Assessing Hydrogen Integration in Steam Boilers: A Comparative Analysis of different Energy Sources for Decarbonisation

A thesis

submitted in partial fulfilment

of the requirements for the degree

of

Master of Engineering

at

The University of Waikato

by

Weicong (Richard) Chen

KO TE TANGATA

THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

2024

Abstract

New Zealand has a goal to achieve carbon zero emissions by year 2050. Fossil fuels are still the main energy sources for steam boilers which are important elements in the process heat sector. Therefore, it is quite important to decarbonise the process heat sector by using low carbon energy sources, such as green hydrogen, grid sourced hydrogen, blue hydrogen, hydrogen blend, wood pellets and electricity. In this research, a comparative analysis of these energy sources is conducted to find out the difference between fuel options in terms of carbon emission reduction, conversion efficiency and the levelised cost of energy. The outcome is that wood pellet boiler system has the best performance with the lowest carbon emission factor from energy delivered to plant, high overall energy conversion efficiency, and low levelised cost of energy.

Further analysis was conducted to find out how the real-time prices of grid electricity impact the levelised cost carbon emissions of energy for grid sourced hydrogen systems. It found that levelised cost of energy of grid sourced hydrogen is less than the one of natural gas boiler system, when spot electricity prices are less than 37.98 NZD/MWh with carbon price at 70 NZD/$t_{CO2\text{-}e}$. Also, grid sourced hydrogen brings more carbon emissions if it is generated by using the real-time grid electricity with higher prices.

The real-time carbon emissions factor and annual carbon emission factor affect the annual amount of carbon emissions and carbon costs when applied to real world case studies of steam boiler systems. The total annual amount of carbon emissions calculated using the average annual carbon emissions factor from the official source was less than that calculated by real-time carbon emission factor for the case studies considered. That would have implications for the carbon costs paid for by companies.

Correlations among the electricity spot price, active lake storage and real-time carbon emissions factor of grid electricity was also found. Low carbon emissions factor of grid electricity occurred most often when the electricity spot price was low and high active lake storage level were available.

Acknowledgements

This work was carried out, part-time, at Ahuora Centre for Smart Energy Systems at the University of Waikato. The thesis would not have been possible without the support of my chief supervisor Dr Martin Atkins. I would like to extend my deepest appreciation and thanks to him. During these two years’ study, he always shared his knowledge with me and encouraged me to keep going during whole process. Also, thanks for Dr James Neale and Dr Timothy Walmsley. They helped me to choose the right area in my research at the beginning.

Thanks for the Kevin Wu who is the Co-founder of one Leawood Group which provides technical service and sales of CHP (combined heat power generator) in Hamilton. He tried his best to provide some active CHP data to support my research, even though the CHP research didn’t carry on in my research.

Thanks for my families who always cheer me up during the study period. It is not easy to study the master programme as a part-time student. The support from families is an important factor to complete this study.

Contents

Nomenclature

m_{CO2-e}	mass of carbon emissions emitted [$t_{CO2\text{-}e}$]
E_f	total fuel energy [GJ]
E_{IS}	total energy from input energy sources [GJ]
E_d	total energy delivered to plant [GJ]
E_s	energy in the steam [GJ]
E_{H2}	the amount of energy from hydrogen
ε	carbon emissions factor [$t_{CO2\text{-}e}$/GJ, $t_{CO2\text{-}e}$/MWh]
η_d	the overall conversion energy efficiency (%)
η_{boiler}	boiler efficiency [%]
η_r	The efficiency of electrolyser
C_b	total capital cost of boiler [NZD]
C_{CE}	the cost of capital and energy per year [NZD/year]
$Capex_A$	the annualized capital cost [NZD/year]
C_E	the cost of energy per year [NZD/year]
LCOE	*the levelized cost of energy [NZD/GJ]*
C_{sp}	*the single price of boiler [NZD/MW]*
P_{boiler}	heat delivery of boiler [MW]
P_r	*the power to electrolyser [MW}*
P_f	*the energy power from fuel [MW]*
V_s	*steam flow [kg/h]*
h	specific enthalpy of steam [KJ/kg]
Q_i	the amount of carbon emission for half hour [t]
E_i	energy from fuel for half-hour real time [GJ]

Subscripts

f	fuel
d	delivered to plant
IS	input energy sources
A	annualised
sp	single price
r	electrolyser
s	steam
CE	capital and energy
I	real time

Abbreviations

PEM	proton exchange membrane electrolyzer	AEC	Alkaline electrolyzer
CEF	Carbon emission factor	PHEF	Process heat emission factor
E	energy	CCUS	carbon capture, utilisation and storage
CCS	carbon capture and storage	PV	Photovoltaics
SOEC	solid oxide electrolyzer	CHP	Combined heat and power
PV	Photovoltaics	LHV	Low heat value
ACI	Aggregate carbon intensity		

List of Figures

List of tables

1. Introduction

1.1. Background

Industrialisation has modernised the society on a global scale, which has a huge impact on the whole environment. More and more industrial factories have been built around the world to meet the need from the society. Tons and tons of fossil fuels are burnt every single day to provide heat and power to these factories. The combustion of fossil fuels causes Greenhouse Gas (GHG) to be released into the air. GHG are comprised of many gases such as carbon dioxide, nitrous oxide, carbon monoxide, sulphur dioxide, and methane. GHG from fossil fuel combustion is partly responsible for the climate change. The greenhouse effect is because the heat is trapped when the gases go up in the atmosphere and form a layer in the stratosphere. After that, the temperature of the planet is increased, which in turn changes the weather pattern around the globe. Nowadays, more and more people suffer from the severe drought or rain which is mainly due to the greenhouse effect.

In New Zealand, one-third of overall energy use is for process heat, and 60% of current process heat powered by fossil fuels in the year 2020. Process heat contributes 8.3 million tonnes of carbon dioxide equivalent released every year (Energy Efficiency and Conservation Authority, 2021).

The New Zealand dairy industry is a big component of energy consumption in the process heat sector. In year 2016, the dairy manufacturing sector consumed 28.4 petajoules (PJ) of fuels to generate process heat. Coal makes up 54% and natural gas 38% of the 28.4 PJ used. Other fuels, which include liquid fuels (e.g., diesel), accounted for the remaining 7%. There are 66 dairy manufacturing sites using process heat on the North Island and 33 on the South Island. In the North Island, natural gas supplied 75% of the fuel demand. In the South Island, coal supplied 89% of fuel demand. The number of GHG emissions on the South Island is much more than that of the North Island because natural gas is a lower-emission fuel than coal (Ministry of Business, Innovation & Employment, 2021).

New Zealand has started to make plan to reduce carbon emissions from the process heat sector. As shown in Figure 1, the use of diesel, coal and gas gradually reduces from 2020. On the other side, renewable energy (biomass and electricity) becomes alternative energy replacing other types of energy in the next 15 to 20 years. In the year 2035, the use of biomass and electricity will make up over 50% of the whole sector of food process energy use (Climate Change Commission, 2021).

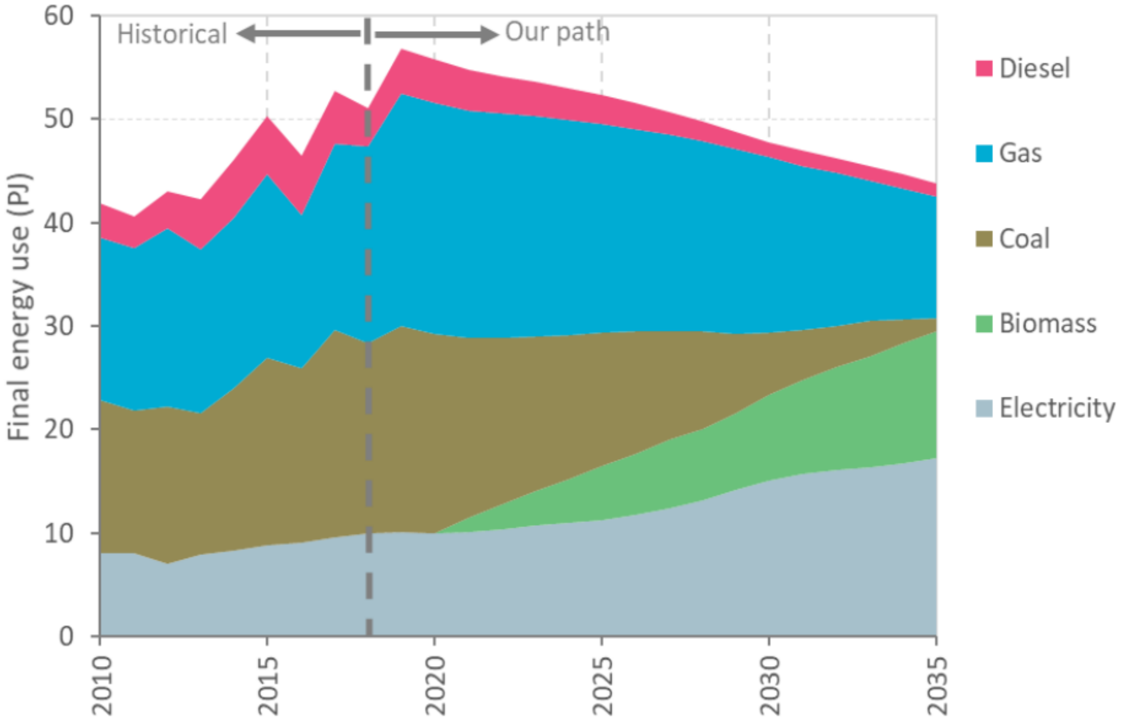


Figure 1. New Zealand food processing energy use in our path (Climate Change Commission, 2021).

Fuel switching is one of ways to dramatically reduce carbon emissions. There are a few types of fuels available to help process heat users to achieve a low-carbon economy. These fuel types include renewable electricity, geothermal energy, biomass and hydrogen. In New Zealand, some dairy and food companies have upgraded their boiler systems to switch to fuels to achieve significant carbon reductions. For example, Fonterra converted an existing 43 MW coal boiler at the Te Awanutu site in year 2020 to use biomass (wood pellets). Fonterra is also currently constructing a new 30 MW biomass boiler at the Waitoa site to replace one of the current coal boilers. Synlait, which is the other big dairy company, has switched on New Zealand's first large-scale electrode boiler at their Dunsandel site in year 2019. The electrode boiler is 6 MW, and this electrode boiler is 99% effient, which is up to 30% more efficient than coal burners. The carbon equivalent saving of this electrode boiler is 13,714 tonnes CO2-e/year (Synlait, 2019).

Green hydrogen is also an energy substitute which could replace natural gas in the future to help to reduce carbon emission. In some countries, they plan to blend hydrogen with natural gas to reduce carbon emission through the gas supply line. For example, hydrogen is to be pumped into Britain's main gas pipeline by 2025 as part of a strategy to replace fossil fuels and move to net zero (HM Government, 2021). First Gas has a viable strategy for converting to a hydrogen blend from 2030 and up to 100% hydrogen in the part of gas network by 2050 (Firstgas, 2022).

1.2. Thesis aim

The primary aim of this thesis is to evaluate the feasibility, efficiency, environmental and economic impact of integrating hydrogen energy sources into steam boilers to achieve decarbonisation of industrial heating processes. Other energy sources (wood pellet, natural gas, electricity) will be analysed as comparison to hydrogen. The analysis is done to determine the implication of introducing the steam boilers in terms of carbon emission reduction, conversion efficiency, and levelised cost of energy (LCOE).

1.3. Thesis outline

Chapter Two, the application of renewable fuel resources (like renewable electricity, biomass, and hydrogen) will be reviewed from technical, economic, and environmental perspectives. Also, how geographical conditions influence the fuel choose and ways to decarbonize process heat in New Zealand will be comprehensively reviewed.

Chapter Three investigates the effect on different types of fuel boilers in terms of carbon emissions, overall energy conversion efficiency and the specific capital and energy cost. In scenarios, these boiler types are powered by different fuel types including biomass (wood pellet), Natural gas, grid sourced electricity, grid sourced hydrogen, green hydrogen, 20% green hydrogen blend and blue hydrogen.

Chapter Four investigates how real-time carbon emission factor from grid electricity bring implication in terms of carbon emission and Levelized cost by use of electrode boiler and hydrogen boiler. Case studies are analysed to determine how real-time carbon emission factor bring the impact on real practice from environmental and economic perspectives. Also, the correlation among the real time carbon emission factor, active lake storage and real-time price of grid electricity will be analysed and discussed in this chapter.

2. Literature Review

2.1. Introduction

The energy consumption of process heat is a critical portion of total energy consumption from all levels. There are three main sections in the literature review below, which includes process heat fuels & emissions, process heat in New Zealand, and renewable process heat. For the section on process heat fuels & emissions, fossil fuels still play a dominant role in process heat supply globally, and measures to reduce emissions and influence on certain industries will be introduced or discussed in this section. For the section on process heat in New Zealand, how fuels choose influenced by geographical conditions and measures to decarbonize process heat will have a comprehensive review. For the section on renewable process heat, the application of renewable electricity, biomass, and hydrogen fuel will be reviewed from technical, economical, and environmental perspectives.

2.2. Process heat fuels and emissions

Currently, the main fuels used in the process heat sectors are fossil fuels, especially natural gas, coal, and petroleum. Renewable energy only contributes a relatively small portion in the process heat sector.

Different countries have their own strategies to apply energy resources into their own national production. As a proportion of national fossil fuel use by the industrial sector, the share for the USA fell from 30 percent in 1971 to 18 percent in 2011, while in China it rose from 33 percent to 48 percent (Pirani, 2018).

Even through fossil fuels have a great contribution on the progress of global process heat sector, some urgent actions need to be taken to reduce the demand for natural gas because the global and European natural gas markets are not yet out of the danger of created by Russia’s cuts to pipeline deliveries of gas. These actions include incentivizing faster improvement in energy efficiency, allowing for more rapid deployment of renewables, accelerating the electrification of heat, and encouraging behaviour changes among process heat consumers (International Energy Agency, 2023). In terms of the development of the renewables, Rehfeldt et al. (2020) presented 34% (184 Mt) of emissions from European industrial sector installations could be avoided from a technical perspective with fuel switch measures using biomass and electricity until 2030.

Iron and steelmaking will be reviewed in detail in the process heat sector. Pirani (2018) presented iron and steelmaking was the largest fossil fuel user around the world, contributing significantly to carbon emissions. If there are more measures which can be used to reduce carbon emissions in the production of iron and steelmaking, that would in turn help to decarbonize the whole process sector.

Iron and steelmaking

There was around 1808 million tons of steel production in 2018 with a 4.5% growth from the 2017 level, which contributes 8 % of energy-related emissions including power consumption emissions (Fan & Friedmann, 2021). There are some energy specialists presenting different views regarding the status or strategies of steel industries in three main countries including China, the USA and the UK. Lin & Wang (2015) pointed out that the growth of China's iron & steel industry during the past decade was directly linked to the consumption of fossil fuels, and the utilization of renewable energy was quite important for the future development of some energy-intensive industries like the steel industry. Griffin & Hammond (2019) mentioned steel industry was the largest industrial sector in the UK in terms of energy demand and greenhouse gas emission, and accounted for 26% of greenhouse gas emission from British industry. Both technologies and policy development need to be taken as a priority to make sure CO2 emissions can be reduced significantly by 2050. Karali et al. (2017) showed the total consumption of the steel industry was expected to be decreased by 13% (180 PJ) in 2050 if energy-efficient technologies could be fully applied to industries in the US. Based on the different comments from the energy specialists above, it shows the emission reduction from the steel industry is quite crucial for the progress of decarbonization in the process heat sector all around the world, especially for some major countries like the US, China, and the UK. Fuel switching is one of options to help to decarbonise the steel industry. Wang et al. (2021) presented green hydrogen applied into steel industry would be expected to be a milestone in the transition of the steel industry to cleaner production.

2.3. Process heat in New Zealand

The energy consumption from the process heat sector is the second largest energy consumption in New Zealand, following the transportation sector. Process heat contributes 8.3 million tonnes of carbon dioxide equivalent released every year (EECA, 2021). In the whole process heat sector in Figure 2, 79% of process heat came from the industrial sector including sawmills, pulp and paper mills, and food processing plants (including dairy). 10% came from commercial sectors. 7% came from the public sector including schools, hospitals, prisons, and public administration buildings. 4% comes from the agricultural sector (MBIE, 2016).

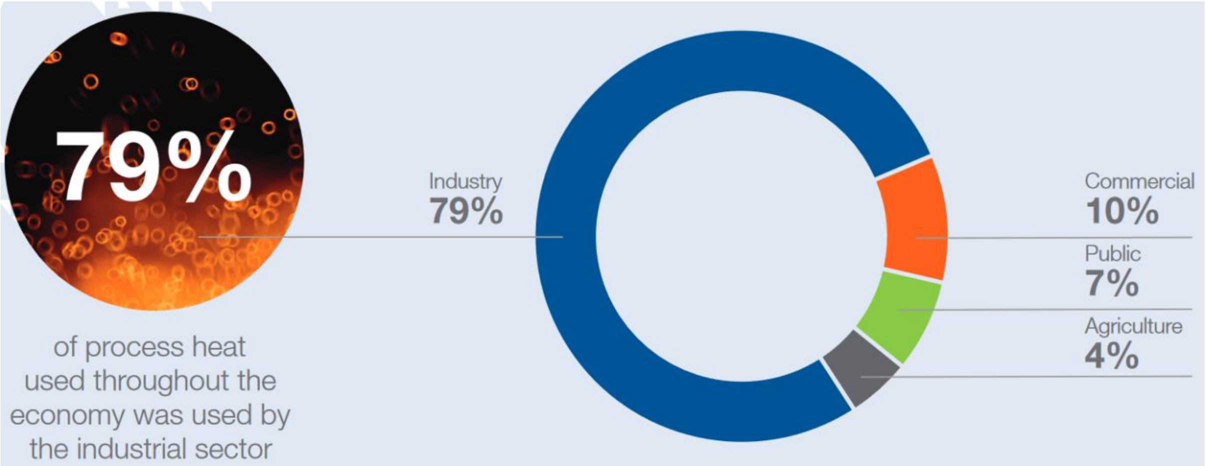


Figure 2. Process heat energy consumption by high level sectors in 2016 (MBIE, 2016).

Also, Figure 3 showed natural gas and coal together comprised 49% of total energy consumption for process heat with 38% for natural gas and 11% for coal, which contributed 76% of the total amount of greenhouse gas emissions from process heat (MBIE, 2016). Based on that information, the process heat in New Zealand has great potential to be decarbonized by fuel switch.

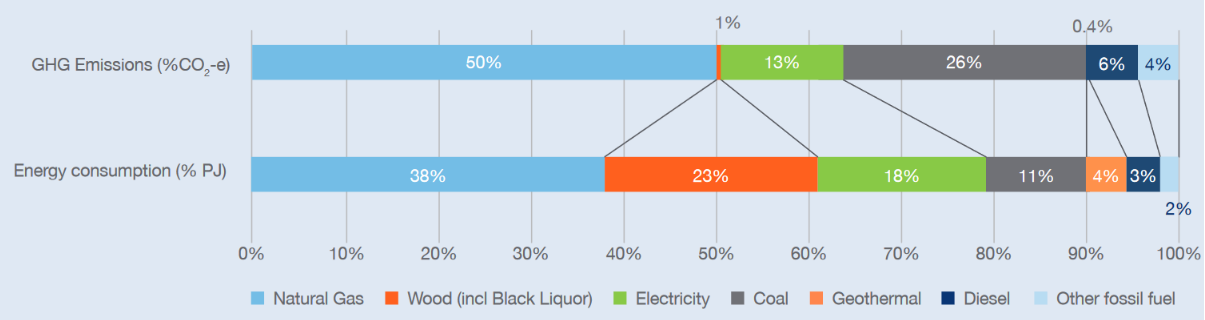


Figure 3. Energy consumption and GHG emissions from process heat in 2016-fuel type (MBIE, 2016).

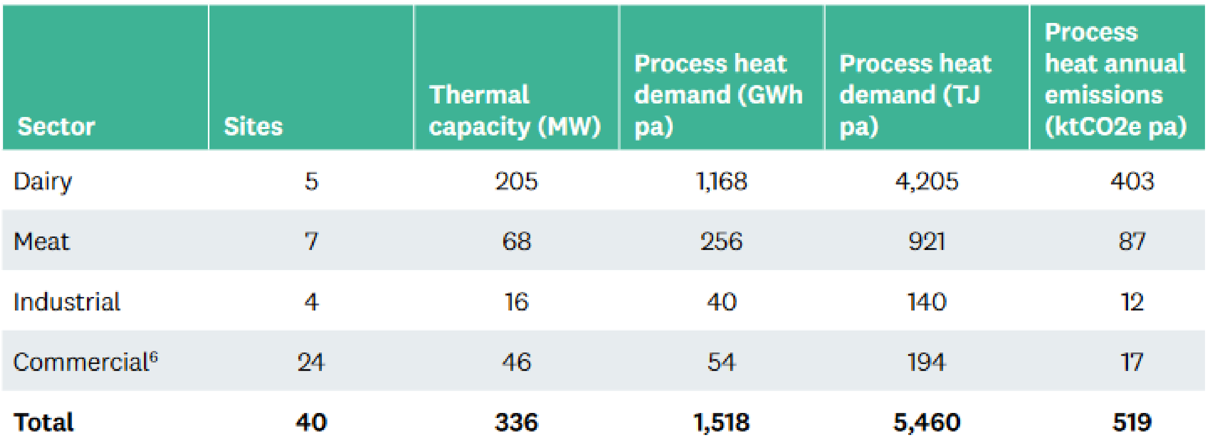
New Zealand is made up of two main islands that are long and slender, and the demand for process heat is quite variable from different locations. Types of energy resources chosen to use in certain industries are affected by geographical conditions. The overall process heat emission factor for New Zealand is 38.6 kt CO2-e/PJ with the Central North Island having the lowest process heat emission factor and the Auckland & Northland regions having the highest (Walmley et al., 2015). The Auckland and Northland region have high process heat demand and high regional process heat emission factor. The high emissions factor for the region is because of the presence of the steel mill, located in South Auckland near the black titanomagnetite iron sand resource, which is easy to be mined directly off

North Island West coast beaches. Also, the mines nearby are able to supply the coal needed in the steel mill, and natural gas is pumped to the mill by pipeline from the Taranaki area in the Central North Island. The Wellington and Hawke's Bay region has small heating demand, and the energy fuels are mainly from wood, natural gas, oil, and coal.

The process heat in South Island still highly relies on fossil fuel as the energy sources, which is similar to the one from North Island. Some regions in the South Island will be taken as examples to be reviewed.

The Southland region has relatively high energy demand and emissions. The main reason for that was due to the expansion of dairy farming and the dairy industries operating in this region. The 40 sites are covered in this calculation which was shown in the Table 1. These sites collectively consumed 1518 GWh/5460 TJ of energy, primarily in the form of coal, and currently produce 519 kt of greenhouse gas emissions (Energy Efficiency & Conservation Authority, 2022).

Table 1. The carbon emission from different sites in Southland (Energy Efficiency & Conservation Authority, 2022)



Sector	Sites	Thermal capacity (MW)	Process heat demand (GWh pa)	Process heat demand (TJ pa)	Process heat annual emissions (ktCO2e pa)
Dairy	5	205	1,168	4,205	403
Meat	7	68	256	921	87
Industrial	4	16	40	140	12
Commercial[6]	24	46	54	194	17
Total	**40**	**336**	**1,518**	**5,460**	**519**

Marlborough and Canterbury region mainly relies on coal, wood, electricity, and some oil as process heat energy supply, and that is because no natural gas pipeline in South Island. Nelson and the Central North Island tend to use wood as an energy supply because of the abundant biomass resources around these two areas.

Fossil fuels still play a critical role in the energy supply in New Zealand, and the price of fossil fuels will strongly influence the levels of carbon emissions reduction in the industrial process heat sector (Walmsley et al, 2014). Hall et al. (2022) presented appropriate management of energy resources and asserts could help to improve its environmental sustainability, particularly for industries which heavily rely on fossil fuels. Also, applying renewable energy sources to process heat sector in New Zealand can strongly help to reduce carbon emissions. These renewable energy sources include geothermal, solar thermal, biomass, renewable electricity from wind, solar PV, hydro, geothermal, biomass via combustion, wave and tidal (Walmley et al, 2015).

Atkins. (2019) presented there are two measures that can be used as options to reduce the carbon emissions for the process heat sector in New Zealand, with demand-side reduction measures and supply-side reduction measures. Demand-side reduction measures are ways to reduce the amount of heat required to produce the final products, and measures include energy efficiency improvement, process technology change, and modifying industry mix. Supply-side reduction measures are to provide industries with the same energy with lower carbon emissions, and methods include improving the efficiency of utility systems or using a lower carbon fuel rather than fossil fuels.

There are two sectors, which are food processing (including dairy) and the methanol industry, contribute a high percentage of carbon emissions for process heat in NZ. The food processing sector took up 31.2% of total emissions from process heat, and the Methanol industry had 20.3% (Atkins, 2019). On the other side, wood processing and kraft pulp industry play a significant role in the country's economy, but these two industries only took up 3.5% of total emissions from the process heat (Atkins, 2019). Therefore, finding proper ways to decarbonize food processing and methanol industry is quite important to achieve the goal of carbon reduction in the process heat sector in New Zealand. Also, how wood processing and kraft pulp industry meet the sustainability and environmental standards will be reviewed below.

Food industry

New Zealand has the largest and the most efficient milk powder dryer in the world, although there are still opportunities for carbon reduction in some areas such as heat efficiency improvement and fuel switch (Walmsley at el, 2018). Increasing heat recovery is one of ways to achieve efficiency improvement. A large amount of heat recovery can be achieved by increasing the heat exchanger surface area. For example, using exhausts from milk powder spray dryers to achieve heat recovery is a method to improve heat efficiency, but some economic and thermodynamic constraints still need to be overcome in further research and development (Atkins et al., 2011). Fuel switching is the other method to achieve carbon reduction, which involved replacing a currently used fuel with a lower emissions alternative. Capital cost and fuel cost played major roles in the economic viability of switching. Currently, wood-based biomass and grid-sourced renewable electricity were the two main options for the New Zealand industry for fuel switching (Atkins, 2019). Hydrogen, as a new green energy carrier, has not yet been considered in detail as a potential for process heat in New Zealand.

Therefore, it is a good opportunity to do a further study regarding whether hydrogen could fit the process heat sector from technical and economic perspectives.

Methanol industry

New Zealand has only one methanol manufacturer which is based in Taranaki. The methanol industry contributes the second largest amount of carbon emission in New Zealand. Methanol is produced by the steam reforming of natural gas to produce synthesis gas before being fed to the reactor that produces a methanol/water mixture. The main technology which is used to reduce carbon emissions in the methanol industry is the technology of carbon capture, storage, and utilization. The carbon dioxide captured from a power plant flue gas is employed to improve the stoichiometric number, methanol efficiency, and carbon efficiency and increase CO_2 conversion. The environmental analysis showed that there is 0.41 kg of CO_2 emitted with every kilogram of methanol produced by using CCSU technology (Ren at el., 2023).

Kraft pulp industry

Kraft pulp industry in New Zealand is an important component of country’s process heat sector. The primary raw material for the kraft pulp industry in New Zealand is wood, and New Zealand has an abundant forest resource around the country. There are several companies for kraft pulp industry in New Zealand. These industries include Oji Fibre solutions, Norske Skog, and Pan Pac Forest Products. Many pulp mills interconnect with kraft pulp production and Combined heat power (CHP) systems. The great amount of heat demand of the Kraft pulping process can be significantly supported by the CHP systems which generate heat and electricity at the same time (Mesfun & Toffolo, 2013). Meanwhile, the energy cost from Kraft pulping process is reduced and the energy efficiency from Kraft pulping process is increased.

There are reasons why kraft pulp industry in New Zealand release less emission compared to other process heat sector. One of them is renewable energy sources are used in the kraft pulp industry. For example, wood waste or black liquor (a byproduct of the pulping process) are applied into the Kraft pulp mill in Oji solution, which significantly reduce the carbon emission compared to the fossil fuels when burned (Ong at el., 2019). In Future, the technology of carbon capture and storage (CCS) can be investigated to see if more carbon emissions could be reduced in the pulp mill processes. Svensson at el. (2021) presented the pulp and paper industry has a great potential to contribute negative carbon emissions through CCS applied to existing processes. Also, implementation of other emerging technologies combined with CCS needs to be investigated to see how this target can be achieved in pulp and paper mills.

Decarbonising process heat sector is complicated in New Zealand. Technical and economic supports are essential for further progress. Also, policy decision makers play a critical role in guiding a proper way to help carbon reduction in the process heat sector. Fuel switch will be analysed in economic and environmental in perspectives in the next chapters.

2.4. Renewable fuels for process heat

2.4.1. Biomass and wood energy

Woody biomass energy is an important energy which can bring the country to a low-carbon economy. Compared to fossil fuels, the use of biomass can help industries reduce carbon emissions significantly for some stages. Some energy specialists offer different views regarding woody biomass energy use in the industry. Abbasi (2009) presented biomass perceived as a carbon-neutral source of energy unlike net carbon-emitting fossil fuels of which copious use has led to global warming and ocean acidification. There are quite a few woody resources available to be used, and these woody resources include fuel wood, sawdust, Bark, Briquettes, pellet, and demolition wood. Raymer (2005) pointed out that there was not much difference in avoiding greenhouse gas emissions from the different kinds of wood energy.

From an economic perspective, Atkins (2019) explained that the major component in the fuel price of the fuel price for biomass was the cost of transportation and rule of thumb was that distance higher than 100 km will be uneconomic. From the Figure 4 below, it showed the volume of wood residues available by regions in New Zealand. The Bay of Plenty has a relatively high take-up of wood residue compared to the ones from the other regions. Hence, in order to achieve more economic benefits from biomass fuel, factories that tend to use biomass as energy fuel may need to consider choosing a site closer to the area where wood residues have high volume density.

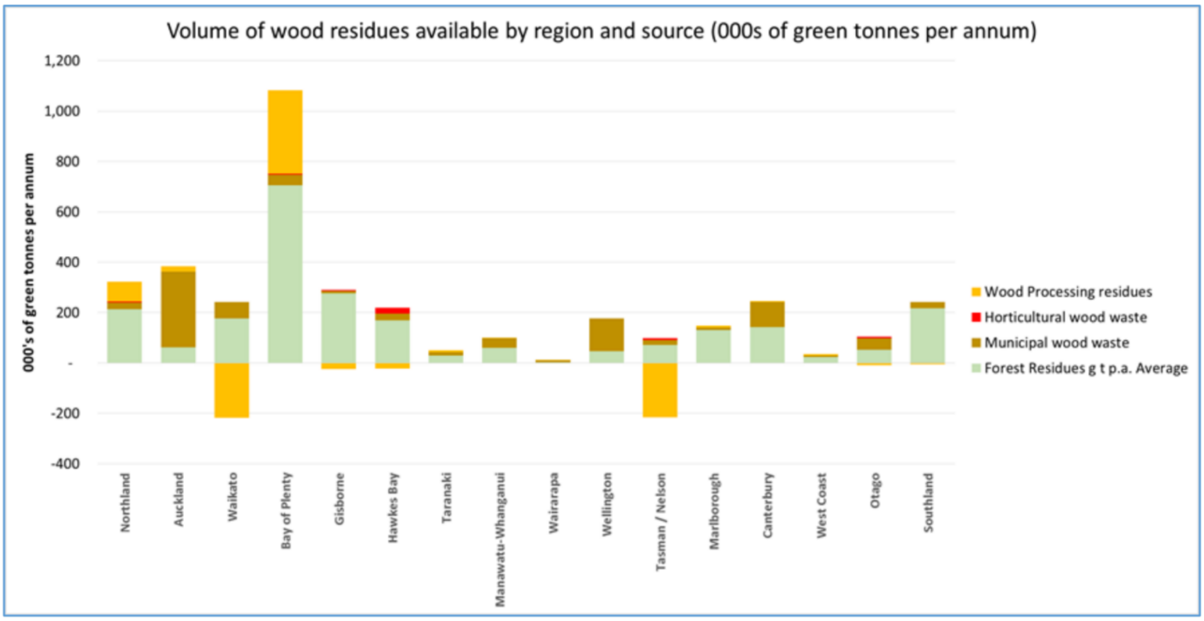


Figure 4. Estimated wood residue volume by region (Hall, 2017).

2.4.2. Renewable electricity

Renewable electricity comes from renewable energy resources such as the sun, wind, and hydro. Geothermal is also considered as the renewable. Renewable electricity makes sure there are no fossil fuels in its creation and no carbon dioxide emissions when it is generated (Mostafaeipour et al., 2022). In past years, many countries put efforts into developing renewable electricity in their countries' supply, which made some countries, such as New Zealand, have high proportions of renewable electricity (Atkins et al., 2010).

Many energy researchers hold positive views on the development of renewable electricity. Bogdanov et al. (2021) presented that the transition to using renewable electricity will result in substantial growth of the system efficiency and enable rapid reduction of greenhouse gas emissions. However, the acceleration of development in renewable electricity is affected by some factors, like policy guideline and carbon price. Daszkiewicz (2020) pointed out policymakers still played a critical role in transferring the global energy sector, even though there were significant benefits of emission reduction by using renewable electricity. Renewable Energy Standard (RES) and Renewable Energy Credit (REC) are two main policies that provided renewable electricity with market demand in some countries, like China. For example, the high setting of the REC policy and the increase in the price of REC will both increase renewable energy investment (Zhu et al., 2022). Hence, fossil fuel-based electricity will still take the dominant role in the whole electricity supply based on the example above, which means carbon emissions will be increased.

Carbon prices play a critical role in the emission reduction from the electricity sector. The increase in carbon price can result in a decrease in the merit order and dispatch of the power stations, which can result in high-emission plants taken out of operation or not being dispatched. Furthermore, increased carbon prices reduced the power demand from industry in response to increased electricity prices, which would result in a lower electricity supply from power stations. Hence, the carbon emission would be reduced in this situation. Especially, some countries, with high carbon emission factors from grid electricity, will have a strong impact due to the high carbon price (O'Gorman & Jotzo, 2014).

