Assessment of the Life Cycle-Based Environmental Impacts of New Zealand Electricity

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Edgar Eduardo Sacayon Madrigal

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ABSTRACT

The life cycle-based environmental impacts of New Zealand electricity arise from the different energy generation systems used to provide electricity to the national grid, and construction, maintenance and operation of the national electricity transmission and distribution system. Due to the high share of hydropower in the New Zealand electricity mix, base load electricity is rainfall dependent and its variable supply is balanced by generation from fossil fuelled power plants, geothermal, and to a lesser extent from wind, biogas and biomass power. This temporal variability of energy sources in the mix changes the Life Cycle Assessment (LCA) results for New Zealand electricity when the environmental impacts are assessed over different time periods. Therefore, this research had two main objectives: to conduct an LCA of electricity generation, and to assess the influence of temporal variation in the electricity mix on LCA results. Using the ecoinvent v 3.1 database and New Zealand-specific data, an LCA model of electricity generation and use was developed for the year 2013. The LCA results, using the CML 2001 – Apr. 2013 impact assessment method, showed that coal and natural gas power plants contributed 10 to 90 % in all impact categories. Electricity transmission and distribution (T&D) infrastructure contributed more than 50 % of the result for Abiotic Depletion Potential (ADP), Terrestrial Ecotoxicity Potential (TETP) and Human Toxicity Potential (HTP) impact categories. The Climate Change Potential (CCP) for 1 kWh of low-voltage electricity was 186 g CO_2-eq; for high and medium-voltage electricity, the CCP results were 172 and 176 g CO_2-eq per kWh respectively. To investigate the variability in LCA results over different time periods 3, 5 and 10 year moving averages (MAVG) were calculated; as expected, the variability decreased as the time period increased. The analysis showed that the 10 MAVG was associated with the lowest variability in LCA results. However a 10 MAVG will not reflect changes in installed power plant capacity. Therefore for attributional LCA studies of products using electricity over a year-to-year time frame, a representative average of the electricity mix or a 3, 5, or 10 year MAVG can be used as long as there are no changes in installed power plant capacity. This information aids New Zealand´s electricity industries understand environmental impacts associated with transitions to renewable energy technologies and meet greenhouse gas reduction targets.

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LIST OF ABBREVIATIONS

INSTITUTIONS

IEA = International Energy Agency
EA= Energy Authority
MBIE = Ministry of Business Innovation and Employment
MFE = Ministry for the Environment
MED = Ministry of Economic Development
OECD = Organization for Economic Co-Operation and Development
BRANZ = Building Research Association of New Zealand
NZGA = New Zealand Geothermal Association
NZWEA = New Zealand Wind Energy Association

COUNTRIES

CH = Switzerland
NZ = New Zealand
DE = Germany
RoW = Rest of the World
GLO = Global

LIFE CYCLE ASSESSMENT METHODOLOGY

LCA = Life Cycle Assessment
LCI = Life Cycle Inventory
LCIA = Life Cycle Impact Assessment
GHG = Greenhouse Gases
ADP Elements = Abiotic Depletion Potential of mineral resources
ADP Fossil = Abiotic Depletion Potential of fossil fuel resources
AP= Acidification Potential
EP = Eutrophication Potential
FAETP = Freshwater Aquatic Ecotoxicity Potential
GWP = Global Warming Potential excluding biogenic carbon
HTP= Human Toxicity Potential
MAETP = Marine Aquatic Ecotoxicity Potential
ODP = Ozone Layer Depletion Potential
POCP = Photochemical Ozone Creation Potential
TETP = Terrestrial Ecotoxicity Potential

POWER AND ELECTRICITY TECHNOLOGIES

1-Flash = Single Flash
2-Flash = Double Flash
3-Flash = Triple Flash
CCGT = Combined Cycle Gas Turbine
OCGT = Open Cycle Gas Turbine
BORC = Binary Organic Rankine Cycle
CCST = Conventional Condensing Steam Turbine
Dec. = Decommissioned
H = Hybrid (referring to the combination of flash and organic cycles in geothermal power production)
T&D = Transmission and Distribution Network
RoR = Run-of-river hydroelectric power plant

UNITS

kg = kilograms
CO_2-eq =carbon dioxide equivalents
k = kilo
t = tonnes
g = grams
kWh = Kilowatt hour.
GWh = Gigawatt hours
MW = Megawatt.
m = metres
km = Kilometres
V = Volts
AC = Alternating Current
DC = Direct Current

GLOSSARY

LCA of energy systems requires a basic understanding of underlying terminology. This Section introduces some of the key concepts and general conventions used throughout this work, so the reader gains a better comprehension of the topic.

Greenhouse gases (GHGs): The term refers to gases that contribute to climate change. The main greenhouse gases are carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrogen oxides (NO_x), nitrous oxide (N_2O) and non-methane volatile organic compounds (NMVOCs) and sulphur dioxide (SO_2). Sulphur hexafluoride (SF_6) is a greenhouse gas associated with the distribution infrastructure and therefore is mentioned separately.

Carbon footprint: total contribution of different greenhouse gases to potential climate change. It is usually measured by multiplying different quantities of greenhouse gases by their respective Global Warming Potential (GWP). Both “carbon footprint” and “climate change potential” are used throughout this work to refer to the same environmental impact. The unit of measure of the carbon footprint is grams of Carbon Dioxide Equivalents (g CO_2-eq), being the climate change potential impact associated with emission of greenhouse gases. Another term that appears in the literature is “Life Cycle Greenhouse Gases”.

Biogenic carbon: source of carbon that follows the natural flow of the carbon cycle through the biosphere, atmosphere, ocean and lithosphere (EPA, 2014).

Electricity grid mix: The “electricity grid” or the “electricity mix” refers to the technologies used to produce high, medium and low-voltage electricity. In New Zealand high-voltage electricity ranges from 400 – 220 kV AC; medium-voltage electricity ranges from 110 – 11 kV AC and low-voltage electricity ranges from 400 – 230 V.

Capacity factor: a measure of how efficiently the power plant produces electricity. This index is estimated by dividing the electricity generated in one year, against the total generation if the power plant was operated at its full capacity.

Abiotic Depletion Potential (ADP Elements): Impact category that quantifies the depletion potential of non-renewable resources found as elements within the earth´s crust. It is defined as the ratio of resource extraction rate and the recoverable reserves of that resource; it is expressed in kg of a reference antimony equivalent (Guinée, 2002).

Depletion of non-renewable resources (ADP Fossil): Impact category that quantifies the amount of fossil energy consumed by the system, and is expressed in mega joules (MJ) (Guinée, 2002).

Acidification Potential (AP): Environmental impact category that quantifies the potential of pollutants to produce hydrogen ions and therefore, acidification on the environment. Expressed in sulphide dioxide equivalents (Guinée, 2002).

Eutrophication Potential (EP): Environmental impact category that quantifies the potential of organic matter, nitrogen and phosphate to cause nutrient enrichment on the environment. Expressed in phosphate equivalents (Guinée, 2002).

Freshwater Aquatic Ecotoxicity Potential (FAETP): Impact category that quantifies the potential impact of toxic substances to aquatic ecosystems (Guinée, 2002). Expressed in kg of 1,4-dichlorobenzene equivalents.

Human Toxicity Potential (HTP): Environmental impact category that quantifies the potential of toxic emissions to cause health risks in human beings (Guinée, 2002).

Marine Aquatic Ecotoxicity Potential (MAETP): Environmental impact category that quantifies the potential of toxic substances to produce damaging effects on marine ecosystems (Guinée, 2002).

Ozone Layer Depletion Potential (ODP): Environmental impact category that quantifies the effects of anthropogenic emissions on the reduction of the earth’s ozone layer in the stratosphere(Guinée, 2002). It is expressed in kg CFC-11-equivalents.

Photochemical Ozone Creation Potential (POCP): Environmental impact category that quantifies the potential formation of reactive chemical compounds by the action of sunlight on volatile organic compounds in the troposphere (Guinée, 2002). Expressed in kg of ethylene equivalents.

Terrestrial Ecotoxicity Potential (TETP): Impact category that quantifies the potential impact of toxic substances to terrestrial ecosystems (Guinée, 2002). Expressed in kg of 1,4-dichlorobenzene equivalents.

Chapter 1 Introduction

1.1 Context

Climate change is one of the biggest environmental issues of our time. Anthropogenic greenhouse gas (GHG) emissions are increasing the rate of global warming with potentially severe consequences for the environment that threaten the livelihoods of humans and continued existence of other living organisms around the world (IPCC, 2008). A growing awareness of climate change has led societies to seek ways to reduce GHG emissions and limit other related human activities that contribute to climate change.

One of the assessment techniques that is being used to understand and measure environmental impacts associated with human activities is Life Cycle Assessment (LCA). LCA is an analytical tool that analyses the emissions, resource consumption and resulting potential environmental impacts of products throughout their life cycles. LCA provides a consistent method to calculate environmental performance indicators based on ISO 14040 and 14044 standards (ISO, 2006a, 2006b). An expanded explanation of the LCA framework is provided in Chapter 2 of this work.

Environmental performance indicators such as the carbon footprint are now being used worldwide to measure the environmental sustainability of products. They are used by government institutions to support decision making, and are also used by companies to support product design and development of product-related strategies. In fact, LCA has become so relevant that the special IPCC[1] report on climate change mitigation used LCA as a basis for a comprehensive review of renewable energy sources as compared with traditional fossil fuel sources (Edenhofer et al., 2012).

In addition, environmental performance indicators are also being used as a basis for environmental certification schemes. Certification enables companies and their products to be recognized worldwide for their environmental credentials. This enhances their reputation and adds value to their products. Additionally LCA is the

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[1] Intergovernmental Panel on Climate Change

“de facto” standard method to support development of Type III environmental product declarations, as defined in ISO 14025 (ISO, 2006c).

In New Zealand a number of companies have used LCA to measure the environmental performance of their products. For example, LCA studies have been undertaken in the New Zealand wine industry (Barry, 2011) and the dairy industry (Basset-Mens, Ledgard, & Carran, 2005). The Building Research Association of New Zealand is using LCA to assess the environmental impacts associated with buildings and houses (Dowdell, 2014).

To undertake an LCA study, comprehensive inventories of resources, materials, energy inputs and outputs of emission are required. Usually, the embodied environmental impacts from the manufacture of materials and extraction of resources used in the supply chain accrue to the reference product. The reference product is the good, service or material that results from the process system under analysis. One of the key challenges when performing an LCA study is to obtain data on site-specific inputs and outputs. Commonly, this problem is addressed by defaulting to values in generic datasets. This introduces the potential for under or over-estimating these data.

Electricity is one of the most common inputs used across the supply chain of products and services. In New Zealand, environmental impact assessment studies of electricity generation have focused on the carbon footprint (Alcorn, 2003; Barber, 2011; Coelho, 2011) or are propriety in nature. In addition, products that use electricity over long time frames need to consider variability in the environmental impacts of electricity generation over several years. Furthermore, the effects of stepping down electricity during transmission and distribution are poorly understood. This lack of knowledge limits the accuracy and consistency of LCA studies of New Zealand products utilising electricity at different life cycle stages. Therefore, this research aimed to resolve the objectives described in Section 1.2.

1.2 Research Aim and Objectives

The aim of this study was to assess the life cycle-based-environmental impacts associated with generation and use of 1 kWh New Zealand electricity. Additionally, it also aimed to understand the effects of:

a. Transmission and associated voltage transformation from the main grid through the consumer.
b. Variability of the LCA results for electricity use over different timescales (1,3,5 and 10 year time frames).
c. Attributional versus consequential modelling perspectives on the LCA results for New Zealand electricity use.

This will provide a basis for making recommendations about preferred datasets for modelling of New Zealand electricity use and their use in different decision situations.

1.3 Approach

To accomplish the aims of this research the following stages were followed. First, an intensive literature review of existing LCA studies on electricity generation systems was undertaken. Second, New Zealand data on electricity generation systems, transmission and distribution infrastructure and their associated environmental inputs and outputs were collected. Third, ecoinvent v 3.1 energy system models were studied and adapted for a New Zealand Electricity Life Cycle Inventory (LCI) model which included coal, natural gas, oil, hydropower, geothermal, biogas, biomass and the transmission and distribution infrastructure. Fourth, Impact Assessment was conducted using the CML 2001- Apr.2013 method. Fifth, parameters were screened for sensitivity. Sixth, different scenarios of the New Zealand electricity grid were built in the LCA software to assess the effects of temporal and technological changes. Finally, the results were exported to Excel spread sheets and analysed using common statistical and graphic representation methods.

1.4 Structure of this Thesis

This thesis is structured in nine chapters. This chapter provides an introduction to the topic. Chapter 2 describes the LCA framework, a four-step iterative method standardised under ISO 14040-14044 (ISO, 2006a, 2006b). Chapter 3 provides an in-depth overview of New Zealand's electricity industry; the most important generation technologies are described using tables and maps updated for the year 2013. Chapter 4 provides an overview of published LCA studies of coal, natural gas, geothermal and hydropower technologies. Chapter 5 outlines the methodology and the sources of data that were used to build the New Zealand electricity life cycle inventory model. Chapter 6 presents the results, including a sensitivity analysis, and Chapter 7 discusses the results and their implications. Chapter 8 concludes with recommendations and areas for future research.

Chapter 2 The Life Cycle Assessment Framework – LCA

Life Cycle Assessment (LCA) is an environmental analysis tool for assessing the environmental impacts associated with a product by analysing the material inputs, resource consumption, outputs and emissions of an entire product system (ISO, 2006a, 2006b). A product system can include the supply chain of a product or the provision of a service over its entire life cycle, including the use-phase, disposal and recycling stages. LCA has been standardized under ISO standards 14040 and 14044 (ISO, 2006a, 2006b) and has become one of the recognised sustainability tools. The LCA methodology follows four stages: goal and scope definition, inventory analysis, impact assessment, and interpretation. These are described in Sections 2.1 to 2.4.

2.1 Goal and Scope Definition

The goal and scope definition phase involve defining the intended purpose of the study, the extent of the system boundaries, the declared functional unit, and the applications of the study (ISO, 2006a, 2006b). If the intention of the study is to assess the present state of a product system, then the method is known as an Attributional Life Cycle Assessment (ALCA); i.e. it assess the attributes of a product system. If the purpose of the study is to assess the consequences of a change in the product system, then the method is known as a Consequential Life Cycle Assessment (CLCA). The functional unit, in both cases, provides a quantitative measure of the function delivered by the product. Parallel to the functional unit, the reference flow determines the quantity of the product to deliver the function. All the relevant processes required to produce the functional unit are represented using a flow chart. The flow chart represents the system under analysis and its boundaries.

2.2 Life Cycle Inventory Analysis – LCI

The Life Cycle Inventory Analysis (LCI) is the phase at which all the relevant data of the product system are compiled and scaled to the declared functional unit. Activities, raw materials, resources, environmental emissions and other exchanges with the technosphere are documented and provide the basic building blocks of the entire product system model. Data to build an inventory can be obtained from different sources: industry reports, literature reviews, manufacturers or experts in a field. In spite of the large amount of time and resources required to compile inventory data on a product system, global LCI databases have been developed and are commonly used. Two of these are the ecoinvent® LCI database developed by the Swiss Ecoinvent Centre and the GaBi Professional database designed by thinkstep®. Both databases are sold under licence user agreements. Other LCI databases exist but have not been used in this research.

2.3 Life Cycle Impact Assessment – LCIA

Based on the LCI, inputs and outputs are classified following the cause-effect chain according to an environmental impact category. Each classified input or output is multiplied by a characterisation factor which represents the relative potential contribution to the environmental impact category. There are different characterisation models to assess environmental impacts at different stages of the cause-effect chain. Endpoint characterisation models assess environmental impacts at the end of the cause-effect chain were three areas of protection are considered ecosystems, human health and depletion of resources. Eco-Indicator 99 and ReCiPe are endpoint characterisation models. Midpoint characterisation models on the other hand assess environmental impacts earlier in the cause-effect chain. These could be resource-based like depletion of abiotic resources, land use or water consumption; or they can be pollution based, like climate change, stratospheric ozone depletion, or eutrophication potential. The CML 2001-Apr.2013 is a midpoint impact assessment model that considers 12 environmental impact categories. These are: Abiotic Depletion Potential (ADP Elements), Depletion of non-renewable resources (ADP Fossil), Acidification Potential (AP), Eutrophication Potential (EP), Freshwater Aquatic Ecotoxicity Potential (FAETP), Global Warming Potential (GWP), Global Warming Potential excluding biogenic carbon (GWP), Human Toxicity Potential (HTP), Marine Aquatic Ecotoxicity Potential (MAETP), Ozone Layer Depletion Potential (ODP), Photochemical Ozone Creation Potential (POCP) and Terrestrial Ecotoxicity Potential (TETP). This research uses the CML 2001-Apr.2013 impact assessment model.

2.4 Interpretation

In the final stage of the LCA, the results of the impact assessment are analysed. Usually, a hot-spot analysis is undertaken to identify the activities that are making the biggest contribution to the life cycle of the product. Conclusion and recommendations are drawn based on the analysis. Sensitivity and uncertainty analyses are also part of the interpretation process.

Chapter 3 The New Zealand Electricity Grid

3.1 The Electricity Mix

The New Zealand, electricity grid is a complex system that integrates electricity generators from the North and the South Island. High voltage electricity is produced from hydropower, geothermal, wind, coal, oil, natural gas, biomass and biogas. In 2013 a total of 41,876 GWh of electricity was produced (MBIE, 2014b); 75% was produced by renewable energy technologies (MBIE, 2014b), and the rest by fossil fuels. The average New Zealand electricity mix for the year 2013 can be seen in Figure 1. In 2013 there were no solar power plants providing electricity to the grid as reported by the Electricity Authority (EA, 2013). Hydropower and geothermal power plants are used for base load generation. Because electricity generation from hydro and wind is influenced by climatic factors, fossil fuel power plants are used to meet any shortfalls in the changing electricity demand; this is also known as peak power demand. Peak demand changes occur on a daily and seasonal basis. Daily peak demands respond to an increase of electricity consumption during evening hours, when office and domestic appliances are being used. Seasonal peak demand on the other hand occurs when there is an increase of electricity consumption for heating appliances during winter or air conditioners during summer.

Five companies are responsible for producing 97% of the total electricity consumed in the country (EA, 2011). Meridian, Contact Energy, Genesis Energy, Mighty River Power and Trust Power share the market; they own 98 power stations and operate an additional 81 on behalf of other owners (EA, 2011). In total, 220 power stations are identified by the Electricity Authority of New Zealand with an operation capacity of 10,000 MW or higher (EA, 2013).

New Zealand occupies third position in the percentage of electricity produced from renewables and the first position in producing geothermal electricity out of all the OECD member countries (OECD/IEA, 2010). In terms of generation, geothermal is the technology that is expected to have the highest rate of increase followed by wind power in the near future (OECD/IEA, 2010). Geothermal electricity annual generation grew from 5,843 GWh in 2012 to 6,053 GWh in 2013, due to the commissioning of the Ngatamariki and Te Mihi geothermal power plants at Lake Taupo (MBIE, 2014b). Other geothermal power plants have already been granted resource consent but are still on the development stage (Harvey & White, 2012).

The industry and residential sectors are driving demand for electricity. The aluminium smelting, wood, paper and pulp industries consume most electricity generated (MBIE, 2014b). Relatively less electricity is used by the public and commercial sectors. Nationally, demand forecasts predict a 1% increase rate per annum (OECD/IEA, 2010). Regionally, Otago and Auckland where the most populated cities are located have the highest electricity demand in New Zealand (MBIE, 2014b).

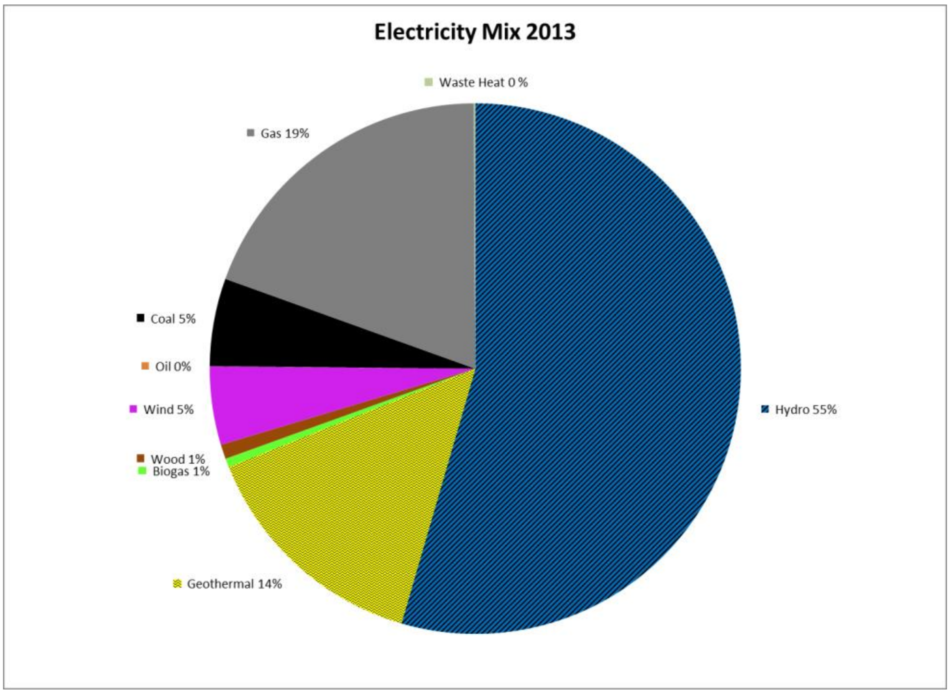

Figure 1 New Zealand Electricity Mix for the Year 2013. Source: MBIE 2014b

3.2 The Transmission and Distribution Network

The national electricity grid is operated by Transpower New Zealand Ltd., a state-owned enterprise that controls 12,000 km of high-voltage lines. The backbone of the electricity network in both the north and south island is a high-voltage 220 kV alternating current (AC) transmission line which connects power stations directly to the most important cities (Transpower, 2009). This 220 kV AC branches out to medium-voltage capacity transmission lines, mainly with three different voltages – 110 kV, 66 kV and 50 kV AC which connect smaller cities and towns. In some places voltage could even be as low as 11 kV AC (Transpower, 2009). Approximately 28 distribution companies step down electricity to 400-230 V AC and distribute it to households through a network of 150,000 km of low-voltage lines (Transpower, 2009). Transpower also owns a 350 kV high-voltage direct current

(HVDC) cable running underground the Cook Strait. This HVDC cable connects and the South and North Islands to transfer electricity.

3.3 Hydropower Generation in New Zealand

Hydropower produces the biggest proportion of electricity in New Zealand. In 2013, it generated 55 % of the total electricity mix. New Zealand's hydropower generation capacity is reported above 5,300 MW (EA, 2013). From 97 hydropower plants, 34 contribute fully electricity to the national grid (EA, 2013). These 34 hydropower plants have a nameplate capacity above 10 MW. The rest are either below 10 MW or are used off-the-grid. In the North Island there are 18 hydropower schemes while in the South Island there are 16 schemes. The South Island generates more electricity than the North Island and the excess is transferred to the North Island via the HVDC link. Electricity generation from hydropower is influenced by seasonal changes in rainfall and other climatic events. This makes capacity factors and the total quantity of electricity generation from hydropower variable each year. The North Island hydropower plants have lower capacity factors (less than 43% on average) than the South Island (57% average) (Eng, Bywater, & Hendtlass, 2008). This tendency is a direct consequence of the catchment conditions where hydropower schemes are located.

Classifications of hydropower plants are based on a number of criteria: the available head, plant capacity, turbine type and location (Boyle, 2012). A low head hydropower plant is considered to have less than 10 m of height, while a high head has more than 100 m (Boyle, 2012). For plant capacity, large scale hydropower refers to power plants above 10 MW; small-scale hydro power has been used for schemes below 10 MW, micro-hydro for plants with less than 100 kW and pico-hydro for plants smaller than 5 kW capacities. However these terms are variable between countries (Boyle, 2012).

All the New Zealand hydropower plants that feed electricity into the grid are large scale hydropower plants (i.e. above 10 MW). Within this category, Wagner and Mathur (2011), describe three types of hydropower schemes, each of them with variation in construction, operation modes and turbine technologies. These are run-of-river, reservoir-dam and pump hydro storage systems. In New Zealand most of the hydropower schemes fall into two categories: reservoir-dam or run-of-river. From these two types, reservoir-dam hydropower produces

94% of annual generation while run-of-river produce the remaining 6%. Table 1 and Figure 2 show the number of grid-connected hydropower plants producing electricity in 2015 (EA, 2013; Martin, 1991).

