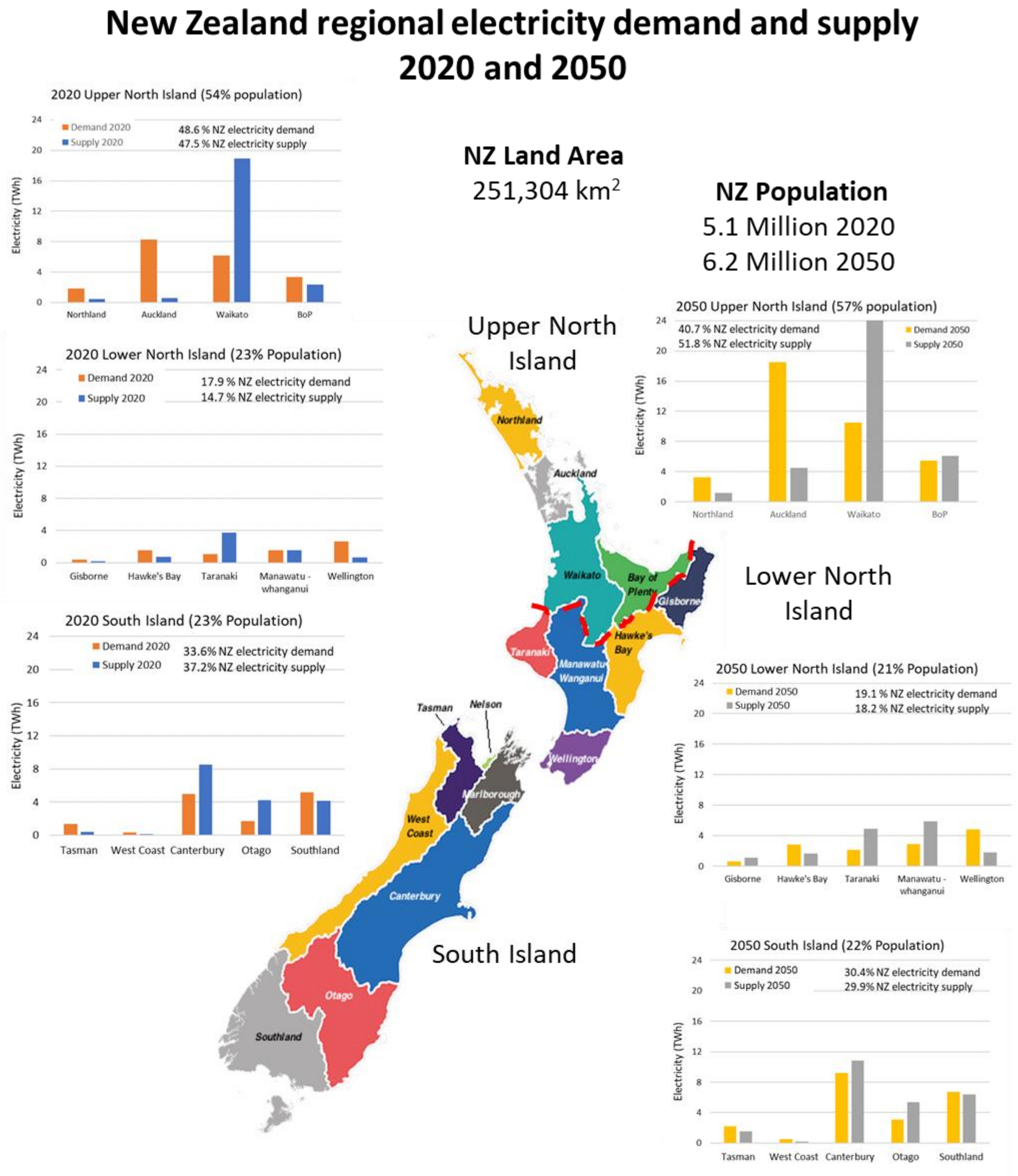
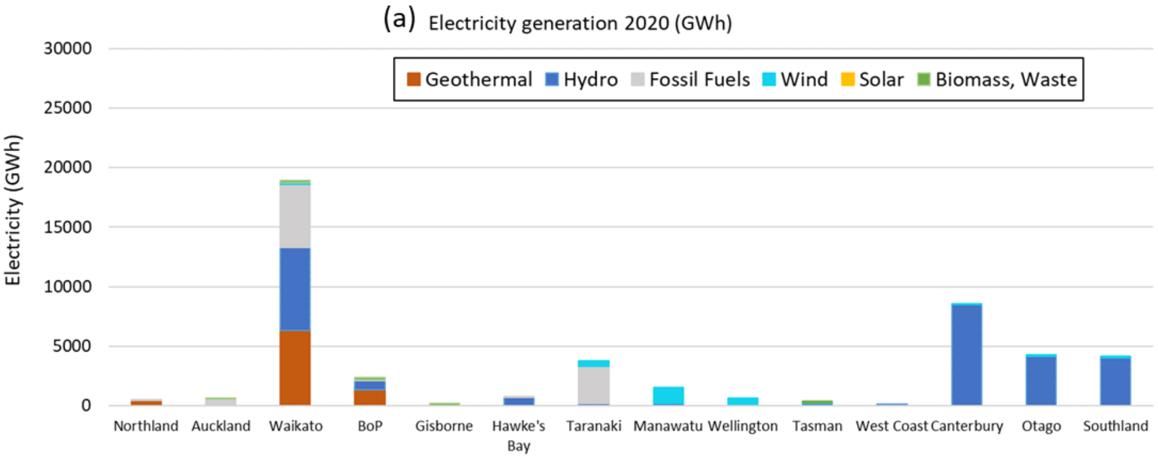