Wind power

Wind power is one of the most promising renewable energy technologies. There are numerous advantages of wind power such as rich resources, strong competitiveness, good capacity factors and climate change mitigation. Wind power has become an important new energy supply in many countries including Denmark, Spain, and Germany (Dai et al., 2017). However, the main disadvantage of wind energy is the working function relies on the weather conditions. Islam et al. (2013) presented some ways to deal with the electricity shortage from wind energy. One is to increase wind turbine capacity in different locations, and others are to use fuel cells and batteries to store electricity from wind energy. Poletti & Staffell (2021) pointed out that the geographical diversity of wind farms in New Zealand still needs to be strengthened, even though the average capacity factor over the existing and proposed wind farms in NZ is higher than the average capacity factor from Europe. The capacity factors from the different wind farms are shown Figure 5.

Wind generation is one of the cheapest ways of new electricity generation in New Zealand. The New Zealand Wind Energy Association (n.d.) estimated the baseline cost for onshore wind is expected to be declined by 25% from NZD$79 / MWh (2014 baseline) to NZD$58.50 / MWh by 2030 with a further decline to NZD$50 / MWh by 2050. Furthermore, the cost of wind energy-based electricity can be cheaper if subsidies can be contributed by the government. Currently, wind farms in New Zealand don’t receive subsidies. Because of this, developers only build a wind farm if the wind farm can produce electricity at a cost that has a competitive capacity with other forms of generation and meets the commercial returns set by the developers (Suomalainen et al., 2015). Many industries in New Zealand are connected to the national electricity grid (with approx. 80% renewable generation), but carbon emission still exists by using grid electricity.

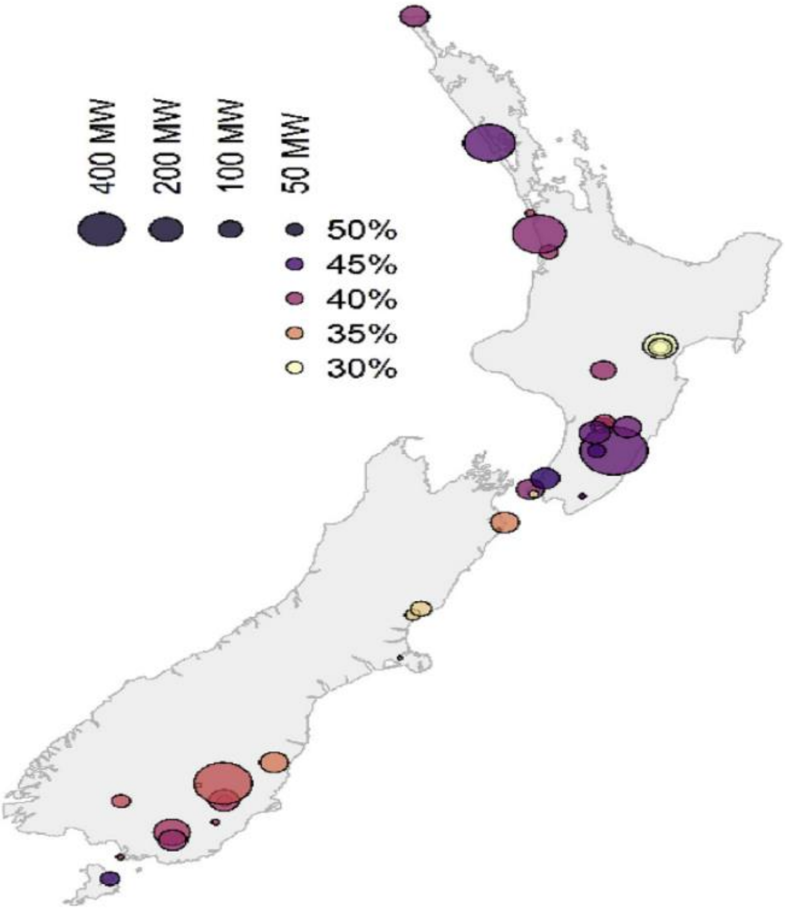


Figure 5. Map of capacity factors. Each circle represents a wind farm, with size proportional to capacity, and colour indicating capacity factor (Poletti & Staffell, 2021).

Solar energy

Solar electricity is a key component of the renewable electricity mixture. Also, solar electricity by Photovoltaics (PV) also has great potential to have a cost reduction. Shahri et al. (2020) presented that the cost of electricity from PV cells dropped by almost three quarters in the period between 2010 and 2017. Victoria et al. (2021) mentioned PV technology could be well-developed soon, because the PV extension will not be prevented by material or land. However, solar variability is one of the main issues during the process of PV development. Solar variability relates to time and location. Solar PV cannot be operated during nighttime, which means some industries need to look for other reliable energy sources as backup to make sure plants can operate 24/7 (Martin, 2022). Regarding to the locations, New Zealand has excellent solar resources, and radiation levels in New Zealand are significantly higher than those from some countries such as Germany and Japan which have the high level of solar PV deployment in the world.

Furthermore, governments' regulations and subsidies are also important to help PV development in their own countries (Anand et al., 2021). The largest PV markets internationally are currently grid-integrated and subsidized for the reason of economic development. However, in New Zealand, most PV projects are off-grid and not subsidized. Some projects are related to setting up solar PV as an alternative to diesel generators and in areas where a grid connection would be too costly.

The reason why the solar thermal is not included in this study is because the solar thermal is not used as energy sources to generate grid electricity in New Zealand. The primary energy sources which are used to generate grid electricity in New Zealand are coal, diesel, natural gas, geothermal, hydro, wind, and wood.

2.4.3. Hydrogen

Hydrogen can be classified into three types of categories which are grey hydrogen, blue hydrogen, and green hydrogen based on the carbon emission intensity(Brandon & Kurban, 2017). According to the IEA report, 60 % of hydrogen globally came from natural gas without CCUS (Carbon capture, utilisation and storage), 19% from coal, and all the rest from industrial by-products in year 2021 (IEA, 2023). Green hydrogen and blue hydrogen only take up with 1% of the global share. The Figure 6 below shows how the different production technologies are classified by colours (Yang et al., 2022)

This section will review the hydrogen production technologies based on their colours, which included factors of carbon emissions and production costs. Also, technologies of hydrogen storage and distribution will be reviewed in a couple of chapters below.

Hydrogen can be produced by different methods based on many different renewable and non-renewable sources. Meanwhile, the carbon dioxide emission and cost will be quite variable from that(Dawood et al.,2020).The Figure 6 below shows the different methods are used for hydrogen production. The technology of grey hydrogen production has more process methods than ones from the other colour types of hydrogen production. Nowadays, most of the hydrogen are still classified as grey hydrogen during the production, which results in a large amount of carbon dioxide emission present (Mosca et al., 2020). Therefore, it is quite important to apply low-carbon hydrogen into the real industry to achieve the Zero-carbon in near future. However, the low carbon hydrogen transition is an expensive process, because it requires new technology and high standards of equipment involved in the whole production (Mohammadi & Mehrpooya, 2019).

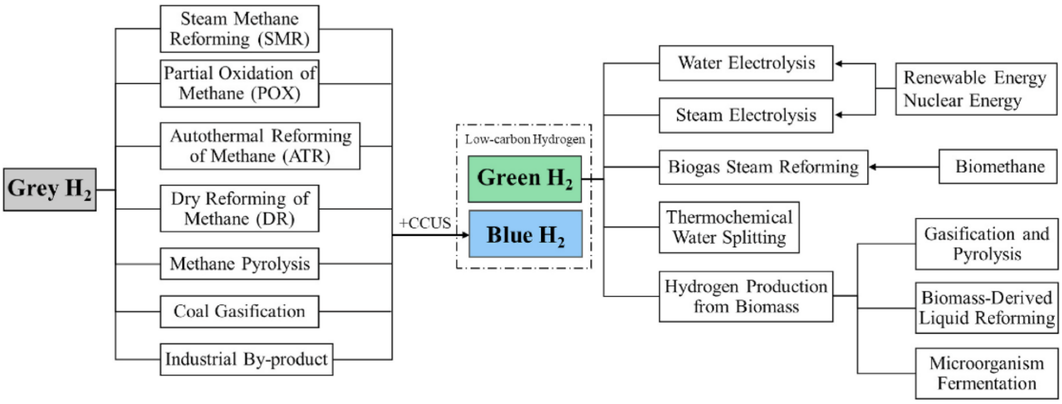
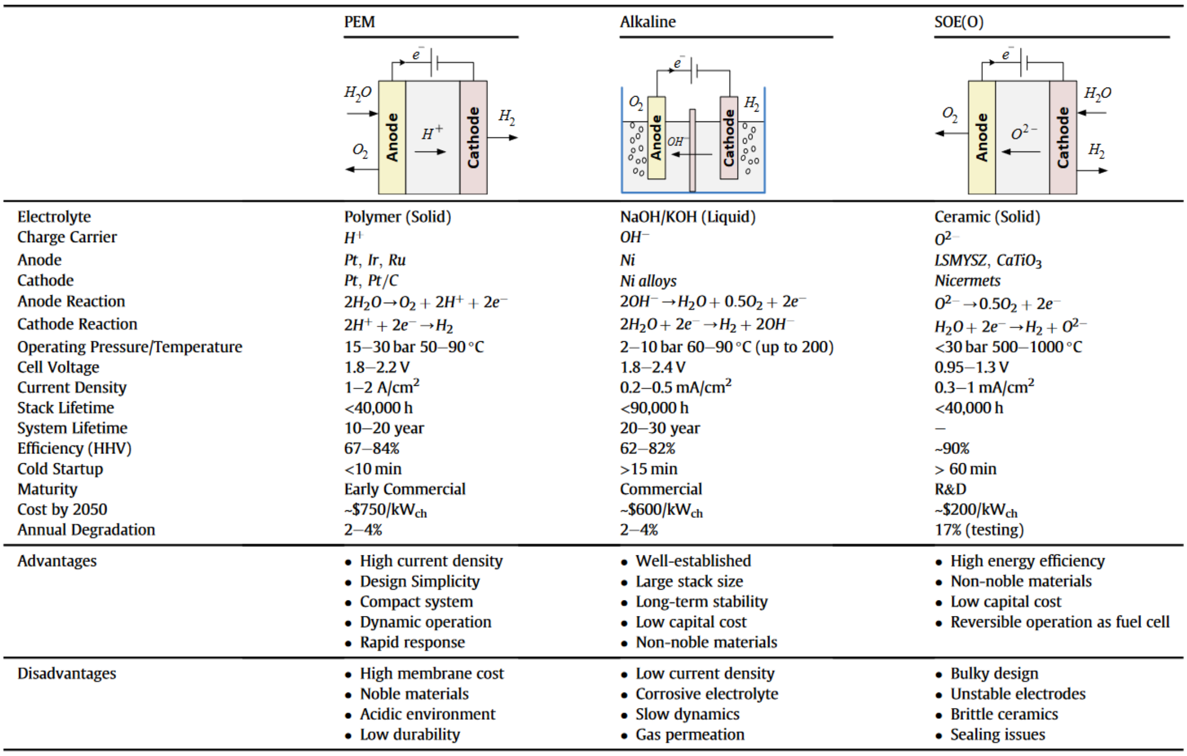


Figure 6. The classification of hydrogen production (Yang et al., 2021).

Green hydrogen

Green hydrogen production can be based on the electrolysis powered by the renewable electricity (wind, solar, hydro) or on biofuel such as biogas (Brandon & Kurban, 2017). From these renewable electricity sources, Bhandari et al. (2014) stated electrolysis by using hydro or wind sourced electricity was one of the best hydrogen production technologies from a life cycle assessment perspective.

What types of renewable electricity using in the hydrogen production is one of factors to affect the life cycle assessment of hydrogen fuel. Also, types of electrolysis applied into production is the other critical factors. Currently, there are three main types of electrolysis technologies available in the reality. They are alkaline electrolyser (AEC), proton exchange membrane (PEM) electrolyser and solid oxide electrolyser (SOEC). Chi and Yu (2018) showed the technical performance data of these three types of electrolysis technologies in the Figure 7 below. The main focuses in this table would be the maturity, efficiency and the cost for these three technologies.



	PEM	Alkaline	SOE(O)
Electrolyte	Polymer (Solid)	NaOH/KOH (Liquid)	Ceramic (Solid)
Charge Carrier	H^+	OH^-	O^{2-}
Anode	*Pt, Ir, Ru*	*Ni*	*LSMYSZ*, $CaTiO_3$
Cathode	*Pt, Pt/C*	*Ni alloys*	*Nicermets*
Anode Reaction	$2H_2O \rightarrow O_2 + 2H^+ + 2e^-$	$2OH^- \rightarrow H_2O + 0.5O_2 + 2e^-$	$O^{2-} \rightarrow 0.5O_2 + 2e^-$
Cathode Reaction	$2H^+ + 2e^- \rightarrow H_2$	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$	$H_2O + 2e^- \rightarrow H_2 + O^{2-}$
Operating Pressure/Temperature	15–30 bar 50–90 °C	2–10 bar 60–90 °C (up to 200)	<30 bar 500–1000 °C
Cell Voltage	1.8–2.2 V	1.8–2.4 V	0.95–1.3 V
Current Density	1–2 A/cm²	0.2–0.5 mA/cm²	0.3–1 mA/cm²
Stack Lifetime	<40,000 h	<90,000 h	<40,000 h
System Lifetime	10–20 year	20–30 year	–
Efficiency (HHV)	67–84%	62–82%	~90%
Cold Startup	<10 min	>15 min	> 60 min
Maturity	Early Commercial	Commercial	R&D
Cost by 2050	~$750/kW$_{ch}$	~$600/kW$_{ch}$	~$200/kW$_{ch}$
Annual Degradation	2–4%	2–4%	17% (testing)
Advantages	• High current density • Design Simplicity • Compact system • Dynamic operation • Rapid response	• Well-established • Large stack size • Long-term stability • Low capital cost • Non-noble materials	• High energy efficiency • Non-noble materials • Low capital cost • Reversible operation as fuel cell
Disadvantages	• High membrane cost • Noble materials • Acidic environment • Low durability	• Low current density • Corrosive electrolyte • Slow dynamics • Gas permeation	• Bulky design • Unstable electrodes • Brittle ceramics • Sealing issues

Figure 7. Characteristics and specification of promising electrolysis technologies (El-Eman & Özcan, 2019).

The efficiency of electrolysis keeps increasing with the increase of temperature during the production. Chi and Yu (2018) pointed out that the temperature ranges from AEC, PEM and SOEC are 20-80℃, 20-200℃ and 500-1000℃. SOEC is a promising technology due to its high energy conversion efficiency, but the method of SOEC is not mature enough and still in the R&D stage (Chi & Yu, 2018). Compared to SOEC, AEC and PEM have relatively lower efficiencies which are between 62% and 84%, and the difference between AEC and PEM is not significant. AEC technologies is in the commercial stages, but the PEM is still in early commercial. Hence, AEC would be the preferred option in the process of electrolysis for the point view of efficiency and maturity.

The cost of the process of electrolysis is also an important factor which needed to be focused. Sapountzi et al. (2017) noted that the key challenge for the green hydrogen was currently combined with the high cost. The price of green hydrogen was influenced by some factors such as the cost of electrolysers and the price of green electricity (Yu et al., 2021).

The cost of electrolyser is a critical element. As the Discussion above, the electrolyser with high efficiency (SOEC) are still required for a great amount of investment to achieve the commercial scale (Sapountzi et al., 2017).

The other factor which influences the cost of green hydrogen is the price of the renewable electricity. Scaling up wind and solar power generation is quite important to reduce the cost of renewable electricity (Yu et al., 2021).

Blue hydrogen

Blue hydrogen is a low-carbon hydrogen which is produced from fossil fuels with the technology of CCUS (Brandon & Kurban, 2017). CCUS means carbon capture, utilisation and storage. Many countries treat blue hydrogen as an economically advantageous and feasible method acceptable for their current industries.

There are many good comments from scholars and specialists in hydrogen production field. Novotny (2022) in his report, found that blue hydrogen derived from fossil fuel connected with CCUS would play an important role in the future transition period, which was mainly because the blue hydrogen was cheaper than green hydrogen now. Pettersen et al. (2022) pointed out greenhouse footprint for end-users based on blue hydrogen will be around 80%-90% lower than for direct supply and use of natural gas. One the other side, Beuerm et al. (2022) posited blue hydrogen was not actually a low carbon fuel without additional CO2 removal. The current practices of extracting fossil methane and converting it to hydrogen are not “blue” and are very far from “green” (Novotny, 2022).

Some Blue hydrogen projects have been already processed in some area in the world, even though the CCUS technology is still in the early stage of technical maturity (Yu et al., 2021). Based on the global carbon capture and storage institute’s 2018 global CCS report, there are 18 large CCS project running at this stage. United stated has ten projects, Canada has two, Norway has two and China has one. Also, Khan et al. (2021) demonstrated Australia has a good opportunity for developing blue hydrogen hub. Oni et al. (2022) talked about Alberta, in Canada, has resources and technology capacity to capture, transport, and sequester CO2 produced from natural gas-based hydrogen production pathways. 14.6 million tonnes of CO2 is captured and sequestered by the Alberta carbon trunk line every year.

Even through blue hydrogen technologies started to be applied into some projects, it still faces some challenges at this stage (Lowes & Rosenow, 2021). Challenges mainly come from high fugitive CH4 emission and low CO2 capture rate (Beuerm et al., 2022). From Table 2, Howarth & Jacobson (2021) illustrated greenhouse gas emission from the production of blue hydrogen were quite high, which was due to the release of fugitive methane. The Fugitive methane come from SMR process, energy to drive SMR and energy to power carbon capture. Also, the efficiency of carbon capture still has a far way to go to actually help blue hydrogen to become low carbon fuel (Domínguez et al., 2022).

Table 2. The amount of carbon emission and CH4 consumed in the process of blue hydrogen generation (Howarth & Jacobson, 2021).

	Blue H2 (w/flue-gas capture)
SMR process	
CH_4 consumed (g_{CH4}/MJ)	14.0
CO_2 produced (g_{CO2}/MJ)	38.5
Fugitive CH_4 emission(g_{CO2eq}/MJ)	42.1
CO_2 capture rate(g_{CO2eq}/MJ)	**85%**
Energy to drive SMR	
CH_4 consumed (g CH_4/MJ)	11.6
CO_2 produced (g CO_2/MJ)	31.8
Fugitive CH_4 emission(gCO_2eq/MJ)	35.3
CO_2 capture rate(gCO_2eq/MJ)	**65%**
energy to power carbon capture	
CH_4 consumed (g CH_4/MJ)	6.0
CO_2 produced (g CO_2/MJ)	16.3
Fugitive CH_4 emission(gCO_2eq/MJ)	18.1
Indirect upstream CO_2 emission (g CO_2/MJ)	6.5
Total CH_4 consumed(g CH_4/MJ)	**31.6**
Total CO2 Emitted (g CO_2/MJ)	39.7
Total fugitive CH4 emission (gCO_2eq/MJ)	95.4
Total emission (gCO_2eq/MJ)	**135**
The carbon emission factor (tCO_2-e/GJf)	**0.135**
Note: the methane leakage rate is 3.5%	

2.4.4. Hydrogen blend

Hydrogen blend is quite new concept in the reality. It is basically a blending with natural gas which is delivered through current natural gas pipeline to public (Mahajan et al., 2022). Currently, many global academic institution, industry and governments are doing support for the development of hydrogen blend all around the world. Notional Renewable Energy Laboratory (2013) showed adding hydrogen to natural gas could greatly reduce the greenhouse emission if the hydrogen was produced by renewable energy sources such as solar, wind, biomass or fossil resources with carbon capture and storage. Pellegrini et al. (2020) presented that blending hydrogen into natural gas network was good for reduction of carbon emission in whole environment and society, but it is still facing technological and economical barriers. Erdener et al. (2022) talked about blending hydrogen into the existing natural gas pipeline network was a promising strategy for incorporating hydrogen in the near future, but the challenge with the ability of current gas infrastructure to operate with blended hydrogen level need be considered.

The scientists and specialists above have provided the public with their professional findings regarding the hydrogen blend. Now, some specific points will be reviewed and discussed below.

Benefits of hydrogen blending

Firstly, hydrogen blending can not only reduce the carbon emission, but also add more heat value to the existing energy supply (Mahajan et al., 2022). From the Figure 8 below, it shows low heat value (LHV) doesn't have significant increase when the blend ratio increases to 80%. After that, LHV have big jump to 120 MJ/kg when the mixture ratio increases to 100%.

Secondly, end-use application doesn't need to have vital modification when the mixture of hydrogen blend is below 20% (Sorgulu & Dincer, 2022). Also, when the mixture ratios need to be between 0%-30, the overall efficiency of appliance changed only about 1-1.5% using the hydrogen blend fuels (Glanville et al.,2022).

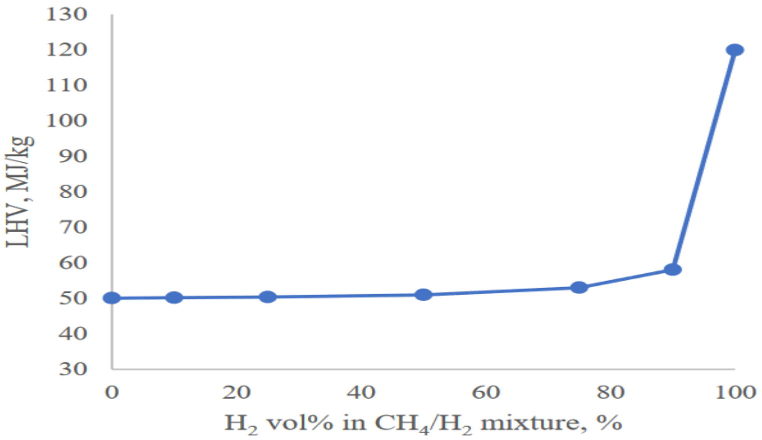


Figure 8. H_2 vol% in CH_4/H_2 mixture (Flekiewicz & Kubica, 2012).

Challenge of hydrogen blending

There are some challenges in the process of hydrogen blending, which will include environmental & safety impacts from leakages in pipe joints and variable hydrogen production costs (Erdener et al., 2022).

The leakages in pipe joint mainly come from the failure of cracked pipeline. Hydrogen embrittlement of steel pipelines in contact with the hydrogen environment, together with the transient gas flow and significantly increased transient pressure value increased the possibility of a cracked pipeline (Bouledroua et al., 2020). Kurz et al. (2019) pointed out hydrogen blending become more flammable with the increase ratio of mixture, which bring the huge risk of gas exploration if the leakage happen on the pipeline. Also, the methane from the leakage gas would release extra carbon emissions to the environment.

The production costs of hydrogen blend become higher with the increase of mixture ratios. Hydrogen production via electrolysis is currently around 5 USD/Kg-7 USD/Kg, and is influenced by various technical and economic factors such as, capital costs, conversion efficiency and electricity cost and carbon prices (Erdener et al.,2022)

2.5 Grid electricity

2.5.1 Formation

There are several ways of electricity generation used in the electricity grid. They include fossil fuel-based energy (coal, natural gas and diesel), renewable energy (hydro, wind and solar and geothermal) and nuclear power. The generation process and theory are different by using different fuel type in certain way of electricity generation.

Fossil fuel-based energy

The fossil fuels (coal, natural gas and diesel) are burnt in the power plants to generate the steam which is used to drive turbines in the generators (Bogdanov at el, 2021). Then, the mechanical energy from the generators is converted into electricity energy. That is the basic process regarding how the fossil fuel-based electricity is produced. After that, the electricity will be distributed to customers by feeding them into the electricity grid.

Renewable energy

The hydroelectricity is generated by the rotation of blades of turbine which is driven by the fast-moving water flow. Normally, the hydroelectricity is generated in large hydroelectric power plants which are located around the rivers, lakes and reservoirs.

The wind sourced electricity is generated by the rotation of blades from the wind turbines. The wind farms are generally located in the places which are enriched with high-speed wind.

Solar electricity is generated by using the energy of sunlight through solar panel. The solar panel is made of multiple photovoltaic cells and the material of the photovoltaic cell is usually silicon.

Figure 9 shows geothermal electricity is generated by using the heat from the earth's interior. The turbine connected with the generator is driven by the steam which is converted from high-pressure hot water in the geothermal reservoir. After that, the low-temperature water with low pressure will be re-injected into underground. Also, the geothermal electricity will be contributed to the customers by electricity grid.

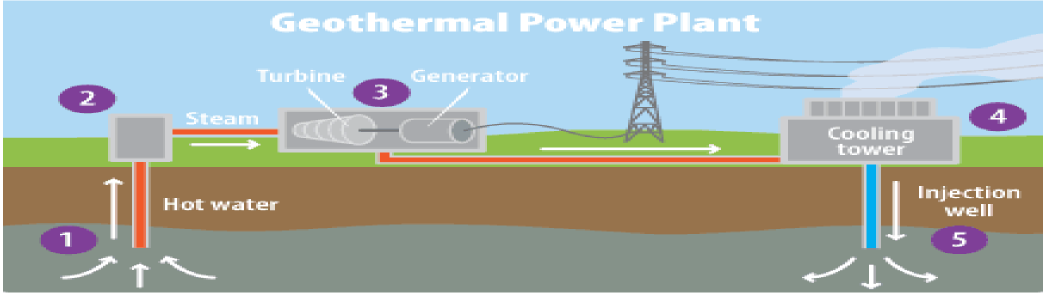


Figure 9. The workflow of geothermal power plant (EPA, n.d.).

Nuclear energy

Figure 10 shows nuclear electricity is the electricity generated by using the energy from the nuclear reaction. To be specific, the electricity is produced through the electromagnetic induction which is driven by the rotation of turbines connected with generator. The turbines are rotated with the help from the energy of steam. The nuclear fission reaction produces heat which is used to heat up water to create steam.

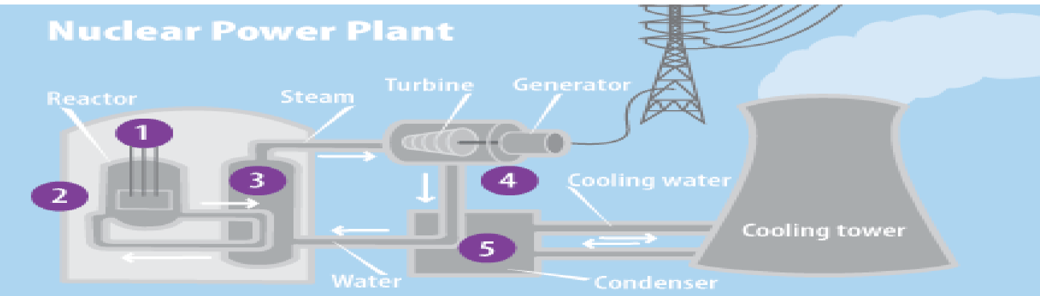


Figure 10. The workflow of nuclear power plant (EPA, n.d.).

2.5.2 Energy integration in the grid electricity

Energy integration in grid electricity is to incorporate different sources of energy into the electricity grid to meet the electricity demand. The energy demand and supply are balanced by different types of fuel sources which includes fossil fuels, renewable energy sources, nuclear energy sources. The main purpose of energy integration is to supply sustainable and stable electricity to customers by using different fuel sources (Mathiesen at el, 2015).

Renewable energy integration

There are some advantages from the renewable energy integration. Firstly, Mohamed et al. presented that integrating renewable energy sources into the grid system can help to reduce the cost of sources required for building extra generators, and the power quality got improved as well. Secondly, renewable energy integration can help to reduce the carbon emissions compared to the fossil fuel-based energy sources. However, there are some challenges from the renewable energy integration. For example, Ahmed et al. presented the integration of wind energy into the existing electricity grids posed operational and control challenges that hamper the reliable and stable operation of grid.

Smart Energy management system

Smart energy management system can improve the function of energy integration in the grid electricity. There were some strategies which could help with the management system. The first is to minimize the system energy loss. The second one is to reduce demand from customers' side. The second strategy is hard because customers need to be introduced to proper ways to reduce demand. The third one is to increase profit, reduce cost and improve utility in terms of electricity generation. The last one is to control the emission by good energy integration, which is the key to achieve the carbon reduction (Mohamed et al, 2015).

2.5.3 Carbon Emission

The level of carbon emissions, or the carbon emission factor of electricity, is the key indicator of cleaner electricity production. There are several studies about the electricity production-based greenhouse gas emissions in the published literature. These studies are related to different topics, like how to calculate carbon emission factor of grid electricity, what factors will impaact the carbon emission factor of grid electricity, carbon emission factors in different countries etc.

Carbon emission factor calculation

Craus and Worrell (2011) compared five methods for calculation of carbon emission factor of power generation, based on different ways to consider combined heat and power generation. These five methods include "power and heat generation", "power generation", "power loss factor", "substitution principle", and "exergy method". In the example, the method of "power and heat generation" brought the lowest emission factors at 252 g/kWh, which is 45% lower than the emission factor calculated by the method of "power generation" which is 448 g/kWh. Craus and Worrell (2011) also investigated the carbon emission factors produced by electricity generation for near 100 countries. It come with a conclusion that the method chosen can have a big impact on carbon emission factor for countries which have large numbers of combined heat and power plants.

Ang and Su (2016) used the term of aggregate carbon intensity (ACI) to present carbon intensity for electricity at global and country level. The ACI is defined as the energy-related carbon emission in the electricity production divided by the electricity produced. The equation below shows how the ACI is calculated. The unit for the ACI is kg CO_2/kWh.

$$V = \frac{C}{G} = \sum_i \frac{Q}{G} \cdot \frac{Q_i}{Q} \cdot \frac{F_i}{Q_i} \cdot \frac{C_i}{F_i}$$

Where V, C, G and Q are respectively the value of aggregate carbon intensity, the total carbon emission, electricity production and electricity production from fossil fuels. Q_i is the electricity production from the fossil fuel i, and F_i and C_i are the associated energy input and carbon emissions.

Long at el. (2015) presented the other equation to calculate the carbon emission. The equation is shown below.

$$C = \sum_{i=1}^{n} C_i = \sum_{i=1}^{n} A_i B_i D_i (1 - E_i) F_i \times \frac{44}{12}$$

Where C is the total carbon emission, i refers to energy types, and C_i is the carbon emission of energy i. A_i is the consumption of energy i. B_i id the conversion coefficient of energy I to standard coal, and D_i is the carbon emission factor of energy i. E_i is the carbon sequestration rate of energy i, and F_i is the oxygenation efficiency of energy i. 44/12 is the carbon conversion factor. The calculation above is used to analysis the carbon emission level in Jiangsu province which is one of big province with strong economy in China.

Impact on grid carbon emission factor

There are several factors which could impact the carbon emission factor from grid electricity generation. Shrestha and Timilsina (1996) investigated the roles of changes in generation mix and fuel intensity to the changes in carbon intensity of thermal power generation in 12 selected Asian countries. They found that the fuel intensity was mainly responsible for the changes in carbon intensity of electricity generation in 8 out of 12 selected Asian countries. Fuel intensities (kg/kWh) of coal and diesel-based electricity generation were decreasing in most of countries, which made the grid carbon emission factor have the decreasing trend as well. There is equation which shows how the fuel intensity is calculated.

$$f_{it} = \frac{F_{it}}{Q_{it}}$$

Where f_{it} is fuel intensity of power generation based on fuel type i in the year t; F_{it} is the amount of fuel type i used for power generation in the year t; Q_{it} is the amount of electricity generation based on fuel type i in year t.

Each country has different strategies for grid electricity production, which would impact the carbon emission factor of electricity in different countries. Scarlat at el. (2022) presented there was a significant decrease in the carbon emission factor of grid electricity in most European countries, mainly due to the increased use of renewable energy such as biogas, solar, wind, and solar. This trend will continue, which was driven by the policies targeting the decarbonization of the energy sector. Furthermore, nuclear energy can help to reduce carbon emissions in terms of electricity generation. For example, the carbon emission factor for grid electricity generation in Japan increased from 416 g CO_2/KWh in 2010 to 548 g CO_2/KWh in 2012 as the share of nuclear power in the nation's generation mix fell from 26% in 2010 to 1.1% in 2012 (World Bank, 2015). China is a country that has a big consumption of electricity, so the carbon emission from electricity generation will have a significant impact on the climate change. Pend and Tao (2018) presented the technological innovation and structural adjustment were two main keys to reduce carbon emission factor during electricity production in China. Also, developing renewable energy is the major measure for reducing carbon emissions from China's power industry in the next few decades. Cheng and Yao (2020) found the carbon intensity was significantly reduced by 0.051% with every 1% increase in the innovation level of renewable energy technology.

Absolute emission approach from the electricity grid

There is a large growing body of literature that investigated carbon emission by using the absolute emission approach or the average carbon emission factor, measured in the tonnes of carbon dioxide equivalent (CO_{2-e}). Based on the literature review, the average carbon emission factor from the grid is quite often used to do the comparison of total carbon emissions in different countries or in different years. Su and Ang (2016) presented the value of the carbon emission factor of electricity production in 124 countries from the year 1990 to 2013. Poland had the largest grid carbon emission factor at around 1.1 kg_{CO2}/kWh on average. Furthermore, the absolute carbon emission approach could be used to measure the annual carbon emissions in different years. For example, Ozcan (2016) presented that the total amount of carbon emissions was 146.019 Mt in the year 2013 and 165.258 Mt in the year 2015, and the annual carbon emissions were calculated from electricity generation according to fuel types in the year 2013 and year 2015.

Time-varying grid carbon emission factor

It is known that the carbon emission factor from grid electricity fluctuates with both hour and day. Thousands of different values can be generated for carbon emissions in the actual context, which is caused to be released to natural for two enterprises with equal electricity consumption on annual basis (Coskun, 2019).

2.6 Conclusion

The literature offers the details about the current situation of carbon emissions from process heat sector in New Zealand and all around the world. The current New Zealand process heat sector still relies on the fossil fuels as the energy sources. That means there is quite important to decarbonize process heat sector, and energy switching to renewable energy sources is one of efficient solutions to achieve that.

Hydrogen and hydrogen blend, as energy sources, are costly, but they have great potential to help to reduce carbon emissions. Biomass is a low carbon fuel, but the use of biomass is restricted by the distance between factories and biomass process sites, because transportation of biomass fuels will release carbon emissions as well. Wind energy become more important to generate electricity in New Zealand, and the cost of wind-base electricity has decreasing trend in next few decades. Furthermore, the carbon emission factor of grid electricity is influenced by using energy sources for electricity generation. In many countries, average carbon emission factor of grid electricity is used to calculate total annual amount of carbon emissions from grid electricity. On the other side, the time-varying grid carbon emission factor is quite useful to assess the real-time change of carbon emissions from grid electricity.