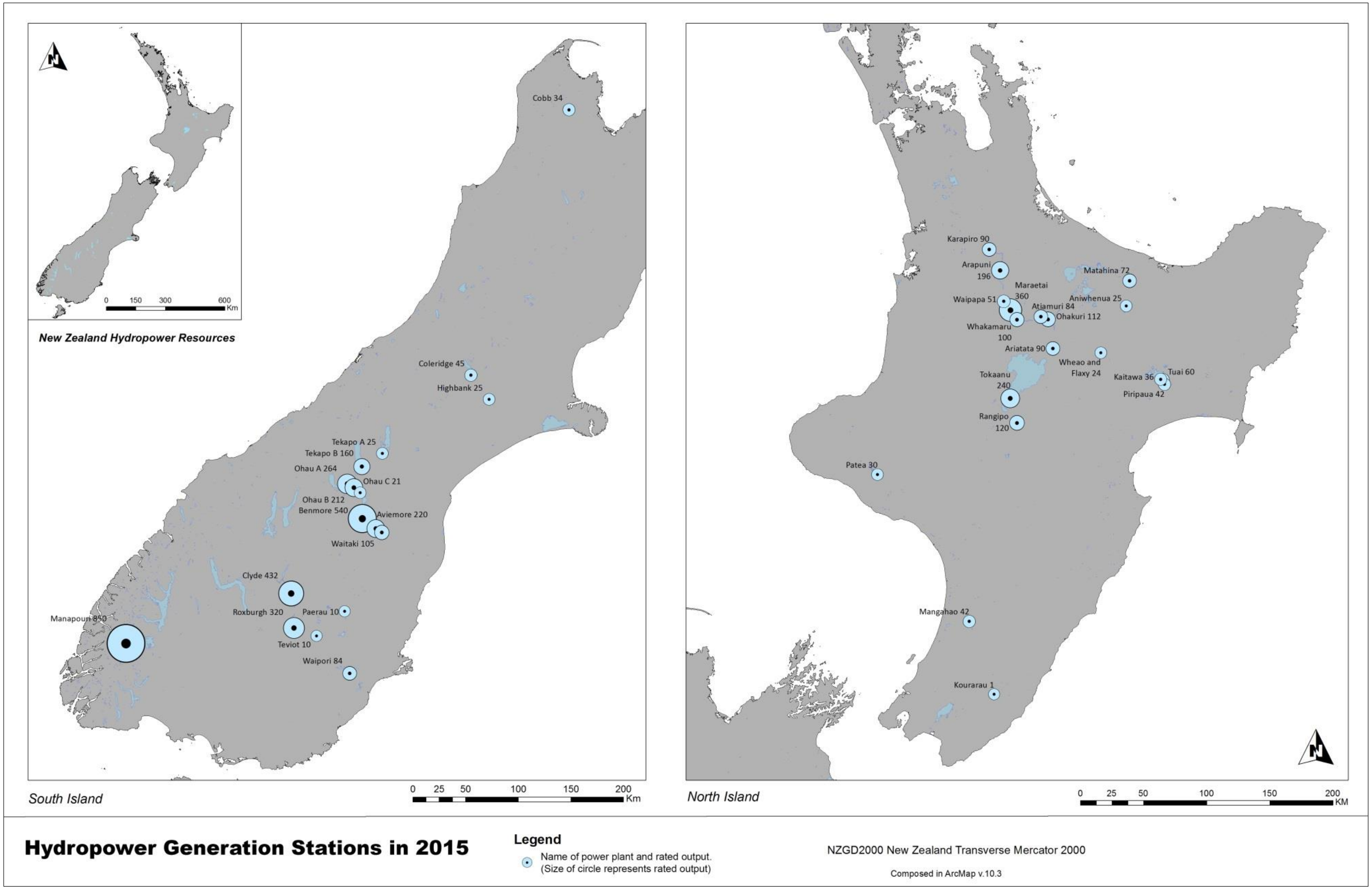

Figure 2 Geographic Location of New Zealand Grid Connected Hydropower Generation Stations

Table 1 New Zealand Grid Connected Hydropower Generation Stations, Date Commissioned, Owner, Type of Scheme and Dam, Rated Output, Annual Generation and Capacity Factors. Source: Eng et al. 2008; EA, 2013; Martin, 1991

No.	Plant Name	Commissioned	Company	Type of Scheme		Type of Dam	Rated Output (MW)	Annual (GWh)	CF
				R	ROR				
North Island									
1	Maraetai I	1971	Mighty River Power	1		Concrete variable radius arch dam	180	442.5	28%
	Maraetai II				1		180	442.5	28%
2	Tokaanu	1973	Genesis Energy	1		Underground Tunnels	240	763	36%
3	Arapuni	1946	Mighty River Power		1	Concrete Arch Gravity Dam	196.7	805	47%
4	Rangipo	1983	Genesis Energy	1		Underground Tunnels	120	580	55%
5	Ohakuri	1962	Mighty River Power	1		Concrete Gravity Dam & Earth Fill Dam	112	400	41%
6	Whakamaru	1956	Mighty River Power	1		Concrete Gravity Dam & Earth Fill Dam	100	494	56%
7	Karapiro	1948	Mighty River Power	1		Concrete Arch Dam	90	525	67%
8	Atiamuri	1962	Mighty River Power	1		Concrete Gravity Dam	84	289	39%
9	Aratiatia	1964	Mighty River Power	1		Underground Tunnels	90	330	42%
10	Matahina	1967	Trustpower	1		Earth Dam	80	290	41%
11	Tuai	1929	Genesis Energy	1		Underground Tunnels	60	218	41%
12	Waipapa	1961	Mighty River Power	1		Earth Dam	51	242	54%
13	Piripaua	1943	Genesis Energy	1		Underground Tunnels	42	133	36%
14	Mangahao	1924	Todd Energy	1		Dams and Tunnels	42	136	37%
15	Kaitawa	1948	Genesis Energy	1		Underground Tunnels	36	91	29%
16	Patea	1984	Trustpower	1		Earth Dam	32	108	39%
17	Aniwhenua	1979	Bay of Plenty Energy		1	Dam	25	105	48%
18	Wheao and Flaxy	1982	Trustpower	1		Underground Tunnels & Canals	26	111	49%
	North Island Total			16	3		**1,787**	**6,505**	**43%**
South Island									
19	Manapouri	1972	Meridian Energy	1		Underground tunnels	850	5100	68%
20	Benmore	1965	Meridian Energy	1		Earth Dam	540	2500	53%
21	Clyde	1992	Contact Energy	1		CGD	432	2050	54%
22	Roxburgh	1956	Contact Energy	1		CGD	320	1610	57%
23	Ohau A	1980	Meridian Energy	1		Canal and Dam	248	1150	53%
24	Aviemore	1968	Meridian Energy	1		Concrete Gravity and Earth dam	220	930	48%
25	Ohau B	1984	Meridian Energy	1		Canal	212	970	52%
26	Ohau C	1985	Meridian Energy	1		Canal	212	970	52%
27	Tekapo B	1977	Genesis Energy	1		Canal	160	800	57%
28	Waitaki	1935	Meridian Energy	1		Concrete Arched Gravity Dam	105	500	54%
29	Waipori	1902	Trustpower	1		Concrete Arched Gravity Dam	84	192	26%
30	Coleridge	1914	Trustpower	1		Underground tunnels	39	270	79%
31	Cobb	1956	Trustpower	1		Earth dam	34	270	91%
32	Highbank	1945	Trustpower	1		Diversion race from Irrigation Canal	29	98	39%
33	Tekapo A	1951	Genesis Energy	1		Reinforced-concrete buttres dam	25	160	73%
34	Paerau	1984	Trustpower		1	Canals and tunnels	10	48	55%
	South Island Total			15	1		**3,520**	**17,618**	**57%**
	NZ Total						**5,307**	**24,123**	

Note: R= Reservoir, ROR = Run-of-river, CF = Capacity Factor

3.3.1 Run-of-River Schemes

Run-of-river schemes use the natural water flow and topography to produce power. A weir and a power house are built directly or besides the river without affecting the flow of the water. Usually, Kaplan, Propeller and Francis turbines are the preferred technologies because they can handle large masses of water at low heads and pressures. These are used for base load capacity, and have the advantage of a reduced impact on natural habitats (Wagner & Mathur, 2011).

3.3.2 Reservoir-dam

Reservoir-dam hydropower plants use the potential energy of water stored in a reservoir to produce power. A dam is constructed to stop the water flow and create a water reservoir. Depending on their shape dams can be classified as arch dams, gravity dams or buttress dams. In addition, they can also be classified by their building structure. For example, earth dams use soil and rocks to create a trapezoid bank. A concrete dam on the other hand uses concrete, a concrete pin and a concrete core to increase its stability. In ferro-concrete dams, the dam structure is reinforced with steel and is commonly used in narrow gorges (Wagner & Mathur, 2011). Therefore, the nomenclature for dams is the result of the shape and structure. Some dam types are: arch-gravity dams, concrete-gravity dams, or earth- and rock-filled gravity dams. Also, hydroelectric dams use penstocks, which are the pipes that carry water from the reservoir to the turbines. These can be constructed with steel or concrete, above or underground depending on the topographic conditions (Wagner & Mathur, 2011). Francis and Pelton turbines are used for reservoir-dam plants because they work at higher pressures and head heights up to 2,000 m. Reservoir-dam power plants can be used to produce base load and have the advantage of storing energy to be deployed when needed. Besides being used for base load reservoir-dams can cover peak loads or seasonal weather variations (Wagner & Mathur, 2011).

3.4 Geothermal Power Generation in New Zealand

In New Zealand high temperature geothermal reservoirs in the North Island are located in the Taupo Volcanic Zone and to a lesser extent in Ngawha; in the South Island there are geothermal reservoirs along the alpine fault (Eng et al., 2008) but these have not been exploited. With the exception of Wairakei's Poihipi dry-steam power plant, all geothermal fields producing electricity are considered as high-temperature hydrothermal reservoirs (DiPippo, 2012). In the year 2015 there were 13 geothermal power plants in operation with a total generating capacity exceeding 1,000 MW (Carey, B. et al.,2015; DiPippo, 2012; EA, 2011,2012; MBIE, 2014b; Parsons Brinckerhoff, 2012a). Table 2 and Figure 3 list geothermal stations operating in New Zealand.

On average geothermal power produces more than 7,000 GWh each year (Brian Carey et al., 2015; DiPippo, 2012; EA, 2011, 2013; MBIE, 2014b; OECD/IEA, 2010; Parsons Brinckerhoff, 2012a) which contributes 12-16 % of the total electricity mix (Harvey & White, 2012). The additional geothermal generation potential that could be exploited has been estimated at 1,000 MW (OECD/IEA, 2010). Geothermal power could increase the share of production to 21 – 29 % of the total mix by the year 2040 (MBIE, 2013b).

3.4.1 Geothermal Flash Power Plants

More than 60% of New Zealand geothermal power plants are considered as single, double or triple flash power plants (Table 3). The rest is either binary[2] or a combination of both, which is here referred to as hybrid flash-binary technology. Usually hydrothermal reservoirs are located up to 3 km deep (Eng et al., 2008) and are exploited using Single-Flash (1-Flash) or Double-Flash (2-Flash) power plants. Flash steam is a combination of high pressure liquid and vapour which releases large amounts of steam when pressure is reduced (Buchla, Kissell, & Floyd, 2014). Thus in a 1-Flash unit, a separator is used to release the pressure and instantly convert the hydrothermal liquid to steam. The steam is piped to a steam turbine to produce electricity (Buchla et al., 2014). The residual water or brine is cooled and re-injected back into the reservoir. In the 2-Flash system, the efficiency is enhanced by adding a secondary flashing unit which uses the energy

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[2] Binary organic rankine cycle geothermal plants use an organic working fluid as iso-pentane to take advantage of the heating properties of lower temperature geothermal brines.

stored in the remaining liquid from the first separator, i.e. the hydrothermal brine is flashed two times. Typical 2-Flash units increase the power outputs by 20-25 % compared with a 1-Flash unit and produce anything between 30-50 MW (Boyle, 2012).

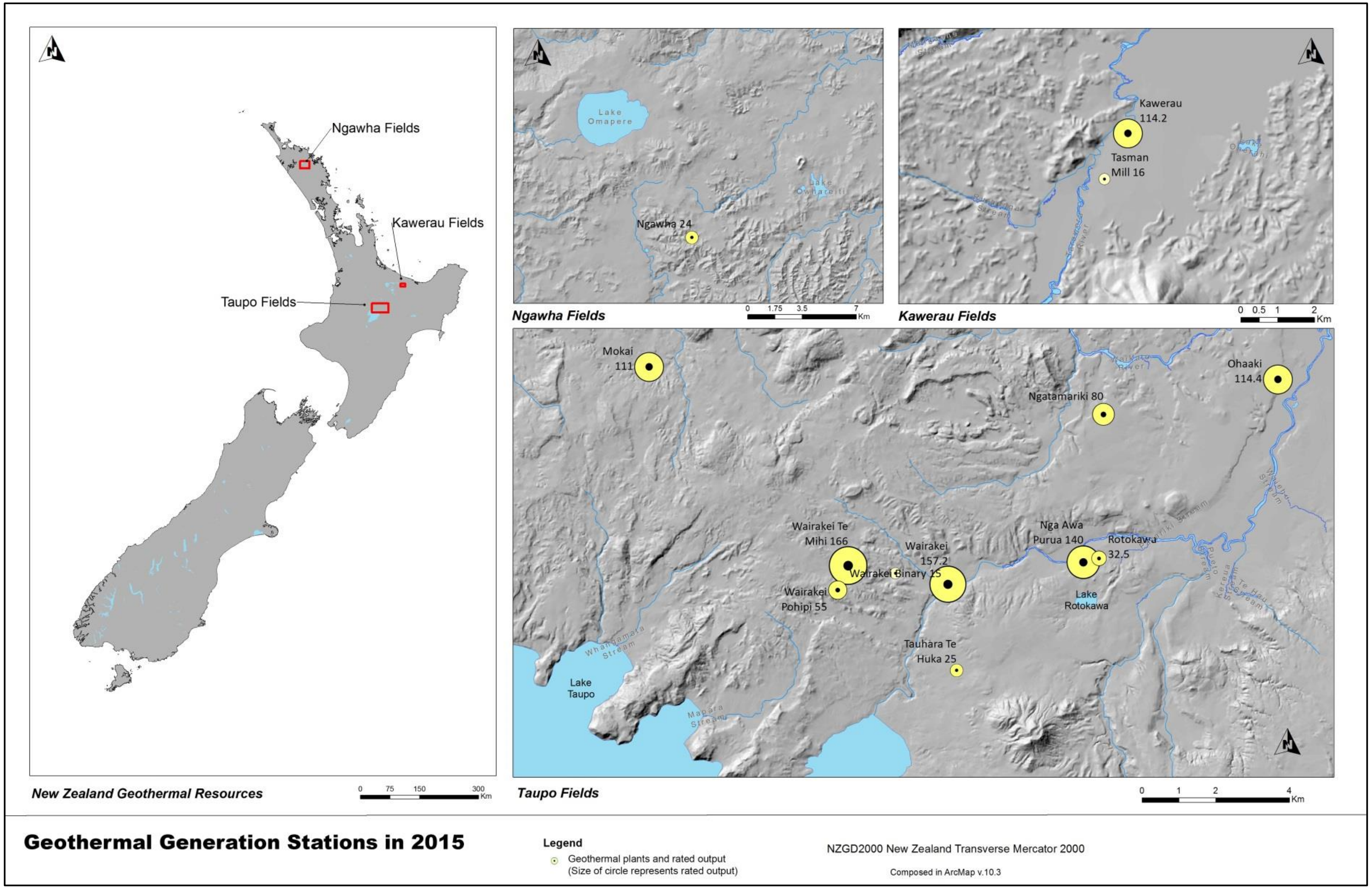


Figure 3 Geographic Location of New Zealand Geothermal Generation Stations

Table 2 New Zealand Geothermal Generation Stations, Date Commissioned, Plant and Generation Technology Used, Capacity Factors and Annual Generation 2015. Source: Carey et al. 2015; DiPippo, 2012; EA, 2011, 2012; MBIE, 2014; MED, 2012; OECD/IEA, 2010.

Field	No	Plant Name	Date Comm.	Company	Plant Tech.	Plant Type	Turbine Capacity	Plant Capacity (MW)	CF	Annual (GWh)	Baseload	Wells Drilled[1]	Well Depth[1]	Pipelines Length[2]	Units	% Contribution
Wairakei	1	**WAIRAKEI**	1958	Contact Energy				159.2	70%	970	Y	150	2,400	4,000		16%
		Station A														
		Unit 1	1959		CCST	2-Flash	11.2								1	
		Unit 2 (Dec.)	1958		CCST	-	-								-	
		Unit 3 (Dec.)	1958			-	-								-	
		Unit 4	1959		CCST	2-Flash	11.2								1	
		Unit 5 (Moved)				-	-								-	
		Unit 6 (Moved)				-	-								-	
		Unit 7	1959		CCST	3-Flash	11.2								1	
		Unit 8	1959		CCST	3-Flash	11.2								1	
		Unit 9	1960		CCST	3-Flash	11.2								1	
		Unit 10	1960		CCST	3-Flash	11.2								1	
		Station B			CCST											
		Unit 11	1962		CCST	2-Flash	30								1	
		Unit 12	1963		CCST	2-Flash	30								1	
		Unit 13	1963		CCST	2-Flash	30								1	
		Unit 14	1996			2-Flash	2								1	
	2	**WAIRAKEI BINARY**	2005		BORC	Binary	15	15	91%	120	Y	N/A			2	1%
	3	**WAIRAKEI POIHIPI**	1996		CCST	Dry Steam Unit	55	55	87%	420	Y	N/A			1	5%
	4	**WAIRAKEI TE MIHI**	2014					166	63%	920	Y	50				16%
		Unit 1			CCST	2-Flash	83								1	
		Unit 2			CCST	2-Flash	83								1	
Kawerau	5	**KAWERAU**		Mighty River Power				134.8	88%	1,036	Y	48	1,650	N/A		13%
		TG1-1 (Dec.)	1989		BORC	-	-								-	
		TG1-2 (Dec.)	1989		BORC	-	-								-	
		TG2	1993		BORC	Binary	3.5								1	
		KA24	2008		BORC	Binary	8.3								1	
		Kawerau	2008		CCST	2-Flash	100								1	
		TOPP 1	2013		BORC	Binary	23								1	
	6	**TASMAN MILL (BP)**	2004	Norske Skog's	BORC	Binary	5	5	100%	44	Y	N/A	N/A	N/A	1	
Reporoa	7	**OHAAKI**		Contact Energy				58	59%	300	Y	29	2,500	3,950		6%
		Unit 1 (From Wairakei) (Dec.)	1989		CCST	-	-								-	
		Unit 2 (From Wairakei)	1989		H	Flash-Binary	11								1	
		Unit 3 (Dec.)	1989		CCST	-	-								-	
		Unit 4	1989		CCST	1-Flash	47								1	
Rotokawa	8	**ROTOKAWA**		Mighty River Power				34	91%	270	Y	30	2,500	N/A		3%
		Unit 1	1997		H	1-Flash	15								1	
		Unit 2	1997		H	Binary	5								1	
		Unit 3	1997		H	Binary	4.5								1	
		Unit 4	1997		H	Binary	4.5								1	
		Extension	2003		BORC	Binary	5								1	
	9	**NGA AWA PURUA**	2010		CCST	3-Flash	140	140	82%	1,000	Y	6	NA	2,561	1	14%
Northland	10	**NGAWHA**		Top Energy				25	64%	140	Y	16	2,300	1,350		2%
		Unit 1	1998		BORC	Binary	5								1	
		Unit 2	1998		BORC	Binary	5								1	
		Unit 3	2008		BORC	Binary	15								1	
Mokai	11	**MOKAI**		Mighty River Power				110	97%	930	Y	22	2,400	4,340		11%
		Mokai I	1999		CCST	1-Flash	25								1	
		Unit 1	1999		BORC	Binary	5								1	
		Unit 2	1999		BORC	Binary	5								1	
		Unit 3	1999		BORC	Binary	5								1	
		Unit 4	1999		BORC	Binary	5								1	
		Unit 5	1999		BORC	Binary	5								1	
		Unit 6	1999		BORC	Binary	5								1	
		Mokai II	2005		CCST	1-Flash	33								1	
		Unit 1	2005		BORC	Binary	1								1	
		Unit 2	2005		BORC	Binary	1								1	
		Unit 3	2005		BORC	Binary	1								1	
		Unit 4	2005		BORC	Binary	1								1	
		Unit 5	2005		BORC	Binary	1								1	
		Mokai IA	2007		BORC	Binary	17								1	
Tauhara	12	**TE HUKA**	2010	Contact Energy	BORC	Binary	26	26	88%	200	Y	25	1,200	N/A	2	3%
Ngatamariki	13	**NGATAMARIKI**	2013	Mighty River Power				82	90%	650	Y	8	3,373			8%
		Unit 1	2013		BORC	Binary	20.5								1	
		Unit 2	2013		BORC	Binary	20.5								1	
		Unit 3	2013		BORC	Binary	20.5								1	
		Unit 4	2013		BORC	Binary	20.5								1	
		Averages						*77.69*	*82%*			*38.4*	*2,290*	*3,240*		
		Total Geothermal Generation						1,010		7,000					51	100%

Plant Technology: CCST = Conventional Condensing Steam Turbine; BORC = Binary Organic Rankine Cycle; H = Hybrid Combination of Flash and Binary Technology; Dec. = Decomissioned

1= Based on the New Zealand Geothermal Association Web Site

2= Based on measurements made in Google Earth

Table 3 Share of Geothermal Technology used in New Zealand for Electricity Generation. Source: Carey et al. 2015; DiPippo, 2012; EA, 2011, 2012; MBIE, 2014; MED, 2012; OECD/IEA, 2010.

Technology	Units	Rated Output	%
1-Flash	3	47	5%
2-Flash	9	380.4	38%
3-Flash	5	184.8	18%
Binary	28	209.8	21%
Dry Steam	1	55	5%
Hybrid Flash-Binary	5	133	13%
	51	1010	100%

3.5 Fossil-Fuel Resources in New Zealand

3.5.1 Coal Resources

In New Zealand, coal is the most abundant fossil fuel (Eng et al., 2008). There are approximate 15 billion tonnes of coal reservoirs (MBIE, 2014b). Steel production and electricity generation are the main activities in which coal is used (MBIE, 2014b) but it is also used as a heat source for the, dairy, meat and timber industries (Eng et al., 2008). Coal fields are found in the Waikato and Taranaki regions in the North Island. In the South Island coal is found in the northern portion of the West Coast, Canterbury and Central Otago (MBIE, 2014b). In 2013 New Zealand produced 4.6 million tonnes of coal, from which only 2.9 million where used in the country (MBIE, 2014b). The largest portion of coal reserves are lignite but the lower heating value makes it unattractive for extraction, therefore 94% of the total production is made up of bituminous and sub-bituminous coals (MBIE, 2014b). In 2013 there were three underground and 18 open-cast mines (MBIE, 2014b). The Huntly Power station used around 0.8 million tonnes of sub-bituminous coal in 2013, (MBIE, 2014b). In total the electricity sector including cogeneration consumed 40% of domestic coal supplies (MBIE, 2014b).

3.5.2 Natural Gas Reservoirs

Natural gas is extracted entirely from the Taranaki basin reservoirs (MBIE, 2014b). Thirteen fields produce New Zealand’s gas supplies (MBIE, 2014b). Pohokura, Maui and Kupe are the main production fields (MBIE, 2014b). A pipeline system owned by Vector, distributes high pressure gas to cities only in the North Island (Eng et al., 2008). Natural gas is used for electricity production, petrochemicals, industrial and domestic purposes (Eng et al., 2008). Electricity production uses 31 % of the total gas produced (MBIE, 2014b).

Additional industrial combined heat and power plants could raise this figure to 48% in the near future (OECD/IEA, 2010). Huntly, Otahuhu B and the Stratford power stations are the main gas consumers in the North Island (MBIE, 2014b).