Figure 9: New Zealand regional energy demand and supply 2020 and 2050. The oil refinery in Northland and the two methanol plants in Taranaki have been excluded.

The predicted increase in wind and solar is unprecedented and will require installation rates every year for the next 30 years that match NZs highest rates to date. The mix of renewables are shown in Figure 10a for 2020 and Figure 10b for 2050. Again, the regional mix of renewables demonstrates the importance of the Waikato region, and the good location of the

University of Waikato Smart Energy Centre team, from both an energy demand and energy supply point of view.



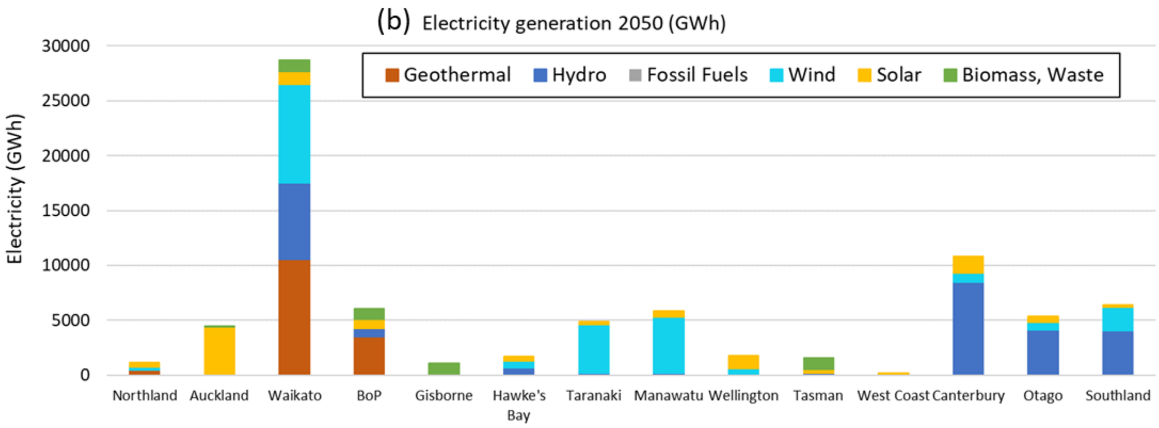


Figure 10: New Zealand electricity generation in GWh by type with (a) 85% renewable in 2020 and (b) 100% renewable generation 2050.

The expansion of distributed renewables of wind and solar in and near the regions of high electricity demand is favourable for reducing transmission losses across the entire grid. In 2019 transmission and distribution losses accounted for approximately 10% (4.3 TWh) of annual electricity generation. In 2050 through a more distributed grid, it is feasible that losses will remain like 2019 and potentially could be less with implementation of localised smart grids in cooperation with large load centres like factories. The integration of renewables with factories and other large loads certainly creates a new paradigm to exploit and it is the goal of the Ahuora project to do so with the aid of the Ahuora open-source Adaptive Digital Twin platform that is supported by a suit of process integration, modelling and optimisation tools.

CONCLUSION

The Ahuora project is working to develop an adaptive digital twin technology platform that can assist NZ industry to re-engineer the way they use, convert, provision and store energy for process heat on the path to delivering Net Zero Energy Factories (NetZEF) across the country by 2050. The Ahuora project is a multidiscipline collaboration across the major branches of engineering and three NZ universities. Digital tools for analysis, optimisation and design are also being developed from the DT, Process Integration and Computer Science expertise within the research team. A high-level study of process heat demand, temperature levels and future 2050 electricity supply and demand of all NZ factories, buildings, residential homes and electrified transport sector also provides a road map for future deployment of medium and high temperature heat pumps, up to 200 °C, biomass for heating over 200ºC, and use of smart microgrids for integrating local renewable electricity with factories, communities and the region. NZ has an abundant supply of renewable electricity options which makes the goal of Net-Zero carbon emissions by 2050 economically achievable, even within the existing electricity market and some government initiatives.

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