3. Techno-economic Evaluation of Low Carbon Fuels for Process Heat

3.1. Introduction

Many countries and industries try to use low-carbon fuels to replace fossil fuel to reduce carbon emission from the business side. For example, Fonterra have strategies to use biomass boilers to replace coal boilers in the several sites. Hot water heat pump and steam heat pump are also important focus to achieve decarbonisation from some areas in business. Also, Fonterra has recently received $90 million government funding to achieve 50% reduction in emission by 2023 from a 2018 baseline, which is 20% increase from Fonterra's previous target (New Zealand Government, 2023). Fuel switching is a quite efficient way to help to reduce carbon emission in the area of process heat, but the capital and energy cost from new fuels may be much more expensive than the current fossil fuels.

To examine the economic feasibility of fuel switching an industrial plant with a 10 MW constant process heat demand will be considered. The plant is supplied with thermal energy via steam which is generated through combustion in a conventional boiler. There are seven types of low carbon fuel types supplied to the site using the scenarios below. Natural gas will be used for comparison as a base case.

The techno-economic evaluation would be taken for further discussion in these different fuel types. The main focus would be on carbon emission factor, overall energy conversion efficiency, and capital and energy costs. For the carbon emissions, the actual carbon emissions level can be fully present by two measures which are "carbon emission factor from fuel" and "carbon emission factor from energy delivered to plant". For overall energy conversion efficiency, it shows which fuels can bring better efficiency in their own energy systems which are shown in the flow charts from Figure 11 to Figure 17. For capital and energy costs, it presents the difference of cost in different energy systems, and the capital and energy costs come from the capital of boilers and the cost of the fuels consumed during operation. Furthermore, the sensitivity analysis will be conducted regarding the hydrogen blend generated by electrolyser, and sensitivity analysis is based on "carbon emission", "overall energy conversion efficiency" and "capital & energy costs".

3.2. Economic and environmental analysis method

The carbon emission of process heat produced using several fuel sources are considered. Capital & energy cost and overall energy conversion efficiency (defined below) are used to compare different fuels sources. The fuel sources and scenarios that were considered are described in detail below and included:

- Natural gas (as a reference or base case)
- Wood pellets
- Grid sourced electricity in electrode boilers
- Green hydrogen blended with natural gas
- Green hydrogen
- Blue hydrogen
- Grid sourced hydrogen

3.2.1. Carbon emission factor

The carbon emission factor (ε) is a coefficient that describes the rate which a given activity releases greenhouse gas into the atmosphere. For example, the emissions factor for fuel (ε_f) is defined in Equation 2.1 and is the ratio of mass of carbon emissions emitted to energy content of the fuel use.

$$\varepsilon_f = \frac{m_{CO2-e}}{E_f} \tag{2.1}$$

Where: ε_f = carbon emission factor of the fuel [$t_{CO2\text{-}e}/GJ_f$]

$m_{CO2\text{-}e}$ = mass of carbon emissions emitted [$t_{CO2\text{-}e}$]

E_f = total fuel energy [GJ]

Table 3. Carbon emissions factor for fuels (input energy)

Fuel	Carbon Emissions Factor for fuel, ε_f, [$t_{CO2\text{-}e}/GJ_f$]
Natural Gas	0.054
Wood pellets	0.004

Electricity Carbon Emissions Factor

The carbon emissions factor for electricity is calculated using the mixture of generation sources which include coal, natural gas, oil, renewable sources (wind, solar, hydroelectric, and geothermal power). This is sometimes referred to as the grid emissions factor but here the term of electricity carbon emission factor will be used and present as $\varepsilon_{elec.}$ The New Zealand electricity carbon emission factor is 0.030 $t_{CO2\text{-}e}$/GJ in year 2020 (Ministry of the Environment, 2022).

Carbon emissions factor for hydrogen

The carbon emissions from the production of hydrogen are dependent on electricity carbon emissions factor, carbon emission factor of natural gas, and electrolyser efficiency. Based on Equation 2.1, the carbon emission factors for different types of hydrogen are shown in Table 4. Also, the results are calculated based on the electrolyser efficiency with 80%.

Table 4. Carbon emissions factor for different types of hydrogen.

Type of Hydrogen	**Carbon Emissions Factor for fuel, ε_f, [$t_{CO2\text{-}e}/GJ_f$]**	**Input fuel/energy**
20% green hydrogen blended with natural gas	0.050	Renewable electricity & natural gas
Green hydrogen	0.000	Renewable electricity
Blue hydrogen	0.135	Natural gas
Grid sourced hydrogen	0.037	Grid electricity

A carbon emissions factor for each unit of energy delivered to the plant (ε_d) is the ratio of the amount of carbon emissions emitted to total energy delivered to plant as shown in Equation 2.2.

$$\varepsilon_d = \frac{m_{CO2-e}}{E_d} \tag{2.2}$$

Where:

ε_d = carbon emission factor about energy delivered to plant [$t_{CO2\text{-}e}/GJ_c$]

$m_{CO2\text{-}e}$ = mass of carbon emissions emitted [$t_{CO2\text{-}e}$]

E_d = total energy delivered to plant [GJ]

3.2.2. Conversion efficiency

Conversion efficiency is a term used to describe the amount of useful energy output that results from a given energy input in a device used to convert energy from one form to the other. If a boiler is used, then the efficiency will be a ratio of the energy in the steam from the boiler to the energy content of the fuel used as in Equation 2.3. Also, the efficiency around the energy delivered to plant will be ratio of the total energy delivered to plant to the energy content of the input energy sources used as in Equation 2.4.

$$\eta_{boiler} = \frac{E_s}{E_f} \tag{2.3}$$

Where: η_{boiler} = boiler efficiency [%]

E_s = energy in the steam [GJ]

$$\eta_d = \frac{E_d}{E_{Is}} \tag{2.4}$$

Where: η_d = efficiency of the energy delivered to plant [%]

E_d = total energy delivered to plant [GJ]

E_{IS} = total energy from input energy sources [GJ]

The input energy sources here include electricity and natural gas which are used to generate the hydrogen.

3.2.3. Capital and energy cost

The two main cost considerations are capital and energy costs. Other operating costs such as maintenance etc. can be assumed to be relatively minor. The annual cost of operating heat plant can be split into the capital and energy cost components by using an annualised capital cost and the energy component based on the specific fuels used. The annual cost can be calculated using Equation 2.5.

$$C_{CE} = Capex_A + C_E \tag{2.5}$$

Where: C_{CE} = annual capital and energy cost [NZD/y]

$Capex_A$ = annualized capital cost [NZD/y]

C_E = total energy cost [NZD/y]

Annualised capital cost

Smith (2005) shows capital cost can be expressed on an annual basis if it is assumed that the capital has been borrowed from bank over a fixed period at a fixed rate of interest, in which case the capital cost can be annualized using Equation 2.6.

$$Capex_A = C_b \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2.6}$$

Where: $Capex_A$ = annualized capital cost [NZD/y]

C_b = total capital cost of boiler [NZD]

i = fractional interest rate per year

n = number of years

The total capital cost of the boiler can vary significantly depending on the type of boiler and fuel used. Table 5 shows typical costs for different types of boiler systems with the wood pellet boiler having the highest capital cost compared to the other boiler types. The total capital cost can be calculated using Equation 2.7.

$$C_b = C_{SP} P_b \tag{2.7}$$

Where: C_b = total capital cost of boiler [NZD]

C_{SP} = cost per unit of heat output of boiler [NZD/MW]

P_b = heat delivery/capacity of boiler [MW]

Table 5. Capital cost for different boiler types

Boiler type	**Min. Single Price [NZD/MW]**	**Max. Single Price [NZD/MW]**
Wood Pellet	600k	800k
Electrode	200k	300k
Hydrogen/Natural gas	250k	400k

Levelized cost of energy (LCOE)

The cost of energy delivered to the plant can be calculated if the annual cost including the capital and energy cost divided by the amount of energy delivered to the plant as in Equation 2.8. This value is roughly equivalent to the levelised cost of energy (LCOE) which is calculated by taking the total life cycle cost of a boiler (e.g. capital, energy operating and maintenance costs, etc.) and dividing it by the total amount generated over the lifetime of the boiler. The time value of money is included in the calculation and both costs and energy generated are discounted using a specified discount rate. Here the operating and maintenance cost are not included in the calculation as they are assumed to be equal and do not make up major portion of the overall costs.

$$LCOE = \frac{C_{CE}}{E_d} \qquad \textbf{(2.8)}$$

Where: LCOE = Levelised cost of energy [NZD/GJ_d]

C_{CE} = annual capital and energy cost [NZD/y]

E_d = total energy delivered to plant [GJ]

3.3. Energy supply scenarios

There are several different scenarios for providing process heat in the form of steam to the plant that were examined. Each scenario is described in the following sections. The methods vary depending on the fuel sources used. The different fuels used in the system will make carbon emissions factor, conversion efficiency and capital and energy costs different for the different scenarios.

In all of the scenarios described below E_{IS} is the total amount of energy from input energy sources (e.g. electricity), E_f is the total amount of energy from the fuel, E_s is the total amount of usable energy contained in the steam, and E_d is the amount of energy which is delivered to plant for use. It is assumed that there is a 10% energy loss when the steam is transferred from boiler to plant.

Grid generated hydrogen

Figure 11 shows how hydrogen is produced as a fuel source to supply the boiler using grid sourced electricity as the input energy source. The process consists of four stages. Grid electricity, as the input energy source, is delivered to hydrogen production plant to generate the hydrogen fuel using electrolysis. After that, the hydrogen is delivered to hydrogen boiler to generate steam which will be then transferred to plant for use via pipeline. The whole process still has carbon emissions generated, because grid electricity has the carbon emissions during electricity production. It is assumed that the boiler using hydrogen would be very similar to a conventional natural gas boiler.

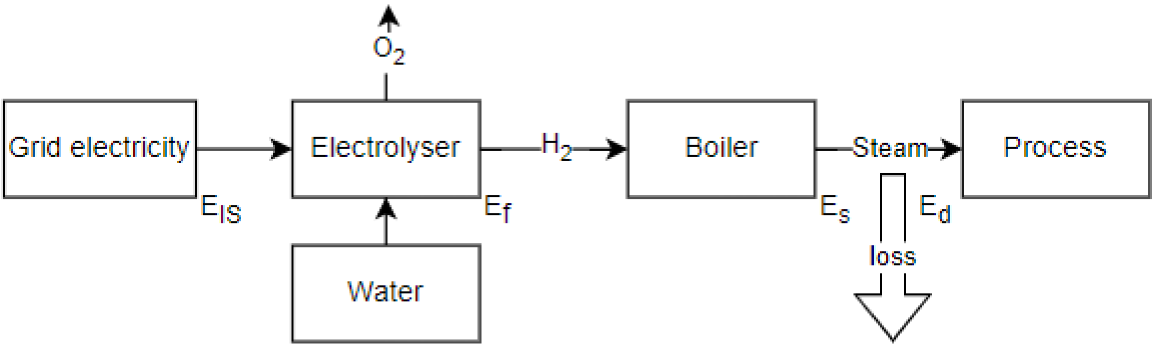


Figure 11. Hydrogen generation and delivery review.

Green hydrogen

Figure 12 presents how the plant is powered by using green hydrogen as fuel. The process is almost the same as the Figure 11 with the only difference being the source of electricity used to generate the hydrogen. In Figure 12, renewable electricity is generated by renewable energy (solar, wind or hydro), which means the whole process can be carbon neutral. Renewable electricity can be converted into hydrogen through the electrolysis of water, passing an electric current through water, to split into oxygen and hydrogen. Hydrogen can be delivered to the boiler by pipeline.

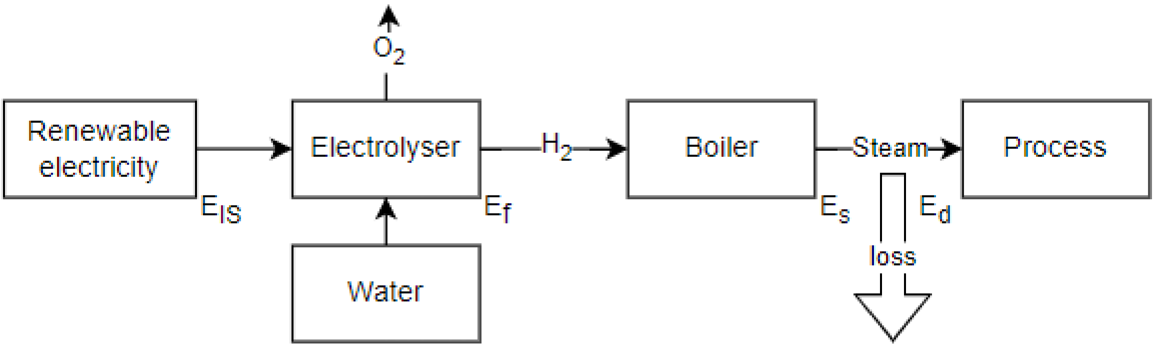


Figure 12. Green hydrogen generation and delivery review.

Hydrogen / natural gas blend

Figure 13 shows how green hydrogen could be blended with natural gas. Blended green hydrogen and natural gas has been considered as a possible way to reduce carbon emissions from natural gas and the blend ratios are typically 20% by volume. Firstly, hydrogen is generated by electrolyser with renewable electricity as in Figure 12 then blended with natural gas before being delivered to a pipeline. In this scenario, hydrogen is blended at a 20% by volume ratio.

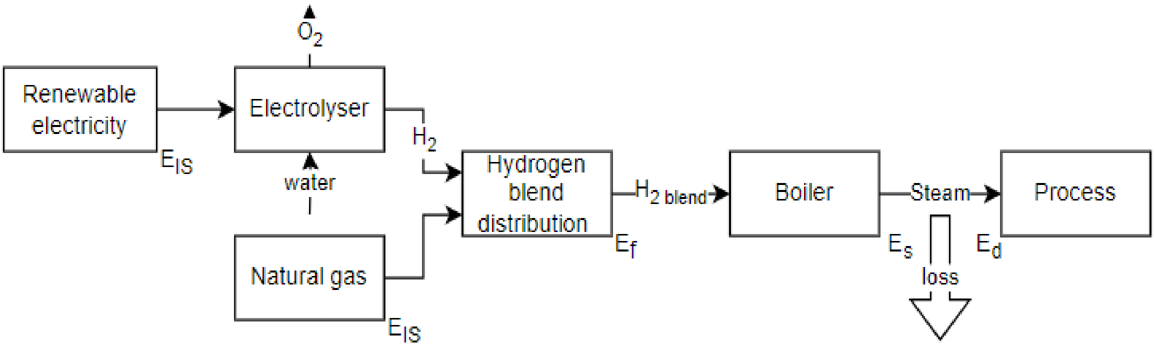


Figure 13.Blended green hydrogen & natural gas and delivery review.

Blue hydrogen

Figure 14 shows how blue hydrogen is produced and energy is delivered to the plant for the process. Most hydrogen produced today is made via steam-methane reforming (SMR process), followed by carbon capture and storage (CCS) to mitigate its carbon emissions. Hydrogen is delivered to boiler through hydrogen pipeline to generate steam through hydrogen boiler. Also, carbon emission and leaked methane can be processed by the technology of carbon capture, utilisation and storage (CCUS).

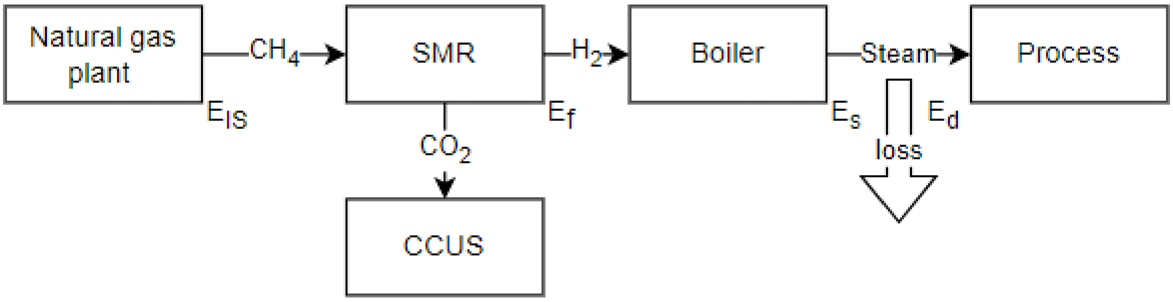


Figure 14. Blue hydrogen generation and delivery review.

Natural gas

Figure 15 shows natural gas is delivered to boiler by natural gas pipeline. Steam is generated by boiler then delivered to the plant. Natural gas boiler is quite mature technology, but the carbon emission is a quite important concern if this type of process is still applied in the future.

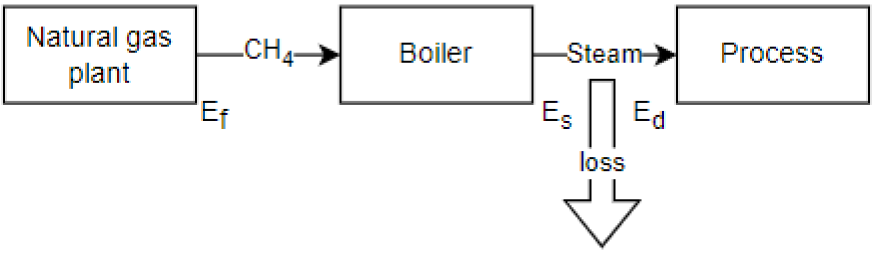


Figure 15. Natural gas delivery review.

Electrode boiler

Figure 16 shows an electrode boiler powered by grid electricity. Steam is generated by the boiler and delivered to plant for process. The carbon emissions factor of grid electricity is not zero, but the carbon emission factor from the grid electricity in New Zealand is lower than that of fossil fuels as shown in Table 4.

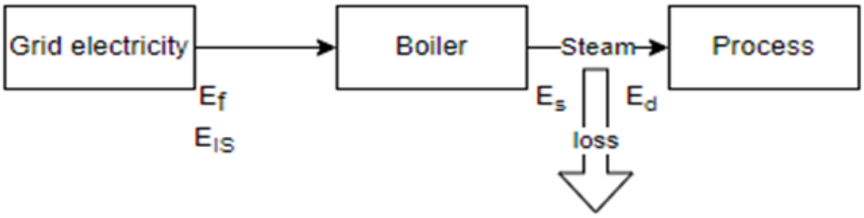


Figure 16. Electricity supplies energy to plant review.

Wood pellets

Figure 17 shows wood pellets are burned in the biomass boiler to generate steam, then the steam is delivered to the plant for the process. The economics of wood pellets is very dependent on the distance of the plant from the wood pellet manufacture site and the delivery cost would become higher and higher with the increase of distance.

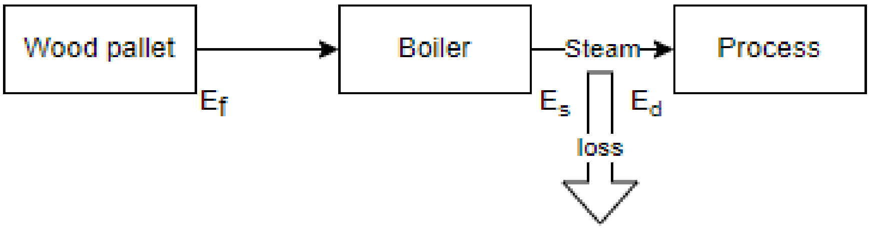


Figure 17. Biomass supplies energy to plant review.

3.4. Data analysis

The data analysis provides insights into the environmental, technical, and economic aspect of various energy sources, highlighting differences in the energy consumption, carbon emissions, efficiency, and energy costs. It underscores the importance of considering these factors when making energy fuel choices, with a focus promoting low-carbon energy options to reduce environmental impact and increase the economic benefits.

Table 6 summarises different results based on the different fuel sources in terms of technical, environmental, and economic performance. The main parameters include the energy consumption from input energy sources, carbon emissions generated from energy delivered to the plant, overall energy conversion efficiency, and Levelized cost of energy for each unit of energy delivered to the process.

3.4.1. Energy consumption and carbon emissions

The total amount of input energy (E_{IS}) and the total amount of fuels consumed in boiler (E_f) are quite variable from different boiler systems with different fuel sources. However, the delivered energy (Ed) is the same for all systems because the E_d is calculated based on 10 MW plant operation. The calculations assume that the plant operates a total of 4,380 hours per year (e.g. 12 hours per day on average).

Variability in the amount of input energy (E_{IS})

The amounts of input energy from different systems are variable, which is due to different compositions and production methods used for heat generation. For example, in Table 6 the input energy (E_{IS}) needed to produce blue hydrogen (348,911 GJ) is higher than that from the natural gas boiler (194,667 GJ). That is because the process to produce blue hydrogen is more complicated and requires significant energy inputs for the carbon capture process. The process to produce blue hydrogen contain three steps which include steam methane reforming (SMR process), energy (natural gas) to drive SMR, and energy to power carbon capture. Also, the release of fugitive methane causes the increase of the consumption of natural gas during the production of blue hydrogen (Howarth & Jacobson, 2021).

Variability in the amount of energy consumed in the boiler (E_f)

The energy consumption in boilers is quite varied, which is mainly due to the different efficiencies of boilers used. The higher efficiency of the boilers is applied, the less fuel would be consumed to supply the same amount of energy delivered to the plant (E_d). Table 6 shows the assumed efficiencies for the boilers considered. The efficiency of the natural gas and hydrogen boilers have assumed to be equal because many of the components are the same with only a few small differences between natural gas boiler and hydrogen boiler. These few differences include burner and flame detector which need to be specifically designed to suit the hydrogen.

Table 6. Analysis of boilers with different fuel sources regarding conversion efficiency, carbon emissions, LCOE, etc.

	Natural Gas	**Wood Pellets**	**Grid Electricity**	**Grid sourced H_2**	**Green H_2**	**H_2 / Natural Gas Blend**	**Blue H_2**
Energy of input source (E_{IS}) [GJ]	**194,667**	**206,118**	**176,970**	**243,333**	**243,333**	**198,048**	**348,911**
Natural Gas	194667	n/a	n/a	n/a	n/a	181,140	348,911
Electricity	n/a	n/a	176,970	243,333	243,333	16,908	n/a
Biomass	n/a	206,118	n/a	n/a	n/a	n/a	n/a
Energy consumed in boiler (E_f) [GJ]	**194,667**	**206,118**	**176,970**	**194,667**	**194,667**	**194,667**	**194,667**
Steam energy (E_s) [GJ]	**175,200**						
Delivered energy (E_d) [GJ]	**157,680**						
Boiler efficiency (η_{boiler})	90%	85%	99%	90%	90%	90%	90%
Overall conversion efficiency (η_d)	81%	77%	89%	65%	65%	80%	45%
The environmental perspective							
Fuel Carbon emissions factor (ε_f) [t_{CO2-e}/GJ]	0.054	0.0009	0.030	0.037	0.000	0.050	0.135
Carbon emission factor from energy delivered to plant (ε_d) [t_{CO2-e}/GJ_d]	0.067	0.0012	0.034	0.046	0.000	0.062	0.167
The economic perspective (Carbon price is based on NZD70/ton)							
Fuel price **[NZD/GJ_f]**	15.79	15.69	49.70	62.10	20.83	16.14	30.96
Specific energy cost **(C_e)[NZD/GJ_d]**	19.49	20.51	55.78	76.67	25.72	19.93	38.22
Specific Annualized capital cost **(C_{cap}) [$/$GJ_d$]**	1.82	3.92	1.40	1.82	1.82	1.82	1.82
Levelized cost of energy **[$/GJ]**	21.31	24.43	57.18	78.49	27.54	21.75	40.04

The environmental aspect for carbon emissions

There is a wide range of carbon emissions factor for energy delivered to plant (ε_d) depending on the fuel source used. There is extremely low ε_d when using wood pellets and green hydrogen. Both have nearly zero carbon emissions (operational emissions). Wood pellets as biomass are treated very low carbon under New Zealand carbon accounting rules due to the assumption that carbon released during combustion would be captured in the growing of new trees. As New Zealand has a long history of sustainable forestry this assumption is defendable. Green hydrogen is generated by renewable electricity (mainly from wind or solar) which has zero emission essentially.

The ε_d from the natural gas boiler is nearly two times higher than that from the electrode boiler, with 0.067 $t_{CO2\text{-}e}$ /GJ_d and 0.034 $t_{CO2\text{-}e}$ /GJ_d respectively. There are two main reasons for the difference. The primary reason is that fuel carbon emission factor (ε_f) of natural gas is nearly double than that of electricity. The ε_f for natural gas is 0.054 $t_{CO2\text{-}e}$ /GJ_f and the ε_f of grid electricity is 0.107 $t_{CO2\text{-}e}$ /kWh (0.03 $t_{CO2\text{-}e}$ /GJ_f) (Ministry of Environment, 2022). The ε_f of grid electricity will vary depending on the generation mix. Also, the electrode boiler has higher efficiency than natural gas boiler, with 99% and 90% respectively.

Not every type of hydrogen is carbon neutral. Blue hydrogen and 20% hydrogen blend have relatively high carbon emissions. Blue hydrogen has the highest ε_d with 0.167 $t_{CO2\text{-}e}$/GJ, so the blue hydrogen would be the last option for energy fuel choices. The hydrogen blend scenario is made up with 20% green hydrogen and 80% natural gas by volume and the resulting ε_d are 0.062 $t_{CO2\text{-}e}$/GJ which is 7.4% lower than that from natural gas (0.067 $t_{CO2\text{-}e}$/GJ).

3.5. Discussion

In this section, the boiler systems from the different energy scenarios will be discussed from technical, environmental, and economic perspectives. Firstly, the efficiency and cost of the options will be compared and discussed. Secondly, hydrogen blending and the impact on carbon emissions, efficiency, and LCOE, with changes in blend ratios and efficiency of electrolyser will be discussed. Lastly, the real-time LCOE will be discussed to analyse impacts of the spot grid electricity price.

3.5.1. Overall conversion efficiency

Figure 18 shows the overall conversion efficiency (η_d) of four types of energy delivery systems (natural gas, wood pellets, 20% hydrogen blend and electrode boiler) is relatively higher than the one from other fuel sourced boiler systems (grid electricity sourced hydrogen, green hydrogen and blue hydrogen). The overall conversion efficiency from these four types of boiler systems (wood pellet, natural gas, 20% hydrogen blend and electrode boiler) are around 80%. Electrode boiler system has the highest η_d which is 89%, and that is mainly because the electrode boiler has the high efficiency which is 99%.

The blue hydrogen has the lowest η_d. That is mainly because the methane leakage rate is 3.5% from the blue hydrogen generation system (Howarth & Jacobson, 2021). In this situation, the consumption of natural gas would be also increased to power the carbon capture. That is why the η_d from blue hydrogen is quite low comparing to other fuel types.

The efficiency of the electrolyser significantly impacts the overall efficiency of the hydrogen boiler.

The overall conversion efficiency of "electricity grid sourced hydrogen" and "green hydrogen" is relatively lower than that from other types of boiler systems, and the overall conversion efficiency of these two is 65%. That is because the efficiency of electrolyser, which is chose as 80% (Chi & Yu, 2018), will be taken account into final calculation for the overall conversion efficiency.

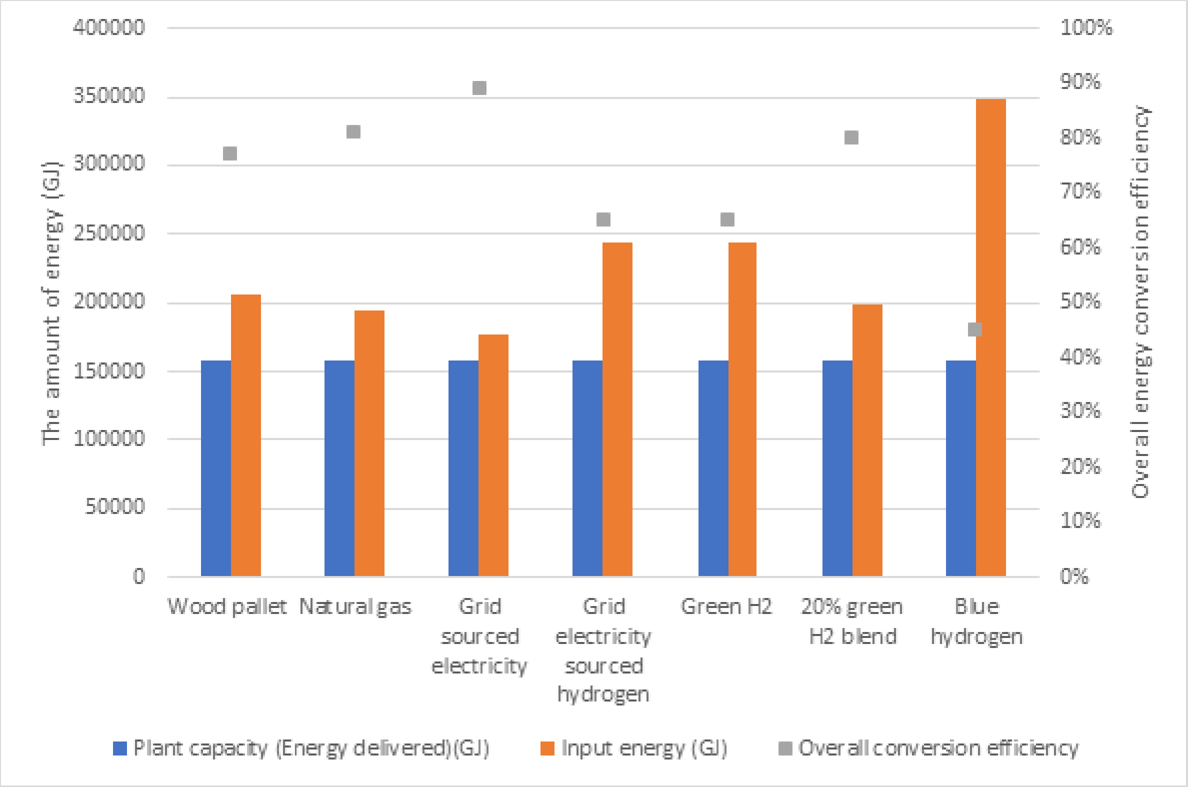


Figure 18. Overall conversion efficiency from different types of energy delivery system.

3.5.2. Cost

Fuel cost and carbon price

Figure 19 shows the impact of the carbon price on the fuel cost. There are a few fuel types which are quite sensitive to changes of carbon price. These fuel types are natural gas, 20% green hydrogen and blue hydrogen. The 20% green hydrogen blend and natural gas have the similar growth trend with the increase of carbon price. The fuel price of these two types of fuels has 33% increase from lowest price to highest price. The increase is due to the relatively high fuel emissions factors of natural gas and blue hydrogen (0.054 $t_{CO2\text{-}e}$/GJ and 0.050 $t_{CO2\text{-}e}$/GJ respectively) and the input energy for these three fuel sources comes from natural gas. The fuel price of blue hydrogen has the biggest jump with increase rate of 46% from NZD 31/GJ_f to NZD 45/ GJ_f. The carbon emission factor of natural gas is significantly higher than that from wood pellets and grid electricity (Ministry of Environment, 2022). Therefore, these three fuel types (natural gas, 20% green hydrogen and blue hydrogen) may not be the best ideal choices to switch for future fuel usage due to the increasing carbon price and its high impact on the effective fuel price. The trigger carbon price of reserve amount of New Zealand unit would be increased from NZD 70/$t_{CO2\text{-}e}$ in 2022 to NZD 110.15/$t_{CO2\text{-}e}$ in 2026 with estimated increase rate at 6% (Ministry of Environment, 2022).

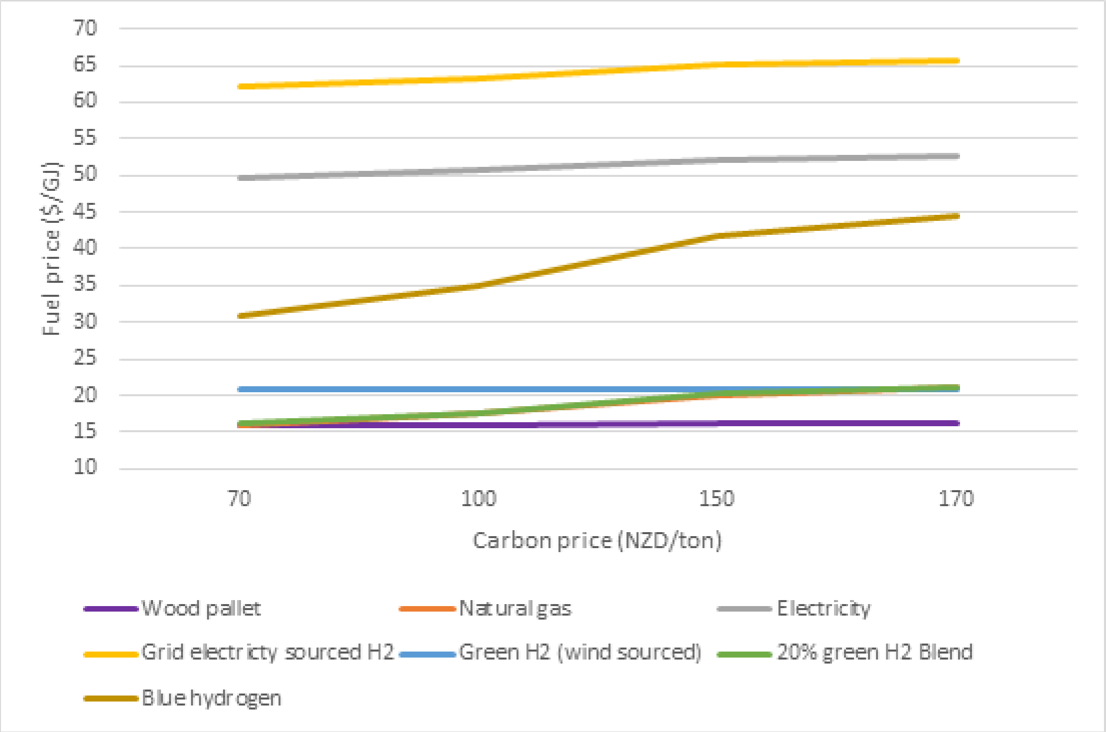


Figure 19. Fuel price changes with carbon prices.

The fuel prices for other types of fuels are quite stable with the increase of carbon prices. These fuel types include grid electricity sourced hydrogen, grid sourced electricity, green hydrogen and wood pellets. The increase rate would be between 2% and 6% when the carbon price increases from NZD 70/$t_{CO2\text{-}e}$ to NZD 170/$t_{CO2\text{-}e}$. Grid electricity sourced hydrogen is the most expensive fuel among all fuel options. Grid sourced electricity is the second expensive fuel type, and the fuel price is around 24% cheaper than from grid electricity sourced hydrogen. Using the current grid electricity to generate hydrogen constantly is not economically feasible, because the average price of grid sourced electricity is relatively high and the conversion efficiency of electrolysers being modest. The fuel price of green hydrogen (renewable sourced) is relatively cheaper compared to most other fuel types, and that is mainly due to relatively low LCOE of renewable (wind and solar) electricity which is between NZD 60 /MWh and NZD70 /MWh (MBIE, 2020). Wood pellets are the least impacted by carbon prices and have a low fuel price due to the availability of wood pellets are low prices. This price may increase as demand for them increases and cheap supplies of biomass are used up.