3.5.3 Oil Deposits

Oil is extracted from New Zealand's oil deposits in combination with gas from the Taranaki basin, near New Plymouth (NZP&M, 2014). In total there are about 20 fields with more than 400 offshore and onshore exploration and production wells (NZP&M, 2014). The main oil extraction fields are Pohokura, Maui, Kapuni and McKee (MBIE, 2014b) . Most of New Zealand´s oil is exported (Pers.comm Sims, R., 2016)

3.6 Fossil-Fuel Power Generation in New Zealand

In 2013, 19.4 % of total electricity was produced using natural gas (MBIE, 2014b) and 5.3 % of the total electricity mix was produced using coal. Total generation capacity from fossil fuelled power stations stands at almost 3,000 MW (Parsons Brinckerhoff, 2012b). A large number of these are co-generation stations producing steam and heat for dairy, steel, pulp and paper industries. Co-generation of heat and power from fossil fuels stands at 2,455 GWh per year (MBIE, 2014b). From the 13 thermal power plants listed by the New Zealand Electricity Authority (EA, 2013), four are used for peak power: Whirinaki, Stratford, Southdown and Huntly Unit 6. Peak power is used to supply electricity in high demand periods or to compensate for renewable energy intermittency.

Huntly is the biggest power plant rated at 1,200 MW and capable of producing 20 % of electricity used in the country (Genesis Energy, 2015). However, two 250 MW turbines were recently decommissioned, one of which is reported as being in storage but "available within 90 days if required" (Genesis Energy, 2015). Huntly Units 1- 4 can burn natural gas or sub-bituminous coal (Parsons Brinckerhoff, 2009). Coal is delivered from the local Waikato and Rotowaro mines. Additional coal is imported from Indonesia (Parsons Brinckerhoff, 2012b) and delivered through the Tauranga port. A storage facility considered as one of the largest of its kind, was built in Tauranga port to store up to 70,000 tonnes of coal (Port of Tauranga, 2012). Whirinaki is the only thermal power plant burning diesel fuel (Parsons Brinckerhoff, 2012b). At full capacity the plant is estimated to burn 1 million litres per day (24 hours) (Parsons Brinckerhoff, 2012b). Figure 4 shows the geographic location of fossil fuelled generation stations while Table 4 lists them with their operational information.

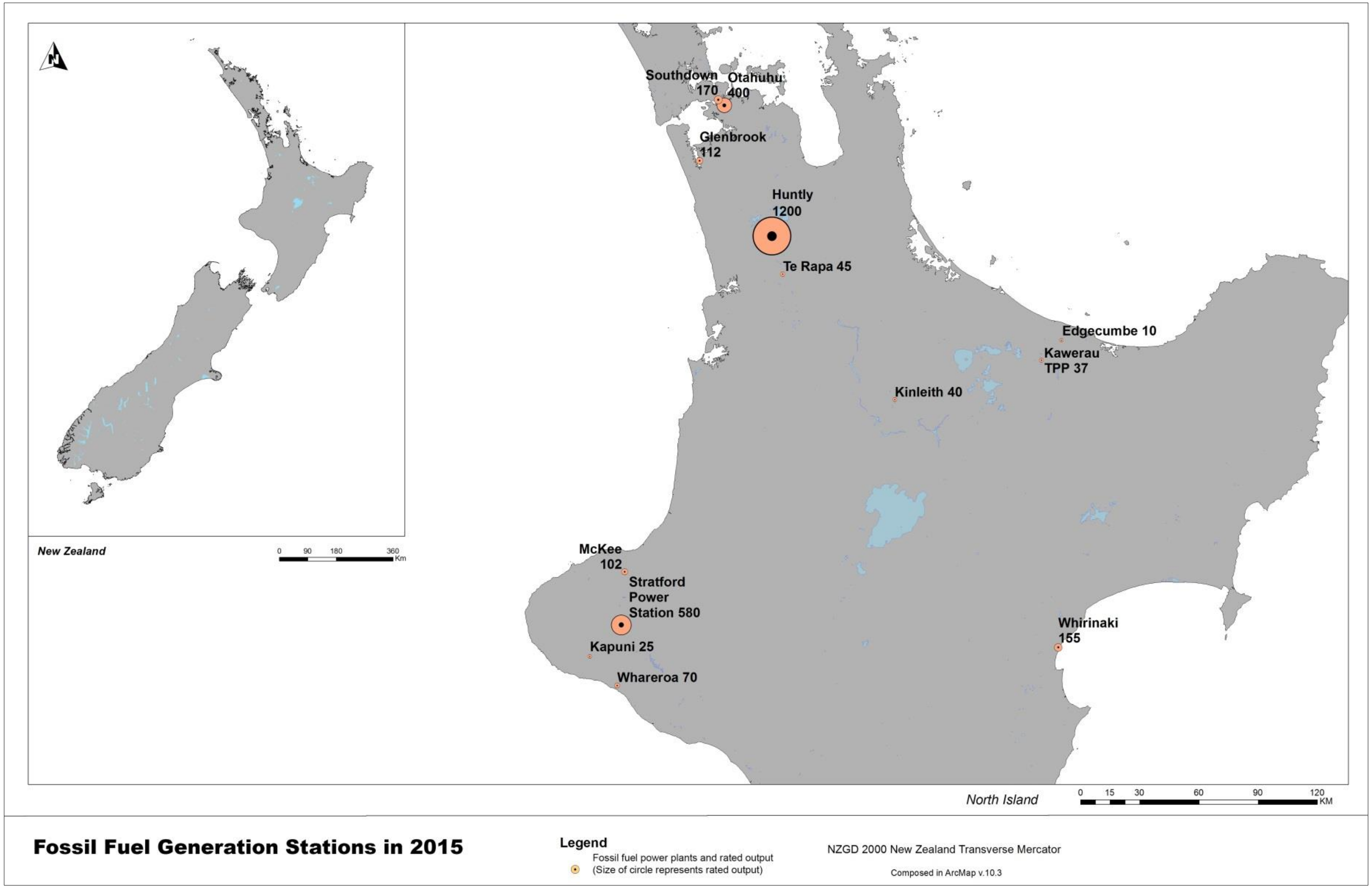


Figure 4 Geographic Locations of New Zealand Fossil-Fuelled Generation Stations

Table 4 Fossil-Fuelled Generation Stations in New Zealand, Commissioned Date, Owner, Fuel, Type of Thermal Technology, Rated Output, Capacity Factor, Annual Generation. Source EA, 2013; Parsons Brinckerhoff 2012a

No.	Plant Name	Comissioned	Owner	Fuel	Type	Technology	Rated Output	Operating Capacity MW	CF%	Annual GWh
1	**Huntly**		**Genesis Energy**		**Thermal**			**750**	**87%**	**5,695**
	Unit 1	1982		Gas/ S-b Coal		Boiler	250			
	Unit 2	185		Gas/ S-b Coal		Boiler	250			
	Unit 3	Storage		Gas/ S-b Coal		Boiler	250			
	Unit 4	Decom.		Gas/ S-b Coal		Boiler				
	Unit 5 (e3p)	2007		Gas		CCGT	403	**403**	**68%**	**2,410**
	Unit 6 (p40) Peaking Unit	2004		Gas/Diesel		OCGT	50.8	**50.8**	**75%**	**335**
2	**Stratford**		**Contact Energy**		**Thermal**					
	Taranaki Combined Cycle	1998		Gas		CCGT	385	**385**	**65%**	**2,200**
	Stratford	2011		Gas		OCGT	200	**200**	**20%**	**350**
3	**Southdown**		**Mighty River Power**		**Co-Gen**			**170**	**57%**	**850**
	Unit 1	1996		Gas		CCGT	45			
	Unit 2	1996		Gas		CCGT	45			
	Unit 3	1996		Gas		CCGT	45			
	Southdown E105	2007		Gas		OCGT	35			
4	**Otahuhu**		**Contact Energy**		**Thermal**			**380**	**71%**	**2,380**
	Otahuhu A	Decom.		-		-		-		-
	Otahuhu B	1999		Gas		CCGT	380			
5	**Kapuni**		**Todd Energy**	Gas	**Co-Gen**			**25.3**	**59%**	**130**
	Unit 1	1998		Gas		CCGT	10.3			
	Unit 2	1998		Gas		CCGT	10.3			
	Unit 3	1998		Steam		ST	3.2			
	Unit 4	1998					1.5			
6	**Whareroa (Hawera) Dairy**		**Todd Energy**		**Co-Gen**			**70**	**29%**	**180**
	Unit 1	1996		Gas		OCGT	10.5			
	Unit 2	1996		Gas		OCGT	10.5			
	Unit 3	1996		Gas		OCGT	10.5			
	Unit 4	1996		Gas		OCGT	10.5			
	Unit 5	1996		Steam		ST	28			
7	**Te Rapa**		**Contact Energy**		**Co-Gen**			**45**	**51%**	**200**
	Unit 1	1999		Gas		CCGT	45			
8	**Kinleith (Carter Holt Harvey)**							**39.6**	**63%**	**109**
	Unit 1			Diverse	**Co-Gen**	CCGT	28			
9	**Glenbrook (NZ Steel)**		**Alinta Energy**					**112**	**56%**	**550**
	Bottoming Unit	1997		Gas	**Co-Gen**	CCGT	112			
10	**Whirinaki**		**Contact Energy**					**155**	**1%**	**9**
	Unit 1	2004		Diesel		OCGT	52			
	Unit 2	2004		Diesel		OCGT	52			
	Unit 3	2004		Diesel		OCGT	51			
11	**Kawerau - TPP**		**Norske Skog Tasman**		**Co-Gen**			**36.7**	**84%**	**271**
	Unit 1	1966		Gas		CCGT	10			
	Unit 2	1966		Gas			8			
	Unit 3	1966		Gas			18.7			
12	**Bay Milk Edgecumbe**		**Nova Energy**		**Co-Gen**			**10**	**62%**	**54**
	Unit 1	1996		Gas		CCGT	5			
	Unit 2	1996		Gas		CCGT	5			
13	**McKee**		**Todd Energy**		**Thermal**			**102**	**34%**	**300**
	Unit 1	2013		Gas		OCGT	50			
	Unit 2	2013		Gas		OCGT	50		Na	
	Unit 3	2013		Gas		R	1			
	Unit 4	2013		Gas		R	1			
	Total							**2,934**		**16,023**

Technology: CCGT = Combined Cycle Gas Turbine, OCGT = Open Cycle Gas Turbine, ST = Steam Turbine, R = Reciprocating Engines

Fuel: S-b = Sub-bituminous

3.7 Wind Power Generation

In New Zealand there are 19 wind farms, 8 of which provide electricity into the national grid (NZWEA, 2015). The total rated output wind capacity in the country is about 650 MW. On average these wind farms can produce more than 2,000 GWh per year. In 2013 wind generation accounted for 5% of the total electricity mix (MBIE, 2014b). There is an additional 2,500 MW of wind generation available that has already been consented (NZWEA, 2015). The size of wind turbines used in wind farms range between 1-3 MW. Figure 5 shows the geographic locations of wind farms. Table 5 shows the listed wind farms and their operational details.

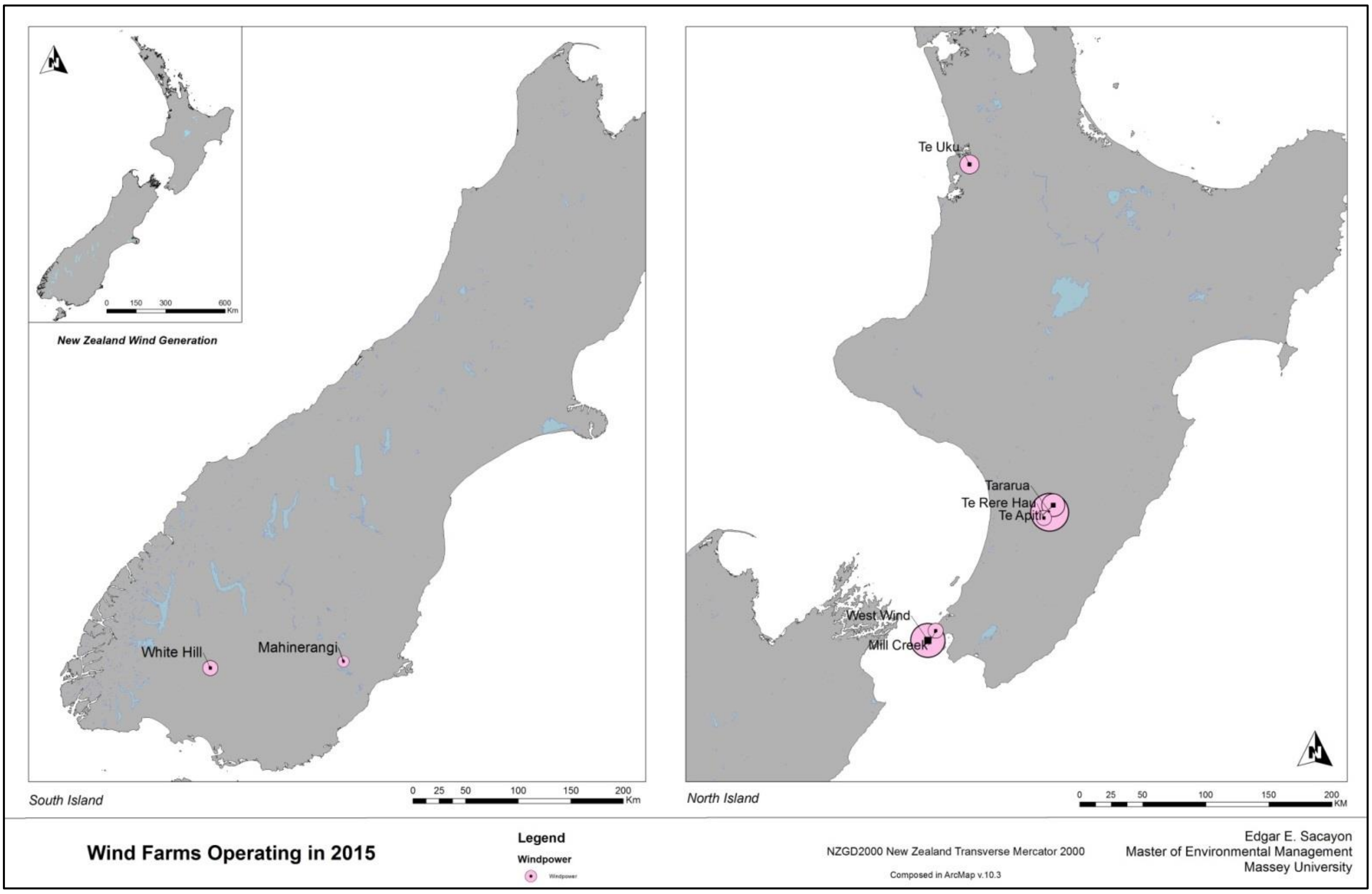


Figure 5 Geographic Locations of Windfarms in New Zealand 2015

Table 5 Wind Farms, Date Commissioned, Owner, Turbine Technologies, Rated Outputs, Capacity Factors and Average Annual Generation. Source: NZWEA, 2015

Wind Farm	Commision Date	Operator	No. of Turbines	Turbine capacity (MW)	Farm Capacity	Total Capacity MW	C.F %	Average annual output (GWh)
1 Tararua		Trust Power				161.0		650
Stage 1	1999		48	0.66	31.7		46%	128
Stage 2	2004		55	0.66	36.3		46%	147
Stage3	2007		31	3	93.0		46%	375
2 Te Apiti	2004	Meridian	55	1.65	90.8	90.8	32%	258
3 Te Rere Hau	2006	NZ Windfarms	97	0.5	48.5	48.5	38%	160
4 White Hill	2007	Meridian	29	2	58.0	58.0	39%	200
5 West Wind	2009	Meridian	62	2.3	142.6	142.6	44%	550
6 Te Uku	2011	Meridian	28	2.3	64.4	64.4	40%	225
7 Mahinerangi	2011	Trust Power	12	3	36	36.0	36%	112
8 Mill Creek	2014	Meridian	26	2.3	59.8	59.8	45%	236
9 Hau Nui	1996	Genesis Energy	15	0.55	8.71	8.7		
Total						**669.7**		**2,391**

There are a number of wind farms that were not considered in the table. Flat Hill, a 6.8 MW wind farm, was under construction during the analysis period. Mount Stuart, a 7.65MW wind farm feeds electricity to the local Otago network, using nine 850 kW wind turbines. These wind farms, do not contribute electricity to the national grid, and therefore were excluded from the analysis. Wind power is increasing in New Zealand and it is expected to continue growing due to the country´s high eolic energy potential.

Chapter 4 Life Cycle Assessment Studies of Energy Systems

Life Cycle Assessment (LCA) studies have been used in the energy industry to understand life cycle emissions and to benchmark technological developments. Carbon footprinting studies are more common than complete LCA studies. LCA studies of complete grid systems are very scarce, therefore to understand the electricity life cycle-based impacts, coal, natural gas, hydro and geothermal power LCA studies were reviewed. New Zealand specific LCA studies on energy systems are presented first. Fossil fuel LCA studies are discussed afterwards. Third, hydropower LCA studies are reviewed. And finally, geothermal LCA studies are reviewed.

4.1 New Zealand Electricity and Energy System Life Cycle Studies

In New Zealand, there are a limited number of LCA studies for the energy sector and the focus has been on embodied energy analysis and embodied CO_2. For example, Alcorn (2003) focused on the environmental impacts of building materials. This was one of the earliest studies to provide electricity and fossil fuel life cycle CO_2 emission factors. Rule and colleagues (2009) also used embodied energy analysis and life cycle CO_2 emissions to assess the sustainability of four renewable energy technologies. Fernando (2010) used embodied energy analysis to compare the environmental impacts of natural gas, wind and hydropower generation systems. Another two studies have included life cycle greenhouse gases (GHG); Barber (2011) described primary energy, CO_2 and GHG emission factors for electricity and fuels, and Coelho (2011) measured the New Zealand electricity grid carbon footprint. Finally, one study focused specifically on life cycle GHG emission of geothermal power (Drysdale, 2010).

The most important findings from the studies by Fernando (2010) and Rule et al. (2009) were that the largest contribution to the total embodied energy from hydro and wind power were related to the construction of the power plant infrastructure. More specifically, by looking at run-of-river and reservoir dams, Fernando (2010) concluded that the construction of the hydro dam is the most energy intensive process and therefore embodied most of the life cycle environmental impacts. Similarly, for wind power these studies were in agreement that the construction of a wind farm contributed the most to the embodied energy of the plant and therefore accounted for most of the life cycle CO_2 emissions.

For two natural gas power plants Fernando (2010) found that the fuel combustion and O&M contributed to 90 % of the embodied energy while the fuel cycle contributed 10% (Fernando, 2010). The work by Fernando (2010) presented results that are consistent with other studies of natural gas power plants in the United States (Sullivan, Clark, Han, & Wang, 2010). Life-cycle embodied energy and GHG emissions are higher for the operation and maintenance phases than for the upstream activities of the fuel supply chain.

For GHG emissions per kWh, Rule and colleagues (2009) calculated CO_2 life cycle emissions of 1.8 g CO_2 for tidal, 4.6 g CO_2 for hydro, 3.0 g CO_2 for wind, and 5.6 g CO_2 for geothermal power (Rule, Worth, & Boyle, 2009). However, fugitive CO_2 emissions from geothermal reservoirs and methane emissions from hydropower reservoirs were neglected. Drysdale (2010), on the other hand, included fugitive emissions into his hypothetical assessment of the future second stage of the Tauhara geothermal double flash plant planned to be built in the Wairakei geothermal field. During a 35 year life-span, the Tauhara geothermal plant would produce on average 100 g of CO_2 per kWh. Overall, Drysdale (2010) calculated climate change emission factor of the future Tauhara Stage II geothermal plant at 132 g CO_2-eq per kWh; 98 % could be attributed to the operation phase and 2 % attributed to construction, maintenance and end of life activities (Drysdale, 2010).

4.2 Life Cycle Assessment of Fossil-Fuel Power

Life cycle greenhouse gases (GHG) from gas and coal power generation have been studied extensively. Whitaker, Heath, O'Donoughue, and Vorum (2012) reported 270 studies that assessed life cycle GHG emissions of electricity generation from coal. O'Donoughue, Heath, Dolan, and Vorum (2014) reported over 250 references for life cycle GHG emission studies from electricity produced from natural gas. This has led LCA researchers to have a fairly good understanding of life cycle GHG emissions for these two technologies, positioning natural gas as the best environmental performer of fossil fuel technologies while coal power is ranked as the worst.

In general terms, GHG emission reported in the literature range from 675 - 1,689 g CO_2 per kWh (Masanet et al., 2013; Whitaker et al., 2012). However, the variation in the reported range is a direct consequence of several parameters that affect the life cycle of coal power generation. The most influential parameters found on the literature reviewed seem to be related to the combustion properties of coal; combustion technology used; mining emissions and transportation and storage methods. Other life cycle stages such as the construction of the power plant or the infrastructure for mining appear to make a low contribution to the total life cycle GHG emissions.

One of the most influential combustion properties of coal that affects life cycle GHG emission is the heating value. The International Energy Agency (2002) in their compilation of LCA studies of energy systems identified that countries burning hard coal (anthracite, bituminous and some sub-bituminous coal) had GHG emission lower than countries using brown coal (lignite) (IEA, 2002). Usually countries using hard coal with heating values higher than 23.8 MJ per kg reported GHG emission of 1,070 g CO_2-eq per kWh. In contrast, countries using brown coal with heating values smaller than 23.8 MJ per kg reported GHG emissions of 1,340 g CO_2-eq per kWh. The sulphur content of coal has also been identified as influential specially for air acidification (Gagnon, Belanger, & Uchiyama, 2002).

Combustion technology has also been identified as an important parameter influencing GHG emissions. Gagnon and colleagues (2002) suggested that nitrogen oxide emissions depend on the burning technology used because oxygen from the atmosphere contains 79 % of nitrogen. Recent evidence suggests that supercritical pulverized coal combustion has lower life cycle GHG emissions in comparison with fluidized bed combustion, subcritical pulverized coal combustion (Sub-PCC) and integrated gasification combined cycle (IGCC) (Whitaker et al., 2012). In this regard, thermal efficiency directly affects the amount of GHG emissions from coal fired power plants, because it regulates the amount of coal needed to produce 1 kWh of electricity. The authors argue that there is a rough inverse proportional relationship between the thermal efficiency and life cycle GHG because 99 % of GHG emissions are expected from combustion (Whitaker et al., 2012).

Methane emissions from coal mining and during transportation also play a significant role in life cycle emissions (Whitaker et al., 2012). According to Whitaker and colleagues (2012), methane emissions derived from coal mining could contribute 6 % of total GHG emissions while transportation of coal over long distances could add an additional 8 % of total GHG emissions (Whitaker et al., 2012). Likewise, they also suggested that mining methods also affects the total GHG estimates because underground mining has more methane emissions than surface mining methods (Whitaker et al., 2012).

For natural gas, the life cycle GHG emission ranges are lower than those for coal power. Published values range from 245 – 988 g CO_2-eq per kWh (Masanet et al., 2013; O'Donoughue et al., 2014). O'Donoughue and colleagues (2014) identified methane fugitive emissions and thermal efficiency as the most influential parameters in the natural gas life cycle. Although there is high variability in reported methane fugitive emissions, O'Donoughue et al. (2014) considered liquids unloading as a significant source of methane. Liquids unloading and pneumatic controllers are a confirmed source of methane emissions (David T. Allen et al., 2015; D. T. Allen et al., 2015). This activity is a distinguishing feature of conventional natural gas extraction techniques. Liquids and other debris which accumulate in wells need to be removed on a regular basis, sometimes using plunger lifts or by venting gas into the atmosphere. O'Donoughue and colleagues (2014) suggested that liquids unloading could add 6.6 g of CO_2-eq per kWh to life cycle GHG emissions.

Thermal combustion efficiency in open cycle gas turbines (OCGT) reaches anywhere from 15 – 40 % while combined cycle gas turbines (CCGT) can achieve efficiencies of 55 % (Boyle, Everett, & Ramage, 2003). Harmonization of natural gas LCA studies report median values of GHG emission of 670 g CO_2-eq per kWh for OCGT. Conversely, CCGT technologies have much lower emission, 450 g CO_2-eq per kWh (O'Donoughue et al., 2014). There is also some indication that upstream activities like well explorations and its infrastructure could contribute an additional 6.25 g of CO_2-eq per kWh to the total life cycle emissions (O'Donoughue et al., 2014).

4.3 Life Cycle Assessments of Hydropower Generation

From a life-cycle perspective hydropower generation is considered as one of the better performing electricity generation technologies and is second to wind power (Asdrubali, Baldinelli, D'Alessandro, & Scrucca, 2015; Kumar et al., 2011; Turconi, Boldrin, & Astrup, 2013). Harmonization from GHG studies show that most calculated hydropower GHG emissions cluster from 4 -14 g CO_2-eq per kWh. Maximum reported values are 150 g CO_2-eq per kWh for reservoir-dams (Kumar et al., 2011). Asdrubali and colleagues (2015) reduce the range to 2 – 74.8 g CO_2 eq per kWh. In contrast, fossil-fuelled technologies have GHG emissions above 1,000 g

CO_2-eq per kWh. Importantly, LCA is a developing methodology and is limited in its ability to measure other social and environmental impacts from hydropower. Habitat change, biodiversity loss and social impacts are difficult to assess using LCA methods (Ribeiro & da Silva, 2010). Therefore it has been suggested to avoid generalisations based on LCA results because hydropower development has many site-specific environmental impacts.

Plant construction is the most influential life cycle stage. More than 95% of emissions reported for hydropower are attributed to the construction phase (Dones et al., 2007; Turconi et al., 2013). Using data from Swedish, Norwegian and Japanese hydropower plants, the International Energy Agency (IEA, 2002) described a high degree of consumption of non-renewable resources, especially for cement or concrete gravity dams. Reservoir construction needs site preparation and reservoir development, earth moving, rock quarrying, drilling and blasting, concrete manufacturing, material transport and installation. Ribeiro and da Silva (2010) reported that construction of the dam was the processes with most of life cycle environmental impacts. Rock and earth-filled dams use fewer resources than concrete or cement gravity dams, therefore having lower emissions. Equally run-of-river plants use less material and resources than reservoir dams and thus perform environmentally much better (Denholm & Kulcinski, 2004; Gagnon, Bélanger, & Uchiyama, 2002; IEA, 2002). Others even consider that run-of-river power plants are better environmental performers than wind power plants (Gagnon, Bélanger, et al., 2002; Raadal, Gagnon, Modahl, & Hanssen, 2011)

A significant issue in LCA of reservoir-dam hydropower plants is the inclusion of reservoir biogenic emissions. For example, the Environmental Product Declaration (EPD) for Vatenfall AB hydroelectricity in Nordic countries reported that CO_2-eq emissions from inundated land contributed 72 % of the total life cycle emissions of greenhouse gases (Vatenfall AB, 2011). The inclusion of these emissions in some studies has led to the wide variations of reported GHG emission values (Raadal et al., 2011). As mentioned before these range up to 150 g CO_2-eq per kWh. These emissions are influenced by the geographic location, altitude, vegetation cover and decomposition processes (Denholm & Kulcinski, 2004). In boreal regions some studies report almost equal amounts of carbon emissions as natural lakes (Aberg, Bergstrom, Algesten, Soderback, & Jansson, 2004; Bergström, Algesten, Sobek, Tranvik, & Jansson, 2004). Other authors argue that during the first years after flooding methane emissions are higher and gradually decay (Ometto et al., 2013). Evaluating the literature on emissions from tropical hydropower reservoirs Demarty and Bastien (2011) came to the conclusion that there was not enough scientific evidence to prove the significant contribution of methane and CO_2 from hydropower reservoirs on a global scale. These arguments led to the suggestion made by the IPCC report that GHG emissions from land use changes caused by reservoir flooding are hard to typify and are reported to have a high degree of uncertainty (Kumar et al., 2011).

A general consensus has been reached to use a time horizon of 100 years for the operation phase (Ribeiro & da Silva, 2010). Refurbishment and replacement of electromechanical equipment as well as chemical substances used for maintenance are sources of environmental emissions (Ribeiro & da Silva, 2010). Because many hydropower plants are refurbished by their end of life, the plant decommissioning phase has in many studies been neglected. Pacca (2007) argued that there was enough carbon mineralized in the sediments of reservoirs for this phase to be neglected. He suggested that accumulated sediments are a significant source of methane and carbon dioxide once the reservoir is drained (Pacca, 2007). Kumar et al. (2011) noted that care should be taken in generalising these estimates because these may not be representative of other cases.

Overall complete hydropower LCA studies are limited and the most abundant literature is biased towards measuring GHG emissions and energy payback ratios.

4.4 Life Cycle Assessment of Geothermal Energy Production

Bayer and colleagues (2013) undertook a comprehensive review of LCA studies on geothermal power. Their study managed to build a state-of-the-art inventory dataset of the energy, materials and life cycle emissions of geothermal power generation systems. They also described associated impacts of land use, geological hazards, waste heat, water consumption, solid waste, effects on biodiversity and social impacts (Bayer, Rybach, Blum, & Brauchler, 2013). Even though they emphasized the site-specific characteristics of geothermal emissions and the challenges of assessing a generalized geothermal power plant, they presented average values for land, water and energy use, materials and resource consumption and greenhouse gas emissions (Bayer et al., 2013).

Bayer and colleagues (2013) noted that life cycle environmental impacts from geothermal power plants are associated with emissions at the site during the construction and operation phase rather than “hidden” in the production process of the plant components (Bayer et al., 2013). They agreed with other studies of flash geothermal plants (Sullivan et al., 2010; Sullivan, Clark, Han, & Wang, 2011), that emissions from diesel combustion during the construction phases are relative small (6.8 %) in comparison to emissions coming from permanent steam release during the operation phase. Since natural CO_2 emissions in geothermal steam have been under debate (Ármannsson, Fridriksson, & Kristjánsson, 2005; Bertani & Thain, 2002; Rule et al., 2009), Bayer and colleagues (2013) suggested quantifying them before and after geothermal power development.

Besides CO_2, non-condensable gases from geothermal steam contain hydrogen sulphide (H_2S), sulphur dioxide (SO_2), methane (CH_4) and ammonia (NH_3) (Bayer et al., 2013). Abatement technologies also produce secondary emissions like nitrogen oxides (NO_x) which have also been neglected in the past (Bayer et al., 2013). Other substances like mercury (Hg), arsenic (As) and boron (B) have been reported to be discharged but have not been quantified (Bayer et al., 2013).

Following this line of reasoning Bravi and Basosi (2014) focused their LCA on the airborne emissions of four geothermal flash plants in Italy. For their work they used the air emission inventories measured by the Tuscany Regional Agency for Environmental Protection period of 2002-2009 (Bravi & Basosi, 2014). They found that the main contributions to global warming, acidification and human ecotoxicity potential impacts were from the NH_3, H_2S, CH_4 and CO_2 gases (Bravi & Basosi, 2014). Even though human toxicity potentials were lower than fossil-fuel power plants, their results show that in some cases potential acidification could range from two to four times higher than coal plants, and up to 28 times higher than natural gas plants (Bravi & Basosi, 2014).

Bravi and Basosi (2014) disagreed with the argument that CO_2 emissions in geothermal power plants are natural and criticised current European greenhouse gas accounting protocols that neglected them. They argued that emissions of CO_2 could be of the same order of magnitude as those from fossil-fuelled power plants (Bravi & Basosi, 2014). These authors believe that fractures from geothermal wells increase hydrothermal fluids and CO_2 emissions in "a completely unnatural mode" (Bravi & Basosi, 2014).

Since publication of the Bayer et al. (2013) review, more work has been published by the Argonne National Laboratory (Sullivan, Clark, Han, Harto, & Wang, 2013; Sullivan, Frank, Han, Elgowainy, & Wang, 2012; Sullivan & Wang, 2013a, 2013b); Karsldottir and colleagues (Karlsdóttir, Pálsson, Pálsson, & Maya-Drysdale, 2015), and Martin-Gamboa and colleagues (Martín-Gamboa, Iribarren, & Dufour, 2015). The main findings of these studies are described in the following paragraphs.

In the third report of the Argonne National Laboratory, Sullivan et al. (2012) explored how the life-cycle performance of geothermal power is affected by GHG emissions during the exploration of geothermal power development. They expanded their analysis to include the use of super critical carbon dioxide as a substitute for brine in EGS systems and developed a set of metrics to determine the life cycle pollutant emissions rates in g per kWh from geothermal and other power plants (Sullivan et al., 2012). Their findings suggested that depending on well depth and plant capacity, exploration drilling could account between 27 % of cement and steel resources for a 20 MW EGS plant and 50 % for a 10 MW Binary plant (Sullivan & Wang, 2013a). For a 50 MW Flash plant, the authors found that exploration drilling could account only for 15% of the total cement, steel and diesel use. With these results the authors reinforced the idea that larger geothermal plants have lower impacts over the exploration phase.

In addition to their LCA study, they produced a greenhouse gas emission profile for geothermal Flash plants in California, with emphasis on the operation phase (Sullivan & Wang, 2013b). They reported a range of 0 to 400 g per kWh of GHG emissions from Flash plants. They estimated that 85% of California plants emit 165 g per kWh or less. Finally, using a cumulative distribution function they estimated a weighted average of 117 g per kWh of GHG emissions for California Flash plants (Sullivan & Wang, 2013b). However they also noted that these estimates do not take into consideration the ambient levels of naturally occurring greenhouse gases from geothermal sites (Sullivan & Wang, 2013b).

Recently, Karlsdóttir et al. (2015), built a comprehensive life cycle inventory dataset for single flash (1-Flash) and double (2-Flash) geothermal power plants. This was based on the 303 MW Hellisheidi Combined Heat and Power geothermal plant in Iceland. In their inventory they have scaled the data for site-specific parameters and provided enough information to improve inventory datasets for geothermal LCA studies.

Finally, the study by Martin-Gamboa and colleagues (2015) assessed the environmental performance of two geothermal technologies. A hypothetical Binary cycle power plant using high enthalpy resources for CHP production and a heat pump system used for heat generation using low enthalpy resources (Martín-Gamboa et al., 2015). The Binary plant was assumed to use hydrochlorofluorocarbon (HCFC-124) as organic working fluid. They reported values for Abiotic Depletion Potential (ADP), Global Warming Potential (GWP), Ozone Layer Depletion Potential (ODP), Photochemical Oxidant Formation Potential (POFP), Acidification Potential (AP), Eutrophication Potential (EP) and Cumulative Energy Demand (CED) (Martín-Gamboa et al., 2015). In summary, for the Binary plant, they found that including working fluid losses during the operation phase contributed 73% of ozone depletion and 28% of global warming impacts. Furthermore, they also argued that Binary plants performed worse than fossil-fuelled power plants, for eutrophication and ozone depletion impact categories due to sludge management during drilling operations.

Chapter 5 Life Cycle Assessment of New Zealand Electricity: Goal and Scope Definition and Inventory Analysis

5.1 Goal and Scope Definition

The intended application of this study was to assess the environmental performance of the New Zealand electricity grid. A limited number of publicly available studies exist on carbon footprint and fuel emission factors for New Zealand activities (Alcorn, 2003; Barber, 2011; Coelho, 2011). However, these studies use limited site-specific New Zealand data and are out-of-date. Therefore the reason to undertake this study was to create an up-to-date dataset using as much New Zealand specific data as possible. One of the interested parties for this research was the Building Research Association of New Zealand (BRANZ). BRANZ has developed a "whole-building whole-of-life" assessment framework that provides a level playing field for environmental performance assessment across different industry sectors (Dowdell, 2014), and impacts associated with electricity use are highly relevant throughout the life-time of a building. Therefore one of the target audiences for this study was LCA practitioners within BRANZ. Other parties that will benefit from this study are members of the New Zealand LCA research and practitioner community, and government institutions and companies within the electricity industry.

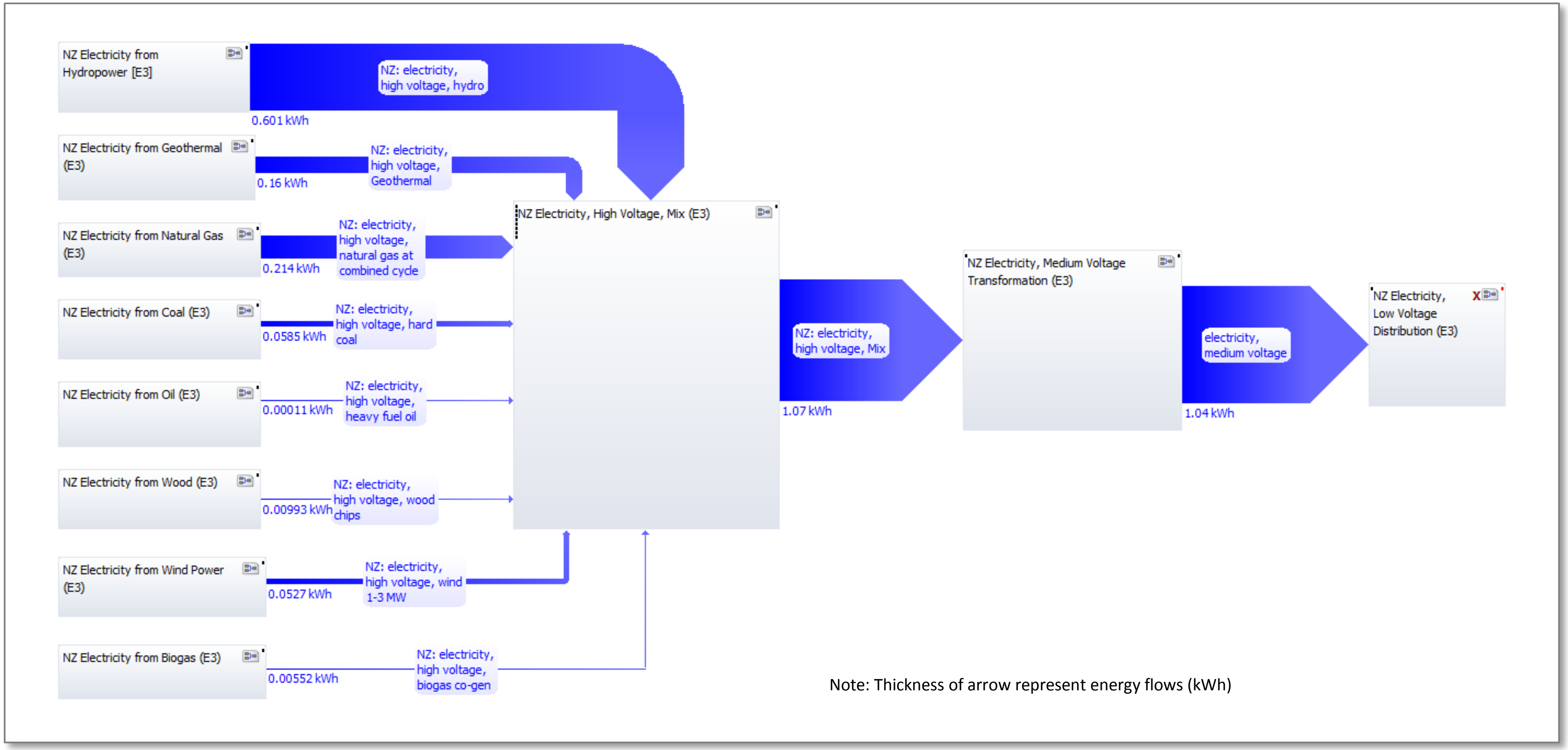
The goal of this study was to assess the life-cycle environmental impacts of generating and using New Zealand electricity. This study used an attributional LCA approach to model the power generation mix for the year 2013 (see Chapter 3, Figure 1).

5.1.1 Functional Unit

The functional unit was defined as "1 kWh of low-voltage electricity delivered to the final consumer at the electrical outlet of an average household". In addition the environmental impacts associated with delivering 1 kWh medium and high-voltage electricity were assessed.

5.1.2 System Boundaries

A cradle-to-grave approach was used in this study. The foreground system included manufacture and construction of the power plants used for electricity generation, the full supply chain of the fuels, infrastructure of the transmission and distribution network, operation of power plants, decommissioning and waste disposal. A system model for the whole grid was built using GaBi® software (Figure 6). This included the transmission and distribution network for high, medium and low-voltage electricity. Independent models were adapted from European datasets, for each energy system contributing electricity into the national grid.



Note: Thickness of arrow represent energy flows (kWh)

Figure 6 New Zealand Electricity Model using GaBi® LCA Software. Note: Solar was excluded from the current analysis as it contributes only 0.04% of the total mix.

5.2 Inventory Analysis

The full supply chain of the generation system was included, i. e. upstream and downstream activities. Except for geothermal power, the life cycle inventories from the ecoinvent 3.1 database were used as generic base models to develop New Zealand electricity generation systems. The geothermal system model was developed using the recently published life cycle inventory from the Hellisheidi geothermal power plant located in Iceland (Karlsdóttir et al., 2015). Throughout the literature reviewed, the most significant life cycle phases of electricity generation systems were identified. These phases were targeted in the generic system models and adapted to New Zealand specific emission values. New Zealand specific emission values were estimated using the references listed in Table 6. The outputs of these systems were scaled accordingly to the contribution of each technology to the generation of 1 kWh high-voltage of the electricity grid mix (see Chapter 3, Figure 1). Transmission and distribution at three different stages was also modelled independently to understand the effect of electricity transformation. The small quantities of electricity used during the fuel production and power plant construction, maintenance and decommissioning were modelled using the existing "NZ: Electricity Grid Mix 1kV-60kV" dataset from thinkstep®.

Table 6 Sources of Information Used to Adapt New Zealand Specific Emissions Values

Information	Source
GHG emissions	New Zealand Greenhouse Gas Inventory 1990-2013 (MFE, 2015) Energy Greenhouse Gas Emission Report (MBIE, 2014a) Energy Sector Greenhouse Gas Emissions Web Tables (MBIE, 2015b)
Fuel Production Volumes	Energy in New Zealand #14 Report (MBIE, 2014b) Gas Data Tables (Appendix 1) Coal Data Tables (Appendix 1)
Power Plant Operation Parameters	New Zealand Generation Data Update (Parsons Brinckerhoff, 2012b)
Geothermal emissions (H_2S, As, Hg)	Waikato Regional Council Consent Monitoring Reports (Appendix 2)

Note: The Ministry of Business, Innovation and Employment (MBIE) is the governmental agency that reports and produces energy related statistics. The New Zealand Greenhouse Gas Inventory 1990-2013 uses the MBIE Energy Sector Annual Greenhouse Gas Emission Reports. Therefore the "MBIE Energy Sector Greenhouse gas emission" web tables and "Energy in New Zealand #14" web tables which are available online were used as a primary source of data to estimate GHG emissions. These sources and their online links are attached in Appendix 1-4.

5.2.1 Natural Gas Electricity LCI Model

There are four life cycle stages in electricity generation from natural gas: 1) exploration, extraction and production of natural gas, 2) transmission and distribution of processed natural gas, 3) construction and decommissioning of the power plant, and 4) operation and maintenance of the power plant.

Exploration, extraction and production of natural gas

Data were required on the infrastructure and associated emissions from construction of extraction wells, processing plants and pipelines to transport natural gas from wells to processing plants. Data were used from the Norwegian and Netherlands ecoinvent datasets to represent offshore and onshore production respectively. To adapt these data for the New Zealand situation the production volumes of New Zealand natural gas at onshore and offshore wells were used to create a mix of 1 m^3 natural gas supplied to a power plant. More than 70% of natural gas is produced from offshore platforms, mainly from Pohokura, Maui and Kupe (Appendix 1); for offshore production, a dehydration process was included because offshore natural gas extracted is dehydrated to remove longer chain hydrocarbons known as condensates (Eng et al., 2008). Figure 7 shows the New Zealand natural gas life cycle model with the mix of onshore and offshore production.

Infrastructure data was scaled according to 1 m^3 of natural gas extracted, processed and distributed. The default European emission values associated with the construction of wells and processing facilities were used as these do not play a significant role in total life cycle impacts. Emissions from gas flaring and venting on the other hand, had previously been determined to contribute 6.6 g of CO_2-eq per kWh to total life cycle impacts on harmonized LCA studies (O'Donoughue et al. 2014). Therefore, emissions from the operation of natural gas wells and processing facilities were estimated using New Zealand data. New Zealand annual GHG emission data were available for "gas extraction and processing" as well as for "processing and flaring" (Appendix 2, Table 29 - Table 35). These are emissions reported for total production volumes of natural gas. Both categories were added up and assigned to exploration, extraction and production (Table 7). To estimate greenhouse gas (GHG) emissions per m^3 of natural gas, the total GHG emission reported were divided by the total production volume of natural gas supplied, which in the year 2013 was reported to be 4,551 Mm^3. Therefore, as an example, the carbon dioxide emission value per m^3 natural gas used for electricity generation was:

$$\frac{877.98\ kt\ CO_2\ (total\ gas\ emissions)}{4{,}551.40\ \ Mm^3\ (natural\ gas\ produced)} = 192.9\ \frac{g\ CO_2}{m^3}$$

Table 7 Exploration, Extraction and Production Emissions Associated with the Production of Natural Gas Used for Electricity Generation in 2013. Source: MBIE, 2015; Energy Sector Annual GHG Emissions Web Tables

Exploration, Extraction and Production		**CO_2**	**CH_4**	**N_2O**	**CO**	**NOx**	**NMVOCs**
Gas Extraction and Processing	kt	350.70	0.01	5.95E-04	0.11	1.49	0.03
Processing and Flaring	kt	527.28	2.16				
Total	kt	877.98	2.16	5.95E-04	0.11	1.49	0.03
Emissions per m3 of natural gas	**g/m^3**	***192.90***	***4.75E-01***	***1.31E-04***	***2.35E-02***	***3.27E-01***	***6.53E-03***

Note: Emissions per m^3 were calculated based on 4,551.4 million m^3 of natural gas supply (Energy Sector Annual Production Volumes and Annual GHG Emissions are attached in Appendix 1, 2)

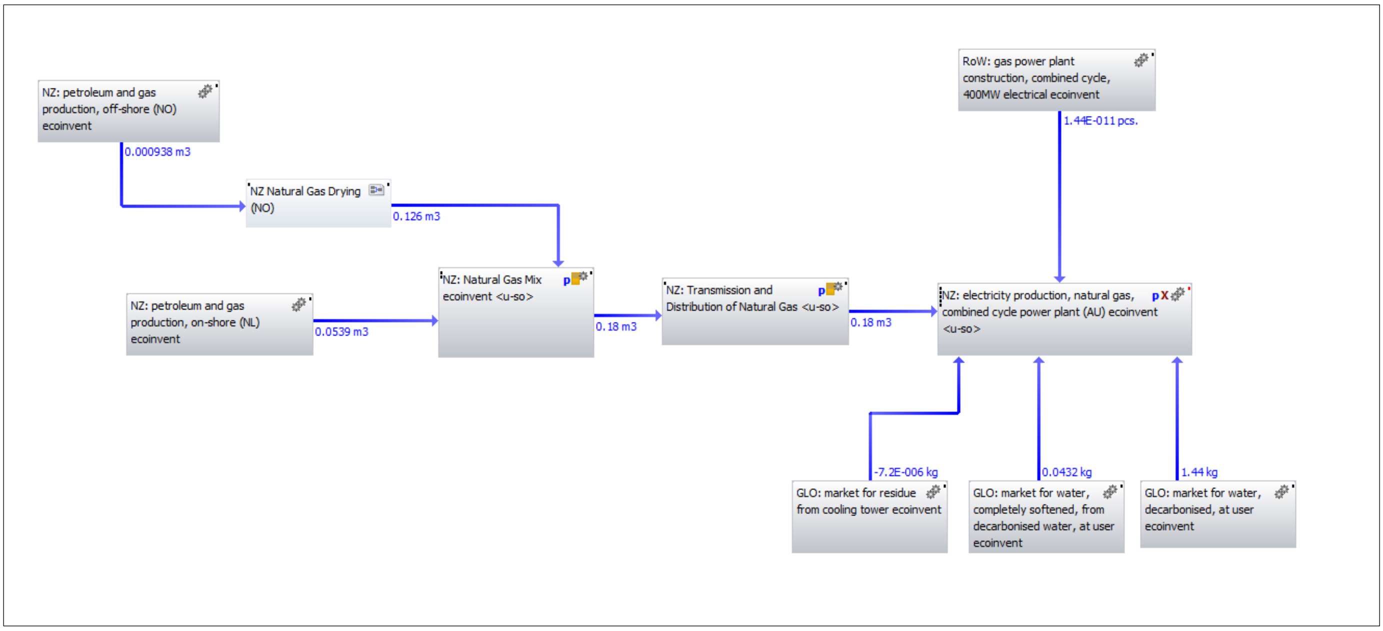


Figure 7 New Zealand Natural Gas Electricity LCI Model

Transmission and distribution of natural gas

The pipeline infrastructure for gas distribution was not included because the European datasets are not representative of New Zealand gas distribution system. The European datasets for gas distribution infrastructure are highly complex and take into account the distribution of natural gas using regional networks and imports to neighbouring countries. Because of the geographic New Zealand situation, using the European dataset could have overestimated natural gas impacts. Presumably, New Zealand's gas distribution infrastructure would have insignificant contributions to life cycle environmental impacts. However this assumption needs to be reviewed in future studies.