LCOE from boiler systems with different fuel sources

Table 7 shows the sensitivity analysis of LCOE from boiler systems with different fuel sources. The analysis will be based on several carbon prices which are 70 NZD/$t_{CO2\text{-}e}$, 100 NZD/$t_{CO2\text{-}e}$, 150 NZD/$t_{CO2\text{-}e}$ and 170 NZD/$t_{CO2\text{-}e}$. The fuel price was varied +- 20% to determine the sensitivity of LCOE to changes in fuel prices.

Table 7. Sensitivity analysis of LCOE from boiler systems with different fuel sources.

Carbon price $[\$/t_{CO2\text{-}e}]$	**Fuel Price** **[+/- 20%]**	**Wood pellets** $[\$/GJ_d]$	**Natural Gas** $[\$/GJ_d]$	**Grid sourced electricity** $[\$/GJ_d]$	**Grid sourced H$_2$** $[\$/GJ_d]$	**20% Green H$_2$ blend** $[\$/GJ_d]$	**Green H$_2$** $[\$/GJ_d]$	**Blue H$_2$** $[\$/GJ_d]$
70	Low	20.32	17.41	46.02	63.15	17.76	22.40	32.40
	Med	24.43	21.31	57.18	78.49	21.75	27.54	40.04
	High	28.53	25.21	68.34	93.82	25.73	32.68	47.68
	Difference among levels	**16.8%**	**18.3%**	**19.5%**	**19.5%**	**18.3%**	**18.7%**	**19.08%**
100	Low	20.35	19.01	46.83	64.25	19.26	22.40	36.40
	Med	24.46	23.31	58.19	79.86	23.62	27.54	45.04
	High	28.57	27.61	69.55	95.47	27.98	32.68	53.68
	Difference among levels	**16.8%**	**18.4%**	**19.5%**	**19.5%**	**18.5%**	**18.7%**	**19.18%**
150	Low	20.40	21.69	48.18	66.09	21.75	22.40	43.06
	Med	24.52	26.65	59.87	82.16	26.73	27.54	53.37
	High	28.64	31.62	71.57	98.22	31.71	32.68	63.68
	Difference among levels	**16.8%**	**18.6%**	**19.5%**	**19.5%**	**18.6%**	**18.7%**	**19.3%**
170	Low	20.42	22.75	48.72	66.82	22.74	22.40	45.73
	Med	24.54	27.99	60.55	83.07	27.97	27.54	56.71
	High	28.67	33.22	72.38	99.32	33.20	32.68	67.69
	Difference among levels	**16.8%**	**18.7%**	**19.5%**	**19.6%**	**18.7%**	**18.7%**	**19.4%**

LCOE from "grid electricity sourced hydrogen" is the highest comparing with other types of fuel sources. LCOE from "grid electricity sourced hydrogen" is nearly three times greater than that from wood pellets, natural gas, 20% green hydrogen blended and green hydrogen, no matter what the carbon price.

On the other hand, Carbon prices did affect the LCOE in some other fuel types. For example, LCOE has a big increase with the increase of carbon price in the fuel types of "natural gas", "20% hydrogen blended with hydrogen" and "blue hydrogen". When the carbon price increases from $100/t to $150/t, the increase rate is between 10% - 20% in terms of LCOE for these three types of fuels which were mentioned above.

LCOE of natural gas and 20% green hydrogen blend start to be higher than that of wood pellet, when the carbon price start to be over NZD 150/t. Like the discussed above, the current increase rate of carbon price is 6% (Ministry of Environment, 2022), so in year 2035 the carbon price in NZ would reach $150/t based on this increase rate, then LCOE of biomass boiler would become the lowest one among all types of boiler systems. Therefore, Biomass boiler would be more acceptable in the economic point of view at that time.

Different levels of carbon price would affect the LCOE from different fuel types. Also, LCOE from hydrogen blend can be affected by different efficiencies of electrolysers. The increase trend in shown below. LCOE is based on carbon price at NZD 70/t.

3.5.3. Hydrogen

Carbon emission from hydrogen blend

Blending green hydrogen with natural gas has been proposed as a way to reduce emissions, however a 20% blend by volume does not result in a 20% reduction in emissions. Different blend percentages (by volume) results in different amount of carbon emissions reduction. Also, methods of hydrogen generation (generated by national electricity grid or green electricity) will indirectly impact the amount of carbon emission from the hydrogen blend. This is illustrated in Figure 20, where the two curves to represent the rate of carbon reduction from different ratio of hydrogen blends, compared to pure natural gas. The pressure used for the volume basis for this calculation is 101.325 kPa (Linke, 2020).

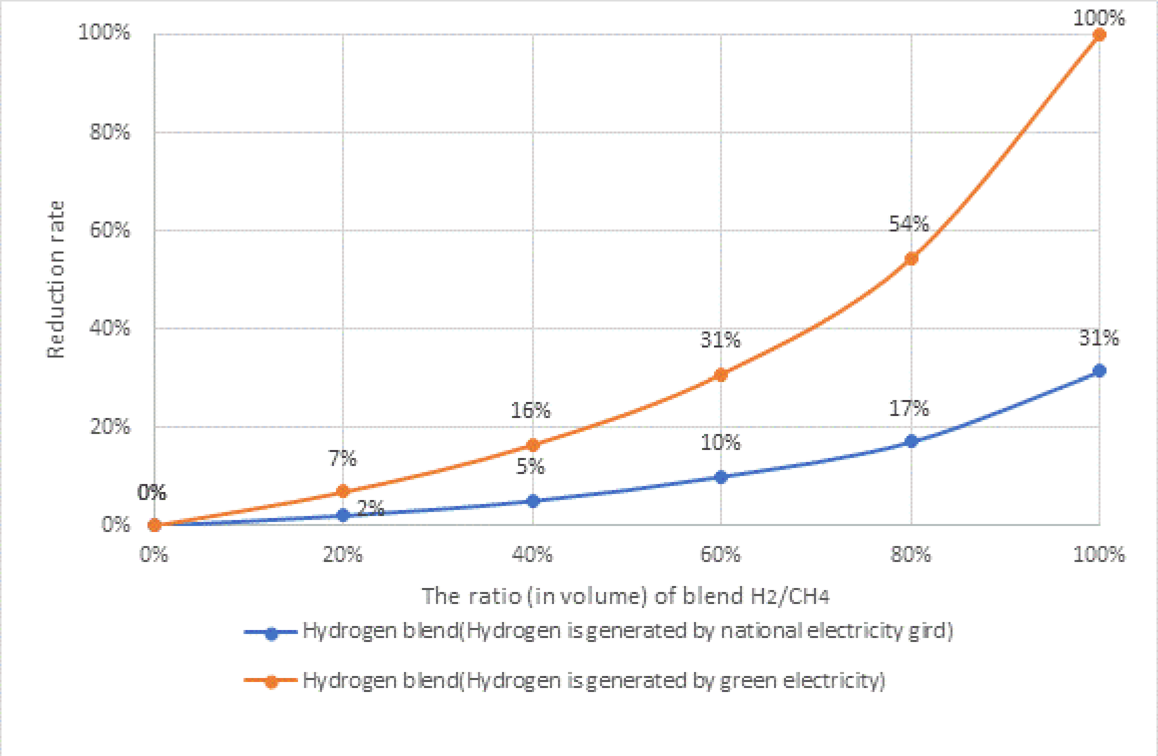


Figure 20. Emissions reduction rate of hydrogen blend compared to CH_4.

In the blue curve in Figure 20, the reduction rate was slightly increased with the increase of H_2/CH_4 mixing ratio. The reduction rate is only 17%, even though the H_2/CH_4 mixing ratio is increased to 80% in volume. The reason why the reduction rate is low even when the blending rate is high is due to the low volumetric energy density (gross calorific value) of hydrogen compared to natural gas. The gross calorific value of natural gas (38 MJ/m^3) is nearly 3 times more than the calorific value of hydrogen (11 MJ/m^3) at 101.325 kPa (Linke, 2020). That means natural gas contributes more energy than that from natural gas under the same pressure.

The source of electricity used in the production of hydrogen plays an important role in carbon reduction from the hydrogen blend. When hydrogen is produced using renewable electricity only (orange curve) electricity), there is a significant increase in the reduction rate when the mixing ratio increases from 20% to 80%. The reduction rate is 7% at 20% hydrogen blend increasing to 54% at an 80% hydrogen blend. Grid sourced electricity using typical grid emissions factors for the New Zealand grid provide moderate emissions reduction. As more zero emissions renewables enter the generation mix the grid emissions factor will reduce thereby increasing the emissions reduction potential of hydrogen blending.

Figure 21 illustrates the energy contribution of hydrogen and natural gas. Natural gas and hydrogen contribute the same amount of energy when the ratio of hydrogen blend reaches 78%. After that, the energy contribution from hydrogen starts to exceed that from natural gas once the blend ratio is more than 78%. Even at an 80% blend ratio there are still significant emissions from the use of natural gas. Overall, the gap of carbon reduction between these two types of fuel sources becomes larger with the increase from hydrogen blend ratio. Therefore, the type of electricity used to generate hydrogen has strong impact on the amount of carbon emission from hydrogen blends.

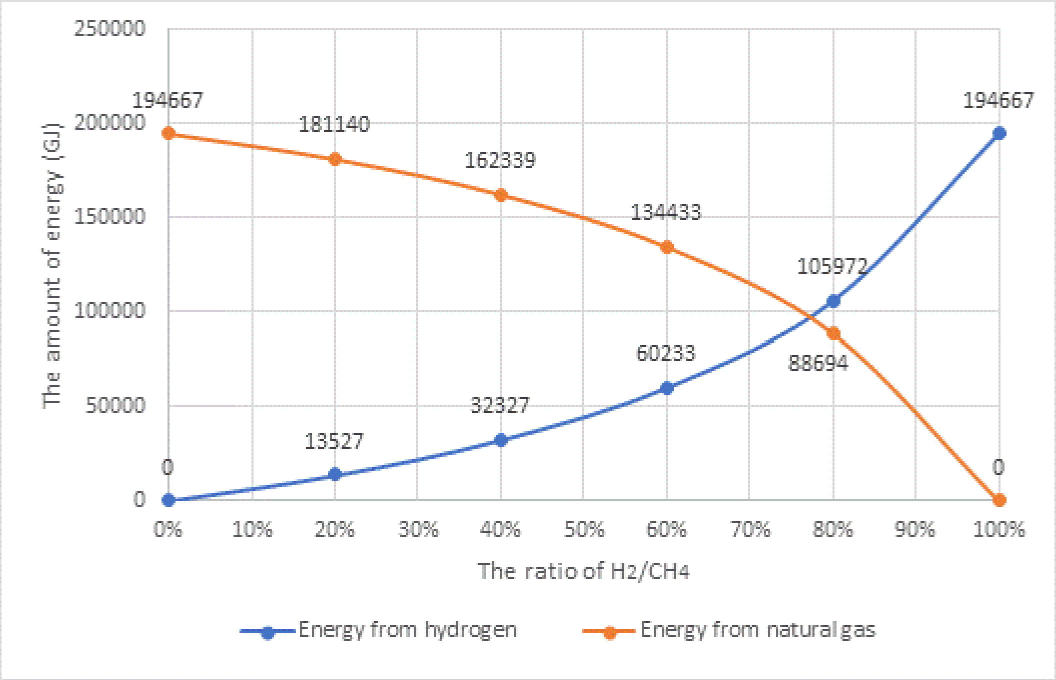


Figure 21. The relationship of energy supply in hydrogen blend.

Efficiency changes with electrolysers from different ratios

The use of different efficiency of electrolysers and different ratios of hydrogen blend would make great impact on the overall conversion energy efficiency. The impact of different electrolyser efficiencies was considered, and three values were selected (60%, 70% and 80%). Two main categories of hydrogen electrolysis technology, alkaline water electrolysis and proton exchange membrane water electrolysis (PEM), are existing at commercial scale. The efficiency of alkaline water electrolysis range between 59% and 70%, and the efficiency of PEM electrolysis is between 65% and 82% (Chi & Yu, 2018).

Figure 22 shows the overall conversion efficiency reduces with the increase of ratio in blending. Also, the overall conversion efficiency is affected by electrolysers efficiencies (η_r). It shows that the difference of overall conversion efficiency among different types of electrolysers increases with the increase in blend ratio. Hydrogen is the component that contributes a small amount of energy in the blend when the blend ratio is low (see Figure 21), so the different electrolysers efficiency has a slight impact on the overall conversion efficiency. As the hydrogen blend increases above 78% hydrogen becomes the main energy contributor and the electrolysers efficiency has a significant impact on the overall conversion efficiency.

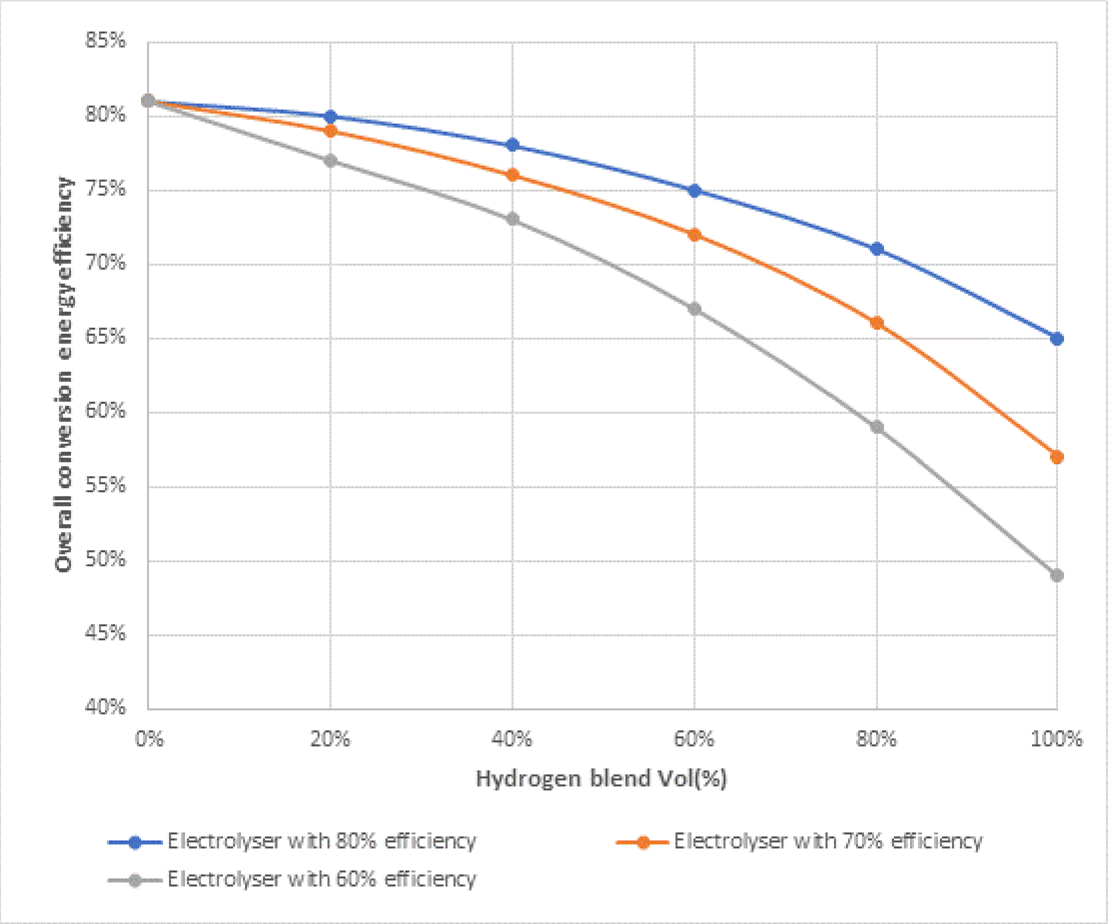


Figure 22. Efficiency changes with electrolysers from different ratios.

LCOE changes with electrolysers from different ratios

Figure 23 show that the efficiency of the electrolyser plays an important part in the specific capital and energy cost for hydrogen. LCOE doesn’t have quite difference when the Ratio of hydrogen blend is below 20%. However, The LCOE from electrolysers with different efficiencies become different with the increase of ratio (more than 20%) from hydrogen blend.

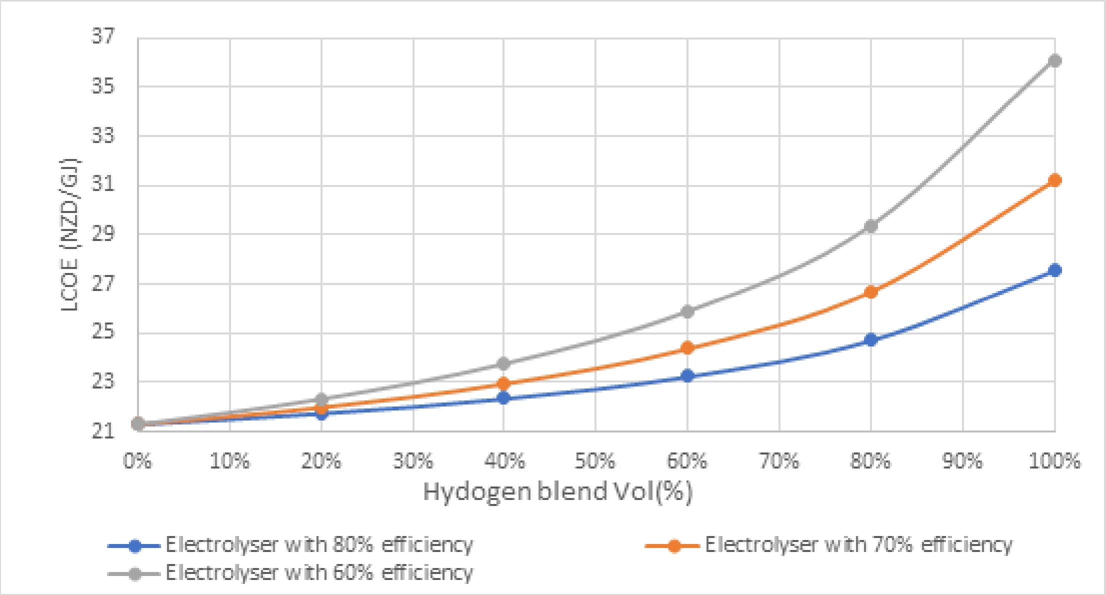


Figure 23. LCOE changes with different ratios of hydrogen blend with different efficiencies from electrolysers.

Real-time analysis of the hydrogen generated by electricity grid

If the spot price of electricity from the grid is below 37.98 NZD/MWh the LCOE of electricity sourced hydrogen would be equal to or less than the LCOE of natural gas (21.31 NZD/GJ) including a carbon price of 70 NZD/$t_{CO2\text{-}e}$. Figure 24, illustrates how average and single prices of electricity change with total amount of hours from 2018 - 2021. From Figure 24, there are 975 hours (average from years 2018 to 2021) where the spot price is below 37.98 NZD/MWh that could be used to make hydrogen at a lower cost than natural gas. The number of hours per year below the price does vary significantly each year (2018 – 786 hours, 2019 – 594 hours, 2020 – 1,399 hours, 2021 – 1,031 hours).

The amount of hydrogen that could be generated based on four different electricity price ranges in shown in Figure 25. The four price ranges are 0 – 10 $/MWh, 10 – 20 $/MWh, 20 – 30 $/MWh and 30 – 37.98 $/MWh. Different years have different hydrogen capacity to make LCOE less than 21.31 NZD/GJ_d. The range is between 22,239 GJ and 52,416 GJ during year 2018 to 2021. This range takes up 11% to 27% of total annual hydrogen fuel demand (194,667 GJ) for the example considered in this chapter.

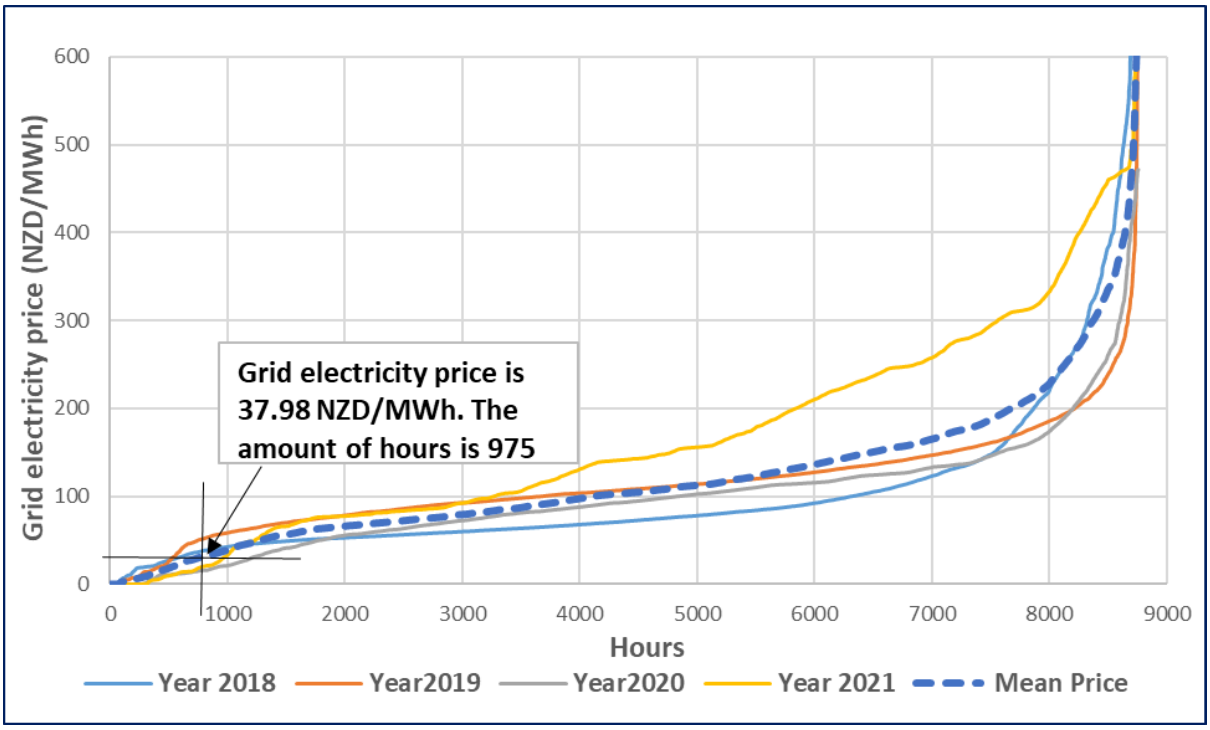


Figure 24. Electricity price of Timaru from year 2018-2021.

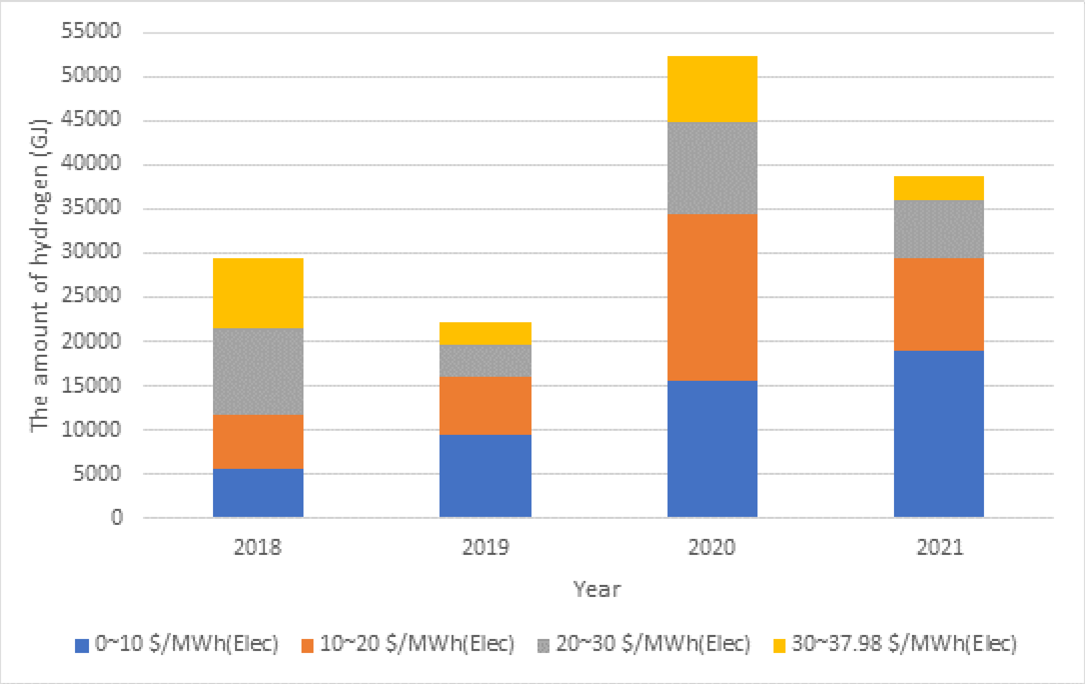


Figure 25. Amount of hydrogen that can be produced at difference electricity prices.

The amount of hydrogen generated with low price (less than 37.98 $/MWh) is quite variable year to year due to the variability of spot electricity prices. Figure 26 shows when the low price occurs from 2018 to 2021 looking at the spot price in Timaru. Timaru was selected as it was the location of a case study in Chapter 4. Figure 26 illustrates that the occurrence of a trading period with the low price of electricity occurs is different from year to year and there is no perceivable pattern behind when it occurs. Therefore, it is hard to fix certain periods to constantly produce low-price hydrogen annually and supply it to end-users through pipeline or some other means. In this situation, it is critical to have hydrogen storage facilities to store hydrogen, when the hydrogen is produced by electrolysis at certain target electricity prices. There will be need for additional investment in storage facilities, which would have in impact on the actual hydrogen fuel price.

3.6. Conclusion

From the carbon emissions perspective, green hydrogen, wood pellets and grid electricity boiler system have the best performance. Also, for the hydrogen blending the carbon emission has a dramatic decrease with the increase the blending ratio, especially for the hydrogen generated by renewable electricity.

From an overall conversion efficiency perspective, some boiler systems are higher than others. Fuels are electricity, natural gas, 20% hydrogen blend, and wood pellets with overall energy conversion efficiencies of 89%, 81%, 80% and 77% respectively. Furthermore, for the hydrogen options the overall conversion energy efficiency has a decreasing trend with two factors. One is the increase of ratio in the hydrogen blending. The other one is the decrease of the efficiency in electrolysers.

From the economic perspective, the LCOE of some boiler systems is low, and the cost is less than 30 NZD/GJ at a carbon price of 70 NZD/$t_{CO2\text{-}e}$. These fuel types from these boiler systems are wood pellets, natural gas, 20% hydrogen blend. Also, LCOE from these three fuel sources will still less than 30 NZD/GJ, even with the carbon price increased to 100 NZD/ NZD/$t_{CO2\text{-}e}$. Furthermore, LCOE has increasing trend with the increase of ratios in the hydrogen blending. Low LCOE of hydrogen (21.31 NZD/GJ) can be achieved by using low spot grid electricity price (less than 37.98 NZD/MWh), but the low-price hydrogen can only be achieved in certain periods because the spot grid electricity price is variable.

In next chapter, the real-time carbon emission factor will be used to analyse how carbon emissions change with real-time carbon emission factor. Also, what kinds of impact brings to real cases will be analysed in terms of environmental and economic perspective.

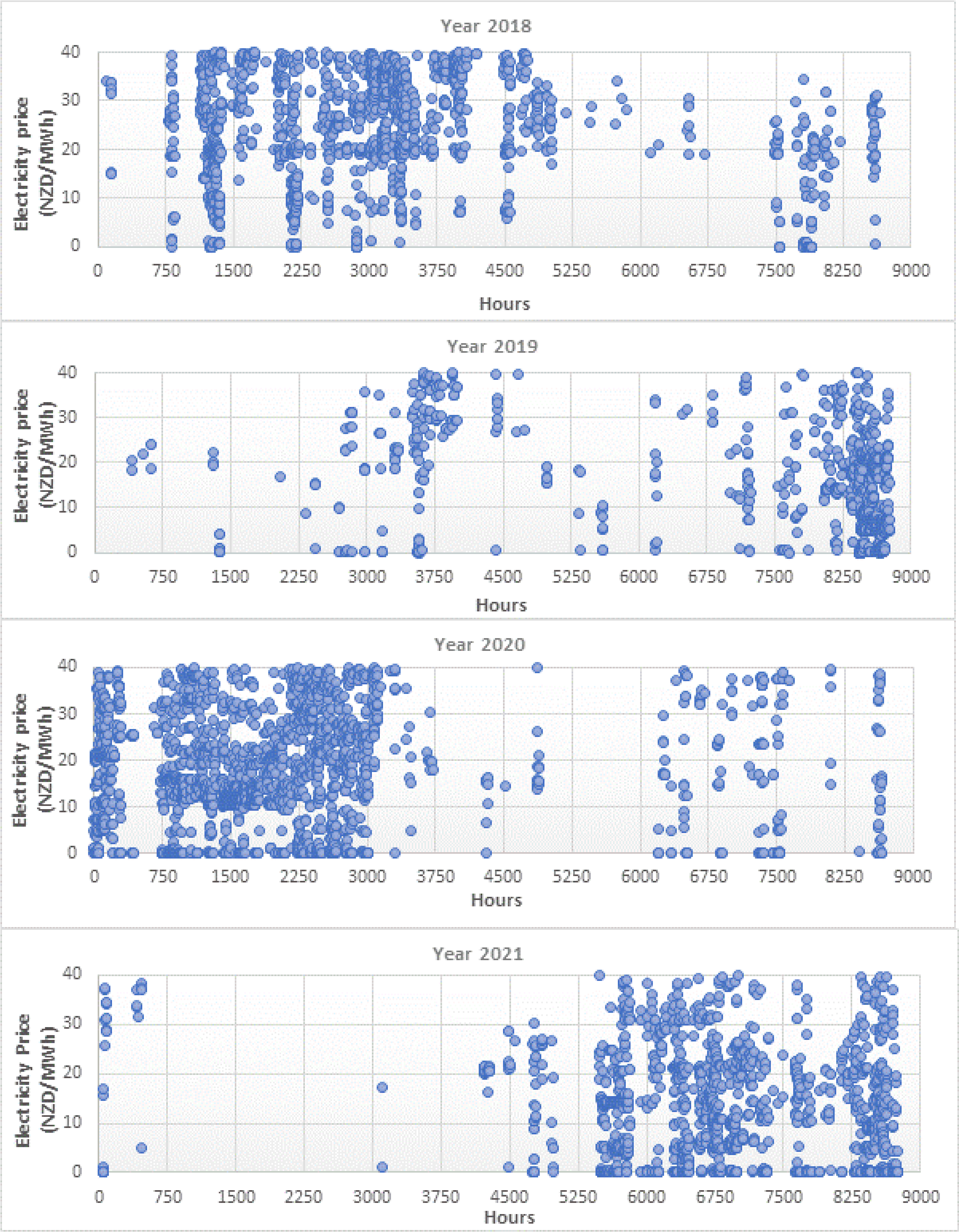


Figure 26. Electricity spot prices from year 2018-2021 in Timaru.

4. Detailed Analysis of Emissions in Real Time (Pseudo-dynamic)

4.1. Introduction

The assessment of energy-related boiler environmental impacts would be more accurate if supply side variability was incorporated into the assessment. Moreover, incorporating grid variability can help to better prioritise energy efficiency measures that bring the largest environmental benefits.

This study aims to propose a method to incorporate greenhouse gas emission intensity changes due to grid variability into boiler environmental assessment. The boilers here include the electrode boiler and grid-source hydrogen boiler. The GHG emissions estimates using this method provide a more accurate representation of the actual carbon emissions and economic performance of boiler systems, accounting for the dynamics of both the supply side (electricity system) and demand side (boiler systems).

4.2. Variable carbon emission factor from grid electricity

In New Zealand's electricity, the system operator forecasts electricity demand/generation across the country in 30-minute trading period throughout the day (Transpower, n.d.). Based on that forecast, there are 48 trading periods per day, which starts from 00:00 am and ends at 23:30 pm. There are a total of 17,520 trading periods per year. In each trading period the generation mix changes as demand and supply changes resulting in a variable emissions factor. A real time emissions factor for electricity from the grid as well as a volume weighted average can be calculated using specific emissions factors from the following generation types; Coal, Diesel, Gas, Geothermal (GEO), Hydro, wind, and Co-generation (COG).

4.2.1. Calculation of real-time carbon emissions factors

The NZ carbon emission factor at time *t* is found by weighting the carbon emission factor for each fuel type ε_i by the generation of that fuel $E_{t.j}$. This is then divided by the total amount of national grid generation in that period time to derive the carbon emission factor for New Zealand as in Equation 4.1. The amount of demand from electricity will be treated to be the same as the one of generation from electricity $E_{t.j(total)}$, that is because there is only slight difference between these two criteria based on data from electricity authority (Electricity Authority, n.d.). The real-time emissions factors were calculated using the methodology used by the EM6 Live – Electricity Market Overview webtool (EM6, 2022).

$$\varepsilon_{t.j} = \frac{\sum(\varepsilon_i \times E_{t.j})}{E_{t.j(total)}} \quad \textbf{(4-1)}$$

Table 8 is an example to show real-time grid carbon emission factor ($t_{CO2\text{-}e}$/MWh) generated by different generation fuel types during one of the trading periods - 18:00:00 to 18:30:00 on 2020-06-25. In New Zealand, there are seven fuel types used to generate grid electricity. Renewable energy resources are available for electricity generation with hydro, geothermal, wind and wood (biomass) accounting for around 80% of generation in 2011 (Walmsley et al., 2014). Non-renewable energy resources (like coal, natural gas, and diesel) are available for traditional thermal electricity generation. The emissions factor for that trading period was 0.192 $t_{CO2\text{-}e}$/MWh.

Table 8. Real-time grid carbon emissions factors with by different generation fuel types.

Time	**Fuel type**	**Generation [MW]**	**Power Generated [MWh]**	**Carbon emission factor [$t_{CO2\text{-}e}$/MWh]**	**Total Emission [$t_{CO2\text{-}e}$]**
2020-06-25 18:00:00 To 2020-06-25 18:30:00	Coal	491.9	245.94	0.996	244.8
	Diesel	33.9	16.96	0.766	13.0
	Gas	1,246.9	623.45	0.480	299.2
	Geothermal (GEO)	857.4	428.69	0.079	33.8
	Hydro	3,331.7	1,665.84	0.000	0.0
	Wind	338.0	169.02	0.000	0.0
	Cogeneration	33.2	16.61	1.092	18.1
	Overall	**6,333.1**	**3,166.53**	**0.192**	**609.0**

Carbon emission factor of grid electricity from certain fuel types

Table 9 shows the carbon emission factors for a range of different fuel and generation methods in New Zealand. The carbon intensities used in the Table 8 are based on the values in the Table 9. Geothermal and cogeneration will be explained with more details below. Geothermal fluids contain some greenhouse gases (carbon dioxide and methane) which are transported to the surface when the fluid is extracted. While amounts vary from field to field and the amount that is released depends on the design of the power station, generally levels are still less than natural gas-fuelled, or coal fired power stations. Co-generation is a system that produce heat and electricity simultaneously in a single plant. The most widely used co-generation technologies involve the combustion of fuel such as natural gas, diesel, biogas, bio-methane, vegetable oil or biomass.

Table 9. Carbon emission factor of grid electricity from certain fuel types (EMS, 2022).

Fuel types	**Carbon emissions factors [$t_{CO2\text{-}e}$/MWh]**
Coal	0.996
Diesel	0.766
Gas	0.400 – 0.594
Geothermal	0.021 – 0.341
Cogeneration	0.341 – 1.092

The range of emissions factors for gas, geothermal and cogeneration is due to the different types of generation for each (e.g., combined cycle gas turbine vs open cycle gas turbine, etc.).

Reference and real-time annual carbon emission factors

The annual real-time carbon emission factor was calculated for the years 2013 to 2022 and compared with the official Ministry for the Environment reference carbon emissions factor. Table 10 compares the reference and real-time emissions factors and the percentage error between the two. There is a delay in the publishing of the reference carbon emissions factors which is why 2021 and 2022 are missing from Table 10.

Table 10. Reference and real-time carbon emissions factors from 2013 to 2022.

Year	$\boldsymbol{\varepsilon}_{A\,(Reference)}$ **[$t_{CO2\text{-}e}$/MWh]**	$\boldsymbol{\varepsilon}_{A\,(Realtime)}$ **[$t_{CO2\text{-}e}$/MWh]**	**Error [%]**	**Renewables [%]**
2022	N/A	0.086	N/A	87
2021	N/A	0.131	N/A	82
2020	0.120	0.122	1.7%	82
2019	0.110	0.115	4.5%	83
2018	0.094	0.103	9.6%	84
2017	0.099	0.111	12.1%	82
2016	0.088	0.093	5.7%	85
2015	0.112	0.116	3.6%	81
2014	0.118	0.119	0.8%	81
2013	0.141	0.152	7.8%	76

From 2013 to 2020, the average based on the real-time emissions factors ($\varepsilon_{A\ (Realtime)}$) is always higher than annual average carbon emission factor from reference ($\varepsilon_{A\ (Reference)}$) (Ministry for the Environment, 2022). The percentage error can be calculated using Equation 4-2 and the error range is between 0.8% and 12.1%. The carbon emissions will be different based on the calculation by different annual carbon emission factors.

$$\delta = \frac{\varepsilon_{A(Realtime)} - \varepsilon_{A(Reference)}}{\varepsilon_{A(Reference)}} \qquad \textbf{(4-2)}$$

Where: δ = percent error

$\varepsilon_{A(Realtime)}$ = annual average carbon emission factor calculated from real time data

$\varepsilon_{A(Reference)}$= annual average carbon emission factor from reference.

In the following two case studies, the total amount of carbon emissions from electricity usage will be calculated using both the real-time and average carbon emissions factors.

Figure 27 and Figure 28 shows the comparison of real-time carbon emissions factor for 2017 and 2020. The carbon emissions factor for every trading period is shown as well as the annual average carbon emission factor from reference (blue line), and the annual average carbon emission factor calculated by real-time carbon emission factor (red line). The emissions factor from reference refers to the official grid emissions factors reported by the Ministry for the Environment (Ministry for the Environment, 2022).

From Figure 27, the annual carbon emission factor of grid electricity from real-time is quite different from the one from reference one in year 2017. In the year 2017, some real-time carbon intensities of grid electricity from trading period (7,000 – 10,500 & 15,000 – 17,520) are higher than average carbon emission factor (shown in the blue and red line in figure). Trading period (7,000 – 10,500) is located between May and August, and trading period (15,000 – 17,520) is located between November and December. That means the wintertime and summertime have relatively higher carbon emission factor than the average one in the year 2017.

In Figure 28, some real-time carbon emission factor of grid electricity from trading period (6,300-11,500 & 100 – 3,500) are higher than average carbon emission factor (shown in the blue and red line in figure). Trading period (6,300 – 11,500) is located between May and August, and trading period (100 – 3,500) is located between January and March. That means the wintertime and summertime have relatively higher carbon emission factor than the average one in the year 2020.

There are a couple of reasons why the carbon emissions factor in certain months are higher than the average ones. The one reason is that much more fossil fuels are used to generate grid electricity, which is to meet the peak demand in some periods (like summer and winter). The other reason is that some dry seasons and months are occur in certain periods, which reduces the hydro storage and the ability of hydro power generation to provide higher levels of generation.

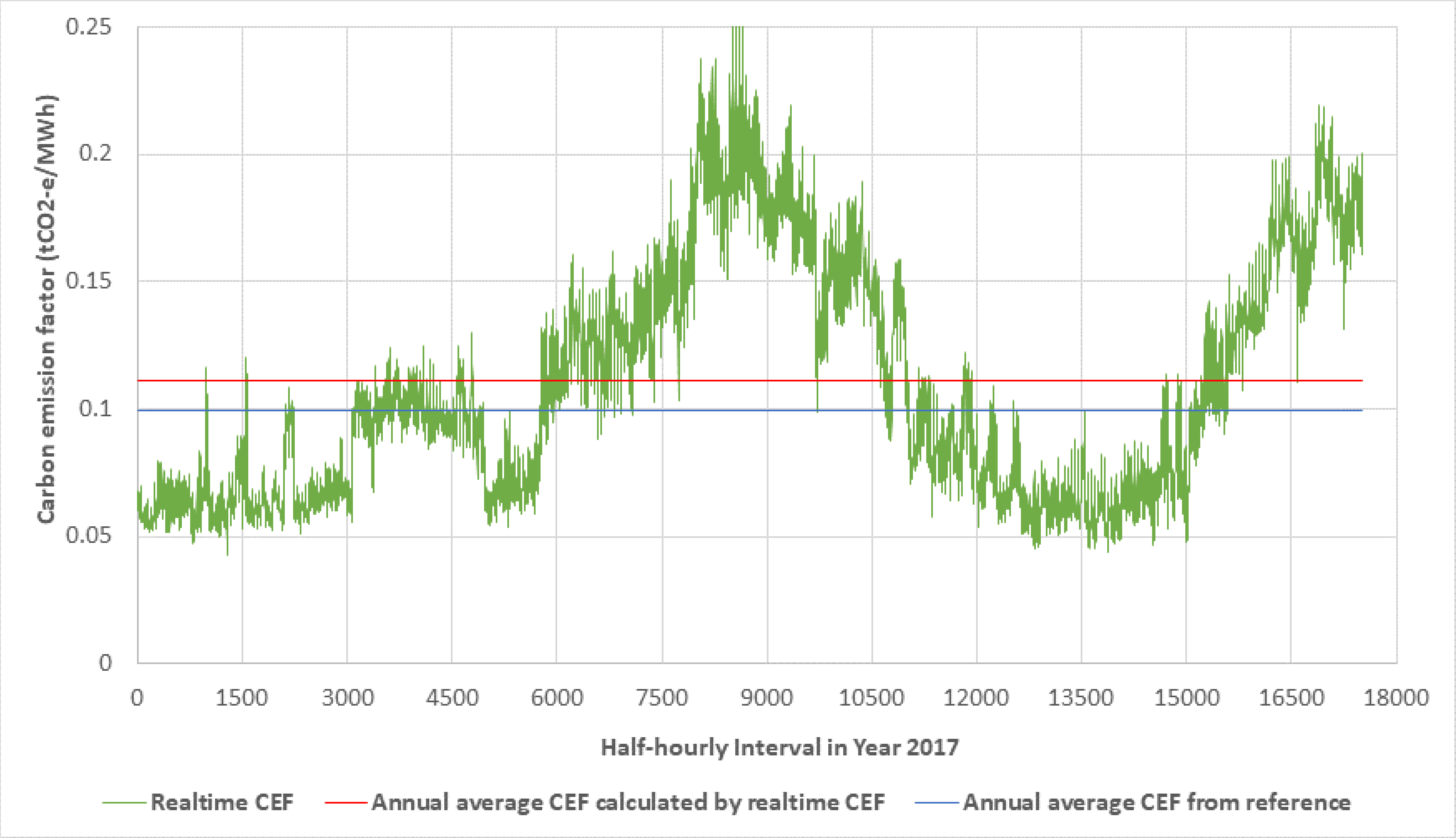


Figure 27. Real-time carbon emission factor in year 2017.

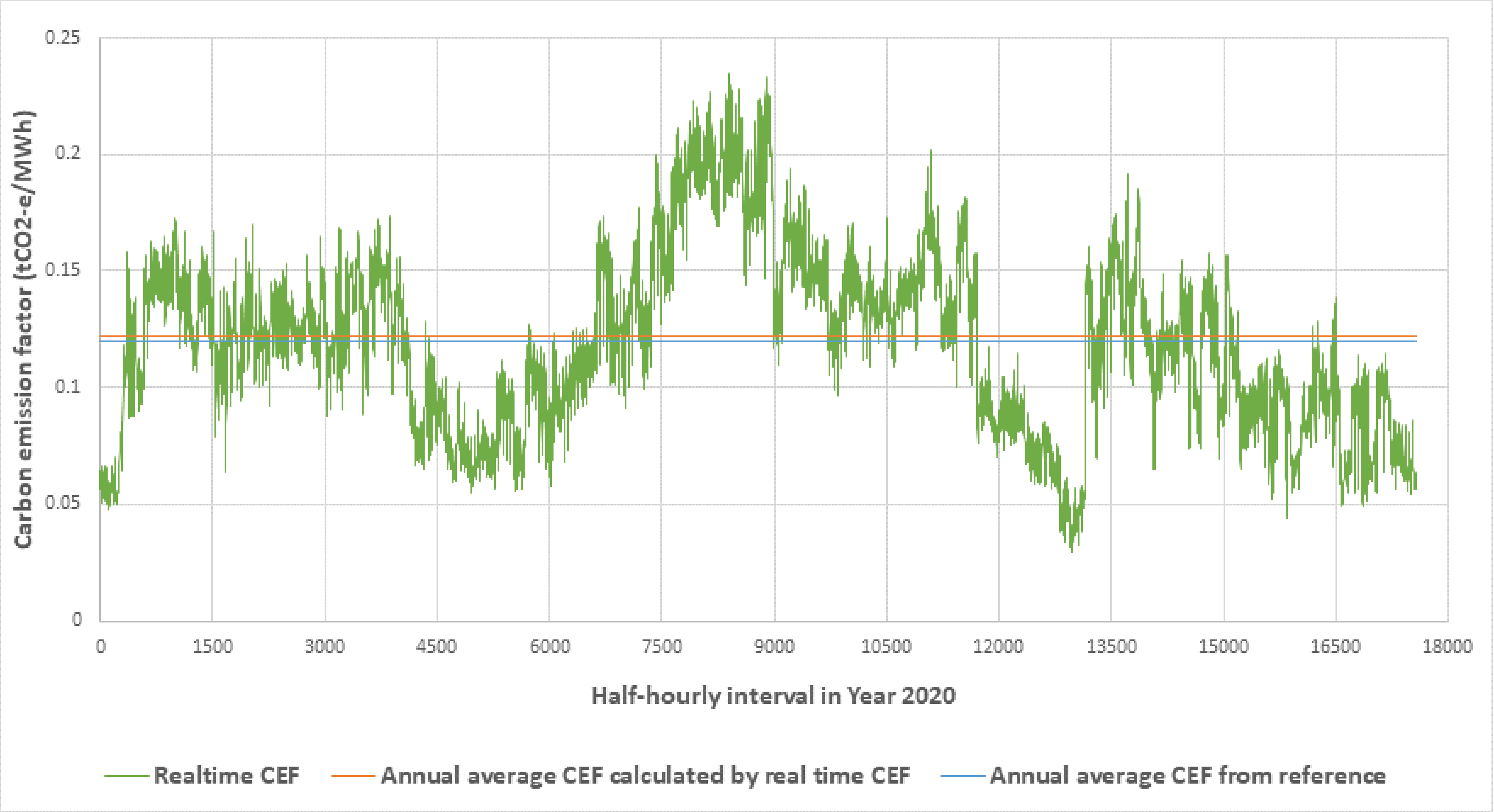


Figure 28. Real-time carbon emission factor in year 2020.

4.2.2. Carbon emission factor and lake storage levels

Typical hydro generation provides around 56 – 58% of the total amount of electricity generated in New Zealand. The more hydro is used to generate electricity, the lower the electricity carbon emissions factor. The total active lake storage impacts the ability of hydro power for electricity generation, which also indirectly affect the carbon emission factor of grid electricity. The assumption is that there is some correlation between electricity carbon emissions factor and total active lake storage.

Figure 29, Figure 30 and Table 11 show the relationship between variable carbon emission factor and total active lake storage. In statistics, the correlation coefficient R measures the strength and direction of linear relationship between two variables on a scatterplot. The value of R is always between +1 and -1. Table 12 explains the meaning of the values which the correlation R is closest to.

Table 11. R value from daily period and half-hour trading period from year 2013 to 2021.

Year	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Daily period	-0.711	-0.634	-0.458	0.033	-0.715	-0.560	-0.694	-0.147	-0.919
Half-hour trading period	-0.684	-0.608	-0.445	0.010	-0.688	-0.544	-0.668	-0.149	-0.899
Error%	4%	4%	3%	70%	4%	3%	4%	-1%	2%

Table 12. The meaning of the values which the correlation R is closest to (Rumsey, 2016).

R value	**Meaning**
Exactly -1	A perfect downhill (negative) linear relationship
-0.7	A strong downhill (negative) linear relationship
-0.5	A moderate downhill (negative) relationship
-0.3	A weak downhill (negative) linear relationship
0	No linear relationship
0.3	A weak uphill (positive) linear relationship
0.5	A moderate uphill (positive) linear relationship
0.7	A strong uphill (positive) linear relationship
Exactly +1	A perfect uphill (positive) linear relationship

From Table 11, it tells there is a moderate downhill relationship or a strong downhill linear relationship in most years from 2013 to 2021, except year 2016 and 2020. That means the annual carbon emission factor would be moderately or strongly impacted by the total active lake storage. Table 11 also shows the R value from the daily period is normally higher than ones from the half-hour trading period from year 2013 to 2021, with error% between 1% and 4%. The year 2016 is unique, because the R value is quite low in this year. That means there is no correlation between the carbon emissions factor and total active storage in the year 2016. Also, the error is significantly high with 70%.

There are two examples (2013, 2021) below showing how different R value based on half-hour trading period and R value based on the daily period can be. Figure 29 and Figure 30 show the correlation between carbon emission factor and total active lake storage by half-hour trading period and daily average for 2021 (Figure 29) and 2013 (Figure 30). The further analysis will be based on daily period because the R value from daily period is higher than that from the half-hour trading period.

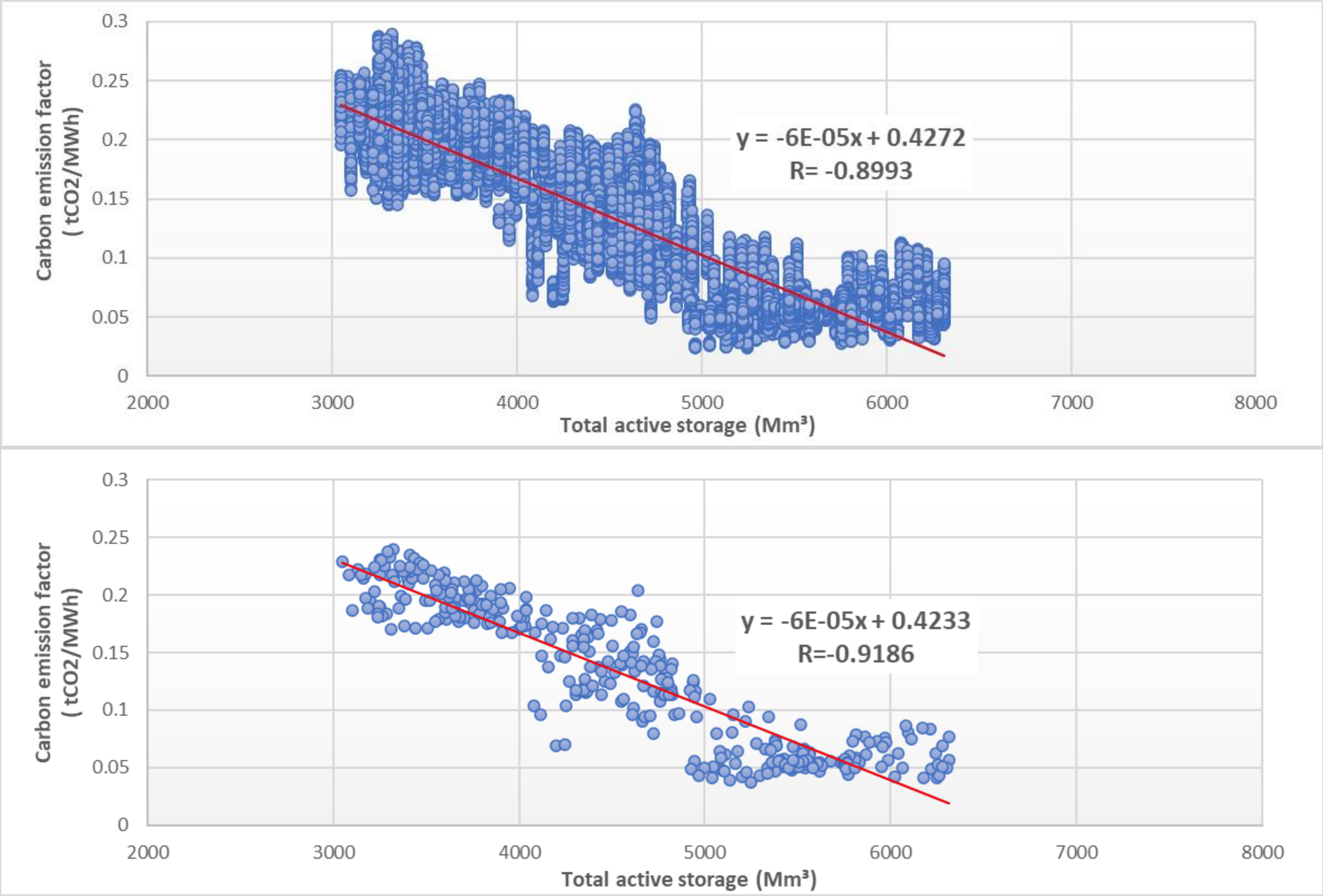


Figure 29. The relationship trend between total active lake storage and carbon emission factor based on daily period and half-hour trading period in year 2021.

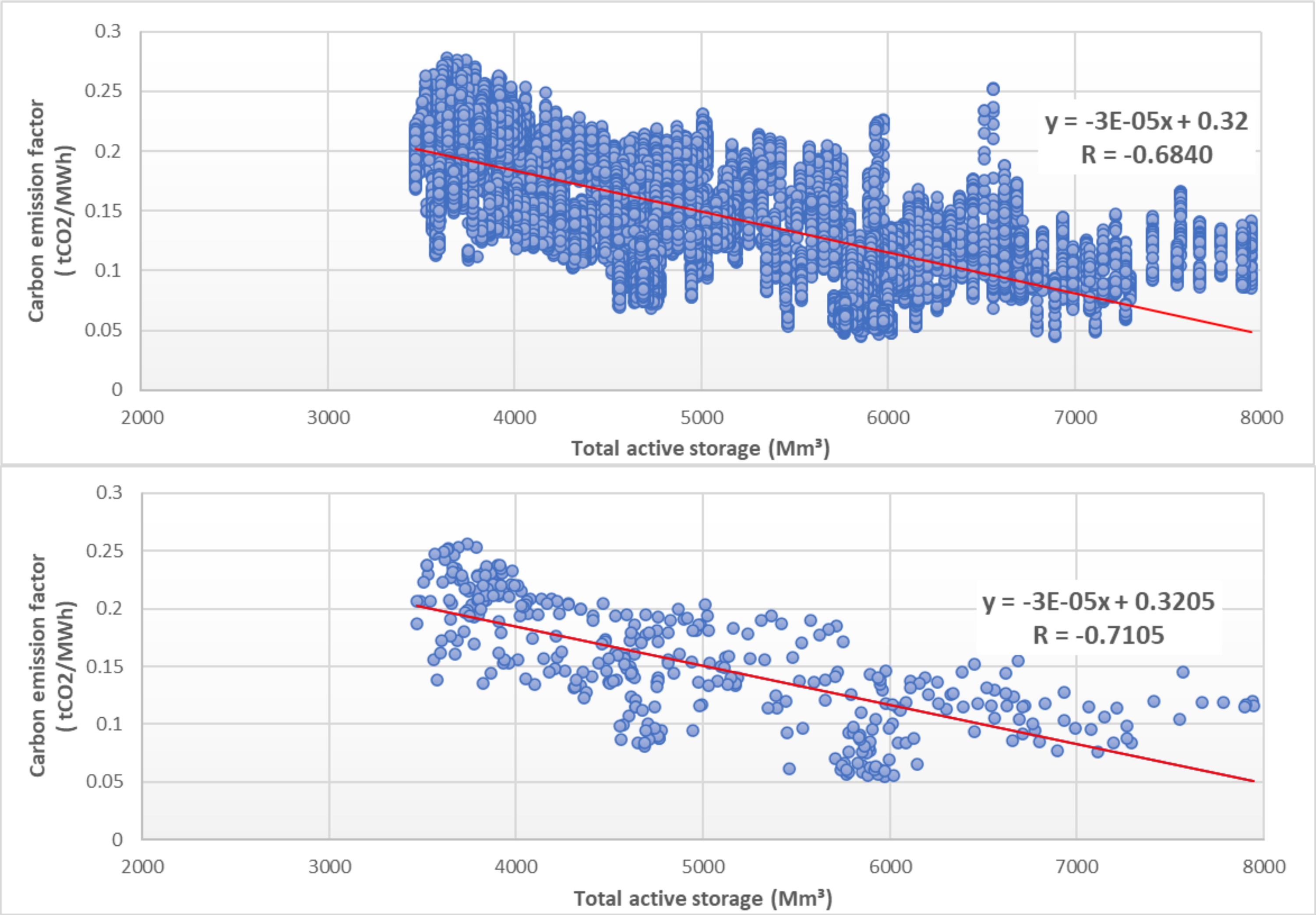


Figure 30. The relationship trend between total active lake storage and carbon emission factor based on daily period and half-hour trading period in year 2013.

From the daily period, Figure 31 shows the correlation between total active storage and carbon emission factor by daily period in year 2013. The orange curve is the trend of daily real-time carbon emission factor. The black curve is the South Island active lake storage with daily change. The Blue curve is the North Island active lake storage with daily change.

The R value (carbon emission factor against active lake storage) in year 2013 is -0.7105, which means carbon emission factor has a strong correlation with active lake storage this year. In day 100, the carbon emission factor has the highest number (0.26 $t_{CO2\text{-}e}$/MWh), with active lake storage in South Island having the lowest point at 3,100 Mm^3. From day 271 to day 361, the carbon emissions factors are low, following with relatively high lake storage in the South Island during this period. Also, the real time carbon emission factor increased from day 60 to day 120, with the daily lake storage gradually decreasing during this day period. Therefore, that means the high lake storage makes real time grid carbon emission factor low, and the real time grid carbon emission factor is decreasing with the increase of lake storage based on Figure 31.

Table 13 presents results about the monthly carbon emission factor and lake storage from year 2013 to year 2022. The active lake storage impacts the carbon emission factor of grid electricity in New Zealand from year 2013 to year 2021. The higher active lake storage brings the relatively lower monthly grid carbon emissions factor and lower lake active storage increases it. There is good downhill relationship between these two variables in this decade, particular in year 2013, 2019 and 2021. From Table 11 the R values in these three years are -0.711, -0.694 and -0.919 respectively.

In year 2013, there is the highest grid carbon emission factor at 0.22 $t_{CO2\text{-}e}$/MWh in April and May, with the lowest storage level in this year. November 2013 has the second lowest monthly grid carbon emission factor at 0.11 $t_{CO2\text{-}e}$/MWh, with the highest storage.

In year 2019, the second highest monthly carbon emission factor (0.15 $t_{CO2\text{-}e}$/MWh) is showing in the September, with the lowest storage level. On the other side, the December has the lowest carbon emissions factor at 0.06 $t_{CO2\text{-}e}$/MWh with the highest active storage.

In year 2021, The April has the highest carbon emissions factor at 0.21 $t_{CO2\text{-}e}$/MWh, followed by the lowest storage level. Also, December has the lowest carbon emissions factor at 0.05 $t_{CO2\text{-}e}$/MWh, with the highest storage in this month.

However, there is no correlation between these two variables with quite low R value existing in year 2016 and 2020. The R value in 2016 is -0.0332, and R value in 2020 is -0.1470. The months in these two years, which has high active storage, don’t have the low grid CEF. Also, low active storage doesn’t make the monthly carbon emissions factor higher in these years.

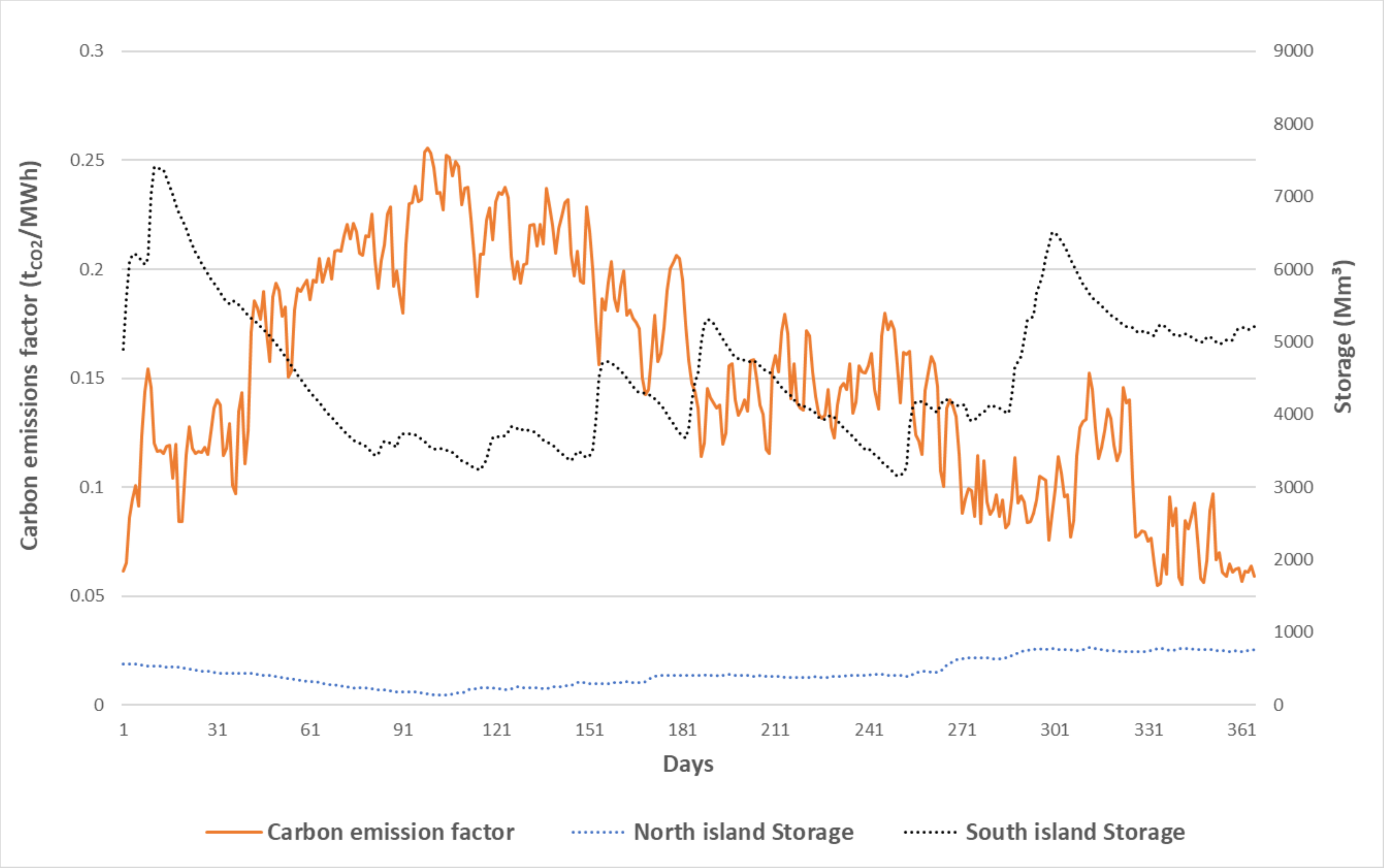


Figure 31. The daily change of carbon emission factor and lake storage in year 2013.

Table 13. Monthly carbon emission factor and lake storage from 2013 to 2022.

		2022	2021	2020	2019	2018	2017	2016	2015	2014	2013	Ave.
Jan	$t_{CO2\text{-}e}$/MWh	0.103	0.128	0.119	0.109	0.177	0.063	0.130	0.132	0.074	0.112	0.115
	Mm^3	n/a	4414	6340	4822	3765	5800	4488	4871	6612	6936	5339
Feb	$t_{CO2\text{-}e}$/MWh	0.108	0.169	0.124	0.131	0.098	0.068	0.103	0.149	0.103	0.157	0.121
	Mm^3	n/a	4169	6751	4795	4744	6490	4931	4790	5321	5537	5281
Mar	$t_{CO2\text{-}e}$/MWh	0.124	0.192	0.126	0.165	0.070	0.095	0.103	0.164	0.170	0.206	0.141
	Mm^3	n/a	3565	5587	4388	5380	5136	5572	3850	4055	4035	4619
Apr	$t_{CO2\text{-}e}$/MWh	0.147	0.213	0.082	0.114	0.074	0.082	0.101	0.148	0.183	0.229	0.137
	Mm^3	n/a	3309	4861	5493	5824	4488	5415	3496	3647	3685	4469
May	$t_{CO2\text{-}e}$/MWh	0.140	0.202	0.114	0.117	0.092	0.123	0.110	0.079	0.111	0.215	0.130
	Mm^3	n/a	3614	4874	5714	5961	3994	5762	5375	4886	3869	4894
Jun	$t_{CO2\text{-}e}$/MWh	0.090	0.188	0.185	0.095	0.097	0.177	0.103	0.076	0.098	0.177	0.129
	Mm^3	n/a	3900	3687	5930	5156	3072	5692	5403	5170	4611	4736
Jul	$t_{CO2\text{-}e}$/MWh	0.085	0.139	0.154	0.102	0.088	0.171	0.084	0.113	0.112	0.139	0.119
	Mm^3	n/a	4634	3316	4777	4767	2665	5534	5000	5021	5138	4539
Aug	$t_{CO2\text{-}e}$/MWh	0.062	0.105	0.142	0.115	0.081	0.117	0.085	0.095	0.095	0.146	0.104
	Mm^3	n/a	4875	2861	4058	4365	3173	5109	4460	5363	4311	4286
Sep	$t_{CO2\text{-}e}$/MWh	0.052	0.069	0.076	0.154	0.099	0.073	0.080	0.101	0.108	0.139	0.095
	Mm^3	n/a	5699	3026	3350	3334	4054	4372	3997	3172	4308	3924
Oct	$t_{CO2\text{-}e}$/MWh	0.046	0.056	0.127	0.135	0.145	0.064	0.075	0.083	0.124	0.094	0.095
	Mm^3	n/a	5525	4175	3505	3138	4389	4047	4034	3578	5675	4230
Nov	$t_{CO2\text{-}e}$/MWh	0.029	0.051	0.098	0.086	0.109	0.106	0.077	0.139	0.127	0.108	0.093
	Mm^3	**n/a**	**5287**	**4664**	**5141**	**4006**	**4075**	**4503**	**4129**	**4503**	**6211**	**4724**
Dec	$t_{CO2\text{-}e}$/MWh	0.033	0.053	0.085	0.061	0.100	0.172	0.061	0.117	0.119	0.069	0.087
	Mm^3	**n/a**	**5897**	**4267**	**7625**	**4348**	**3798**	**5280**	**4937**	**4736**	**5855**	**5194**
Ave.	**$t_{CO2\text{-}e}$/MWh**	**0.085**	**0.130**	**0.119**	**0.115**	**0.103**	**0.109**	**0.092**	**0.116**	**0.119**	**0.149**	
	Mm^3	**N/A**	**4574**	**4534**	**4966**	**4566**	**4261**	**5059**	**4529**	**4672**	**5014**	

4.2.3. Real-time carbon emissions factors and electricity spot price

The relationship between the real-time carbon emissions factors and spot electricity price was investigated. Table 14 presents the R values of correlation between the carbon emission factors and the electricity spot prices. As discussed above, the correlation coefficient R measures the strength and direction of linear relationship between two variables which are real-time carbon emission factor and electricity spot price. The year 2022 has the highest R value, which is 0.7171, and year 2016 has the lowest R value with 0.1637. From year 2013 to 2022, there are three years which have the R value above 0.5, which means there is a moderate (or strong) uphill linear relationship between these two variables. For the other years, the R values are below 0.5, so the correlation between electricity prices and carbon emission factor is weak. The range in R values suggests there is only a moderate relationship between spot prices and emissions factors. The relationship between these two variables in year 2017 will be taken as an example for the analysis.

Table 14. The R value regarding the electricity price against variable carbon emission factor.

Electricity price against variable carbon emission factor										
Year	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
R^2 Value	**0.5074**	**0.2022**	**0.4945**	**0.1637**	**0.6379**	**0.4351**	**0.4834**	**0.3807**	**0.4314**	**0.7171**

The R value in Figure 32 for year 2017 is 0.6379. From Table 11, it defines there is a strong uphill (positive) linear relationship based on the R value calculated in Excel. That means the carbon intensities are more likely to be increased with the increase of the electricity prices in the year 2017.