The Energy Sector Annual Greenhouse Gas Emissions only reports fugitive emissions of methane (CH_4) and carbon dioxide (CO_2) during "transmission and distribution" and for "other leakages". Other leakages are emissions of CH_4 at the point of consumption that escape from valves and pipe systems (MFE, 2015). Therefore, in the gas transmission and distribution stage, these two categories were added. CO_2 and CH_4 emission factors were estimated by dividing the total reported emissions by total volume of natural gas supply, which in 2013 was 4,551 Mm^3. Table 8 shows reported total emissions and estimated emission values per m^3 for transmission and distribution of natural gas considering. The calculation procedure is shown in the following equations:

$$\frac{1.098\ kt\ CO_2}{4{,}551.40\ Mm^3\ (natural\ gas\ produced)} = 0.241\ \frac{g\ CO_2}{m^3}$$

$$\frac{20.207\ kt\ CO_2}{4{,}551.40\ Mm^3\ (natural\ gas\ produced)} = 4.44\ \frac{g\ CO_2}{m^3}$$

Table 8 Natural Gas Transmission and Distribution Emissions for the year 2013. Source: MBIE, 2015

Gas distribution	**Unit**	**kt CO_2**	**kt CH_4**
Transmission and Distribution	kt	1.10	7.51
Other leakages (Point of consumption)	kt		12.69
Total		1.10	20.21
Emissions	**g/m^3**	***0.24***	***4.44***

Note: Emissions per m^3 were calculated based on 4,551.4 million m^3 of natural gas supply (MBIE Energy Sector Annual Production Volumes and GHG Emissions are attached in Appendix 1, 2). CO, N_2O, NO_x, and NMVOCs are not reported by MBIE.

Construction and decommissioning of the power plant

This was represented using a dataset for "construction and decommissioning of a power plant" from the ecoinvent region named "rest-of-the-world[3]". To use this dataset, it was necessary to calculate the fraction of natural gas plants needed to produce 1 kWh electricity. For the whole of New Zealand, 16,023 GWh was generated by natural gas plants in a year (see Table 4) and there was 2,934 MW of installed capacity; therefore 5,461,145.20 kWh was generated per MW Installed. The operational life-time of a 400 MW natural gas CCGT

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[3] Ecoinvent RoW regions are those that are currently not represented in the regional datasets. They are estimated based on the difference between global averages minus the smaller regions available for a given activity.

was assumed to be 40 years. Therefore over its lifetime this CCGT generated 8.74 E^{10} kWh per plant as noted below:

$$16{,}023\ GWh\ x\ \frac{1{,}000\ MWh}{1\ GWh}\ x\ \frac{1{,}000\ kWh}{1\ MWh} = 16{,}023{,}000{,}000 = 1.6023E^{10}\ kWh$$

$$\frac{1.6023E^{10} kWh\ annual}{2{,}934\ MW\ installed}\ x\ 400\ MW\ plant\ x\ 40\ Years = 8.74\ E^{10}\ total\ kWh\ per\ plant\ installed$$

With the total amount of electricity generated by a natural gas plant over its life-time, it is possible to estimate the amount of natural gas plants needed per kWh of electricity:

$$\frac{1\ Natural\ Gas\ Plant}{8.74E^{10} kWh} = 1.14\ E^{-11}\ plants\ per\ kWh\ produced$$

Operation and maintenance of the power plant: Based on the reviewed information on natural gas power plant installed and operating capacity (Table 4, Section 3.6) it was determined that 57% of annual electricity is generated using CCCT technology. Table 9 shows natural gas power plant technology used to produce electricity during 2013. Huntly fossil fuel power station was designed with four 250 MW Rankine Cycle boilers but two units were recently decommissioned. These boilers can burn a combination of gas and coal. In addition, a 403 MW combined cycle gas turbine (CCGT) was commissioned in 2007[4]. Accordingly, the dataset for a 400 MW CCGT operating in Australia was selected to be representative of Huntly power plant. The operation of a CCGT plant included waste treatment of abatement technologies, water consumption and emissions from natural gas combustion. Because upstream infrastructure data and GHG emission are scaled to 1 m^3 of natural gas before reaching the power plant, and GHG combustion emission are scaled to 1 kWh of electricity produced; the volume of natural gas used to produce 1 kWh of electricity needs to be estimated.

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[4] Genesis Energy Web Site: https://www.genesisenergy.co.nz/huntly-power-station-plant-description

Table 9 Natural Gas Power Plant Turbine Technology Used for Electricity Generation in New Zealand, During 2013. Based on Table 4, Section 3.6

Gas Technology	Annual Generation GWh	%
OCGT	1,174	7%
CCGT	9,154	57%

OCGT = Open Cycle Gas Turbine

CCGT = Combined Cycle Gas Turbine

The volume of natural gas needed to produce 1 kWh at the power plant was estimated using the energy content of the fuel. Natural gas produced in New Zealand has an average gross calorific value of 40.09 MJ per m^3 (Appendix 3, Table 36). The efficiency reported from New Zealand combined cycle natural gas power plants is 55% (MBIE, 2014b) and the efficiency embedded in the dataset of the 400 MW CCGT power plant is 50%. Also, the literature reports efficiencies of natural gas power plants above 50 % (Kehlhofer, Hanneman, Strirnimann, & Rukes, 2009). Hence, it was determined that the efficiency of the Australian dataset was approximately representative of New Zealand CCGT power plants. To produce 1 kWh or 3.6 MJ of electricity using 50 % combustion efficiency requires 7.2 MJ of energy input. Since each m^3 of natural gas has energy content of 40.09 MJ; 0.18 m^3 are needed to produce 7.2 MJ of energy or 1 kWh of electricity with a 50 % efficiency. The calculation procedure is shown in the following equations:

$$1\ kWh = 3.6\ MJ$$

$$Efficiency\ = \frac{Energy\ Output}{Energy\ Input}$$

$$\frac{Energy\ Output\ (3.6\ MJ)}{50\%\ Efficiency} = Energy\ Input\ (7.2\ MJ)$$

$$7.2\ MJ\ x \frac{1\ m^3\ Natural\ Gas}{40.09\ MJ} = 0.18\ m^3\ of\ Natural\ Gas$$

Combustion emission factors were estimated by dividing total GHG emission reported in 2013 from natural gas used for electricity generation by the annual electricity generated from natural gas (Appendix 2), which in 2013 was 8,133.8 GWh (MBIE, 2014b). For example, the New Zealand emissions were 3,409 kt CO_2 in 2013, which produces an emission factor of 419 g CO_2 /kWh electricity generation from natural gas. Table 10 presents the combustion emission factors for natural gas power calculated in this way.

Table 10 Natural Gas Combustion Emission Factors per kWh for the year 2013. Source: MBIE, 2015a, 2015b

Combustion emissions	**Unit**	**CO_2**	**CH_4**	**N_2O**	**CO**	**NOx**	**NMVOCs**
Total annual emissions	**kt**	3,409.03	0.18	0.005832	1.8663447	12.83112	0.29161636
Emissions per kWh	**g/kWh**	***419***	***0.022***	***0.001***	***0.229***	***1.577***	***0.036***

Note: Combustion emissions were estimated based on 8,133.8 GWh of electricity generated with natural gas. (MBIE Energy Sector Annual GHG Emissions and Annual Electricity Generation are attached in Appendix 2 and 4)

Table 11 lists a summary of GHG emissions and parameters used for the natural gas LCI model.

Table 11 GHG Emissions and Parameters Used for the New Zealand Natural Gas Electricity Generation Model in 2013.

Emissions	**Exploration, extraction and production of natural gas**	**Transmission and distribution**	**Construction and decomissioning of the power plant**	**Operation and maintenance of the power plant**
CO_2	190 g/m^3	0.241 g/m^3	-	419 g/kWh
CH_4	0.475 g/m^3	4.44 g/m^3	-	0.0219 g/kWh
N_2O	1.31 E-3 g/m^3		-	7.17E-3 g/kWh
CO	2.35 E-1 g/m^3		-	2.29E-1 g/kWh
NOx	0.327 g/m^3		-	158 g/kWh
NMVOCs	6.53 E-2 g/m^3		-	3.59E-1 g/kWh
Parameters	Offshore production 70% Onshore production 30%	Pipeline infrastructure not included	Rated Output 400 MW Life Time 40 years	Capacity Factor 55% Thermal efficiency 50% Energy content of gas 40.09 MJ/m^3

5.2.2 Coal Electricity LCI Model

There are five stages in electricity generation from coal: 1) coal mining, 2) coal storage and transportation, 3) coal import, 4) power plant construction and decommissioning, and 5) operation and maintenance of a coal power plant. The coal electricity LCI model is shown on Figure 8.

Coal mining

Data were required on the infrastructure and associated emissions for mining operations. In New Zealand only sub-bituminous coal is used for electricity generation (MBIE, 2014b). Therefore, the Australian "hard coal mine operation" dataset were used to model New Zealand's sub-bituminous coal mining. Sub-bituminous coal is mined either by open cast mines or underground mining methods. Hence, to adapt the Australian dataset to the New Zealand situation the infrastructure associated with local mining methods needed to be estimated. Based on New Zealand annual production volumes of coal (Appendix 1, Table 28), it was determined that 91%[5] of sub-bituminous coal is extracted from open cast mines and 9% is extracted from underground mines.

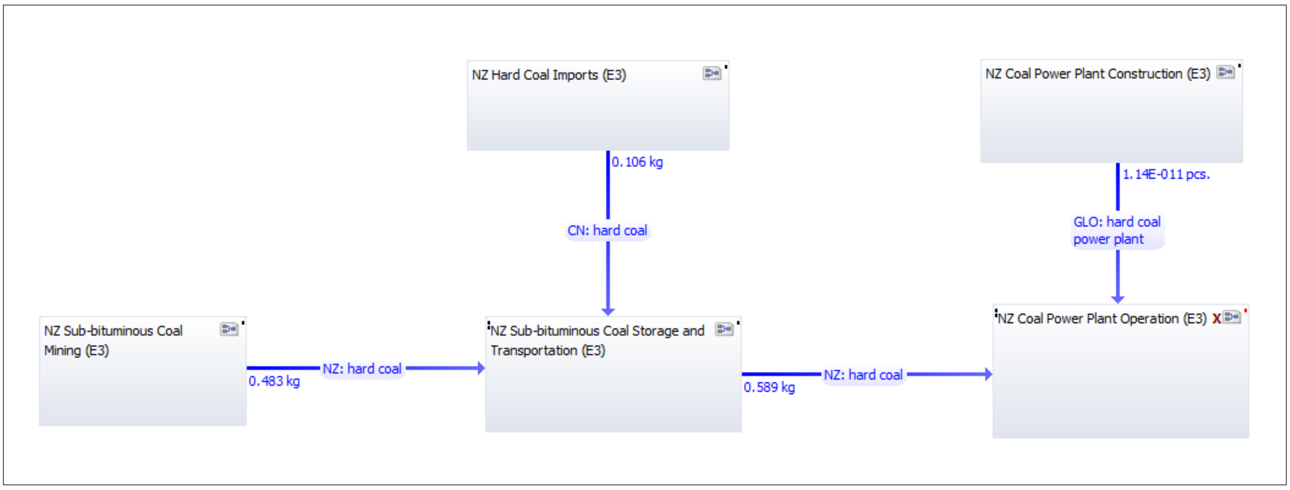

Figure 8 New Zealand Coal Electricity LCI Model

Methane emissions from mining operation have previously found to play a significant role on total life cycle impacts. These could contribute up to 6% to total GHG emissions associated with electricity generation from coal (Whitaker et al., 2012). Therefore fugitive CH_4 emissions from mining operations were estimated. Fugitive CH_4 emissions are reported annually for mining operations at 12.45 kt (Appendix 2, Table 30). According to the Energy in New Zealand #14 Annual Report 40% of native sub-bituminous coal produced in the country is used for electricity generation and co-generation (MBIE, 2014b; Figure C.5, page 20). Consequently, methane emissions in the model were estimated by dividing total CH_4 emissions by annual coal production volumes.

$$\frac{12.45\ kt\ CH_4}{2{,}055{,}801\ t\ Sub\ bituminous\ coal}\ x\ \frac{1000\ t}{1k} = 6.1\ \frac{g\ CH_4}{g\ Sub\ bituminous\ coal\ mined}$$

Because the Energy Sector Greenhouse Gas Emission Report (Appendix 2) does not distinguish between the different mining activities (post-mining operations, transportation and storage) the assumption was made that 70% of these emissions derived exclusively from mining. The other 30% were allocated to the

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[5] This proportion was calculated based on 1,878,809 Mm^3 of Sub-bituminous coal mined from open cast mines divided by the total Sub-bituminous coal produced in 2013 which was 2,055,801 Mm^3 (Appendix 1, Table 28)

“coal storage and transportation” stage. Hence, CH_4 emissions per kg of coal mined were estimated in the following way:

$$6.1\, g \frac{CH_4}{kg\ Sub\ bituminous\ coal}\ x\ 0.70\ (\%\ mining) =\ 4.2\ \frac{g\ CH_4}{kg\ SbCoal\ mined}$$

Coal Storage and Transportation

Coal extracted from New Zealand mines is transported to Huntly power station where it is stored at storage facilities. A portion of particulate emissions, greenhouse gases and heavy metals are expected at this point. To resemble storage facilities in New Zealand, the Australian dataset “market for hard coal” was used. This dataset includes all operational emissions (particulates, GHG and heavy metals); however, only CH_4 emissions were estimated for New Zealand storage facilities, the rest use the default Australian emission values. As mentioned in the previous Section, 30 % of the annual reported emissions from coal were assumed to come from coal stored and transported:

$$6.1\, g \frac{CH_4}{kg\ Sub\ bituminous\ coal}\ \ x\ 0.30\ (\%\ storage\ \&\ transport) =\ 1.8\ \frac{g\ CH_4}{kg\ Sub\ bituminous\ coal\ transported\ \&\ stored}$$

To resemble the transportation of coal from mines to the storage facility a “transport, freight train, diesel” dataset was used from the ecoinvent database. Transport distance from local mines in the North Island to Huntly power station in Waikato was assumed to be 100 km with load capacity of 1,200 t of coal per freight train.

Because a portion of sub-bituminous coal used to produce electricity is imported from Indonesia (Parsons Brinckerhoff, 2012b), the ratio of native coal and imported coal needed to be estimated. Based on New Zealand annual production volumes (Appendix 1, Table 28) it was determined that 82% of sub-bituminous coal used for electricity is produced natively in New Zealand and 18% of sub-bituminous coal is imported[6]. These proportions were considered in the “market for hard coal” dataset.

Coal import

Coal imported from Indonesia is used to supply Huntly power station to produce electricity (Parsons Brinckerhoff, 2012a). To this end, the Chinese “hard coal mine operation” dataset were used to represent coal mining operations in Indonesia. Default Chinese emission values were used because Indonesian mining operation emissions were unknown. Ship transport distance from Indonesia to New Zealand was estimated with Google Earth to be 7,500 Km, with an average transport load of 35,000 tonnes per ship (Port of Tauranga, 2012). Freight rail travel distance from Tauranga to Huntly was estimated to be 100 km with a load of 35,000 tonnes (Port of Tauranga, 2012).

Construction and decommissioning of the power plant

Because the 400 MW Huntly power plants burns natural gas and coal, the dataset for a 500 MW “hard coal power plant construction” from the ecoinvent global region was used[7]. In order to use this dataset, the value for the number of power plants needed per kWh of electricity produced was assumed to be the same as for natural gas (i.e. 1.14 E^{-11}).

Operation and maintenance of a coal power plant

Operation and maintenance of a coal power plant used the default values of an average German hard coal power plant for the supply of light fuel oil, chlorine, decarbonised water, abatement technologies of nitrogen oxides by catalytic reduction, flue gas desulfurization and ash treatment. To represent New Zealand coal power plant operations, the volume of coal needed to produce 1 kWh of electricity was needed. The default efficiency in the dataset of 36 % was determined to be representative of New Zealand coal power plants (MBIE, 2014b; Table B.1 page 13). The net heating value of coal 20.39 MJ/kg was used to estimate the

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[6] This relationship was estimated based on the annual sub-bituminous coal produced in New Zealand, which in 2013 was 2,055,801 t. Sub-bituminous coal imported was reported to be 457,628 t. Total sub-bituminous coal supply in 2013 was 2,513,429 t. (Appendix 1, Table 28)

[7] Ecoinvent v 3.1 only provides datasets for a 100 MW and a 500 MW coal power plant.

mass of New Zealand sub-bituminous coal (Appendix 3, Table 37). Therefore the calculation procedure is shown in the following equations:

$$1\ kWh = 3.6\ MJ$$

$$Efficiency\ = \frac{Energy\ Output}{Energy\ Input}$$

$$\frac{Energy\ Output\ (3.6\ MJ)}{36\ \%\ Efficiency} = Energy\ Input\ (10\ MJ)$$

$$10\ MJ\ x \frac{1\ kg\ Sub\ bituminous\ coal}{20.39 MJ} = 0.49\ kg\ of\ Sub\ bituminous\ coal$$

Combustion emissions are known to contribute significantly to life cycle impacts. Therefore, combustion emissions specific to New Zealand were estimated. To determine sub-bituminous coal combustion emissions during operation the energy sector annual GHG emissions from coal combustion (Appendix 2, Table 29 to Table 35) were divided by the total annual electricity generation from coal which for the year 2013 was 2,238 GWh (MBIE, 2014b). For example for CO_2 the total reported emissions from electricity generation from coal were 1,615.90 tonnes:

$$\frac{1{,}615.9\ t\ CO_2}{2{,}238\ GWh} = 722 \frac{g}{kWh}$$

Table 12 Coal Combustion Emissions for the year 2013. Source: MBIE, 2014b, 2015b

	CO_2	**CH_4**	**N_2O**	**CO**	**NO_X**	**NMVOCs**	**SO_2**
kt	1,615.90	0.0117	0.0267	0.1502	6.3407	0.0834	6.8003
g/kWh	***722***	***0.005***	***0.012***	***0.067***	***2.833***	***0.037***	***3.04***

Note: combustion emissions were estimated based on the total annual electricity generated from coal which in 2013 was 2,238 GWh. (Appendix 4)

Table 13 Summary of New Zealand Specific Life Cycle Emissions for Coal Electricity in the year 2013

Emissions	Coal Mining	Coal Storage and Transportation	Coal import	Operation and maintenance of the power plant
CO_2	-		-	722 g/kWh
CH_4	4.2 g/kg coal	1.8 g/kg coal	-	0.005 g/kWh
N_2O	-	-	-	0.0119 g/kWh
CO	-		-	0.0671 g/kWh
NOx	-		-	2.83 g/kWh
NMVOCs	-		-	0.0373 g/kWh
SO_2	-		-	3.04 g/kWh
Parameters			Native production 82% Indonesian import 18%	Capacity Factor 55% Thermal efficiency 36% Energy content of coal 20.39 MJ/kg

5.2.3 Oil Electricity Model

The life cycle stages modelled for electricity generated from oil were: 1) oil exploration and extraction, 2) oil refining, 3) petroleum refinery construction, 4) oil transport 5) oil power plant construction and 6) oil power plant operation. Figure 9 shows the oil electricity LCI model. Due to the low contribution of oil electricity to New Zealand electricity mix (less than 1%), except for the oil power plant operation stage, the default ecoinvent values were used for all other life cycle stages. For oil exploration and extraction, the "rest-of-the-world" dataset was used; for petroleum refining and its associated infrastructure, a Swiss oil refinery dataset was used. Oil transport was represented with a Swiss "Market for heavy fuel oil" dataset. The power plant construction was adopted from a Regional European 500 MW oil power plant dataset. The number of power plants needed to produce 1 kWh over the entire lifetime of the power plant was estimated as being equivalent to New Zealand coal and natural gas power plants (1.14E-11).

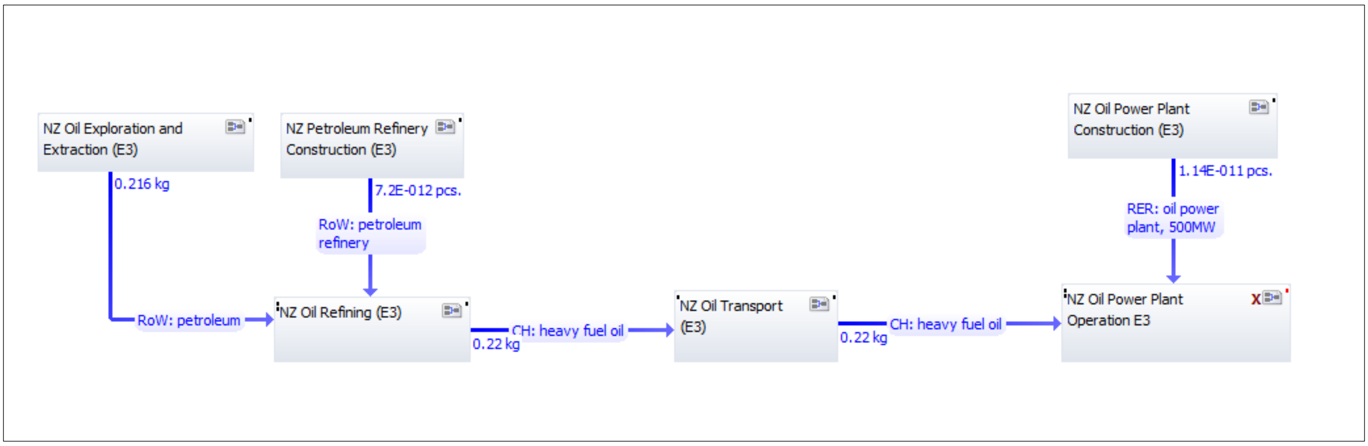

Figure 9 New Zealand Oil Electricity LCI Model

Oil power plant operation

The procedure to adapt the ecoinvent “electricity production, oil” dataset for the “rest-of-the-world” region, was similar to the one applied to coal and natural gas. First, the quantity of oil needed to produce 1 kWh needed to be estimated. The default thermal efficiency in the dataset of 40.3% was used to estimate the amount of fuel energy input per fuel energy output. Using the lower heating value of New Zealand oil (Appendix 3, Table 38) the quantity of oil needed to produce 1 kWh was determined:

$$1\ kWh = 3.6\ MJ$$

$$Efficiency\ = \frac{Energy\ Output}{Energy\ Input}$$

$$\frac{Energy\ Output\ (3.6\ MJ)}{40.3\ \%\ Efficiency} = Energy\ Input\ (8.93\ MJ)$$

$$8.93\ MJ\ x \frac{1\ kg\ oil}{40.6\ MJ} = 0.22\ kg\ of\ oil$$

To estimate New Zealand combustion emissions from oil power plants the energy sector annual GHG emissions reported (Appendix 2) were divided by the total electricity generated with fuel oil, which was 3 GWh for 2013 (MBIE, 2014b).

Table 14 Fuel Oil Combustion Emissions Factors in 2013. Source: MBIE, 2014b, 2015b.

	Units	**CO2**	**CH4**	**N2O**	**CO**	**NO x**	**NMVOCs**	**SO2**
Total emission Reported	kt	2.33	2.86E-05	1.27E-05	5.08E-04	6.99E-03	1.59E-04	3.49E-03
Combustion emissions	**g/kWh**	***776.7***	***0.010***	***0.004***	***0.169***	***2.330***	***0.053***	***1.164***

Note: Combustion emission factors were estimated based on the annual oil electricity generation in 2013 of 3 GWh (Appendix 4).

5.2.4 Geothermal LCI Electricity Model

The life cycle stages included in the model for geothermal power generation were: 1) the construction of a 2-Flash power plant, 2) operation of a geothermal 2-Flash power plant and 3) geothermal maintenance well. Figure 10 shows the geothermal electricity LCI model. A 2-Fash geothermal power plant was chosen to be representative of the New Zealand situation because geothermal generation is predominantly made with 2-Flash power, (see Table 3 in Chapter 3).

Construction of a 2-Flash power plant

Construction activities in this stage included drilling of exploration, production and reinjection wells; materials for wellhead casings, infrastructure for collection pipelines, infrastructure for the power plant building; and the machinery for electricity generation. LCI data for the construction of a 2-Flash geothermal plant were based on the inventory data calculated for the 303 MW Hellisheidi geothermal power plant (Karlsdóttir et al., 2015) To adapt these data to represent New Zealand geothermal electricity generation, materials and resources for drilling and casing were scaled to the number of wells and the depth of wells drilled for an average New Zealand geothermal power plant. Based on suggestions from the New Zealand Geothermal Association one well in a geothermal power plant produces an output of 4 MW (B. White, personal communication, June 16th 2015). Hence, an average New Zealand geothermal plant of 80 MW (Table 2, Chapter 3) would need 20 wells. Although the NZGA web sites reports higher well depth values, based on the suggestions by White (personal communication, June 16th 2015) the average well depth of a geothermal reservoir was assumed to be 1,000 m. Thus, total metres drilled per power plant were 20,000 m. Materials and resources for the power plant building and machinery were scaled to the rated output of 80 MW. Materials and resources for the pipeline infrastructure were scaled to an average pipe length of 3,000 m. This rounded value was obtained by measurements using Google Earth Pro's measuring tool on several New Zealand geothermal fields (Table 2 Chapter 3). Looking at the infrastructure of all the geothermal plants with Google Earth Pro, also led to the assumption that each geothermal field probably needs about 10 pipelines per plant; this makes a total of 30,000 m of pipelines for an average NZ geothermal power plant. Recycling of the power plant buildings, infrastructure and machinery at end-of-life were excluded from the model.

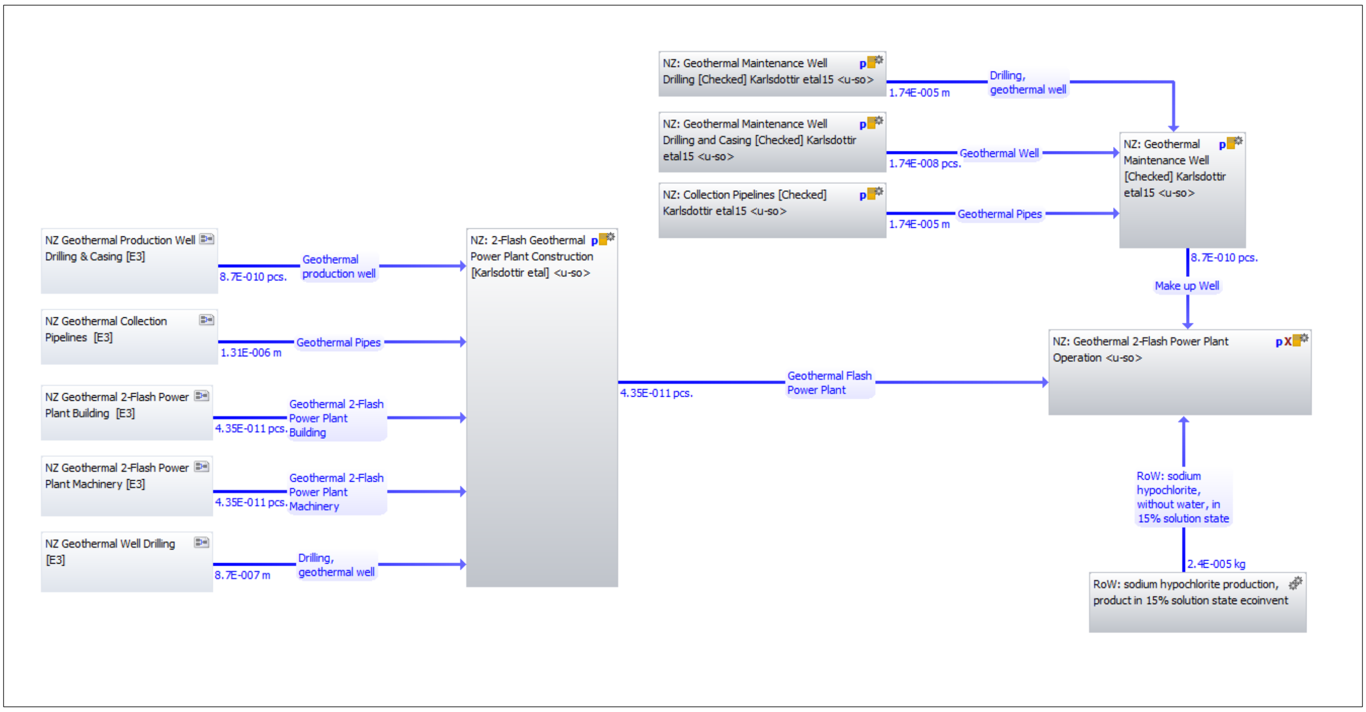

Figure 10 New Zealand Geothermal LCI Model

To use the power plant construction dataset it was necessary to estimate how many geothermal power plants are needed to produce 1 kWh of electricity. The power plant parameters for an average New Zealand power plant (Table 2 Chapter 3) were used as shown in the following equations:

$$Annual\ Generation = 80\ MW\ x\ 82\ \%\ C.F.x\ 8760\ h\ x\ 1000\frac{kW}{MW} = 574{,}656{,}000\ kWh$$

Where C.F = Capacity factor

$$Life\ Time\ Generation = 574{,}656{,}000\ kWh\ x\ 40\ years = 2.30\ E^{10}\ kWh$$

$$\#\ of\ power\ plants\ needed\ per\ kWh = \frac{1\ Geothermal\ Power\ Plant}{2.30\ E^{10} kWh} = 4.35E^{-11}\frac{plants}{kWh}$$

Operation of 2-Flash geothermal power plant

In the operation stage, electricity is produced by flashing geothermal brines into steam turbines. Emissions are expected from a portion of the geothermal brine flashed into the atmosphere. These are known as non-condensable gases and contain CO_2, CH_4, traces of metals (arsenic, cadmium, chromium, copper, lead, manganese, niquel, selenium and vanadium), ammonia (NH_3), carbon monoxide (CO), NO_x, sulphur dioxide (SO_2) and hydrogen sulphide (H_2S).

To estimate CO_2 and CH_4 emission factors, the energy sector annual greenhouse gas emissions (Appendix 2) were divided by the total annual generation from geothermal power which in 2013 was 6,053 GWh (Appendix 4). Table 15 shows the New Zealand CO_2 and CH_4 emission factors, estimated with this method.

Table 15 CO_2 and CH_4 Emission Factors for Electricity Produced From Geothermal Power in the Year 2013. Source: MBIE, 2014b, 2015b

	Unit	CO2	CH4
Fugitive emissions	kt	597	6
Emission Factor	g/kWh	***98.7***	***1***

Note: estimated based on 6,053 GWh produced in the year 2013 (Appendix 4)

Traces of metals, NH_3 and CO atmospheric emission values were calculated based on a study by Bravi and Basosi (2014) on four geothermal fields in Italy using data compiled by the Tuscany environmental agency (Bravi & Basosi, 2014). Since geothermal emissions are site specific, using average values from Italy could over estimate emissions. Therefore only the minimum values were selected as it was assumed that these could represent the minimum expected from any geothermal field in the world. These values are presented in Table 16.

Table 16 Minimum and Maximum Values of Atmospheric Emissions of Four Geothermal Fields in Italy. Source: Bravi and Basosi, 2014

Geothermal Emissions	Units	Italy (Bravi and Basosi 2014)	
		Min	Max
Air emissions			
Ammonia	g/kWh	8.59E-02	2.89E+01
Arsenic	g/kWh	5.73E-07	8.48E-05
Cadmium	g/kWh	1.59E-10	1.08E-07
Carbon monoxide	g/kWh	6.85E-03	8.25E-02
Chromium	g/kWh	9.73E-09	1.20E-05
Copper (+II)	g/kWh	1.52E-08	7.73E-07
Lead	g/kWh	1.95E-09	5.15E-07
Manganese (+II)	g/kWh	1.96E-08	5.21E-07
Nickel (+II)	g/kWh	2.16E-08	4.95E-06
Selenium	g/kWh	3.53E-08	8.59E-05
Vanadium	g/kWh	3.51E-09	5.15E-07

Emissions factors for mercury (Hg) and hydrogen sulphide (H_2S) were obtained from the Waikato Regional Council consent monitoring reports for six geothermal fields (Contact Energy, 2014a, 2014b; Contact Energy/GNS Science, 2014a, 2014b; Mighty River Power, 2014; Mighty River Power, 2014a, 2014b). In these reports, emissions values for Hg and H_2S are reported in kg/hour since 1998 (Table 40 Appendix 5). Emissions per kWh were estimated for each geothermal field by weighting the average emission rate to the output of the power plant. The estimated H_2S and Hg emission factors for six geothermal plants are presented in Table 17. A New Zealand average H_2S and Hg emission value was determined and used in the geothermal LCI model.

Table 17 Average Annual H_2S and Hg Emission Factors for Six Geothermal Power Plants in New Zealand. Source: Based on the Waikato Regional Council H_2S and HG Consent Monitoring Reports

Plant	Units	H2S	Hg
Wairakei	g/kWh	3.31E-01	1.65E-05
Te Huka	g/kWh	1.05E+00	1.36E-05
Mokai	g/kWh	1.80E+00	6.06E-05
Rotokawa	g/kWh	3.57E-03	8.76E-04
Nga Awa Purua	g/kWh	4.27E-03	1.31E-04
Ngatamriki	g/kWh	1.69E+00	1.39E-04
Average	**g/kWh**	**8.13E-01**	**2.06E-04**

Note: Appendix 5 shows the original sources of information and procedure to estimate these values.

Because Wairakei and Kawerau geothermal plants produce water emissions[8], freshwater emissions of arsenic were estimated from annual emission factors from Wairakei (Contact Energy, 2010). Table 18 lists emission factors of arsenic from 2006 – 2010 and the estimated average used for the New Zealand geothermal electricity model.

Table 18 Contact Energy Annual Geothermal Generation, Annual Discharge of Arsenic into the Waikato River and Estimated Arsenic Emissions Factors. Source: Contact Energy, 2010.

	Units	2006	2007	2008	2009	2010	NZ Average
Generation from Contact Energy Geothermal Plants	GWh	1,820	1,968	2,180	2,312	2,238	
Annual arsenic discharge to Waikato River	t		90.6	90.2	99.85	93.65	
As emission factor	**g/kWh**		*4.60E-02*	*4.14E-02*	*4.32E-02*	*4.18E-02*	*4.31E-02*

Note: Contact Energy geothermal assets in 2010 included the Wairakei, Ohaaki and Te Huka fields with a generating capacity of 327 MW. The 166 MW Te Mihi geothermal plant in the Wairakei field was not yet operational.

SO_2 and NO_x New Zealand emission values were sourced from a report on the Waikato geothermal resources (Luketina, 2012). These are presented on Table 19.

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[8] According to the NZGA web site Wairakei and Kawerau are the only geothermal power plants in New Zealand that have separated water and condensate discharge into the Waikato and Tarawera rivers respectively. http://www.nzgeothermal.org.nz/emissions.html

Table 19 Sulphur Dioxide and Nitrogen Oxides Geothermal Emission Values Used for the Geothermal Electricity LCI Model for the Year 2013. Source: Luketina, 2012

Sulphur dioxide and Nitrogen Oxides	Unit	Emission Factor
SO_2	g/kWh	***0.02***
NO_x	g/kWh	***0.28***

Bleach is used on a regular basis to clean the cooling water circuits, and so a production process for “sodium hypochlorite 15%” from the ecoinvent “rest-of-the-world” region was included in the model. There is no reported value on the amount of bleach used in New Zealand geothermal plants, and so the default quantity of bleach $2.4E^{-2}$ g used per kWh reported by Karlsdottir et al. (2015) was used.

Geothermal maintenance well

Make-up wells are needed throughout the operational life-time of the power plant to maintain the power output. Based on suggestions by the NZGA (B. White, personal communication, June 16th, 2015) an assumption was made that 2.5 % of the initial number of wells are used for the entire life-time of the plant. As a result, 20 make-up wells would need to be drilled during the 40 years of operational life-time of the power plant. Materials and resources for drilling make-up wells (Karlsdóttir et al., 2015) were scaled from the Hellisheidi LCI using the same method that was described for the construction of the power plant. However, to use the maintenance well data it was necessary to estimate the number of make-up wells per kWh of electricity needed by a New Zealand average geothermal power plant. Since the life-time electricity generation had been previously estimated to be $2.30\ E^{10}$ kWh, this value was used to determine the quantity of make-up wells per kWh:

$$\#\ make\ up\ wells\ per\ kWh = \frac{20\ make\ up\ wells}{2.30E^{10}\ kWh} = 8.70\ E^{-10}\ \frac{make\ up\ wells}{kWh}$$

5.2.5 Hydropower LCI Electricity Model

The life cycle stages modelled for the hydropower electricity LCI model were: 1) hydropower plant construction (reservoir and run-of-river) and 2) hydropower plant operation (reservoir and run-of-river). Because in New Zealand both types of hydropower plant exist, the relative contribution of run-of-river versus reservoir hydropower needed to be estimated. Based on the construction parameters of hydropower plants in

New Zealand (Martin, 1991) and visual analysis using Google Earth, hydropower plants were classified either as reservoir or run-of-river (Table 1, Chapter 3). The annual generation produced by each type of hydropower plant was used to estimate the relative contribution of electricity to the grid mix. Table 20 shows the relative contribution of reservoir and run-of-river hydropower plants to the grid and Figure 11 shows the hydropower mix for the electricity LCI model.

Table 20 Relative Share of Electricity Generated by Reservoir and Run-of-River Hydropower Plants. Source: Martin, 1991

Average Technology	Annual GWh	%
Reservoir	22,723	94%
Run-of-River	1,401	6%

Note: Annual generation figures were obtained from Table 1, Chapter 3.

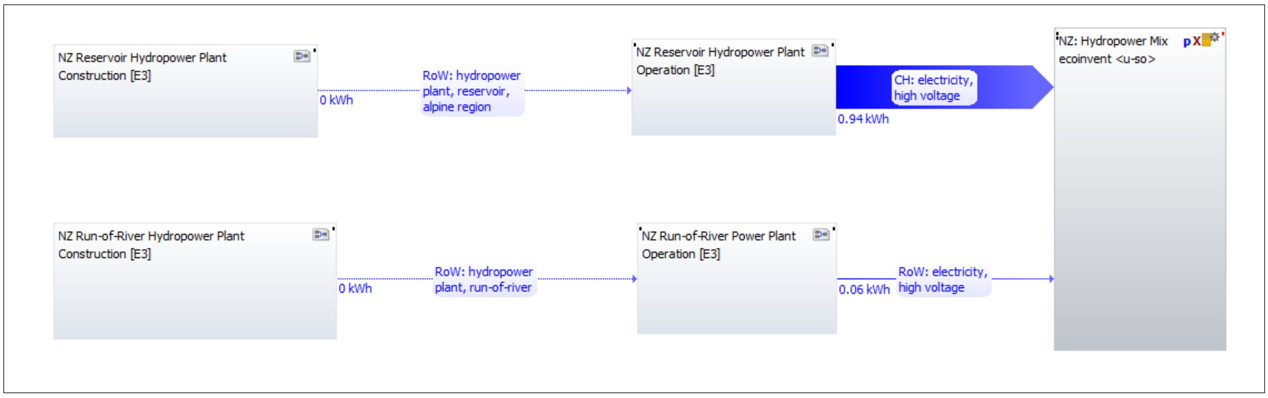

Figure 11 New Zealand Hydropower LCI Model

Hydropower plant construction

Construction and decommissioning of reservoir hydropower were considered using the “hydropower plant construction, reservoir alpine region” dataset from the ecoinvent region of the “rest-of-the-world”. For run-of-river plants the “hydropower plant construction, run-of-river” dataset from ecoinvent region of the “rest-of-the-world” was used. Both these datasets used default ecoinvent values for materials and resources needed to build reservoir and run-of-river hydropower plants.

Hydropower plant operation

Activities during this stage included production of lubricating oil, waste treatment methods for mineral oil used by turbines, land transformation and occupation of water bodies. These activities were represented using the default ecoinvent values in the dataset “electricity production, hydro, reservoir” and "electricity production hydro, run-of-river". Operational emissions from run-of-river hydropower plants were excluded from the model as they are insignificant. For reservoir plants, N_2O and biogenic emissions of CH_4 can be expected from biomass decomposition in the flooded reservoir. The magnitude of biogenic CH_4 emissions from flooded biomass in reservoirs is still under debate (Kumar et al., 2011). However, CH_4 emissions are correlated with the natural net primary productivity of the area (Hertwich, 2013) and the amount and type of biomass flooded (Dones et al., 2007). Therefore, for New Zealand CH_4 emissions from biomass decomposition were assumed to be relevant. Because non-alpine regions have relatively higher amounts of biomass than alpine regions (Dones et al., 2007), the CH_4 emission value from non-alpine regions was used as representative of New Zealand hydropower plants. Hence, 6 g CO_2-eq per kWh (0. 286 g/kWh of CH_4 using a methane GWP of 21 CO_2-eq) was assigned to reservoir hydropower plants. For nitrous oxide (N_2O) the default ecoinvent value $7.7E^{-4}$ g/kWh was used. The default operational life-time in the dataset was 150 years for both reservoir and run-of-river hydropower plants.

5.2.6 Wind, Biomass and Biogas Electricity LCI Models

For electricity generated with wind, biomass and biogas, the default cumulative LCI datasets from the ecoinvent region of the "rest-of-the-world" were used as representative of New Zealand conditions. Because in New Zealand most of the wind farms use turbines with a rated capacity above 2 MW (Table 5, Chapter 3), the dataset for "electricity production, wind, 1-3 MW turbine onshore" was used. Biomass electricity was modelled using a "heat and power co-generation, wood-chips 2000 kW" dataset. Biogas was represented using the "heat and power co-generation, biogas, gas engine" dataset.

5.2.7 Electricity Transmission and Distribution (T&D) LCI Model

As described previously in Section 3.2, there are 12,000 km of high-voltage transmission networks and 150,000 km of low-voltage distribution lines. Figure 6 shows the New Zealand electricity LCI model with its associated T&D processes. To build the New Zealand electricity transmission and distribution (T&D) LCI model, infrastructure data and its associated emissions were needed for: materials and resources required for lines, pylons, cables transformers, switch gear and buildings, transportation of materials and disposal, metal emissions from wooden pole production, and emissions of sulphur hexafluoride and carbon dioxide.

Therefore, to represent New Zealand T&D networks the ecoinvent Swiss cumulative LCI datasets for high, medium and low-voltage transmission networks were used. Table 21 shows a comparison between Swiss and New Zealand T&D networks (Swiss Grid, 2015; Transpower, 2015).

Table 21 Comparison of New Zealand and Swiss Transmission and Distribution Network, Voltage Levels and Lengths. Source: Swiss Grid, 2015; Transpower, 2015

Country	Length	High Voltage	Medium Voltage	Low Voltage
New Zealand	12,000 km	400 - 220 kV AC	110 -11 kV AC	
New Zealand	150,000 km			400 – 230 V
Switzerland	250,000 km	380 - 220 kV AC	35 - 10 kV AC	400 – 230 V

To adapt the Swiss datasets, it was necessary to estimate the length of networks needed per kWh of electricity transmitted and distributed. Studies that have assessed life cycle impacts of T&D networks have used operational life-times of 40 years (Hauan, 2014; Jorge, Hawkins, & Hertwich, 2011a, 2011b). However, the New Zealand T&D network components are not replaced as often and some have been in operation since early 1900's (Martin, 1991). Therefore, a higher operational life-time of 50 years was assumed for the New Zealand context. The electricity supply and demand energy balance (Appendix 6) reports 41,616 GWh entering the system. Hence over the life-time of T&D network a total of $2.08E^{12}$ kWh are expected to be transmitted. For 12,000 km of high and medium voltage transmission network produces a value of $5.77E^{-6}$ m/kWh. In the same way for low voltage distribution 150,000 km of distribution network would produce $7.21E^{-5}$ m/kWh. The calculation procedure is shown in the following equations:

$$HV\ Trans.network = \frac{12{,}000\ km\ x\ (1000\frac{m}{km})}{41{,}616\ GWh\ x\ \left(1{,}000{,}000\frac{kWh}{GWh}\right) x\ 50\ years} = \frac{12{,}000{,}000\ m}{2.08\ E^{12}kWh} = \frac{5.77E^{-6}m}{kWh}$$

$$MV\ Trans.network = \frac{12{,}000\ km\ x\ (1000\frac{m}{km})}{41{,}616\ GWh\ x\ \left(1{,}000{,}000\frac{kWh}{GWh}\right) x\ 50\ years} = \frac{12{,}000{,}000\ m}{2.08\ E^{12}kWh} = \frac{5.77E^{-6}m}{kWh}$$

$$LV\ Dist.\ network = \frac{150{,}000\ km\ x\ (1000\frac{m}{km})}{41{,}616\ GWh\ x\ \left(1{,}000{,}000\frac{kWh}{GWh}\right) x\ 50\ years} = \frac{150{,}000{,}000\ m}{2.08\ E^{12}kWh} = \frac{7.21E^{-5}m}{kWh}$$

Because electrical losses occur during transmission and distribution, losses were estimated based on the New Zealand electricity supply and demand energy balance (Appendix 6). During high-voltage generation, electricity is used by the power companies to cover energy demands in their power plants. This is known as the "parasitic load". In 2013 parasitic loads reached 1,382 GWh. Parasitic load was 3.2 % of the total gross generation which in 2013 was 43,258 GWh. Similarly losses from transmission and distribution were 1,303 GWh and 1,600 GWh respectively, which in relation to the gross generation are 3% and 3.7%. In total losses add up to 10 % of the total gross generation. This trend is shown in Table 22.

Table 22 Estimation of Transmission and Distribution Losses of the New Zealand Electricity Grid. Source: MBIE, 2014b; Page 55

	2009	2010	2011	2012	2013
Own Use ~ Parasitic Load	**-3.2%**	**-3.2%**	**-3.0%**	**-3.3%**	**-3.2%**
Losses ~ Transmission	-3.1%	-3.0%	-3.0%	-3.1%	-3.0%
Losses ~ Distribution	-3.8%	-3.9%	-3.8%	-3.7%	-3.7%
Total Lines Losses	**-6.9%**	**-6.9%**	**-6.8%**	**-6.8%**	**-6.7%**
Total losses					**-9.9%**

Note: Percentage losses were estimated based on total gross generation which in 2013 was 43,258 GWh.