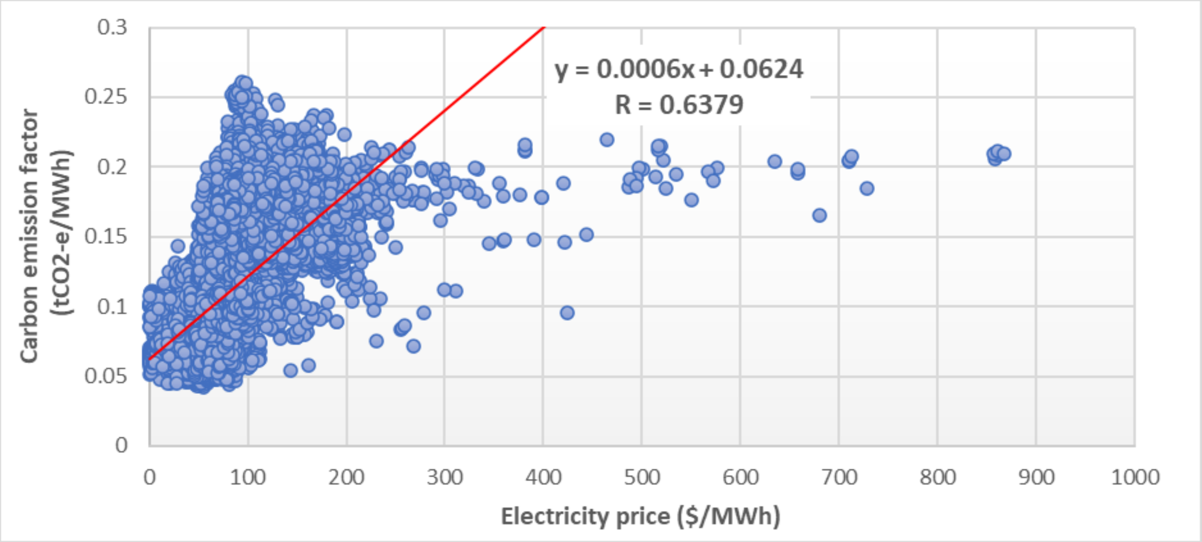


Figure 32. Correlation between carbon emission factor and electricity price in year 2017.

Figure 33 shows the carbon emissions factors have the same trend the electricity spot prices. Both carbon emissions factors and electricity price increase from trading point 4,500 (March) and reach the peak at trading point 8,550 (June). After that, both carbon emissions factor and electricity price decrease from the peak to the low point at trading point 13,050 (September). Basically, wintertime and summertime have relatively higher carbon intensities in the year 2017, which positively affects the electricity prices in these two periods. Conversely, the spring and the fall have the relatively lower carbon intensities in this year, with low electricity prices.

There are some reasons why this trend exists. The first reason is the electricity demand is higher in the winter, so more electricity would be generated by using non-renewable and renewable sources to support the demand. The second reason is that the lake storage levels are not enough to generate enough grid electricity. In 2017 there was a so called “dry year”, with June and July having the lowest active lake storage, so fossil fuels needed to be used to support the electricity generation, thus increasing the carbon emissions factor of grid electricity during that period. The third reason is that the electricity generated by non-renewable is much more expensive than that from hydro power. Therefore, the grid electricity price and carbon intensities are extremely high in these two months (June and July).

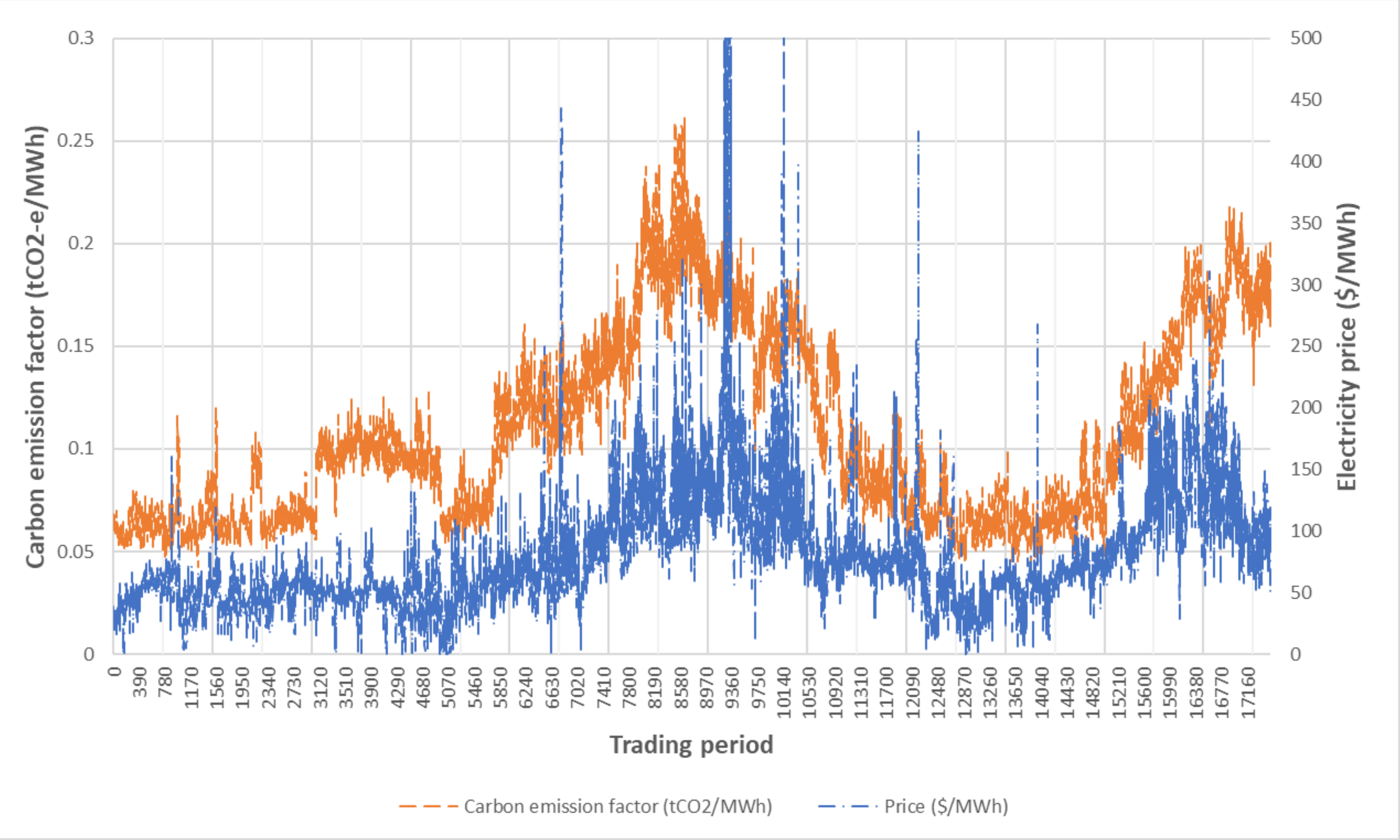


Figure 33. The trend of carbon emission factor and electricity price change within trading period in 2017.

4.3. Case studies

The case studies below are to see how much carbon emission can be reduced if the current gas steam boilers and coal steam boilers are replaced by the electrode boilers. Also, these case studies are to determine how real-time carbon emissions factors and annual carbon emissions factors impact the calculated carbon emission and carbon cost in the real practice of electrode boilers.

4.3.1. Case study one – Meat processing

A meat processing company based in Timaru was used to examine the potential emissions impacts of electrification and using real-time carbon emissions factors to quantify emissions from the supply of process hear. The plant uses a coal boiler to supply heat to the process. Steam generated using a coal boiler which has 85% boiler efficiency. The steam supply is logged every hour (kg/hr) for each day during the year 2022. The nominal steam conditions are provided in Table 15. The absolute pressure of steam is 20 bar, and the specific enthalpy of steam is 2,797.21 kJ/kg.

Sub-bituminous coal is used for the fuel to the boiler. The emission factor of sub-bituminous coal is 2.01 $t_{CO2\text{-}e}$/t (0.403 $t_{CO2\text{-}e}$/MWh or 0.112 $t_{CO2\text{-}e}$/GJ) (Ministry of Environment, 2022). The heat value of sub-bituminous coal is 18 GJ/t.

Table 15. Steam conditions of coal boiler.

Absolute pressure [bar]	**Boiling point [°C]**	**Specific volume (steam) [m^3/kg]**	**Density (steam) [kg/m^3]**	**Specific enthalpy of steam (total heat) [kJ/kg]**
20	212.37	0.1	10.047	2797.21

Table 16 shows the amount of carbon emission generated by different types of boilers from the trading time (1 & 2). The types of boilers include coal boiler and electrode boiler. Comparing to the coal boiler, the electrode boiler system has much lower carbon emissions which is due to grid electricity having lower carbon emission factor (0.0086 $t_{CO2\text{-}e}$/MWh) and electrode boiler having higher efficiency (98%).

Table 16. The amount of carbon emissions generated by different types of boilers from trading time (1 & 2).

Trading time	**1**	**2**	**1**	**2**
Time	2022-01-01 0:00:00	2022-01-01 0:30:00	2022-01-01 0:00:00	2022-01-01 0:30:00
Boiler type	Coal boiler		Electrode boiler	
Steam flow [kg/h]	1		1	
Specific enthalpy of steam [kJ/kg]	2,797.21		2,797.21	
The efficiency of boiler η_{boiler} (%)	85		98	
The energy power from fuel [MW]	0.0009	0.0009	0.0008	0.0008
Energy from fuel for real time (half-hour) [MWh]	0.00046	0.00046	0.0004	0.0004
Carbon emission factor ε_f [$t_{CO2\text{-}e}$/MWh]	0.403	0.403	0.086	0.086
The amount of carbon emission from fuel [t]	0.00019	0.00019	0.00003	0.00003

The Figure 34 shows the difference of carbon emissions by using three types of carbon emission factor which are real-time grid carbon emission factor, annual carbon emission factor of grid electricity and annual carbon emission factor of coal. Also, the energy demand from plant is also variable. The change trend of carbon emission calculated by annual carbon emission factor of grid electricity has the same trend as the one calculated by annual carbon emission factor of coal. That is because the value of annual CEF from coal and grid electricity is constant, and the only changing value is from the real-time energy demand from plant. The real-time carbon emission was zero during certain trading period which is between 9000 and 9500. That is mainly because the industry got the winter shut during this trading period (during the July).

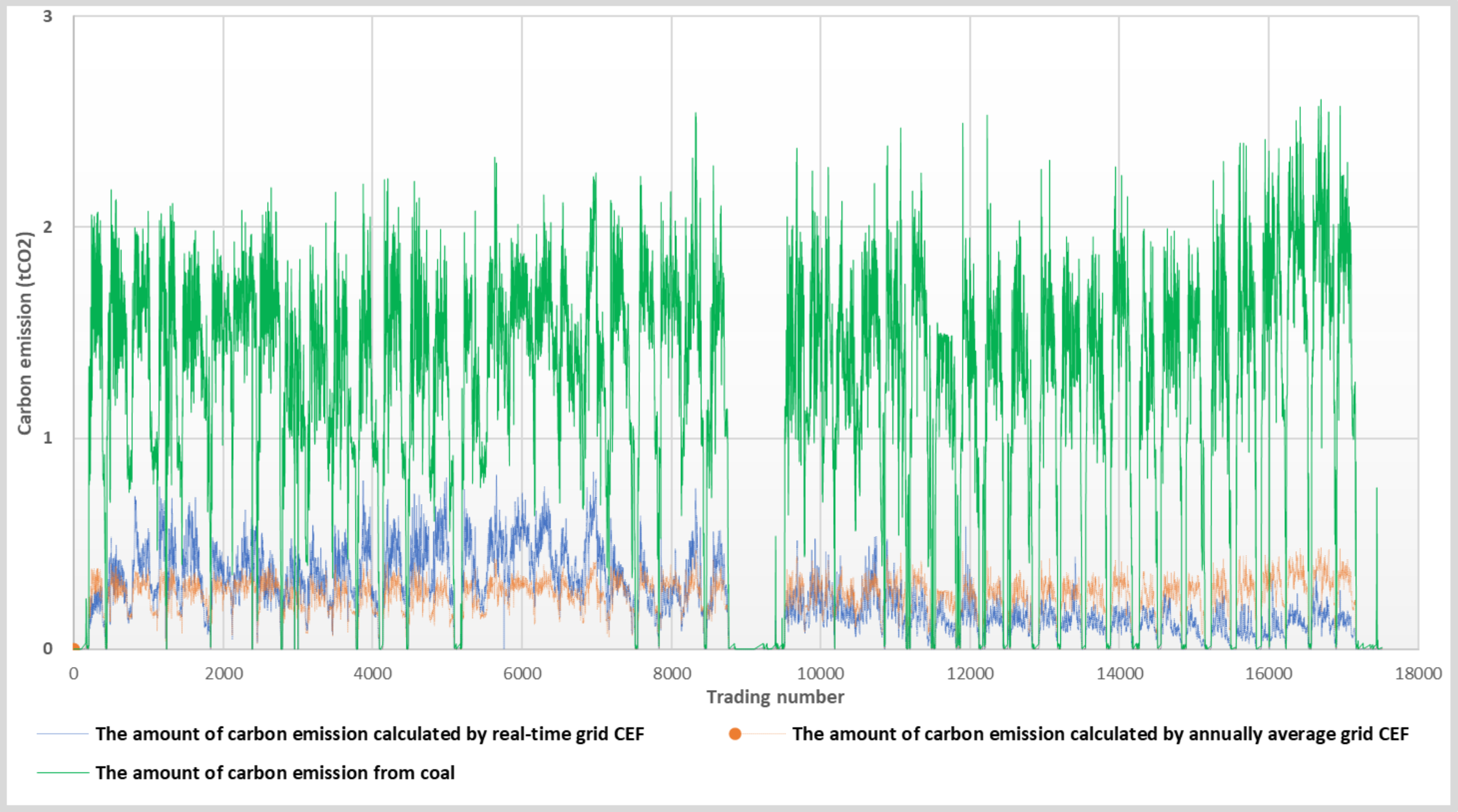


Figure 34. Real-time carbon emission changes by trading period based on steam energy demand in plant (2022).

Table 17. Comparison of total carbon emissions from different fuel types which are used to generate steam in year 2022.

	Coal boiler	**Electric boiler**
Boiler Efficiency [%]	85%	98%
Fuel energy required [MWh]	52,626	45,645
Carbon emission factor of fuel [$t_{CO2\text{-}e}$/MWh]	0.403	0.086
Total carbon emissions [$t_{CO2\text{-}e}$]	21,208	3,925

There are two reasons why the total carbon emission from electricity boiler is much lower than that from coal boiler, as shown in Table 17. One is that the efficiency of electric boiler (98%) is higher than that of coal boiler (85%). The other one is that the carbon emissions factor of grid electricity (0.086 $t_{CO2\text{-}e}$/MWh) is much lower than that of coal (0.403 $t_{CO2\text{-}e}$/MWh).

Table 18 compares the amount of carbon emissions calculated using the real-time carbon emissions factor and the annual average real-time carbon emissions factor from January to December 2022. During the whole year of 2022, the carbon emissions based on the real-time carbon emissions factor is around 2% higher than that based on the annual average real-time carbon emission factor.

Table 18. Comparison of total amount of carbon emissions calculated by real-time carbon emissions factor and average annual carbon emissions factor in 2022.

Month	**Energy from fuel (Electric boiler) (MWh)**	**Amount of carbon release calculated using annual average real-time carbon emissions factor (0.086 t_{CO2-e}/MWh) [t_{CO2-e}]**	**Amount of carbon released using real-time carbon emissions factor [tCO2-e]**	**Error %**
January	3,864	332	427	29%
February	4,212	362	460	27%
March	3,875	333	489	47%
April	3,730	321	553	72%
May	4,745	408	671	64%
June	4,351	374	399	7%
July	2,211	190	165	-13%
August	4,177	359	268	-25%
September	3,285	282	171	-40%
October	3,483	300	161	-46%
November	3,654	314	114	-64%
December	4,059	349	142	-59%
Total	**45,645**	**3,925**	**4,021**	**2%**

In the first half year of the year 2022, the total amount of carbon emission based on the real-time emissions factor is higher than that based on the annual average real-time factor. However, in the second half year, the error percentages were mostly negative results. The reason why the error percentage has difference between the first half-year and the second half-year is because the real-time carbon emission factor is higher than the average for the most time during the first half-year (January to June). Compared to results from the first half year, the real-time carbon intensities were less than that of the average carbon emission factor in the second half-year in 2022. The reason why the real-time carbon intensities in the first half-year are higher than from the second half-year for the most of time is because more renewable resources are used to generate electricity, which would bring less carbon intensities. From Table 19 the renewable percentage for grid electricity generation during the first six months (January to June) is 82%, and the for the last six months (July-December) is 93% resulting in much lower emissions factors.

Table 19. Electricity generation from different energy fuels and renewable percentage.

Time period (Year 2022)	January-June	July-December	Whole year
Total generation (MWh)	19,650,770	20,802,136	40,452,906
Coal	733,069	222,140	955,209
Diesel	1,778	1,570	3,348
Gas	2,843,403	1,307,569	4,150,972
Geo	3,738,694	3,686,777	7,425,470
Hydro	11,068,837	14,150,132	25,218,969
Wind	1,154,980	1,327,796	2,482,776
Wood	112,125	107,876	220,001
Renewable percentage	**82%**	**93%**	**87%**
Coal	4%	1%	2%
Diesel	0%	0%	0%
Gas	14%	6%	10%
Geo	**19%**	**18%**	**18%**
Hydro	**56%**	**68%**	**62%**
Wind	**6%**	**6%**	**6%**
Wood	**1%**	**1%**	**1%**

Table 19 illustrates more fossil fuels (from January to June) are used to generate grid electricity, which leads to higher carbon emission factor during the first six months than that from the second six months. During the first six months in year 2022, fossil fuel (coal, diesel and gas) takes up 18% of electricity generation compared with 7% from the second six months. Also, hydro make up 68% of electricity generation in the second half-year, which is much higher than that from first half-year with 56%.

Methods to calculate the total amount of carbon emissions

The amount of carbon emissions will be analysed from year 2013 to year 2022, by using the production data of this case study. Different total amount of emissions will be calculated by using different types of carbon emission factor data from different years.

The total amount of annual carbon emission is calculated based on the three types of carbon emission factor, which is shown as A, B and C in the next several figures.

The blue dot (A) shows the amount of carbon emissions is calculated by using annual average carbon emissions factor from the MfE guidebook (Reference) (CEF_A) (Ministry of environment, 2022).

The orange dot (B) shows the amount of carbon emissions is calculated by using annual average carbon emissions factor calculated from real-time (CEF_B).

The grey dot (C) shows the amount of carbon emission is calculated by real-time carbon emissions factor (CEF_C).

Figure 35 shows the amount of carbon emissions calculated by different methods from 2013 to 2022. In 2021 and 2022, the carbon emissions factor (A) from reference (Ministry of environment, 2022) is not available. Therefore, only the total amount of carbon emissions calculated by CEF_B and CEF_C will be compared for year 2021 and year 2022. In year 2022, the total amount of carbon emission calculated by CEF_C is around 2.4% higher than that calculated by CEF_B, which means more carbon emission is produced by using CEF_C. In the year 2021, the total amount of carbon emission calculated by CEF_C is 2.2% higher than that calculated by CEF_B , which has the similar situation as the one from year 2022.

From 2013 to 2020, the carbon emissions calculated by CEF_A is lower than that calculated by CEF_A. The error is between 0% to 9.2% which is shown in the Table 20, and 2017 has highest error which is 9.2%. Also, the carbon emissions calculated by CEF_B is higher than that calculated by CEF_C among these years, but the errors are quite small (within 2.6%).

Table 20. Comparison of carbon cost gap based on different CEF for different year.

	2022	**2021**	**2020**	**2019**	**2018**	**2017**	**2016**	**2015**	**2014**	**2013**
Emission gap A [$t_{CO2\text{-}e}$]	**n/a**	**n/a**	**-17**	**189**	**360**	**414**	**284**	**181**	**-2**	**447**
Error	**n/a**	**n/a**	**-0.3%**	**3.8%**	**8.4%**	**9.2%**	**7.1%**	**3.5%**	**0.0%**	**6.9%**
Emission gap B [$t_{CO2\text{-}e}$]	**96**	**129**	**-109**	**-39**	**-50**	**-134**	**56**	**-2**	**-48**	**-55**
Error	**2.4%**	**2.2%**	**-2%**	**-0.7%**	**-1.1%**	**-2.6%**	**1.3%**	**0%**	**-0.9%**	**-0.8%**
Carbon price [NZD/$t_{CO2\text{-}e}$]	**80**	**40**	**23**	**22**	**20**	**19**	**10**	**16**	**8**	**8**
Carbon cost gap A in total [NZD]	**n/a**	**n/a**	**-391**	**4,158**	**7,200**	**7,866**	**2,840**	**2,896**	**-16**	**3,576**
Carbon cost gap B in total [NZD]	**7,680**	**5,160**	**-2,507**	**-858**	**-1,000**	**-2,546**	**560**	**-32**	**-384**	**-440**

Note: The gap A= the value from real-time (CEF_C) – the value based on average CEF from reference (CEF)

The gap B= the value from real-time (CEF_C) – the value based on average CEF calculated by real-time CEF (CEF_B)

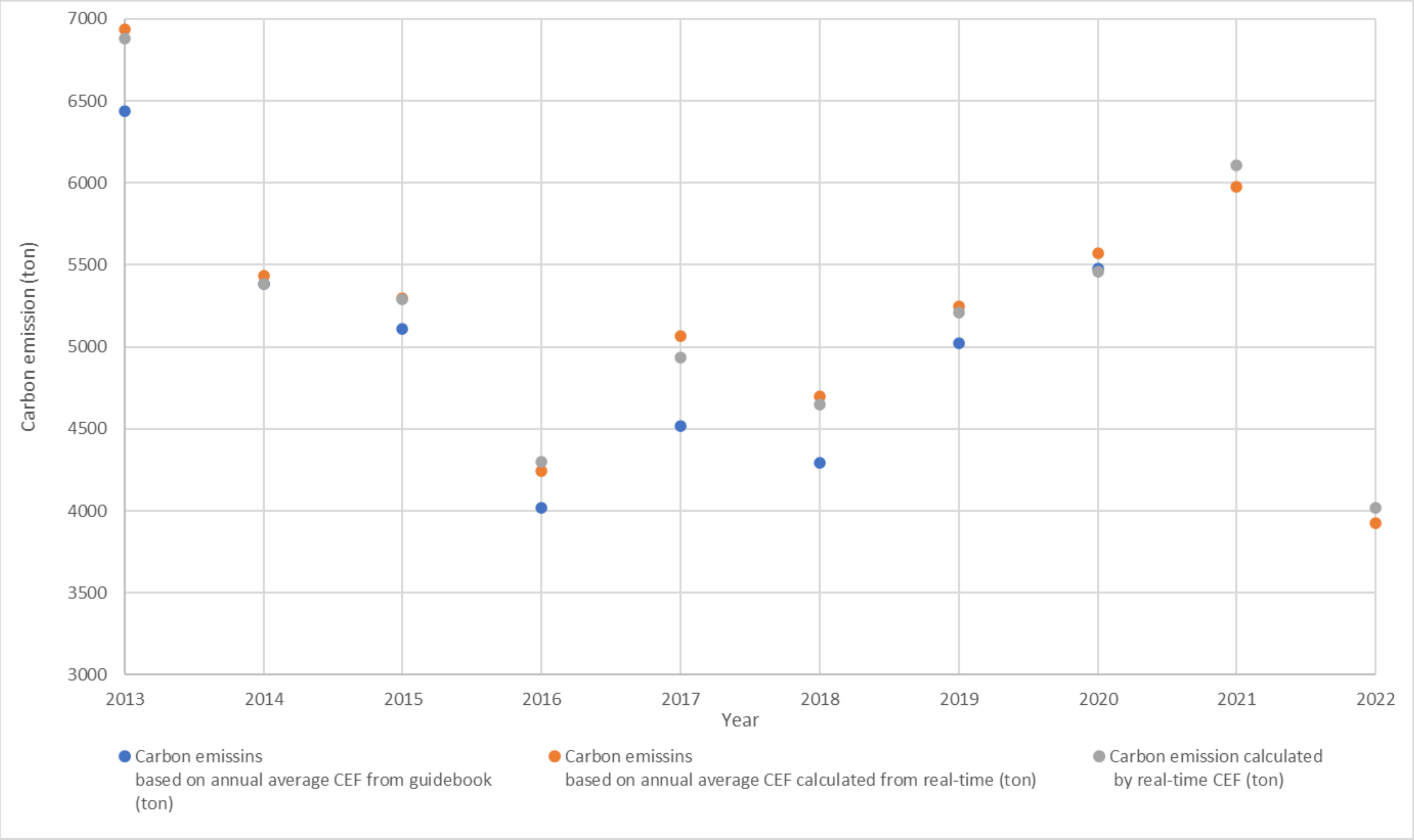


Figure 35. The carbon emissions based on different carbon emissions factor for case study 1.

The comparison of carbon cost difference for different years

The carbon cost is variable from year to year. There are two factors which impact this. One is the total amount of carbon emission for certain years. The second one is carbon price for different years. Figure 36 shows the carbon price from 2010 to 2023 and illustrates a sharp increase between 2020 and 2023.

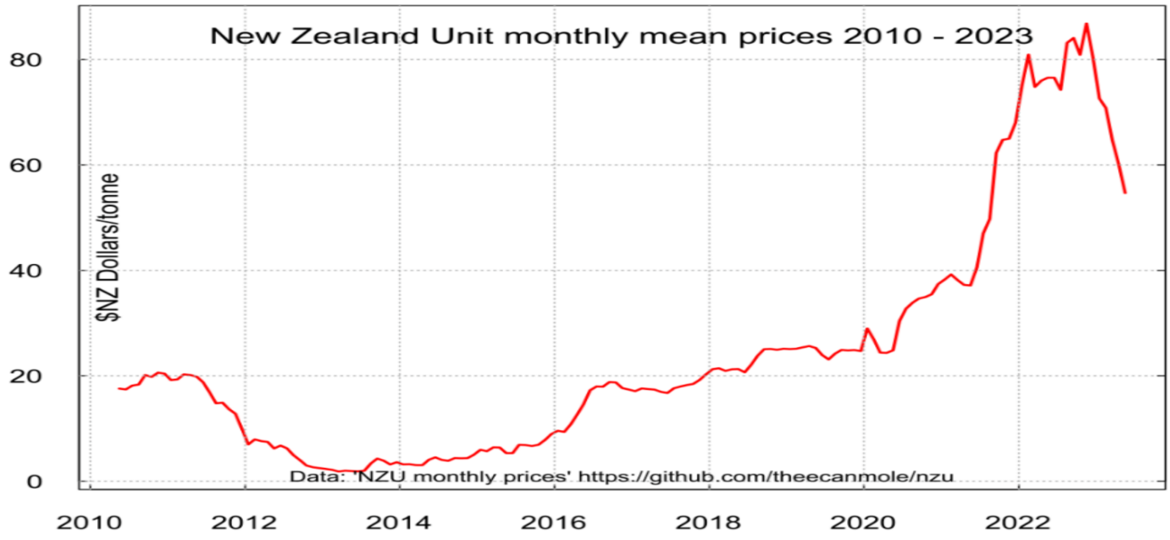


Figure 36. The estimated trend line for carbon price in New Zealand.

Table 20 shows the company will pay NZD 7,680 more every year by using CEF_C instead of using CEF_B to calculate the amount of carbon emissions from process heat in 2022.

In the section outlining gap A, the results are positive for most year from 2013 to 2020, except the 2020 and 2014. That means the company can save certain amount of carbon costs from calculation by using “the annual reference CEF” CEF_A rather than “the real-time CEF” CEF_C.

In the section outlining gap B, the results are negative for most years from 2013 to 2020, except year 2016. It means the company can save certain amount of carbon costs from the calculation by “the real-time CEF” CEF_C rather than “average annual CEF calculated by real-time CEF” CEF_B .

4.3.2. Case study two – Dairy Processing

A North Island based New Zealand dairy company uses steam to supply heat during production, and the steam is generated by natural gas boiler which has 90% heat efficiency. Table 21 shows the characteristics of steam produced in the gas boiler. The absolute pressure of steam is 25 bar, and the specific enthalpy of steam is 2,800.91 kJ/kg.

Table 21. The characteristics of steam.

Absolute pressure [bar]	**Boiling point [°C]**	**Specific volume (steam) [m^3/kg]**	**Density (steam) [kg/m^3]**	**Specific enthalpy of steam (total heat) [kJ/kg]**
25	223.94	0.08	12.52	2800.91

Table 22. Carbon emission generated by different types of boilers from trading time (1 &2).

Trading time	**1**	**2**	**1**	**2**
Time	1/01/2016 0:00	1/01/2016 0:30	1/01/2016 0:00	1/01/2016 0:30
Boiler type	Gas boiler		Electric boiler	
Steam flow [kg/h]	90%		98%	
Specific enthalpy of steam [kJ/kg]	43	42	43	42
The efficiency of boiler η_{boiler} (%)	2,800.91		2,800.91	
The energy power from fuel [MW]	38	37	35	34
Energy from fuel for real time (half-hour) [MWh]	18.90	18.50	17.36	16.99
Carbon emission factor ε_f [$t_{CO2\text{-}e}$/MWh]	0.195*	0.195	0.093	0.093
The amount of carbon emission from fuel [t]	3.69	3.61	1.61	1.58

* the carbon emission factor of natural gas is 0.195 $t_{CO2\text{-}e}$/MWh (Ministry of Environment, 2022).

Figure 37 illustrates the low energy demand occurs in two production periods. One existed around trading number 6,100 which is the beginning of May. The other one existed around trading number 14,800 which is in the beginning of November. That is mainly due to plant experiencing maintenance or low production.

From Table 23 the carbon emission from gas boilers is nearly two times higher than that from the electric boiler. There are two reasons why the total carbon emission from electricity boiler is much lower than that from gas boiler. One is that the efficiency of electricity boiler (98%) is higher than that of natural gas boiler (90%). The other one is that the carbon emission factor of grid electricity (0.093 $t_{CO2\text{-}e}$/MWh) is only half of that of gas boiler (0.195 $t_{CO2\text{-}e}$/MWh).

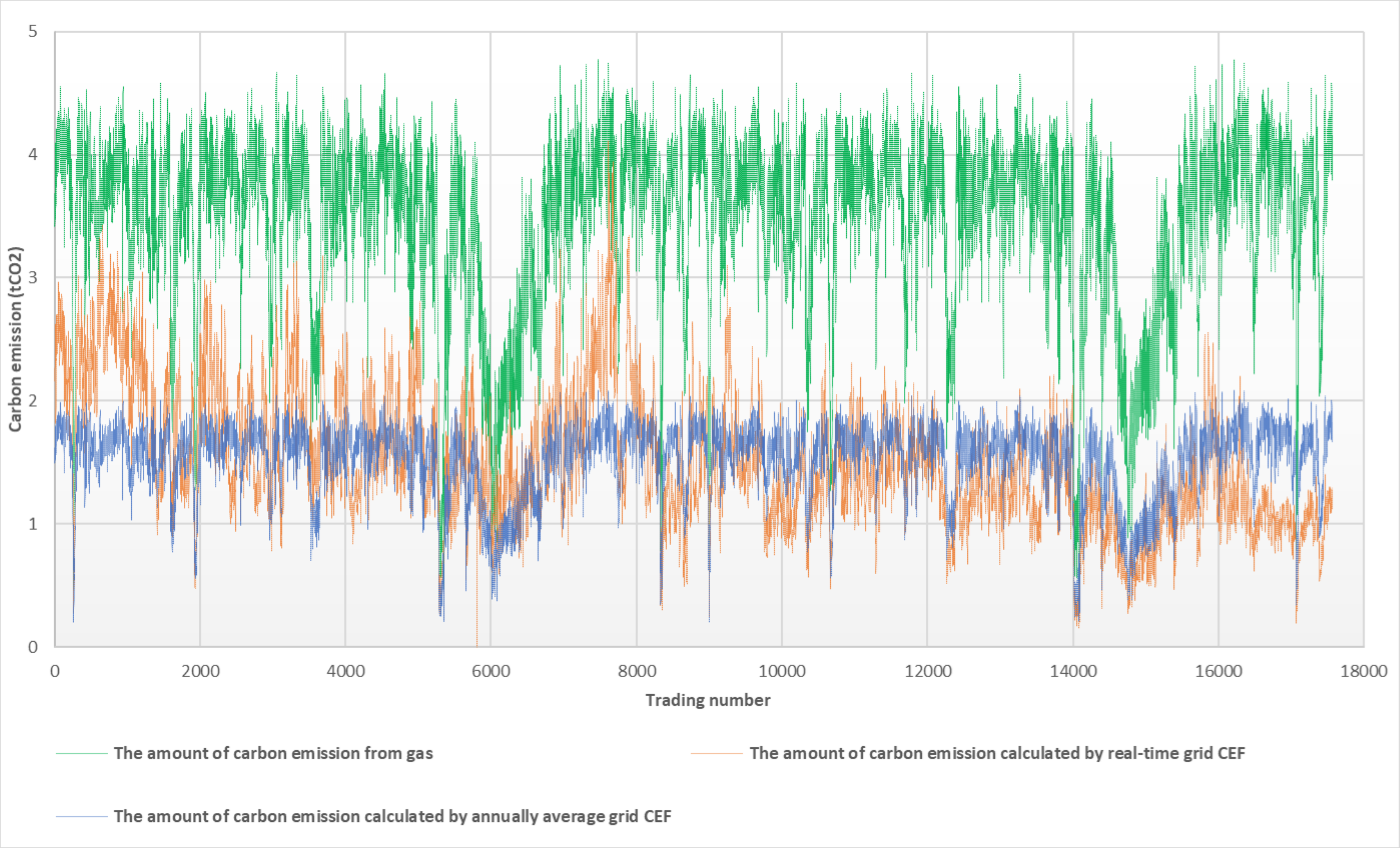


Figure 37. Real-time carbon emission changes by trading period based on steam energy demand in plant (2016).

Table 23. The comparison of total carbon emissions from different fuel types which are used to generate steam in year 2016.

	Gas boiler	**Electric boiler**
Boiler Efficiency [%]	90%	98%
Fuel energy required [MWh]	312,979	287,429
Carbon emission factor of fuel [$t_{CO2\text{-}e}$/MWh]	0.195	0.093
Total carbon emissions [$t_{CO2\text{-}e}$]	61,031	26,731

From Table 24, the amount of carbon emissions calculated by "real-time CEF" and "annual average carbon emissions factor calculated by real-time value" will be compared from January to December in year 2016.

Table 24. Comparison of total amount of carbon emission from real-time value and average annual value base in 2016.

Month	**Energy from fuel (Electric boiler) (MWh)**	**Amount of carbon release calculated using annual average real-time carbon emissions factor (0.093 $t_{CO2\text{-}e}$/MWh) [$t_{CO2\text{-}e}$]**	**Amount of carbon released using real-time carbon emissions factor [tCO2-e]**	**Error %**
January	25,808	2,400	3,368	40%
February	23,800	2,213	2,441	10%
March	24,970	2,322	2,561	10%
April	22,952	2,135	2,271	6%
May	20,153	1,874	2,157	15%
June	25,124	2,337	2,608	12%
July	25,808	2,400	2,147	-11%
August	25,267	2,350	2,151	-8%
September	24,312	2,261	1,910	-16%
October	23,387	2,175	1,772	-19%
November	19,759	1,838	1,543	-16%
December	26,090	2,426	1,579	-35%
Total	**287,429**	**26,731**	**26,509**	**-1%**

During the whole year 2016, the carbon emissions based on the real-time CEF is 1% lower than that based on the annual average carbon emission factor calculated by real-time CEF.

In the first half-year of the year 2016, the total amount of carbon emission based on the real-time carbon emissions factor is higher than that based on the annual average carbon emissions factor. However, in the second half year, the error percentages were mostly negative results. The reason why the error percentage has difference between the first half-year and the second half-year is because the real-time carbon emission factor is higher than the average carbon emissions factor for the most time during the first six months (January to June). Compared to results from the first half year, the real-time carbon intensities are less than that of the average carbon emission factor in the second half-year in 2016. The reason why the real-time carbon intensities in the first half-year are higher than from the second half-year for the most of time is because more renewable resources are used to generate electricity, which would bring less carbon intensities. From Table 25 renewable percentage for grid electricity generation during the first six months (January to June) is 84%, and the one for the last six months (July-December) is 87%.

Table 25. Electricity generation from different energy fuels and renewable percentage.

Time period (Year 2016)	**January-June**	**July-December**	**Whole year**
Total generation (MWh)	19,760,320	20,564,685	40,325,005
Coal	630,574	200,135	830,710
Diesel	399	1,083	1,482
Gas	2,656,233	2,410,769	5,067,002
Geo	3,709,929	3,566,482	7,276,411
Hydro	11,723,470	13,279,306	25,002,777
Wind	1,036,986	867,321	1,904,307
Wood	129,516	116,746	246,262
Renewable percentage	**84%**	**87%**	**85%**
Coal	3%	1%	2%
Diesel	0%	0%	0%
Gas	13%	12%	13%
Geo	**19%**	**17%**	**18%**
Hydro	**59%**	**65%**	**62%**
Wind	**5%**	**4%**	**5%**
Wood	**1%**	**1%**	**1%**

Table 25 shows more fossil fuels (from January to June) are used to generate grid electricity, which makes the carbon emission factor from the first six months higher than that from the second six months. During the first six months in 2016, fossil fuel (coal, diesel and gas) makes up 16% of electricity generation compared with 13% from the second six months. Also, hydro makes up 65% of electricity generation in the second half-year, which is much higher than that from first half-year with 59%.

Ways to calculate the total amount of carbon emissions

The amount of carbon emissions will be analysed from 2013 to 2022, by using the production data of this case study. Different total amount of emissions will be calculated by using different carbon emission factor data from different years.

The total amount of annual carbon emission is calculated based on the three types of carbon emission factor, which is shown as A, B and C as in the previous case study.

Figure 38 shows the amount of carbon emissions is calculated by different types of carbon emission factor from year 2013 to year 2022. In year 2021 and year 2022, The carbon emission factor (A) from reference (Ministry of environment, 2022) is not available. Therefore, only the total amount of carbon emissions calculated by CEF_B and CEF_C will be compared for year 2021 and year 2022. In year 2022, the total amount of carbon emission calculated by CEF_C is 2.4% less than that calculated by CEF_B, which means less carbon emission is produced by using CEF_C. in the year 2021, the total amount of carbon emission calculated by CEF_C is 1.1% less than that calculate by CEF_B, which has the similar situation as the one from year 2022.

From the 2013 to 2020, the carbon emissions calculated by CEF_A is lower than that calculated by CEF_C. The error is between 0% to 11.0% which is shown in Table 26, and 2017 has highest error which is 11%. The carbon emissions calculated by CEF_B is higher than that calculated by CEF_C among these years, but the errors are quite small (within 2.9%).

Comparison of carbon cost gap for different years

The carbon cost is quite different from year to year. There are two factors which impact that. One is the total amount of carbon emission for certain years. The second one is the carbon price for different years. From Table 26, it shows that the company will pay more NZD 12,150 every year by using CEF_C instead of using the CEF_A to calculate the amount of carbon emission in year 2016. On the other hand, it shows that the company will pay less NZD 2,220 every year by using CEF_C instead of using the CEF_B to calculate the amount of carbon emission in year 2016.

In the section of the gap A, the results are positive for most years from 2013 to 2020, except in 2020 and 2014. That means the company can save certain amount of carbon costs from calculation by using “the annual guidebook CEF” (CEF_A) rather than “the real-time CEF” (CEF_C).

In the section of gap B, the results are negative for most years from 2013 to 2020, except 2015. It means the company can save certain amount of carbon costs from the calculation by “the real-time CEF” (CEF_C) rather than “average annual CEF calculated by real-time CEF”(CEF_B) .

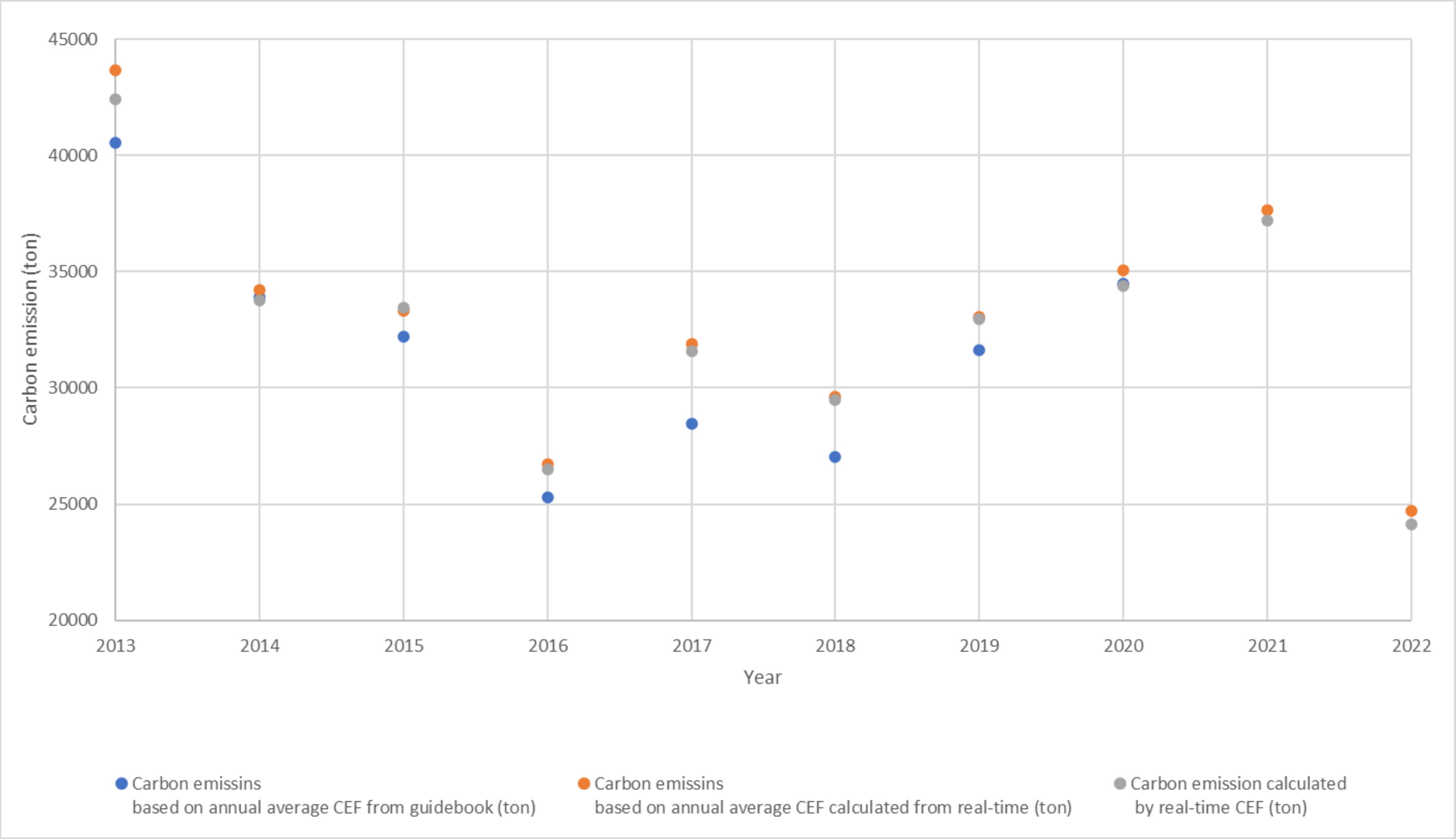


Figure 38. Carbon emissions based on different types of carbon emission factor case study 2.

Table 26. Comparison of carbon cost gap based on different CEF for different years.

	2022	2021	2020	2019	2018	2017	2016	2015	2014	2013
Emission gap A [$t_{CO2\text{-}e}$]	N/A	N/A	-98	1,354	2,466	3,119	1,215	1,263	-133	1,892
Error	N/A	N/A	-0.30%	4.30%	9.10%	11.00%	4.80%	3.90%	-0.40%	4.70%
Emission gap B [$t_{CO2\text{-}e}$]	-595	-431	-672	-83	-121	-330	-222	113	-420	-1269
Error	-2.4%	-1.1%	-1.9%	-0.3%	-0.4%	-1.0%	-0.8%	0.3%	-1.2%	-2.9%
Carbon price [NZD/$t_{CO2\text{-}e}$]	80	40	23	22	20	19	10	16	8	8
Carbon cost gap A in total [NZD]	N/A	N/A	-2,254	29,788	49,320	59,261	12,150	20,208	-1,064	15,136
Carbon cost gap B in total [NZD]	-47,600	-17,240	-15,456	-1,826	-2,420	-6,270	-2,220	1,808	-3,360	-10,152

Note: The gap A= the value from real-time (CEF_C) – the value based on average CEF from reference (CEF)

The gap B= the value from real-time (CEF_C) – the value based on average CEF calculated by real-time CEF (CEF_B)

4.3.3. Summary of case studies

The carbon emission from coal boiler in this case study one is 5.4 times higher than that from electrode boiler for the same amount of heat generation. The carbon emissions from gas boiler in case study two is 2.3 times higher than that from the electrode boiler. Therefore, using the electrode boiler can save much more carbon emissions compared to the other two boiler types, especially from coal boiler.

From analysis based on three types of carbon intensities applying for the electrode boilers during the period (year 2013-year 2022). There are more possibilities to have minimal amount of annual carbon emissions and carbon cost by using CEF_A ("the annual guidebook CEF") for calculation rather than using the CEF_B (average annual CEF calculated by real-time CEF) and CEF_C (the real-time CEF).

From these two case studies, real-time carbon intensities in the first half-year are higher than that from the second half-year. That is mainly because the renewable percentage in first half-year is lower than that from the second half-year.

4.4. Real time emissions of hydrogen

A major conclusion of chapter 3 was that the LCOE from electricity sourced hydrogen is equal to the one from natural gas when the grid electricity is 37.98 NZD/MWh. Furthermore, the LCOE from electricity sourced hydrogen will become less than that from natural gas once the price of grid electricity is less than 37.98 NZD/MWh. In this case, the real-time carbon emission factor will be analysed and discussed when grid electricity price is less than 37.98 NZD/MWh.

4.4.1. Trading periods against the low grid electricity price

Figure 39 shows the increasing trend of electricity price from 2013 to 2022. The number of trading periods is quite variable from year to year, when the electricity price is less than 37.98 NZD/MWh. Low electricity prices (less than 37.98 NZD/MWh) only take up a small portion of annual electricity prices from 2013 to 2022. Table 27 shows the specific details about how many trading numbers which have electricity price less than 37.98 NZD/MWh. It also shows the percentage trading periods that occur annually when the electricity price is less than 37.98 NZD/MWh. The percentages, regrading low electricity that could be economically used to generate hydrogen, range from 7% to 32%. 2022 and 2013 have relatively high percentages which are 32% and 22% respectively. The percentages for other years are only around 10%. Based on these ten years' figures, most years have a small number of hours available to generate hydrogen economically. 2021 will be taken as an example to show the single trading time (half-hour) against the electricity price.

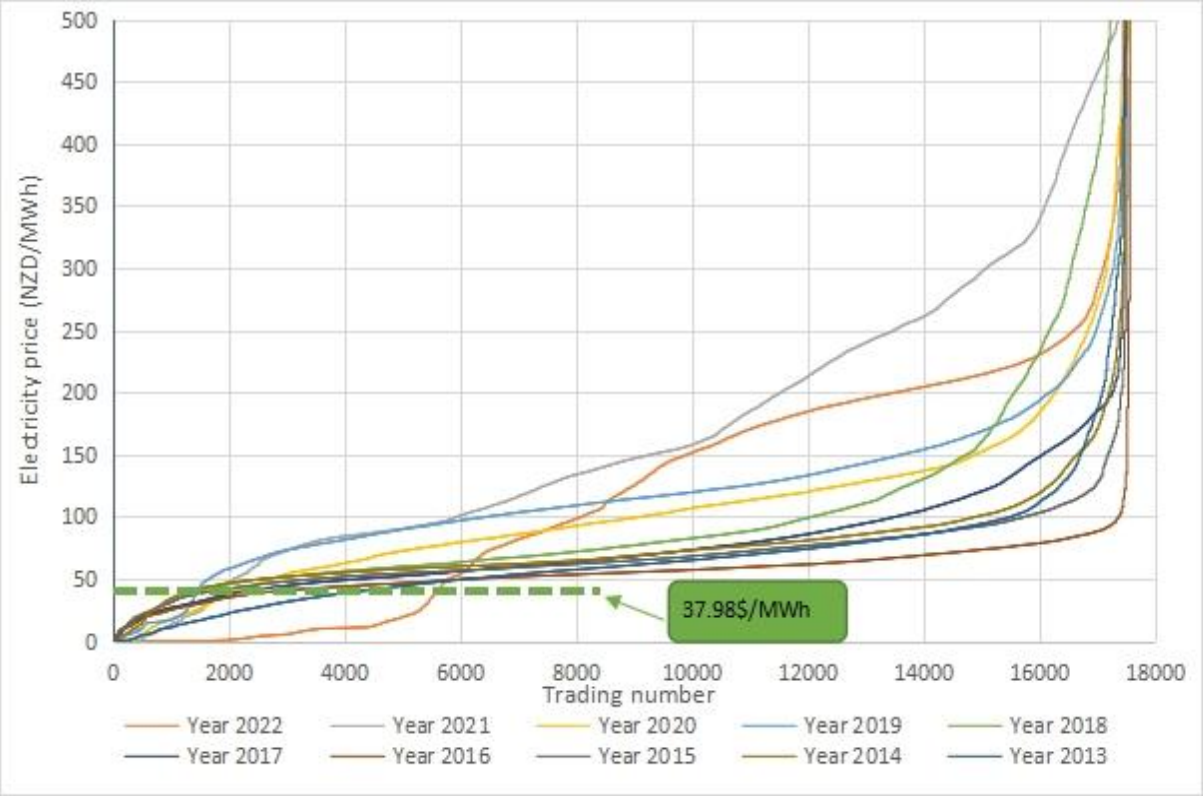


Figure 39. The electricity price from year 2013 to year 2022.

Table 27. the specific details regarding certain trading numbers and percentage from 2013 to 2022.

Year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Number of trading periods less than 37.98 NZD/MWh	3,920	1,181	1,453	2,402	2,039	1,314	1,434	1,981	1,807	5,560
Percentage*	22%	7%	8%	14%	12%	8%	8%	11%	10%	32%

* the total number of trading periods per year is 17,520

Figure 40 shows the occurrence of the trading period which have electricity price less than 37.98 NZD/MWh from 2021. It shows low electricity prices (below 37.98 NZD/MWh) are quite variable around the year 2021. In the first half year in 2021, there is just a few certain trading times to have electricity price less than 37.98 NZD/MWh. Most of trading times, which are available to have electricity price less than 37.98 NZD/MWh, concentrate in the second half year.

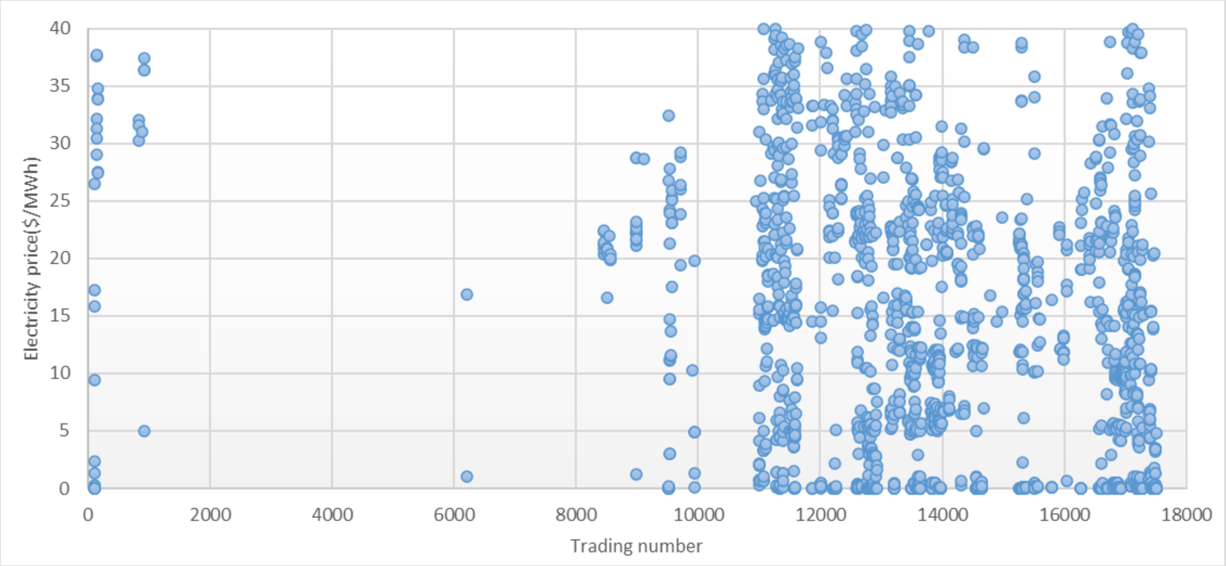


Figure 40. The electricity price against trading number in the year 2021.

The low electricity price against carbon emission factor

There is correlation between spot electricity price and the real-time carbon emission factor. The low electricity prices are likely to come with the low carbon intensities. In this section, the real-time carbon intensities would be analysed to see how they are allocated once the grid electricity price is less than 37.98 NZD/MWh. The year 2018 would be taken as an example to analyse the real-time carbon intensities when the grid electricity price is less than 37.98 NZD/MWh.

Figure 41 illustrates that most carbon emissions factors that occur during trading periods when the spot price is than 37.98 NZD/MWh are less than the annual average carbon emission factor (shown in orange).

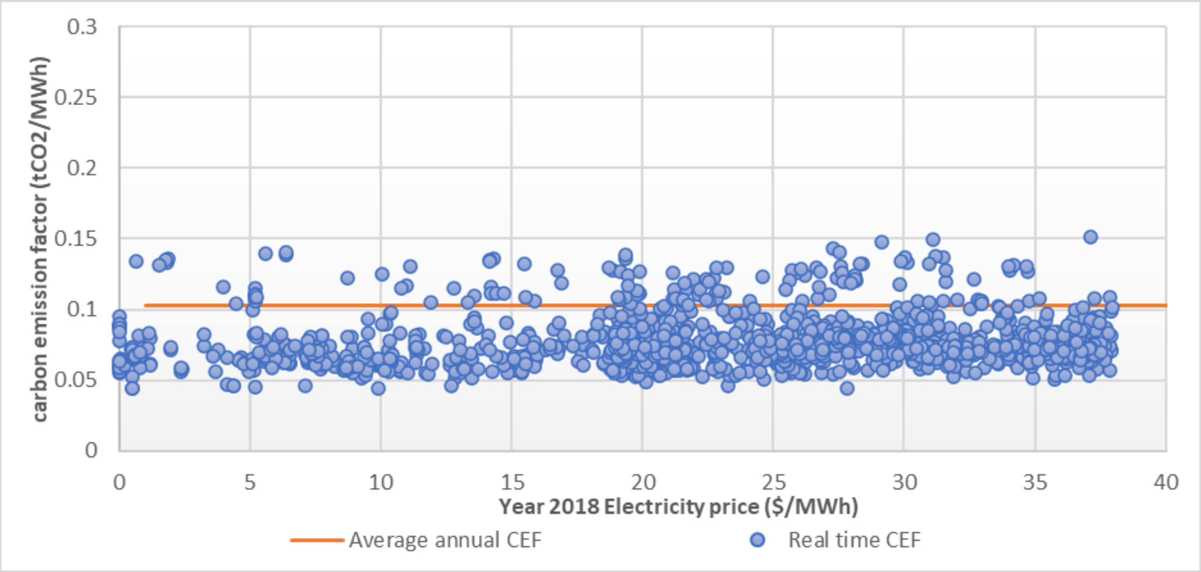


Figure 41. The electricity price against CI in year 2018 (only the electricity price below 37.98 NZD/MWh).

In 2018, the total trading periods are 17,516, and there are 1,314 trading periods (the blue dots above) which have the electricity prices below 37.98 NZD/MWh. Among these 1,314 trading numbers, there are 89% of them which has the real-time CEF below the annual average carbon emissions factor. The annual average carbon emissions factor is shown as the red line above. Based on the calculation, the average carbon emissions factor from these certain blue trading times above is 0.078 $t_{CO2\text{-}e}$/MWh which is 24% lower than that of annual average carbon emissions factor (0.103 $t_{CO2\text{-}e}$/MWh).

Table 28. The average CEF when electricity price less than 37.97 ton/MWh from year 2013 to 2022.

Year	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Annual average carbon emissions factor [t_{CO2-e}/MWh]	0.152	0.119	0.116	0.093	0.111	0.103	0.115	0.122	0.131	0.086
Average CEF when electricity price lower than 37.98 [NZD/MWh]	0.102	0.083	0.083	0.073	0.072	0.078	0.066	0.092	0.06	0.045
Difference between "Annual average CEF" and "The average CEF when electricity price lower than 37.98 NZD/MWh"	33%	30%	28%	22%	35%	24%	43%	25%	54%	48%
The percentage of trading numbers which has CEF lower than annual average CEF	93%	96%	93%	88%	98%	89%	96%	86%	99%	96%

Table 28 shows the difference between two types of carbon emission factor. Compared to the amount of carbon emission calculated by annual average emissions factor, 22% to 54% of carbon emissions can be reduced by using low-price grid electricity which is below 37.97 NZD/MWh. Also, the carbon intensities of trading periods, which have low price of grid electricity (37.98 NZD/MWh), are almost below the annual average electricity CEF of their associated year. The percentage is between 88% and 99% in the ten-year period (2013 – 2022).

Sensitivity analysis regarding the carbon emission factor and emissions

From this section, the sensitivity analysis would be calculated to see how some variables are changed with the increase of electricity prices. The main variables are "the specific capital and energy cost of hydrogen boiler", "total trading numbers when electricity price below a certain price", and "the percentage regarding Trading numbers when electricity price below a certain price and annual average CEF". The year 2018 will be taken as an example for the analysis in Table 29.

Table 29. The sensitivity analysis for some variable with the increase of electricity price.

2018				
Electricity price [NZD/MWh]	37.98	60	80	100
Average CEF when the electricity below certain price [t_{CO2-e}/MWh]	0.078	0.081	0.085	0.090
Average annual CEF [t_{CO2-e}/MWh]	0.103			
Difference between A1 and A2	-24%	-22%	-17%	-13%
Total trading periods	17,520			
Trading periods when electricity price below a certain price and annual average CEF	1,175	4,405	7,892	9,229
Trading periods when electricity price below a certain price	1,314	5,040	9,522	12,075
Percentage (B1/B2)	89%	87%	83%	76%
LCOE of hydrogen boiler system [NZD/GJ]	21.31	30.75	39.32	47.9

A1 is average carbon emission factor when the electricity below the certain prices
A2 is the average annual carbon emission factor
B1 is the trading numbers when the electricity price below a certain price and annual average CEF
B2 is the trading number when the electricity price below a certain price

The LCOE of hydrogen boiler system changes with the increase of grid electricity price. When the electricity price is increased from 37.98 NZD/MWh to 100 NZD/MWh, The A1 is increased from 0.078 t_{CO2-e}/MWh to 0.090 t_{CO2-e} MWh which is still less than the average carbon emissions factor (0.103 t_{CO2-e}/MWh).

Figure 42 shows the trading numbers of grid electricity become more and more with the increase of limit in electricity price. The trading periods increase from 1,314 to 12,075, with price limit increasing from 37.98 NZD/MWh to 100 NZD/MWh. Also, the trading periods increase from 1,175 to 9,229 to meet the electricity price limit and annual average carbon emissions factor limit at the same time. That means there are more trading number available to use to generate hydrogen with the setting limit increasing.

There is less possibility to use every single trading number to make real-time carbon emissions factor always less than annual average carbon emissions factor as the electricity price become higher and higher. In the year 2018, when the spot electricity price is less than 37.98 NZD/MWh, 89% of blue dots are below the annual average carbon emissions factor. With the increase of electricity prices, the number of blue dots would become equally spread over each side the orange line. When the electricity price reaches to 100 NZD/MWh, there are 76% blue dots which have real-time carbon emission factor below the average carbon emissions factor. That means there is only 76% possibility to make real time carbon emissions factor below the annual average by using the real-time grid electricity with electricity price below 100 NZD/MWh.

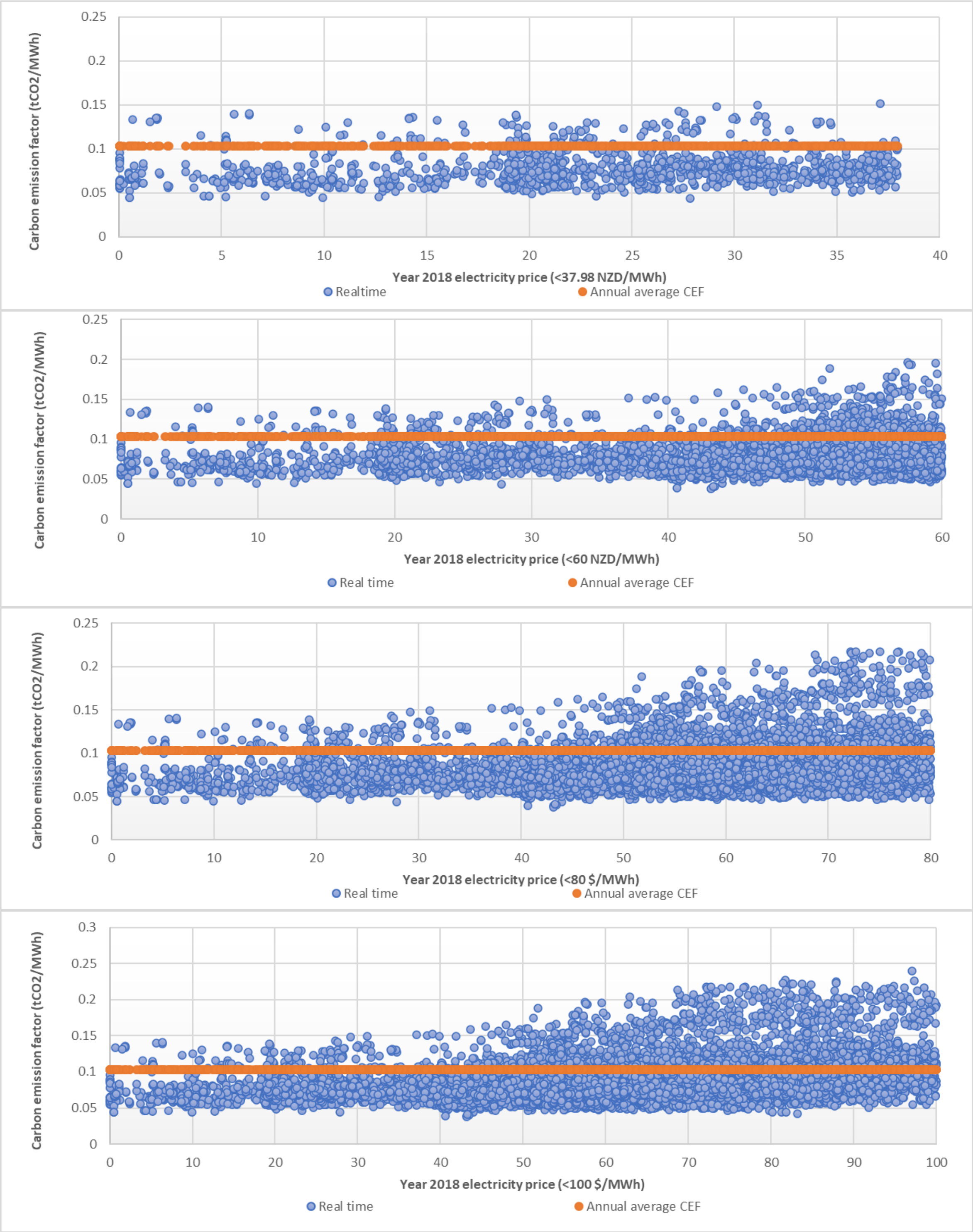


Figure 42. Carbon emission factor change with the increase of electricity price in year 2018.

Sensitivity analysis regarding the carbon emission factor applying for 10 years

From year 2013 to 2022, the A1 is going up with the increase of grid electricity prices in Table 30. The A1 reaches the highest point when the limit of electricity price is set up to 100 NZD/MWh. Also, the A1 is always less than the A2, even though the limit is set to 100 NZD/MWh which is the highest one in the sensitivity analysis.

In the year 2016, when the grid electricity price is less than 100 NZD/MWh, the average CEF of real-time electricity is 0.092 ton/MWh which is quite similar as the annual average one (0.093 ton/MWh). That means 100 NZD/MWh is not the good price to generate hydrogen to reduce the carbon emission in year 2016. However, the year 2021 and 2022 are quite special with extremely low carbon emission factor around the year. The A1 is around 50% lower than that of A2 even though the electricity price is set up to 100 NZD/MWh. Therefore, year 2021 and year 2022 are good year to use low-price grid electricity to generate hydrogen with low carbon emission.

From the year 2013 to 2022 in Table 31, the spot electricity with higher electricity price will have less possibility to have real-time CEF which is less than the average annual CEF. The possibility keeps at 90% level when the electricity price is required to be less than 37.98 NZD/MWh. That means almost every single trading time which has electricity price below 37.98NZD/MWh can be used to generate hydrogen to keep grid CEF less than the average one.

The year 2015 and 2016 is dry year, the possibility is at only around 56% when the hydrogen is generated by using grid electricity less than 100 NZD/MWh.

The year 2021 and 2022 is wet year, the possibility is always kept at 90% level when the electricity price is increased from 37.98 NZD/MWh to 100 NZD/MWh.

Table 30. Average carbon emission factor when the electricity below the certain prices from year 2013 to 2022.

Year	Electricity Price [NZD/MWh]	<37.98	<60	<80	<100
2013	A1 [$t_{CO2\text{-}e}$/MWh]	0.102	0.113	0.13	0.141
	A2 [$t_{CO2\text{-}e}$/MWh]	0.152			
	Error gap between A1 and A2	-33%	-26%	-15%	-7%
2014	A1 [$t_{CO2\text{-}e}$/MWh]	0.083	0.095	0.105	0.112
	A2 [$t_{CO2\text{-}e}$/MWh]	0.119			
	Error gap between A1 and A2	-30%	-20%	-12%	-6%
2015	A1 [$t_{CO2\text{-}e}$/MWh]	0.083	0.092	0.106	0.113
	A2 [$t_{CO2\text{-}e}$/MWh]	0.116			
	Error gap between A1 and A2	-28%	-20%	-9%	-3%
2016	A1 [$t_{CO2\text{-}e}$/MWh]	0.073	0.082	0.090	0.092
	A2 [$t_{CO2\text{-}e}$/MWh]	0.093			
	Error gap between A1 and A2	-21%	-12%	-3%	-1%
2017	A1 [$t_{CO2\text{-}e}$/MWh]	0.072	0.079	0.085	0.093
	A2 [$t_{CO2\text{-}e}$/MWh]	0.111			
	Error gap between A1 and A2	-35%	-29%	-24%	-16%
2018	A1 [$t_{CO2\text{-}e}$/MWh]	0.078	0.081	0.085	0.090
	A2 [$t_{CO2\text{-}e}$/MWh]	0.103			
	Error gap between A1 and A2	-24%	-22%	-17%	-13%
2019	A1 [$t_{CO2\text{-}e}$/MWh]	0.066	0.072	0.083	0.093
	A2 [$t_{CO2\text{-}e}$/MWh]	0.115			
	Error gap between A1 and A2	-43%	-37%	-28%	-19%
2020	A1 [$t_{CO2\text{-}e}$/MWh]	0.092	0.096	0.102	0.109
	A2 [$t_{CO2\text{-}e}$/MWh]	0.122			
	Error gap between A1 and A2	-25%	-21%	-17%	-11%
2021	A1 [$t_{CO2\text{-}e}$/MWh]	0.060	0.061	0.064	0.064
	A2 [$t_{CO2\text{-}e}$/MWh]	0.131			
	Error gap between A1 and A2	-54%	-53%	-51%	-51%
2022	A1 [$t_{CO2\text{-}e}$/MWh]	0.045	0.048	0.047	0.049
	A2 [$t_{CO2\text{-}e}$/MWh]	0.086			
	Error gap between A1 and A2	-48%	-47%	-45%	-43%

A1 is average carbon emission factor when the electricity below the certain prices
A2 is the average annual carbon emissions factor

Table 31. The possibility which makes real-time carbon emission factor below the certain annual average CEF and certain electricity price.