Sulphur hexafluoride (SF_6) leakages and CO_2 emissions are expected to occur from transformers and switchgear equipment. Emissions of SF_6 and CO_2 for the New Zealand T&D network were estimated based on the data published by Transpower (Transpower, 2015). In 2013, emissions reported were 9,950 tonnes of CO_2-eq. From this, 49% was attributed to SF_6 and 51% to CO_2 emissions. The global warming potential for SF_6 is 23,500 CO_2-eq (IPCC, 2014). Using the total electricity entering the system 41,616 GWh, the SF_6 and CO_2 emission factors for the T&D network can be estimated:

$$Annual\ SF_6 emissions = 9{,}950\ t\ CO_{2-eq}\ x\ 0.49 = 4{,}876\ t\ CO_{2-eq}\ from\ SF_6$$

$$Annual\ SF_6 emissions = 4{,}876{,}000\ \ kg\ CO_{2-eq}\ \ from\ SF_6\ x \frac{1\ kg\ \ SF_6}{23{,}500\ kg\ CO_{2-eq}} = \ 2{,}075\ g\ \ SF_6$$

$$SF_6\ emisison\ factor = \frac{2{,}075\ \ g\ \ SF_6}{41{,}616\ GWh\ x\ \left(1{,}000{,}000 \frac{kWh}{GWh}\right)} = \frac{4.99E^{-6} g}{kWh}$$

$$Annual\ \ CO_2\ emissions = 9{,}950\ t\ CO_{2-eq}\ x\ 0.51 = 5{,}075\ t\ CO_{2-eq}\ from\ CO_2$$

$$Annual\ \ CO_2\ emissions = 5{,}075\ \ t\ CO_{2-eq}\ \ from\ CO_2\ x \frac{1\ kg\ \ CO_2}{1\ kg\ CO_{2-eq}} = \ 5{,}074{,}000\ kg\ CO_2$$

$$CO_2\ emissions\ factor = \frac{5{,}074{,}000\ kg\ CO_2}{41{,}616\ GWh\ x\ \left(\ 1{,}000{,}000 \frac{kWh}{GWh}\right)} = \frac{0.122\ \ \ g}{kWh}$$

Because Transpower reports total emissions from the whole T&D network and does not identify at which stages they occur, a third of the emission factor was allocated to each of the three voltage levels of the T&D datasets.

$$\frac{4.99E^{-9}kg\ SF6\ /kWh}{3} = 1.66\ E^{-6}\ \ g\ SF6/kWh$$

$$\frac{1.31\ E^{-4}\ kg\ CO2/kWh}{3} = 4.06\ E^{-2}\ \ g\ CO2/kWh$$

5.3 Uncertainty, Limitations and Completeness of Inventory Data

In this Section the limitation and uncertainties inherent in the LCI models are discussed. For all the power generation methods, except for geothermal power, the infrastructure datasets from the ecoinvent database were used and represent European power and T&D infrastructure which may not be representative of New Zealand conditions. This is an acknowledged limitation due to the lack of data available from the New Zealand power generation industry for infrastructure.

For fossil fuelled power specifically, only GHG emission values were adapted using New Zealand site-specific data. Therefore environmental impacts related to other emissions might not be well represented by the European datasets.

For geothermal electricity generation, the plant construction dataset from a 2-Flash plant in Iceland used in this study is likely to be more representative than previous models which used data for Enhanced Geothermal Systems in the United States. New Zealand specific geothermal plant operation emissions were estimated from the environmental reports of a limited number of geothermal plants and assumed to represent the average New Zealand geothermal scenario. Emission data from all geothermal plants would produce more accurate averages, but were not available at the time of this study.

For hydropower, two key assumptions have been made. The first one is the quantity of biogenic methane produced by New Zealand hydropower reservoirs. Although there is a high uncertainty (Kumar et al.,

2011) and variability (Hertwich, 2013) in estimations from biogenic emissions, tropical regions are more likely to have higher GHG emission factors than boreal regions (Kumar et al., 2011). In the ecoinvent datasets, usually non-alpine regions have higher methane emissions than alpine region hydropower reservoirs (Dones et al., 2007). Therefore, the emission factor for methane of 0.000286 kg/kWh taken from Swiss non-alpine conditions is more likely to represent a minimum expected emission rate for New Zealand hydropower reservoir plants.

The second assumption made for hydropower model is the relative contribution of run-of-river and reservoir power plants. This was one of the issues described on a previous carbon footprint study as being relevant (Coelho, 2011), Attention was given to the classification of both types of hydropower plants by reviewing historical documents (Martin, 1991) and visual analysis of each of the hydropower schemes using Google Earth Pro. Therefore, this assumption is likely to be relatively accurate.

For transmission and distribution of electricity, emissions of SF_6 and CO_2 are reported annually for the whole system. Therefore, emissions at each stage of the voltage transformation are uncertain. In this study a third of the total emission factor has been shared between high, medium and low-voltage transformation. Emissions of SF_6 and CO_2 at each voltage level should be addressed in future studies.

Chapter 6 Results: Life Cycle Impact Assessment of Electricity Use

In this Chapter, the Life Cycle Impact Assessment results for the delivery of electricity are presented. Section 6.1 presents the impacts of using 1 kWh low-voltage electricity. Section 6.2 describes the environmental impacts of voltage transformation and the transmission and distribution network. Section 6.3 illustrates the New Zealand electricity carbon footprint at three voltage levels and the contribution of each generation system.

6.1 Impact Assessment of 1 kWh Low-Voltage Electricity

Based on the suggestions made in the New Zealand "Whole Building Whole of Life Framework" (Dowdell, 2014), the life cycle impact assessment method selected was the CML 2001 - Apr. 2013 developed by Leiden Institute of Environmental Sciences. Twelve impact indicators were calculated and are discussed in this study (Figure 12). These indicators characterise environmental impacts arising from resource consumption and emissions from the delivery of 1 kWh low-voltage electricity in 2013. The bar graph shows the percentage contribution of each power generation technology feeding electricity into the grid and the contribution from the transmission and distribution (T&D) network.

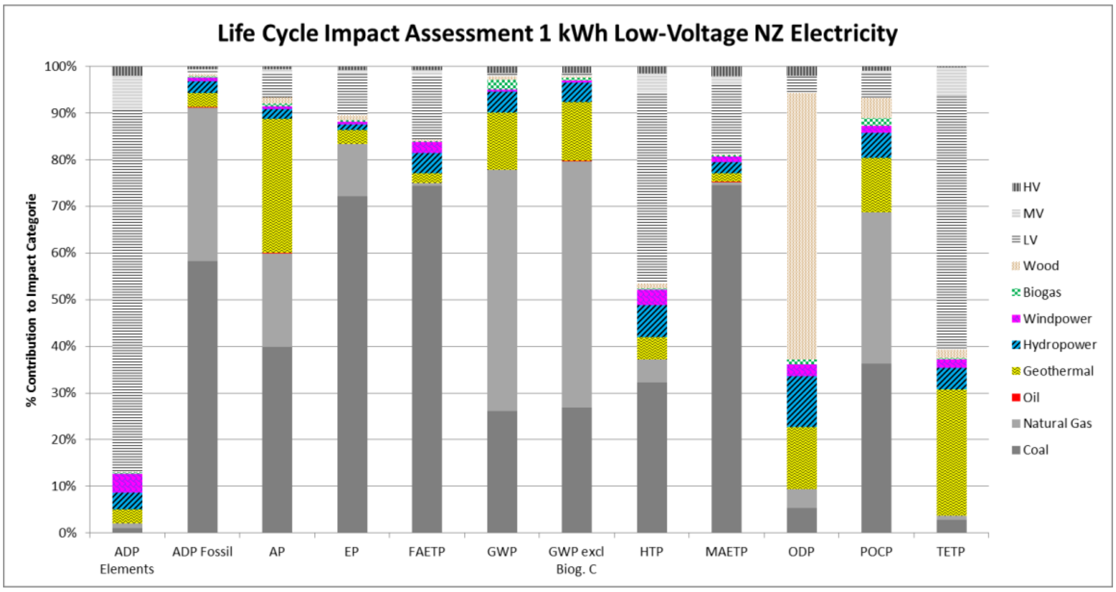

Figure 12 Life Cycle Environmental Impacts of 1 kWh Low-Voltage Electricity. ADP Elements= Abiotic Depletion Potential of Elements; ADP Fossil = Abiotic Depletion of Fossil Resources; AP= Acidification potential; EP = Eutrophication Potential; FAETP = Freshwater Aquatic Ecotoxicity Potential; GWP = Global Warming Potential; GWP excl. Biog. C.= Global Warming Potential excluding Biogenic Carbon; HTP = Human Toxicity Potential; MAETP = Marine Aquatic Ecotoxicity Potential; ODP = Ozone Depletion Potential; POCP = Photochemical Ozone Creation Potential; TETP = Terrestrial Ecotoxicity Potential; LV = Low-voltage distribution network; MV = Medium-voltage transmission network; HV = High-voltage transmission network.

In general, most of the environmental impacts across the different impact categories come from fossil fuel power generation. These are represented by the grey bars in Figure 12. Specifically, electricity produced from coal contributes more than 70% of the total impact of EP, FAETP and MAETP; between 50 and 69% of the total impact for ADP and between 30 and 49% of the total impact for AP, HTP and POCP. Natural gas, on the other hand, only contributes close to 50% to the two Global Warming Potential (GWP) categories and between 20% and 30% for ADP Fossil, AP and POCP. The T&D network has a contribution that ranges from 50 to 90% of the total impacts for ADP Fossil, HTP and TETP. In particular, the low-voltage distribution network (horizontal lined bars on Figure 12) contributes almost 80% to ADP Elements, more than 50% to TETP and nearly 40% to HTP. For the rest of impact categories the low-voltage distribution network contributes between 5 and 20% of the total impacts. The high and medium-voltage transmission networks have a relative low contribution (less than 5%) to all the impact categories. Geothermal electricity (yellow colour in Figure 12) contributes almost 30% of TETP and AP impacts. It also contributes nearly 10% of the total impact for both GWP categories, ODP and POCP. Electricity from biomass is the only technology that produces more than 50% of the total ODP impacts.

Due to the relative higher contribution of coal and gas electricity to total environmental impacts, the life cycles of coal and gas electricity were analysed independently. The life cycle analysis for coal electricity revealed the life cycle stages causing most of the environmental impacts (Figure 13). Impacts are shared between mining and coal combustion during operation of the power plant. Mining contributes to more than 70% of the total impact for ADP Fossil, EP, FAETP, HTP and MAETP. For ADP Elements, ODP POCP and TETP, the contribution of mining to the total impacts ranges from 15 to 40%. Combustion of coal produces 70 to 80% of GWPs, AP, POCP and TETP categories. For the rest of impact categories combustion produces less than 30% of the total impacts.

For electricity produced from natural gas (Figure 14), environmental impacts are shared between exploration, extraction and production of natural gas, power plant construction and combustion during operation. Exploration, extraction and production of natural gas caused almost 100% of ADP fossil impact and 80% of ODP impact. The construction of the gas plant contributed between 50 and 69% of the total impacts for

ADP elements, FAETP, MAETP and TETP. Operation of the power plant contributed 70 to 90% of AP, EP, GWPs, HTP and POCP impact categories.

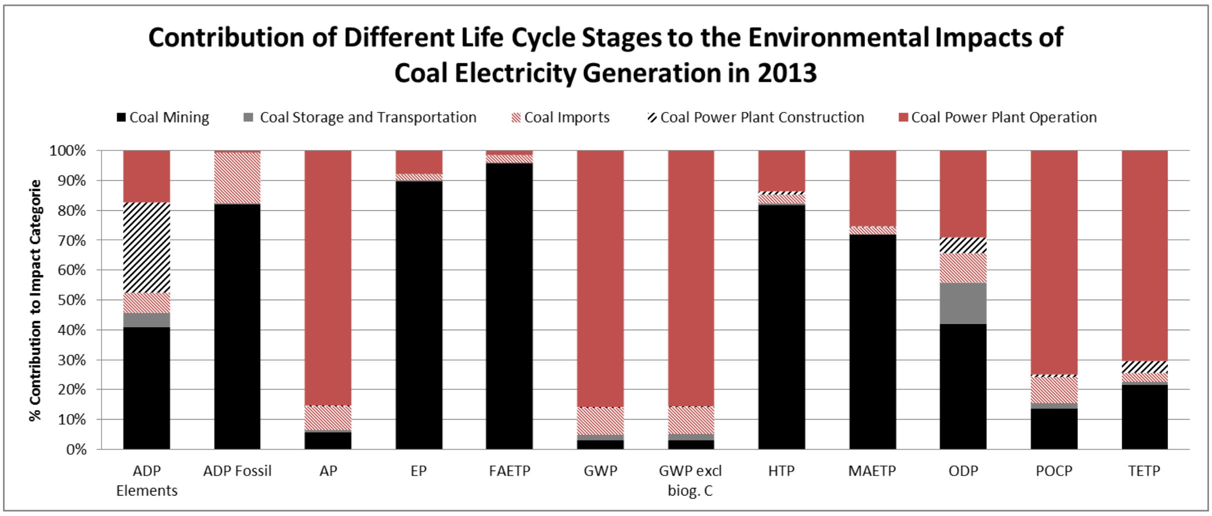

Figure 13 Life Cycle Environmental Impacts of 1 kWh High-Voltage Coal Electricity. ADP Elements= Abiotic Depletion Potential of Elements; ADP Fossil = Abiotic Depletion of Fossil Resources; AP= Acidification potential; EP = Eutrophication Potential; FAETP = Freshwater Aquatic Ecotoxicity Potential; GWP = Global Warming Potential; GWP excl. Biog. C.= Global Warming Potential excluding Biogenic Carbon; HTP = Human Toxicity Potential; MAETP = Marine Aquatic Ecotoxicity Potential; ODP = Ozone Depletion Potential; POCP = Photochemical Ozone Creation Potential; TETP = Terrestrial Ecotoxicity Potential

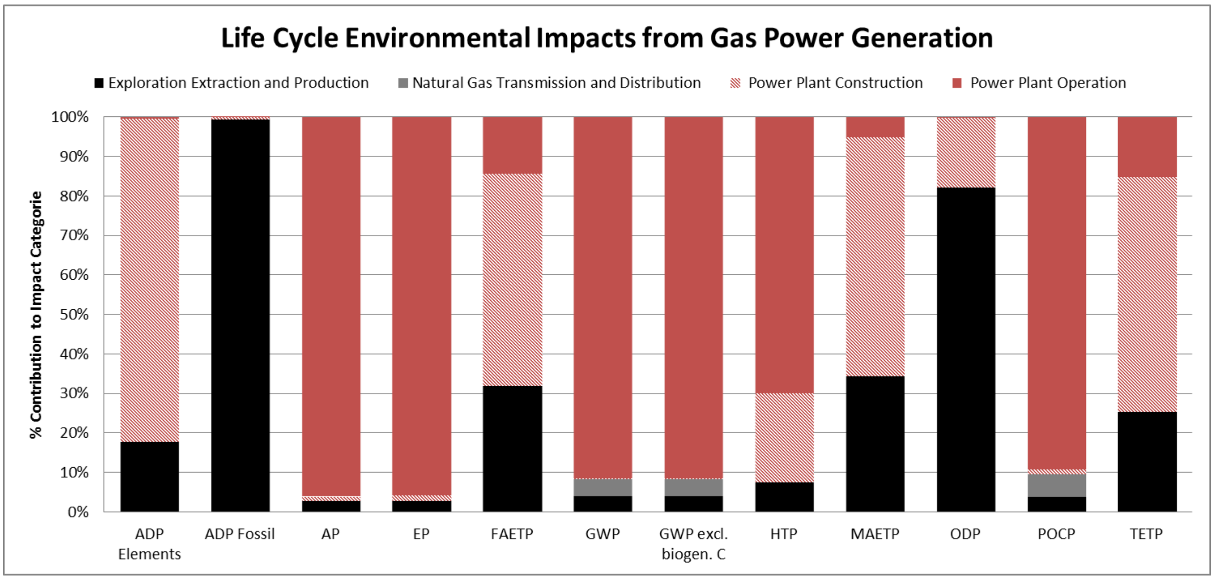

Figure 14 Life Cycle Environmental Impacts of 1 kWh High-Voltage Natural Gas Electricity. ADP Elements= Abiotic Depletion Potential of Elements; ADP Fossil = Abiotic Depletion of Fossil Resources; AP= Acidification potential; EP = Eutrophication Potential; FAETP = Freshwater Aquatic Ecotoxicity Potential; GWP = Global Warming Potential; GWP excl. Biog. C.= Global Warming Potential excluding Biogenic Carbon; HTP = Human Toxicity Potential; MAETP = Marine Aquatic Ecotoxicity Potential; ODP = Ozone Depletion Potential; POCP = Photochemical Ozone Creation Potential; TETP = Terrestrial Ecotoxicity Potential

To understand what is causing the impacts associated with New Zealand electricity generation and use, a hotspot analysis was done. Figure 15 shows the substances contributing more than 1% to each impact category result and Table 42 in Appendix 8 shows the quantity of each substance produced per kWh of electricity. In Figure 15, the ADP Fossil impact category shows that extraction of sub-bituminous coal (hard coal) and natural gas, are the primary raw materials being depleting during the production of electricity of these two fuels. Besides depletion, coal mining also release phosphates, nitrates, and heavy metals (nickel, vanadium, cobalt, beryllium selenium, and thallium). These substances are responsible for the high contribution of mining to EP, FAETP, HTP and MAETP impact categories.

Emissions of carbon dioxide (CO_2) from the combustion of natural gas and coal are responsible for 90% of the results of both GWP impact categories. Other greenhouse gases that are emitted in considerable quantities during combustion of natural gas and coal are carbon monoxide (CO), nitrogen oxides (NO_x), methane (CH_4) and non-methane volatile organic compounds (NMVOCs). These substances are responsible for the high contribution to POCP results. In addition, coal combustion also produces sulphur dioxide (SO_2) which is responsible for the high contribution of coal to AP impacts. New Zealand natural gas doesn't produce SO_2 emissions, instead high quantities of NO_x contribute to AP impacts.

The high contribution of the T&D network to ADP Elements is caused by the extraction of copper, zinc, lead, silver, nickel and molybdenum. More specifically the low-voltage distribution network requires a high quantity of copper. The low-voltage distribution network also produces high quantities of arsenic, selenium, thallium, cadmium and chromium emissions. These are responsible for the high contribution of the low-voltage distribution network to HTP and TETP impacts, shown on Figure 12.

Geothermal power generation produces a relative high amount of H_2S which contributes to the results of AP impacts. CO_2 emissions from geothermal power are smaller than those from fossil fuels but still contribute 10% of the climate change result. HTP impacts from geothermal power are caused by chromium released into the atmosphere. Geothermal well drilling produces halon emissions which caused, 10% of the total ODP impacts. TETP impacts are caused by high emissions of mercury (Hg) to the atmosphere.

Finally, biomass electricity produces a large amount of thrichlorotrifluoroethane, which is why biomass is the leading contributor to ODP total impact.

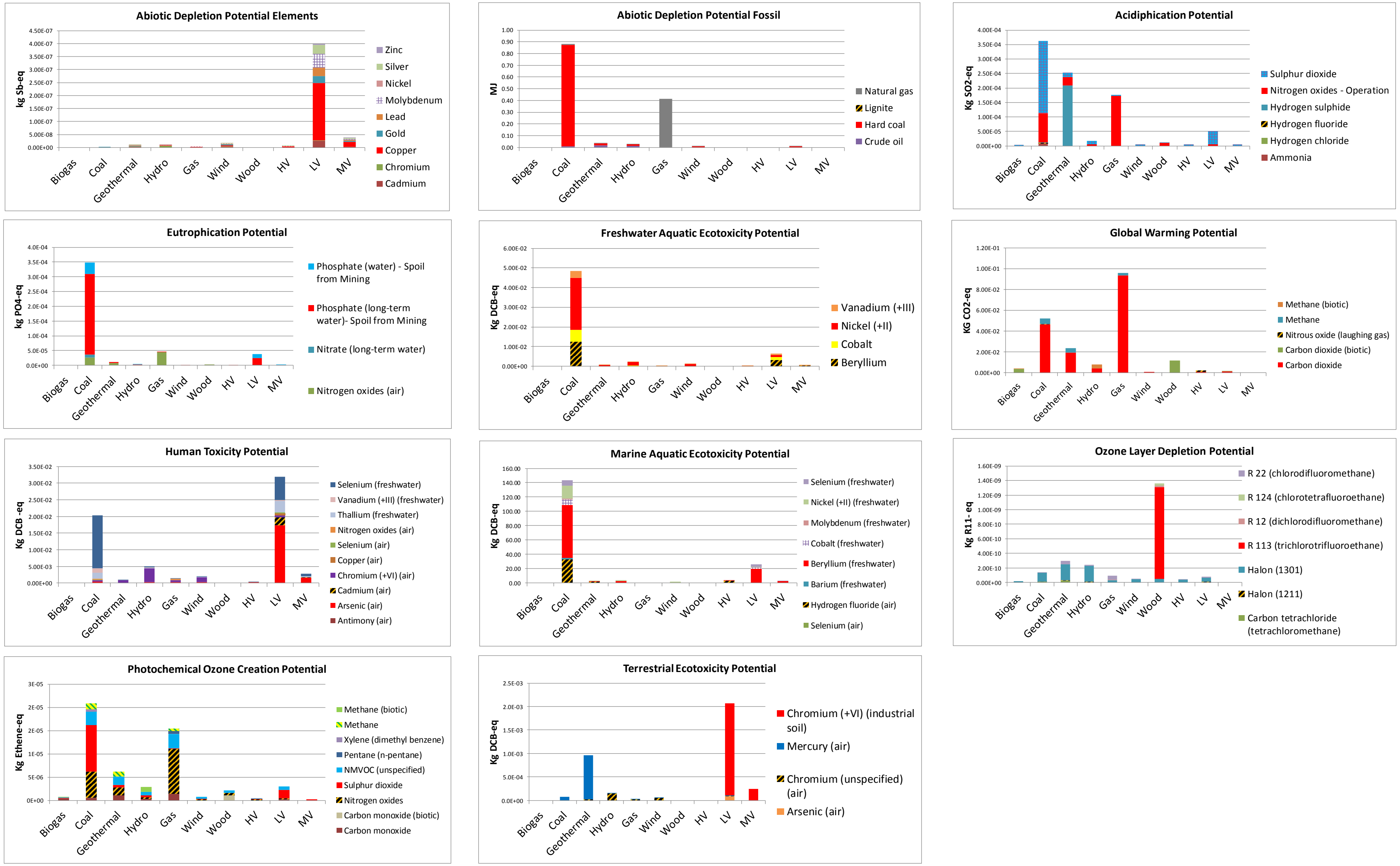

Figure 15 Hotspot Analysis for Substances Contributing More than 1% To Each Impact Category Result for 1kWh New Zealand Low-voltage Electricity. HV = High-voltage transmission infrastructure; MV = Medium-voltage transmission infrastructure; LV = Low-voltage distribution infrastructure; Only One GWP Category is Presented to Avoid Redundancy.

6.2 Effects of the T&D Network and the Associated Voltage Transformation

The results for the twelve impact categories are presented in Table 23. Four sets of results are presented. The first set of results is for high-voltage grid electricity; this is electricity delivered from the power companies directly to the grid. There is no T&D infrastructure at this stage, and only 3% losses from parasitic loads are considered. The second set of results is for high-voltage electricity with transmission infrastructure; these include, in addition to parasitic losses, the infrastructure comprises 12,000 km of transmission network. The third set of results is for medium-voltage electricity; these results include 3% losses from parasitic loads plus an additional 3% loss due to transmission, infrastructure for 12,000 km of high-voltage transmission lines, and 12,000 km of medium-voltage transmission lines. The fourth set of results is for low-voltage electricity distribution; these results include the infrastructure for both high and medium-voltage electricity transmission lines plus 150,000 km of infrastructure for low-voltage distribution lines. This fourth sets of results also includes 4% losses from the distribution network which are added to the previous 6%, this makes a total of 10% losses for delivery of low-voltage electricity.

The effect of the stepping down electricity from high to low-voltage is presented in Table 24. The percentage increase in each of the impact category results is presented in the table. The infrastructure for high-voltage transmission and associated losses increases the results for all impact categories between 2% and 6%. Adding the medium-voltage infrastructure network increases impacts anywhere from 10 to 14%. The effects of stepping down electricity from medium to low-voltage increase environmental impacts from 10 to 41%, except for ADP Elements, HTP, and TETP. For this three impact categories, stepping down to low-voltage electricity increases total results more than 100%.

Table 23 Life Cycle Impacts per 1 kWh New Zealand Electricity at High, Medium and Low-Voltage Levels for the Year 2013

	ADP elements [kg Sb-Equiv.]	ADP fossil [MJ]	AP [kg SO2-Equiv.]	EP [kg Phosphate-Equiv.]	FAETP inf. [kg DCB-Equiv.]	GWP 100 years [g CO2-Equiv.]	GWP 100 years excl biogenic carbon [g CO2-Equiv.]	HTP inf. [kg DCB-Equiv.]	MAETP inf. [kg DCB-Equiv.]	ODP, steady state [kg R11-Equiv.]	POCP [kg Ethene-Equiv.]	TETP inf. [kg DCB-Equiv.]
High-voltage Without T&D	5.96E-08	1.159	7.70E-04	3.45E-04	0.046	176	170	0.043	130.1	2.09E-09	4.80E-05	1.32E-03
High-Voltage	6.84E-08	1.166	7.75E-04	3.46E-04	0.046	176	172	0.045	133.5	2.13E-09	4.85E-05	1.32E-03
Medium-voltage	1.05E-07	1.202	8.03E-04	3.60E-04	0.048	182	178	0.049	140.3	2.21E-09	5.02E-05	1.58E-03
Low-voltage	4.85E-07	1.263	8.82E-04	4.11E-04	0.058	191	186	0.087	171.8	2.38E-09	5.51E-05	3.59E-03

Table 24 Percentage Increase in Impact Category Result When Stepping Down Electricity from High-Voltage Without T&D Infrastructure to Low-Voltage.