Year/Price(NZD/MWh)	<37.98	<60	<80	<100
2013	93%	54%	70%	61%
2014	96%	85%	71%	63%
2015	93%	83%	65%	56%
2016	88%	73%	61%	58%
2017	98%	92%	84%	76%
2018	89%	87%	83%	76%
2019	96%	94%	88%	78%
2020	86%	81%	74%	63%
2021	99%	99%	98%	97%
2022	96%	96%	95%	93%

4.5. Conclusions

The active lake storage is likely to have moderate/strong downhill (linear) relationship with real-time carbon emission factor based on the analysis from year 2013 to year 2021. Also, the spot electricity price tends to have a moderate uphill (positive) linear relationship with real-time carbon intensity based on these ten years' analysis.

Based on the case studies, different amount of carbon emissions would be calculated based on the real-time carbon intensities in different time. There are more possibilities to have minimal amount of annual carbon emissions and carbon cost by using CEF_A (the annual guidebook CEF) for calculation instead of using the CEF_B (average annual CEF calculated by real-time CEF) and CEF_C (the real-time CEF).

Grid source hydrogen gains more carbon emissions by using the spot electricity with higher price. As the spot electricity price increase from 37.98 NZD/MWh to 100 NZD/MWh, the spot electricity with higher electricity price will have less possibility to have real-time CEF which is less than the average annual CEF. The possibility keeps at 90% level when the electricity price is required to be less than 37.98 NZD/MWh. That means almost every single trading time which has electricity price below 37.98 NZD/MWh can be used to generate hydrogen to keep grid CEF less than the average one.

5. Hydrogen Integration and Safety

There are several factors which would affect the hydrogen is applied into the real practice of process heat sector. In this chapter, some hydrogen characteristics will be reviewed, with more focus on the hydrogen delivery, hydrogen storage and hydrogen application in the process heat sector.

5.1. Hydrogen characteristics

Hydrogen is a flammable and explosive gas. Crowl and Jo (2017) presented hydrogen has higher probability of a fire and explosion, which is based on a larger flammability zone and a lower minimum ignition energy from hydrogen. Also, there are a couple of more characteristics which would add additional hazards to the real application of hydrogen. Firstly, hydrogen burns with a colourless flame, so it is hard to detect. Secondly, hydrogen would self-heats when it leaks from a high-pressure source.

5.2. Hydrogen delivery

Hydrogen is currently transported through pipelines and on road using cylinders, tube trailers, cryogenic tankers and so on (Pudukudy et al., 2014). For the long distances, the hydrogen is generally transported in the form of liquid by the insulated tankers, railcars and so on, and is vaporised for the use at the customer site. Najjar (2013) presented that hydrogen condense to liquid at -253 °C and to sloid at -259 °C.

Furthermore, the pipeline network infrastructure is mostly used in transporting a large quantity in the long distance, that is because the pipeline network is safe in operation under a low and constant pressure (Adams et al, 2005). However, all liquid and gas fuels have a risk of leaking during the period of transportation. The hydrogen is undetectable by human senses because it is odourless. Adding odorants may be a good option for leak detection because people could smell that, but these odorants doesn't suit hydrogen because they are not light enough to travel with hydrogen and disperse at the same dispersion rate.

Sensors are required to detect the hydrogen leaks in the hydrogen delivery infrastructure. The sensor needs to exhibit high sensitivity and rapid response capability to enable early leak detection, allowing for intervention before the air reaches its explosive limit. Employing a fibre-optic sensor configuration offers the most promising prospect for achieving swift response time while remaining cost-effective and dependable (Adams et al., 2005).

5.3. Hydrogen storage

The compressed gas method and liquid state storage method are widely used in the hydrogen storage, and the method to be used for the future is the solid-state storage method (Tarhan & Cil, 2021).

5.3.1. Compressed gas method

The compress gas method involved pressurizing hydrogen gas and storing it high-pressure containers or tanks. The hydrogen is normally stored as a compressed gas at pressure up to 700 bar (Hosseini et al., 2012). Handling high-pressure hydrogen can be dangerous, so the safety measures are quite important during the storage. Also, the hydrogen tanks are made of special materials, which would increase the cost of establishing the infrastructure of storage. Hassan et al. (2021) presented cost is still an obstacle in the way towards hydrogen economy future in the field of energy application, even through the high-pressure containers had many advantages like storing a significant amount of energy in the relatively small volume.

5.3.2. Liquid state storage method

There are three steps for the hydrogen stored as the liquid form in the specialised tank. The first step is compression and purification. The hydrogen gas is firstly compressed to increase its intensity. After that, other elements such as moisture, oxygen, and trace gases are removed by the process of purification to avoid contamination. The second step is cooling. The cryogenic refrigeration systems are used to cool the compressed and purified hydrogen gas, which make it the temperature below the boiling point then condense into liquid. The third step is storage. The liquid hydrogen is stored in specialized cryogenic tanker or container to keep temperature inside at -253 ℃ (Zhao et al., 2019). There are a few challenges in terms of infrastructure and safety in the liquid state storage method. Firstly, specialized infrastructure and equipment are required to handle and store cryogenic hydrogen, and these infrastructure and equipment can be expensive to establish and maintain. Secondly, the special safety precautions are required when dealing with liquid hydrogen, that is because liquid hydrogen is extremely cold and can cause frostbite by contacting with skin.

5.3.3. Solid state storage method

Solid state hydrogen storage is a method for storing hydrogen in a solid material, and this method is still in the area of research and development. In terms of safety and energy-effectiveness, this method has more advantages than that from forms of gas and liquid. That is because solid state storage operates at lower pressure and temperature, and it has higher volumetric density than high-pressure gas and cryogenic liquid storage (Boateng & Chen, 2020).

5.4. Hydrogen application

Hydrogen compatibility is also quite important when the hydrogen is applied to the process heat sector. The existing boiler system may need to be changed and updated to ensure compatibility with hydrogen fuel. That is because hydrogen has different combustion characteristics compared to other fossil fuels.

Equipment and site safety

The existing boiler system needs to be changed and upgraded to ensure compatibility with hydrogen fuel, which is because hydrogen has different combustion characteristics and flame properties compared to natural gas and oil. The burner system is one of the critical components to upgrade, and burners need to be well designed to suit the difference.

Securing a suitable space on site for hydrogen production and storage is also quite important, and that is because they will impact site productivity and cost-effectivity from hydrogen production and storage. There are two types of electricity which can be used to power electrolyser. One is grid electricity and the other one is renewable electricity. If the electrolyser is powered by renewable electricity, the additional space and infrastructure are required to set up solar panel or wind turbine on site.

Safety equipment and systems are quite important when the hydrogen is used on site. These safety equipment and systems includes hydrogen gas detectors, fire suppression systems, emergency shutdown systems, ventilation systems, and explosion relief systems. Also, the regular testing and maintenance are so crucial to make sure these equipment and system can be working properly to response to the hydrogen-related incidents, like fire, leak, and explosion.

Safety compliance and training

Safety compliance is quite important to help to utilise hydrogen as fuel in the industry site. Safety compliance for hydrogen production onsite includes using different regulations and practices to make sure the safe operation of the hydrogen production facility. For example, the regulations and check lists of fire suppression system need to be established and published in company's procedure system which can be easily checked and followed by staffs. Also, detailed records of safety inspection need to be maintained to demonstrate compliance with safety regulations.

Staffs need to be trained to how to response to the hydrogen-related incidents, like fire, leak, and explosion. Also, hydrogen energy operators need to be trained to use personal protective equipment, such as flame-resistant clothing, safety goggles and respirators, to protect from the hydrogen-related hazards.

6. Conclusions & Future Work

Boiler systems powered by different types of hydrogen are compared with ones powered by other types of energy sources (natural gas, wood pellet and electricity). Among these energy sources, the wood pellet boiler has a relatively good performance with low carbon emissions factor from energy delivered to plant, high overall energy conversion efficiency, and low levelized cost of energy. Electrode boiler has the highest energy conversion efficiency, but the key issue is the LCOE of electrode boiler is highest. From these four types of hydrogen boiler systems, blue hydrogen boiler and 20% hydrogen blend boiler are not environmentally friendly, because the carbon emission factor from energy delivered to plant is quite high. Also, the grid sourced hydrogen boiler and green hydrogen boiler is not quite efficient with the low overall energy conversion efficiency. Therefore, using wood pellet boiler to replace fossil fuel boiler is good option in current New Zealand process heat sector from environmental, technical, and economic perspective.

The efficiency of electrolyser and the ratio of hydrogen blend play an important role in terms of environmental, technical, and economic perspective. The amount of carbon emissions from hydrogen boiler systems has a dramatic decrease with the increase of the blending ratios. The overall conversion energy efficiency has decrease trend with the increase of the blending ratios or the decrease of the efficiency in electrolysers. LCOE has increase trend with the increase of ratios in the hydrogen blend or decrease of ratios in the hydrogen blend.

The prices of grid electricity directly affect the LCOE of grid sourced hydrogen boiler system. The LCOE of grid source hydrogen boiler system is less than the one of natural gas boiler system, when spot electricity prices are less than 37.98 NZD/MWh with carbon price at 70 NZD/ton. However, constantly producing low-cost hydrogen by grid electricity is hard to achieve, because the price of spot electricity changes every half-hour, and there is a small portion of real time grid electricity is available to have price less than 37.98 NZD/MWh. Furthermore, the price of real time grid electricity has trend to have great impact on the carbon emissions from the generation of grid sourced hydrogen. Grid sourced hydrogen brings more carbon emissions by using the real time grid electricity with higher prices.

Real-time electricity price and active lake storage have a positive correlation with the real-time carbon emission factor of grid electricity. Low carbon emission factor of grid electricity can be achieved by using the low price of electricity, and high active lake storage level can make real-time grid electricity have low carbon emission factor.

The amount of carbon emissions from electrode boilers can be calculated by two types of carbon emission factor of grid electricity. One is the electricity carbon emission factor, and the other one is annual carbon emission factor from guidebook. Based on the case studies, the total annual amount of carbon emission calculated by CEF from guidebook is quite less than that calculated by real-time carbon emission factor. That means the more carbon cost would be charged by using real-time carbon emission factor for calculation.

One of limitation of this study is that the carbon emissions from the whole boiler system only consider the carbon emissions from the input energy sources. In the future work, the life cycle assessment of carbon emissions will be conducted to calculate the carbon emission factor of whole boiler systems.

The additional limitation is that determining the LCOE for a grid-source hydrogen boiler system and comparing it to natural gas from various years is solely reliant on a fixed carbon price of 70 NZD/ton. In future work, the carbon prices aligned with different years will be taken into consideration for the further analysis.

References

Abbasi, T. & Abbasi, S.A. (2010). Biomass energy and the environmental impacts associated with its production and utilization. *Renewable and Sustainable Energy Review, 14(*3*)*, 919-937. https://doi.org/10.1016/j.rser.2009.11.006

Anand, B., Shankar, R., Murugavelh, S., Rivera, W., Prasad, K.M., & Nagarajan, R. (2021). A review on solar photovoltaic thermal integrated desalination technologies. *Reviewable and Sustainable Energy Reviews, 141,* 110787. https://doi.org/10.1016/j.rser.2021.110787

Atkins, M.J. (2019). Options to reduce New Zealand's process heat emissions. *The University of Waikato*. https://www.eeca.govt.nz/insights/eeca-insights/options-to-reduce-process-heat-emissions/

Atkins, M.J., Morrison, A.S., & Walmsley, M.R.W. (2010). Carbon emission pinch analysis (CEPA) for emissions reduction in the New Zealand electricity sector. *Applied Energy, 87*(3), 982-987. https://doi.org/10.1016/j.apenergy.2009.09.002

Atkins, M.J., Walmsley, M.R.W., & Neale, J.R. (2011). Integrating heat recovery from milk powder spray dryer exhausts in the dairy industry. *Applied thermal engineering, 31*(13), 2101-2106. https://doi.org/10.1016/j.applthermaleng.2011.03.006

Beuerm, C., Treyer, K., Antonini, C., Bergerson, J., Gazzani, M., Gencer, E., Gibbins, J., Mazzotti, M., McCoy, S.T., Mckenna, R., Pietzcker, R., Ravikumar, A.P., Romano, M.C., Ueckerdt, F., Vente, J., & Spek, J.V. (2022). On the climate impacts of blue hydrogen production. *Sustainable Energy Fuel, 6*(1), 66-75. https://doi.org/10.1039/D1SE01508G

Bhandari, R., Trudewind. C.A., & Zapp, P. (2014). Life cycle assessment of hydrogen production via electrolysis- a review. *Journal of Cleaner Production, 85,* 151-163. https://doi.org/ 10.1016/j.jclepro.2013.07.048

Bogdanov, D., Ram, M., Aghahosseini, A., Gulagi, A., Oyewo, A. S., Child, M., ... & Breyer, C. (2021). Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. *Energy*, *227*, 120467. https://doi.org/10.1016/j.energy.2021.120467

Bogdanov, D., Ram, M., Aghahosseini, A., Gulagi, A., Oyewo, A.S., Child, M., Caldera, U., Sadovskaia, K., Farfan, J., Barbosa, L., Fasihi, M., Khalili, S., Traber, T., & Breyer, C. (2021). Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. *Energy, 227*, 120467. https://doi.org/10.1016/j.energy.2021.120467

Bouledroua, O., Hafsi, Z., Djukic, M.B., & Elaoud, S._(2020). The synergistic effect of hydrogen embrittlement and transient gas flow condition on integrity assessment of a precracked steel pipeline. *International Journal of Hydrogen Energy, 45*(35), 18010-18020. https://doi.org/10.1016/j.ijhydene.2020.04.262

Brandon, N.P., & Kurban, Z. (2017). Clean energy and the hydrogen economy. *Philosophical Transactions of Royal Society: Mathematical, Physical and Engineering Science, 375*(2098). https://doi.org/ 10.1098/rsta.2016.0400

Chau, J., Sowlati, T., Sokhansanj, S., Preto, F., Melin, S., & Bi, X. (2009). Techno-economic analysis of wood biomass boilers for the greenhouse industry. *Applied Energy*, *86*(3), 364–371. https://doi.org/10.1016/j.apenergy.2008.05.010

Chi, J., & Yu, H. (2018). Water electrolysis based on renewable energy for hydrogen production. *Chinese Journal of Catalysis*, *39*(3), 390–394. https://doi.org/10.1016/S1872-2067(17)62949-8

Climate change Commission. (2021). *Draft Advice for Consultation.*

Dai, J., Yang, X., & Wen, L. (2017). Development of wind power industry in China: A comprehensive assessment. *Renewable and Sustainable Energy Review, 97*, 156-164. https://doi.org/10.1016/j.rser.2018.08.044

Daszkiewicz, K. (2020). Policy and regulation of energy transition. *The geopolitics of the global energy transition*, 203-226. https://doi.org/10.1007/978-3-030-39066-2_9

Dawood, F., Anda, M., & Shafiullah, G.M. (2020). Hydrogen production for energy. *International Journal of Hydrogen Energy, 45*(7), 3847-3869. https://doi.org/ 10.1016/j.ijhydene.2019.12.059

Domínguez, S., Cifuentes, B., Bustamante, F., Cantillo, N.M., Barraza-Botet, C.L. & Cobo, M. (2022). On the potential of blue hydrogen production in colombia: A fossil resource-based assessment for low-emission hydrogen. *Sustainability*, *14*(18), 11436. https://doi.org/10.3390/ su141811436

Electricity Authority. (n.d.). Demand trend. https://www.emi.ea.govt.nz/Wholesale/Reports

Electricity Authority. (n.d.). Generation output by plant. https://www.emi.ea.govt.nz/Wholesale/Datasets

Electricity Authority. (n.d.). Generation trends. https://www.emi.ea.govt.nz/Wholesale/Reports

El-Emam, R.S. & Özcan, H. (2019). Comprehensive review on the techno-economic of sustainable large-scale clean hydrogen production. *Journal of cleaner Production, 220*, 593-609. https://doi.org/10.1016/j.jclepro.2019.01.309

EM6. (2022). EM6: Carbon Methodology. https://www.ems.co.nz/em6-carbon-methodology/

Energy Efficiency & Conservation Authority. (2022). Regional energy transition accelerator. https://www.eeca.govt.nz/co-funding/regional-decarbonisation/about-reta/

Energy Efficiency and Conservation Authority. (2021). *Accelerating the Decarbonisation of Process Heat.*

Energy Efficiency and Conservation Authority. (2021). *Accelerating the Decarbonisation of Process Heat.* https://www.eeca.govt.nz/insights/eeca-insights/accelerating-the-decarbonisation-of-process-heat/

Erdener, B.C., Sergi, B., Guerra, O.J., Chueca, A.L., Pambour, K., Brancucci, C., & Hodge, B. (2022). A review of technical and regulatory limits for hydrogen blending in natural gas pipelines. *International Journal of Hydrogen Energy.* https://doi.org/10.1016/j.ijhydene.2022.10.254

Fan, Z., & Friedmann, S.J. (2021). Low-carbon production of iron and steel: Technology options, economic assessment, and policy. *Joule, 5*(4), 829-862. https://doi.org/10.1016/j.joule.2021.02.018

Firstgas. (2022). *Hydrogen blending: A big step on the path to net zero.* https://firstgas.co.nz/what-is-green-hydrogen-blending/#:~:text=Hydrogen%20blending%20starts%20small.,it%20to%20homes%20and%20businesses.

Flekiewicz,M., & Kubica, G. (2012). An influence of methane/hydrogen proportion in fuel blend on efficiency of conversion energy in SI engine. *Journal of KONES Powertrain and Transport, 19*(3), 117-124. https://doi.org/10.5604/12314005.1137955

Garnett, T. (2011). Where are the best opportunities for reducing greenhouse emission in the food system (including the food chain)? *Food Policy, 36*, S23-S32. https://doi.org/10.1016/j.foodpol.2010.10.010

Gas Turbines for Energy Network. (2019). Hydrogen In Natural Gas -Combustion and Compression. (Technical Report#19-GTEN-302)

Glanville, P., Fridlyand, A., Sutherland, B., Liszka, M., Zhao, Y., Bingham, L., & Jorgensen, K. (2022). Impact of Hydrogen/Natural Gas Blends on Partially Premixed Combustion Equipment: NOx Emission and Operational Performance. *Energies, 15*(1706), 1-31. https://doi.org/10.3390/en15051706

Griffin, P.W., & Hammond, G.P. (2019). Industrial energy use and carbon emission reduction in the iron and steel sector: A UK perspective. *Applied Energy, 249*, 109-125. http://dx.doi.org/10.1016/j.rser.2015.03.056

Hall, K. K., Walmsley, T. G., Nemet, A., & Walmsley, M. (2022, September). Open-source tool for heat exchanger network synthesis. In *PRES'22*. https://hdl.handle.net/10289/15682

Hall, P (2017). Residual biomass fuel projections for New Zealand-indicative availability by region and source. *Scion contract report for Bioenergy Association of New Zealand and the Energy Efficiency and Conservation authority*. Scion SIDNEY No. 59041. https://www.bioenergy.org.nz/documents/resource/Reports/Woodresidue-resources-report-2017_170824.pdf.

HM Government. (2021), UK Hydrogen Strategy. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011283/UK-Hydrogen-Strategy_web.pdf

Howarth, R. W., & Jacobson, M. Z. (2021). How green is blue hydrogen? *Energy Science & Engineering*, *9*(10), 1676–1687. https://doi.org/10.1002/ese3.956

International Energy Agency. (2023). How to avoid gas shortages in the European union in 2023. https://www.iea.org/news/how-the-european-union-can-avoid-natural-gas-shortages-in-2023

International Energy Agency. (2023). *CO_2 Emissions in 2022.* https://iea.blob.core.windows.net/assets/3c8fa115-35c4-4474-b237-1b00424c8844/CO2Emissionsin2022.pdf

Islam, M.R, Mekhilef, S., & Saidur, R. (2013). Progress and recent trends of wind energy technology. *Renewable and sustainable Energy Review, 21,* 456-468. https://doi.org/10.1016/j.rser.2013.01.007

Karali, N., Park, W.Y., & McNeil, M. (2017). Modeling technological change and its impact on energy saving in the U.S. iron and steel sector. *Applied Energy, 202*, 447-458. http://dx.doi.org/10.1016/j.apenergy.2017.05.173

Khan, M.D., Daiyan, R., Neal, P., Haque, N., MacGill, I & Amal, R. (2021). A framework for assessing economics of blue hydrogen production from steam methane reforming using carbon capture storage & utilisation. *International Journal of Hydrogen Energy, 46*(44), 22685-22706. https://doi.org/10.1016/j.ijhydene.2021.04.104

Kurz, R., Cowell, L., Tarver, T., & Singh, A. (2019). Hydrogen in Natural Gas–Combustion and Compression. In *Gas Turbines for Energy Network Symposium, Banff, Alberta, Canada*.

Lin, B., & Wang, X. (2015). Carbon emissions from energy intensive in China: Evidence from the iron & steel industry. *Renewable and sustainable energy reviews, 47*, 746-754. http://dx.doi.org/10.1016/j.rser.2015.03.056

Linke, Gerald (2020) Keynote address at the ENTSOG 2050 Roadmap for Gas Grids Workshop 3: Principles for EU Gas Qualities, handling of hydrogen and CO2 transportation 29.04.2020 (online)https://entsog.eu/sites/default/files/2020-4/Workshop3_masterpresentation_Rev1.pdf

Lowes, R., & Rosenow, J. (2021). Will blue hydrogen lock us into fossil fuels forever? *One Earth, 4*(11), 1527-1529. https://doi.org/10.1016/j.oneear.2021.10.018

Mahajam, D., Tan, K., Venkatesh, T., Kileti, P., & Clayton, C.R. (2022). Hydrogen Blending in Gas Pipeline Networks- A Review. *Energies*, *15*(10), 3582. http://doi.org/10.3390/en15103582

Marco, P., Alessandro, G., & Cesare, S. (2020). A preliminary assessment of the potential of low percentage green hydrogen blending in the Italian natural gas network. *Energies*, *13*(21), 5570. https://doi.org/10.3390/en13215570

Martin, M. (2022). Challenges and opportunities of solar thermal energy towards a sustainable chemical industry. *Computers and Chemical Engineering, 165,* 107926. https://doi.org/10.1016/j.compchemeng.2022.107926

Mathiesen, B. V., Lund, H., Connolly, D., Wenzel, H., Østergaard, P. A., Möller, B., ... & Hvelplund, F. K. (2015). Smart Energy Systems for coherent 100% renewable energy and transport solutions. *Applied energy*, *145*, 139-154. https://doi.org/10.1016/j.apenergy.2015.01.075

Mesfun, S., & Toffolo, A. (2013). Optimization of process integration in a Kraft pulp and paper mill–Evaporation train and CHP system. *Applied energy*, *107*, 98-110. https://doi.org/10.1016/j.apenergy.2013.02.016

Ministry of Business, Innovation & employment. (2016). *Process Heat-Overview*. https://www.mbie.govt.nz/dmsdocument/ 152-process-heat-current-state-fact-sheet-pdf&lang=en

Ministry of Business, Innovation & Employment. (2021). *Dairy Manufacturing-Process Heat and Greenhouse Gas Emission.* https://www.mbie.govt.nz/dmsdocument/151-dairy-maufacturing-fact-sheet-pdf

Ministry of Business, Innovation & employment. (n.d.). *Electricity generation emissions.* https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-statistics-and modelling/energy-statistics/new-zealand-energy-sector-greenhouse-gas-emissions/

Ministry of Business, Innovation & employment. (n.d.). *Provisional estimates of greenhouse gas emissions from the energy sector.* https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-statistics-and-modelling/energy-statistics/new-zealand-energy-sector-greenhouse-gas-emissions/

Ministry of Business, Innovation and Employment. (2020). *Wind Generation Stack Update.* https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-statistics-and-modelling/energy-publications-and-technical-papers/nz-generation-data-updates/

Mohamed, M. A., Eltamaly, A. M., Farh, H. M., & Alolah, A. I. (2015, August). Energy management and renewable energy integration in smart grid system. In *2015 IEEE international conference on smart energy grid engineering (SEGE)* (pp. 1-6). IEEE. 10.1109/SEGE.2015.7324621

Mohammadi, A., & Mehrpooya, M. (2019). Thermodynamic and economic analyses of hydrogen production system using high temperature solid electrolyzer integrated with parabolic trough collector. *Journal of Cleaner Production*, *212*, 713-726. https://doi.org/ 10.1016/j.jclepro.2018.11.261

Mosca, L., Jimenez, J.A.M., Wassie, S.A., Gallucci, F., Palo, E., Colozzi, M., Taraschi, S., & Galdieri, G. (2019). Process design for green hydrogen production. *International Journal of Hydrogen Energy*, *45*(12), 7266-7277. https://doi.org/ 10.1016/j.ijhydene.2019.08.206

Mostafaeipour, A., Bidokhti, A., Fakhrzad, M., Sadegheih, A., & Mehrjerdi, Y.Z. (2022). A new model for the use of renewable electricity to reduce carbon dioxide emission. *Energy, 238,* 121602. https://doi.org/10.1016/j.energy.2021.121602

National Renewable Energy Laboratory. (2013). *Blending hydrogen into natural gas pipeline network: a review of key issue.* (Technical report#NREL/TP-5600-56995)

New Zealand Government. (2023). *Government partners with Fonterra to cut coal use & boost NZ's Climate credentials.* https://www.beehive.govt.nz/release/government-partners-fonterra-cut-coal-use-boost-nz%E2%80%99s-climate-credentials

New Zealand wind energy association. (n.d.). The cost of wind energy. https://www.windenergy.org.nz/the-cost-of-wind-energy

Novotny, V. (2022). Blue hydrogen can be a source of green energy in the period of decarbonization. *International Journal of hydrogen Energy.* https://doi.org/*10.1016/j.ijhydene.2022.11.095*

O'Gorman, M., & Jotzo, F. (2014). Impact of the carbon price on Australia's electricity demand, supply and emissions. *Crawford School of Public Policy, The Australian National University CCEP Working Paper*, (1411). http://dx.doi.org/10.2139/ssrn.2731384

Ong, B. H., Walmsley, T. G., Atkins, M. J., Varbanov, P. S., & Walmsley, M. R. (2019). A heat-and mass-integrated design of hydrothermal liquefaction process co-located with a Kraft pulp mill. *Energy*, *189*, 116235. https://doi.org/10.1016/j.energy.2019.116235

Oni, A.O., Anaya, K., Giwa, T., Lullo, G.D., & Kumar, A. (2022). Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing region. *Energy conversion Management*, *254*, 115245. https://doi.org/10.1016/j.enconman.2022.115245

Pellegrini, M., Guzzini, A., & Saccani, C. (2020). A preliminary assessment of the potential of low percentage green hydrogen blending in the Italian Natural Gas Network. *Energies*, *13*(21), 5570. https://doi.org/10.3390/en13215570

Pettersen, J., Steeneveldt, R., Grainger, D., Scott, T., Holst, L., & Hambory, E.S. (2022). Blue hydrogen must be done properly. *Equinor*, *10*(9), 3220-3236. https://doi.org/10.1002/ese3.1232

Pirani. S. (2018). *Burning Up: A Global History of Fossil Fuel Consumption.* Pluto Press. https://doi.org/10.1093/ahr/rhac276

Poletti, S., & Staffell, I. (2021). Understanding New Zealand's wind resources as a route to 100% renewable electricity. *Renewable Energy, 170*, 449-461. https://doi.org/10.1016/j.renene.2021.01.053

Raymer, A.K.P. (2005). A comparison of avoided greenhouse gas emissions when using different kinds of wood energy. *Biomass and Bioenergy, 30*(7), 605-617. https://doi.org/10.1016/j.biombioe.2006.01.009

Rehfeldt, M. Worrell, E., Eichhammer, W., & Fleiter, T. (2020). A review of the emission reduction potential of fuel switch toward biomass and electricity in European basic materials industry until 2030. *Renewable and Sustainable Energy Review.* https://doi.org/10.1016/j.rser.2019.109672

Ren, B., Xu, Y., Huang, Y., She, C., & Sun, B. (2023). Methanol production from natural gas reforming and CO2 capturing process, simulation, design, and technical-economic analysis. *Energy, 263*, 125879. https://doi.org/10.1016/j.energy.2022.125879

Rumsey, D. J. (2016). How to interpret a correlation coefficient r. *Statistics for dummies*, 26.

Sapountzi, F.M., Gracia, J.M., Weststrate, C.J., Fredriksson, H.O.A., & Niemantsverdriet, J.W. (2017). Electrocatalysts for the generation of hydrogen, oxygen and synthesis gas. *Process In Energy and Combustion Science, 58*, 1-35. https://doi.org/10.1016/j.pecs.2016.09.001

Schiro, F., Stoppato, A., & Benato, A. (2020). Modelling and analyzing the impact of hydrogen enriched natural gas on domestic gas boilers in a decarbonization perspective. *Carbon Resources Conversion*, *3*, 122–129. https://doi.org/10.1016/j.crcon.2020.08.001

Shahri, O., Ismail, F.B., Hannan, M.A., Lipu, M.S., Shetwi, A., Begum, R.A., Muhsen, N. & Soujeri, E. (2020). Solar photovoltaic energy optimization method, challenges and issues: A comprehensive review. *Journal of Cleaner Production, 284,* 125465. https://doi.org/10.1016/j.jclepro.2020.125465

Smith, R. (2005). *Chemical process: design and integration*. John Wiley & Sons.

Sorgulu, F. & Dincer, I. (2022). Analysis and techno-economic assessment of renewable hydrogen production and blending into natural gas for better sustainability. *International Journal of Hydrogen Energy, 47*(46), 19977-19988. https://doi.org/10.1016/j.ijhydene.2022.04.133

Suomalainen, K., Pritchard, G., Sharp, B., Yuan, Z., & Zakeri, G. (2015). Correlation analysis on wind and hydro resources with electricity demand and prices in New Zealand. *Applied Energy*, *137*, 445–462. https://doi.org/10.1016/j.apenergy.2014.10.015

Svensson, E., Wiertzema, H., & Harvey, S. (2021). Potential for negative emissions by carbon capture and storage from a novel electric plasma calcination process for pulp and paper mills. *Frontiers in Climate*, *3*, 705032. https://doi.org/10.3389/fclim.2021.705032

Synlait. (2019). *Synlait has switched on New Zealand's first large-scale electrode boiler.* https://www.synlait.com/news/synlait-has-switched-on-new-zealands-first-large-scale-electrode-boiler/

The Ministry of Environment. (2022). *ETS Auction Noticeboard.* https://www.etsauctions.govt.nz/public/auction_noticeboard

The Ministry of Environment. (2022). *Measuring emissions: A guide for organizations.* https://environment.govt.nz/publications/measuring-emissions-a-guide-for-organisations-2022-detailed-guide/

The United States Environmental Protection Agency. (n.d.). Georhermal Power Plants. https://archive.epa.gov/climatechange/kids/solutions/technologies/geothermal.html

Transpower. (n.d.). Operating the wholesale electricity market. https://www.transpower.co.nz/system-operator/about-system-operator/operating-wholesale-electricity-market

Victoria, M., Haegel, N., Peters, I., Sinton, R., Waldau, A., Canizo, C., Breyer, C., Stocks, M., Blakers, A., Kaizuka, I., Komoto, K, & Smets, A. (2021). Solar photovoltaics is ready to power a sustainable future. *Joule, 5*(5)*,* 1041-1056. https://doi.org/10.1016/j.joule.2021.03.005

Walmsley, M. R. W., Walmsley, T. G., Atkins, M. J., Kamp, P. J. J., Neale, J. R., & Chand, A. (2014). Minimising carbon emissions and energy expended for the New Zealand transport sector through to 2050. In Proceedings of the 9th Conference on Sustainable Development of Energy, Water and Environment Systems. Venice, Italy: SDEWES.

Walmsley, M.R.W., Walmley, T.G., Atkins, M.J., Kamp, P.J.J., & Neale, J.R. (2014). Minimising carbon emission and energy expended for electricity generation in New Zealand through to 2050. *Applied Energy, 135*, 656-655. http://dx.doi.org/10.1016/j.apenergy.2014.04.048

Walmsley, M.R.W., Walmsley, T.G., Matthews, L., Atkins, M.J., Neale, J.R., & Kamp, P. (2015). Pinch analysis techniques for carbon emissions reduction in the New Zealand industrial process heat sector. *Chemical Engineering Transactions*, *45*, 1087-1092 https://doi.org/10.3303/CET1545182

Walmsley, M.R.W., Walmsley, T.G., Atkins, M.J., Kamp, P.J.J., & Neale, J.R. (2014). Minimising carbon emission and energy expended for electricity generation in New Zealand through to 2050. *Applied Energy, 135*, 656-665. http://dx.doi.org/10.1016/j.apenergy.2014.04.048

Walmsley, T.G., Atkins, M.J. Walmsley, M.R.W., Philipp, M., & Peesel, R. (2018). Process and utility system integration and optimization for ultra-low energy milk powder production. *Energy, 146*, 67-81. http://dx.doi.org/10.1016/j.energy.2017.04.142

Wang, R. R., Zhao, Y. Q., Babich, A., Senk, D., & Fan, X. Y. (2021). Hydrogen direct reduction (H-DR) in steel industry—An overview of challenges and opportunities. *Journal of Cleaner Production*, *329*, 129797. https://doi.org/10.1016/j.jclepro.2021.129797

World Nuclear. (n.d.). Heat value of various fuels. https://world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx

Yang, Y., Tong, L., Yin, S., Liu, Y., Wang, L., Qiu, Y., & Ding, Y. (2022). Status and challenges of applications and industry chain technologies of hydrogen in the context of carbon neutrality. *Journal of Cleaner Production*, 134347. https://doi.org/10.1016/j.jclepro.2022.134347

Yu, M., Wang, K., & Vredenbury, H. (2021). Insight into low carbon hydrogen production methods: Green, blue and aqua hydrogen. *International Journal of Hydrogen Energy*, *46*(41), 21261-21273. https://doi.org/10.1016/j.ijhydene.2021.04.016

Zhu, Q., Chen, X., Song, M., Li, X., & Shen, Z. (2022). Impact of renewable electricity standard and Renewable Energy Certificates on renewable energy investments and carbon emissions. *Journal of Environmental Management*, 303, 114495. https://doi.org/10.1016/j.jenvman.2022.114495