Percentage Increase	ADP elements [kg Sb-Equiv.]	ADP fossil [MJ]	AP [kg SO2-Equiv.]	EP [kg Phosphate-Equiv.]	FAETP inf. [kg DCB-Equiv.]	GWP 100 years [kg CO2-Equiv.]	GWP 100 years excl biogenic carbon [kg CO2-Equiv.]	HTP inf. [kg DCB-Equiv.]	MAETP inf. [kg DCB-Equiv.]	ODP, steady state [kg R11-Equiv.]	POCP [kg Ethene-Equiv.]	TETP inf. [kg DCB-Equiv.]
High-voltage	15%	1%	1%	0%	1%	0%	0%	3%	3%	2%	1%	0%
Medium-voltage	77%	4%	4%	4%	5%	4%	4%	13%	8%	5%	5%	20%
Low-voltage	714%	9%	15%	19%	27%	9%	9%	100%	32%	14%	15%	172%

6.3 The Carbon Footprint of New Zealand’s Electricity Grid

Using the 100 year horizon GWP CML 2001-Apr.2013 impact method, the carbon footprint of New Zealand electricity is 186 g CO_2-eq per kWh of electricity (Figure 16). The relative contribution of each of the power generation technologies to the production of 1 kWh of electricity is presented in Figure 17. This shows that the majority of the carbon footprint result is associated with fossil fuel power. Geothermal power makes the largest contribution to the carbon footprint out of the renewable energy technologies.

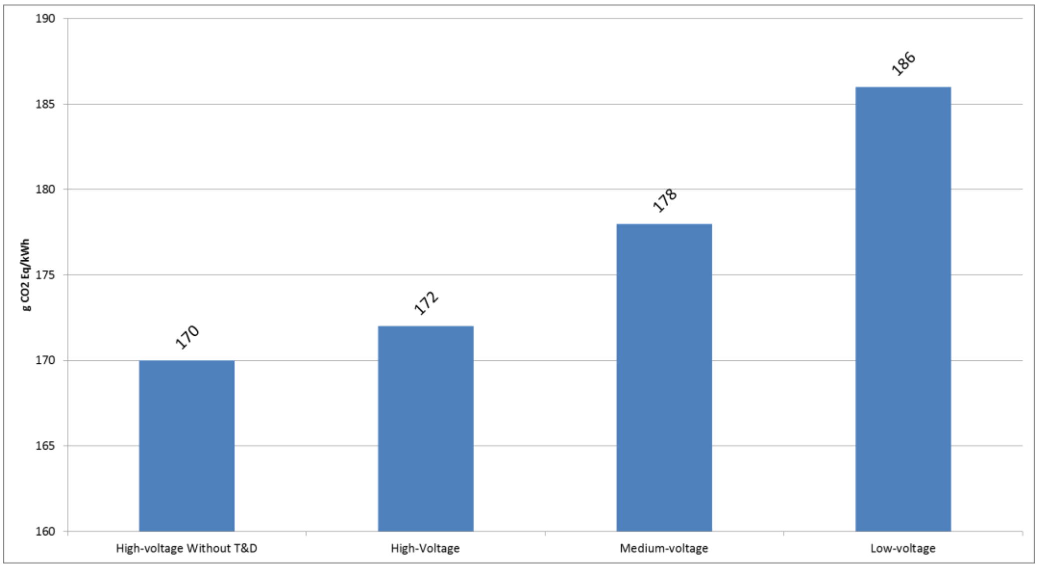

Figure 16 New Zealand Electricity Carbon Footprint During Generation, High-Voltage Transmission, Medium-Voltage Transmission and Low-Voltage Distribution

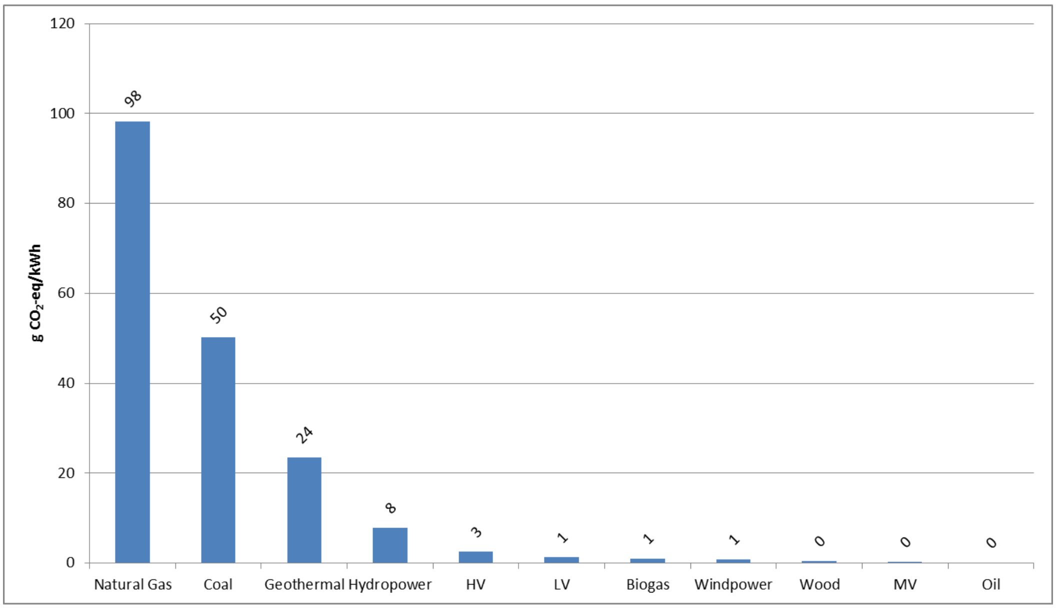

Figure 17 Contribution of Each Power Generation Technology to the Total Grid Carbon Footprint

6.4 Sensitivity Analysis

The adaptation process of the ecoinvent models for New Zealand specific values were reviewed with a sensitivity analysis. All the decisions, assumptions, and emission values were screened using the GaBi® parameter explorer and sensitivity analysis module. For the sensitivity analysis, these parameters are termed as “input parameters”. Input parameters were changed in steps of ± 10, ± 25, ±50, ±100 % of their original input value. Variations in the LCA impact category results were measured as a percentage change of the original value and were labelled as “% change in output”. These variables were plotted in a graph using the X-axis for the % change in input parameter and the Y-axis for the % change in output (i.e. LCA impact category results). The most significant parameters presented on Figure 18 were those that made a percentage change on LCA impact category results above 10% and had the steepest line on the graphs. Asymmetrical lines on Figure 18 represent a non-linear relationship between input parameters and LCA impact category results. The technologies not shown in Figure 18 were:

- Wind, Biomass and Biogas electricity used the aggregated European dataset default values, and therefore were not subject to any modification.
- Oil electricity generation in the grid mix is less than 1%, consequently, a change in parameters used in the oil LCI model does not have any significant effect on the impact assessment results.
- For hydropower electricity generation, it was found that changing the hydropower share and methane emissions did not have a significant effect on environmental impacts. It is recognized that construction of hydro dams is the stage responsible for most of the emissions, and it has been demonstrated that the infrastructure life-time is a more determinant parameter (Hondo, 2005). The default life-time values in the ecoinvent datasets used in the New Zealand electricity LCI model are 150 years. Hence, whether the infrastructure is RoR or reservoir-dam appears not to be important in this model.

For coal electricity generation, two parameters were identified as more significant on LCA impact category results: the heating value of coal and the share of native production from New Zealand coal mines. The heating value of coal plays a significant role in several impact categories. A lower heating value of coal increases FAETP, EP, MAETP and HTP impacts. This effect reflects the fact that higher amount of coals are needed to produce 1 KWh of electricity. An increase in the share of New Zealand coal (native production) used to produce electricity would increase environmental impacts of FAETP, EP, MAETP and HTP.

For natural gas electricity generation, three significant parameters influence LCA impact category results: the power plant output, GHG emission values and the share of offshore vs. onshore production. The heating value of natural gas does not have a significant effect on LCA impact results and therefore is excluded from the graphs. In terms of power plant output, an increase in plant output would reduce GHG emissions in this model because the estimation of emissions are based on the Energy Sector annual GHG emission totals (MBIE, 2015b) which are divided by the total output of a natural gas power plant. As a result, a direct relationship between emissions per electrical output is expected. Referring to GHG emissions values, particularly CO_2, NO_x and NMVOCs emissions directly influence GWP, AP, and POCP respectively. And in terms of the share of natural gas production, an increase in offshore production would increase ADP Fossil impacts. The efficiency of natural gas power plants was not included in the present sensitivity analysis because the study by Coehlo (2011) had already proven the significant effects of combustion efficiency. In her work, Coelho showed that increasing the natural gas power plant efficiency from 30 % to 43 % would reduce the carbon footprint by 15%. Because the inventory analysis for natural gas power shows that most of the electricity generated in 2013 was made with CCGT, the assumption was made that CCGT represents the average technology. However, a proportion of the electricity generated with OCGT has a lower combustion efficiency than 30%. In addition, Huntly switches fuel from sub-bituminous coal to natural gas depending on the electricity market. These issues, were not explored in the current study but could provide increased resolution in future LCA studies.

For geothermal electricity generation, three parameters are significant to LCA impact category results: emission of mercury, emissions of hydrogen sulphide, and the power plant capacity factor. The quantities of mercury emissions are highly influential on the TETP results. Hydrogen sulphide emissions are slightly influential on the AP results. An increase in capacity factor of geothermal power plants would reduce the ADP Element and ODP results.

For the transmission and distribution infrastructure, the most influential parameters were the low-voltage infrastructure length and its life-time. Changes in the parameters for the transmission infrastructure for medium and high-voltage had no significant effects. Increment in losses from stepping down the voltage also did not seem to have any significant effect. Changes in the emission factor of SF_6, did not show any effects. These parameters were therefore excluded from the graphs. An increase in the low-voltage infrastructure length would increase TETP, HTP, and FAETP impacts, while a reduction in the life-time would increment TETP, HTP, FAETP and EP impacts.

For the grid mix parameters, fossil fuels are the most important technologies affecting environmental impacts. Increments in the electricity share of coal and natural gas would directly increase impacts on AP, EP, MAETP, FAETP, GWPs and POCP categories. The increment in geothermal electricity would increase AP impacts and to a lesser extent AP impacts. Increments in the share of biomass electricity would produce an increase in ODP impacts.

In summary, the most important parameters determining LCA impact category results for each of the generation technologies are:

- Coal electricity:
    - **Heating value** of coal and the **share of native production**.
- Natural gas electricity:
    - The power **plant output**.
    - **CO_2, NOx** and **NMVOCs** emissions**.**
    - Share of **onshore** and **offshore** gas production**.**
- Geothermal electricity:
    - **Mercury** and **hydrogen sulphide** emissions
    - **Capacity factor**
- Transmission and distribution infrastructure:
    - Low-voltage distribution infrastructure **length**
    - Low-voltage distribution infrastructure **life-time**

- Electricity grid mix
    - Share of **coal**, **natural gas**, **geothermal** and **biomass** electricity on the grid mix.

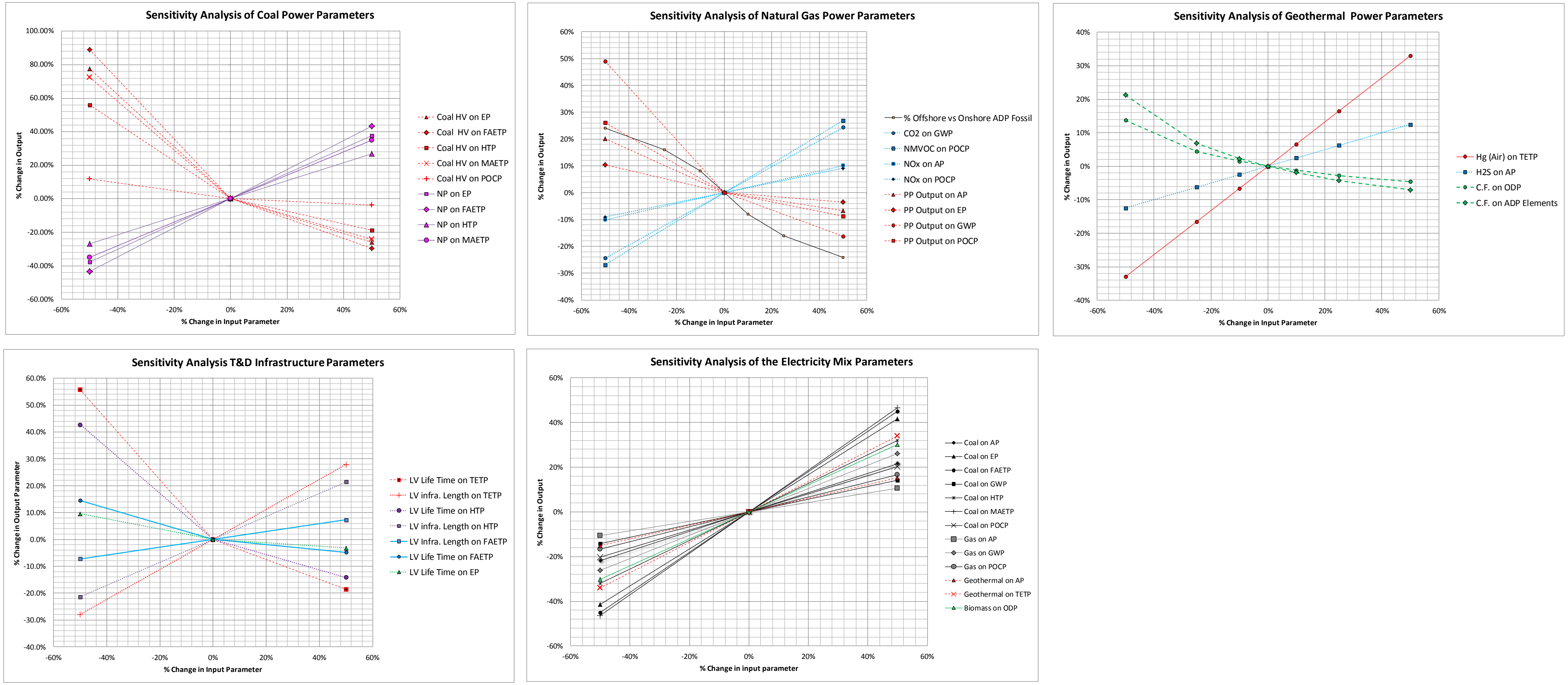

Figure 18 Sensitivity Analysis of the New Zealand Electricity LCI Model. PP = Power Plant; NP = Native Production; HV= Heating Value; LV infra. = Low-voltage Infrastructure; C.F. = Capacity Factor

Chapter 7 Interpretation of the Life Cycle Impact Assessment of 1 kWh New Zealand Electricity

In this chapter the Life Cycle Impact Assessment results are discussed. Section 7.1 discusses the New Zealand Electricity Life Cycle Inventory developed in this research using the sensitivity analysis to understand the most relevant parameters in the model. Section 7.2 examines the effects of the transmission and distribution network. Section 7.3 compares LCA results with other studies using the Carbon Footprint as a benchmark. Section 7.3 examines the variability of LCA results over different time scales. Finally, Section 7.5 reviews attributional and consequential modelling perspectives.

7.1 Inventory Analysis

The New Zealand electricity life cycle inventory model in this study was developed targeting issues that were highlighted in a previous New Zealand electricity carbon footprint study (Coelho, 2011) and was expanded to include 11 additional environmental impacts. Table 25 shows a comparison of the carbon footprint study with respect to the present LCA study. As a result, 12 environmental impacts were assessed with distinction from upstream and downstream activities of complete electricity supply chains from coal, natural gas, oil, geothermal, hydropower and transmission and distribution.

Table 25 Comparison between Carbon Footprint Study (Coehlo, 2011) and Present LCA Study for the New Zealand Electricity Grid

	Carbon footprint Study (2011)	Present Study (2013)
Database	Ecoinvent 2.0	Ecoinvent 3.1
Fossil fuel power plants	*Thermal Efficiencies* Natural gas 30%, Coal 30%, Oil 30%	*Thermal Efficiencies* Natural Gas 50%, Coal 36% and Oil 40.3%
	Heating Values EU Default	*Heating Values* NZ Fuels
	Combustion Emission Factors CO_2 , CH_4,N_2O	*Combustion Emission Factors* CO_2, CO, CH_4, N_2O, NO_x, NMVOCs,SO_2
	Upstream activities EU Default NZ medium voltage electricity for coal storage	*Upstream Activities* NZ share of open cast (91%) and underground mines (9%) International and national coal transportation CH_4 fugitive emissions from post-mining activities Natural gas share of offshore vs onshore production CH_4 and CO_2 fugitive emissions

Hydropower	*Type of scheme* 100% run-of-river	*Type of scheme* 94% reservoir, 6% run-of-river
	Emissions none	*Emissions* Swiss non-alpine CH_4 emissions
Geothermal	*Infrastructure* US, 50 MW, Enhanced Geothermal System	*Infrastructure* Iceland, 80 MW, 2-Flash System
	Fugitive emissions NZ specific CO_2, CH_4 to air	*Fugitive emissions* NZ specific CO_2, CH_4, SO_2, H_2S, to air NZ specific As and Hg to water Italy, minimum values for traces of metals (As, Cd, Cr, Cu,Pb, Mn, Ni, Se and Vd); ammonia (NH3), carbon monoxide (CO), NO_x

In the sensitivity analysis in Coehlo (2011), the combustion efficiencies of fossil fuel power plants were the most influential parameters on the carbon footprint results. Coelho (2011) considered a 30% combustion efficiencies for coal, natural gas and oil electricity. However, most of the electricity produced from fossil fuels in New Zealand is produced at Huntly power station using combined cycle gas turbines (CCGT) with reported efficiencies of 55% (MBIE, 2014b; page 13). The efficiency considered in the present study for natural gas (50%), oil (40.3%) and coal (36%) are therefore more representative of New Zealand fossil fuelled power plants.

The sensitivity analysis in the present study showed that the heating value of coal and the share of native coal production are significant parameters likely to influence upstream environmental impacts of the coal supply chain. In the present study the net heating value of New Zealand sub-bituminous coal estimated at 20.39 (MJ/kg) is based on a weighted average from New Zealand coal fields (Appendix 3, Table 37). The heating value of coal is a product of its physical properties. These physical properties can have wide variations even within the same coal deposit (Eng et al., 2008). In the present study, the origin of coal and their heating values was not assessed. Furthermore, the heating value of Indonesian coal used to supply Huntly power was not determined. Therefore, improvements in the coal electricity model could be made by enhancing the accuracy of coal properties used by Huntly power station and understanding the correct share of Indonesian and native coal used as fuel.

For natural gas, the sensitivity analysis shows a strong correlation between the CO_2 combustion emission factor and the climate change potential. The combustion emission factor in this study (42 g CO_2 per kWh) is much higher than 191 g CO_2 per kWh reported by Coehlo (2011), Barber (2011) and the Ministry for the Environment (MFE, 2015). The original Australian dataset emission value is 38 g CO_2 per kWh. Therefore the CO_2 emission value calculated in the present study might be overestimating natural gas CO_2 emissions.

For hydropower, the LCI model developed in the present study considered the share of run-of-river (RoR) and reservoir-dams, and assigned a non-alpine value for methane emissions from hydropower reservoirs. In the sensitivity analysis, both of these assumptions did not have any significant effect on the LCA impact category results. The value assumed here of 6 g CO_2-eq per kWh is similar to the 7.1 g per kWh of CO_2 emission estimated for Vattenfall hydropower portfolio in Nordic countries (Vatenfall AB, 2011). Direct measurements of reservoir emissions might provide a better estimation bearing in mind that emissions from reservoirs have been under constant debate. Hertwich (2013) suggests that the most influential parameter for methane emissions is related to the net primary productivity of the area, the age of the reservoir and the inclusion of bubbling emissions. Quantifying reservoir emissions should be addressed in future life-cycle studies of New Zealand hydropower stations.

The geothermal LCI model in the present study was developed using a state-of-the-art 2-Flash plant inventory dataset (Karlsdóttir et al., 2015), which is more representative than the " hypothetical enhanced geothermal system" from the United States (Sullivan et al., 2010) used by Coelho (2011). The sensitivity analysis of the model showed that the assumptions of heavy metals emissions using the minimum values from the Italian case study (Bravi & Basosi, 2014) do not have any significant effect on LCA results. As a matter of fact, the more important model parameters are those from site-specific atmospheric emission values from mercury (Hg) and hydrogen sulphide (H_2S). Although some authors (Rule et al., 2009) have neglected geothermal emissions, there is strong evidence to suggest that in New Zealand heavy metal emissions are a source of concern. For example, Wairakei and Kawerau geothermal power plants discharge the flashed brine to the Waikato and Tarawera River (NZGA, 2015). Pollution of the Waikato River by the Wairakei power plant has been documented since the 1970s (DiPippo, 1978). Based on a study by Axtmann (1975), concentrations of Hg and arsenic (As) were recorded at levels of concern. According to the World Health Organization, the permissible drinking water quality levels of arsenic are 0.01 ppm (WHO, 2008). Arsenic in the Waikato River was found at 0.039 ppm (Axtmann, 1975). Measured at the inlet of the Wairakei village water supply arsenic was found at 0.07 ppm and in drought periods at higher concentrations (0.25 ppm) (Axtmann, 1975; DiPippo, 1978). Presently, the Waikato Regional Council reports that the arsenic concentrations in the Waikato River have doubled and the values along the river range from 0.011 to 0.032 (Waikato Regional Council, 2015). Mercury was also found at high concentrations (1.5 E^{-6} ppm) (DiPippo, 1978). In trout, they were 4.4 times the accepted values for human consumption (DiPippo, 1978). Timperley and Hill (2010) reported annual discharge values of Hg of 465 g, and average daily values of 53 g. In the case of the Kawerau geothermal plant, discharges from the geothermal fluid were reported to increase arsenic and chloride concentrations (Mroczek, 2005). Upstream of the geothermal fluid effluent estimated arsenic and chloride concentrations were 0.021 ppm and 39 ppm respectively (Mroczek, 2005). Geothermal effluent discharge increased the arsenic and chloride concentration to 0.038 ppm[9] and 50 ppm respectively (Mroczek, 2005). Although it appears that some of these emissions might not violate any New Zealand water or air quality standards, there is a need to understand the long-term effects of heavy metal emissions from New Zealand geothermal plants on the environment.

Looking at the effect of the mix parameters, i.e. which aspects have a more influential role in the environmental impact results, coal power is the most influential technology for most of the impact categories while geothermal has a significant influence on the TETP impacts. Biomass power strongly affects ODP impacts. The LCA shows that most of the environmental impacts from electricity use in New Zealand are associated with fossil fuel power plants and to a lesser extent the transmission and distribution (T&D) network, and geothermal power plants. Mining in the coal electricity supply chain contributes significantly to several impact categories.

LCA studies of electricity grid mixes from other countries are difficult to compare due to differences in the share of electricity generation and technologies used to produce it. In particular, this study shows that by building a New Zealand specific electricity LCI model and expanding the impact categories to include a wider

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[9] The author reported values are in mg/l and it is assumed here that 1 mg/l = 1 ppm

range of indicators, leads to a more comprehensive understanding of the environmental impacts of the electricity supply chain. Therefore the results presented here can be used in the future to improve the environmental performance of electricity generation and assess future electricity generation scenarios.

7.2 Comparison of Carbon Footprint Results

The carbon footprint (climate change potential) of the present study was compared with other New Zealand GHG emission values and, for verification purposes, the carbon footprint of each independent electricity system model developed here was compared with other life cycle GHG studies of fossil and renewable energy technologies.

For New Zealand low-voltage electricity, the carbon footprint calculated in the present study of 186 g CO_2-eq per kWh is similar to other estimated GHG emission values. Barber (2011) reported an electricity life cycle emission factor of 192 g CO_2-eq per kWh. The New Zealand electricity dataset from thinkstep® reported a carbon footprint of 165 g CO_2-eq per kWh (this is the “NZ: Electricity Grid Mix 1kV-60kV” dataset) . Although both values were estimated based on LCA methods, they do not consider the associated emissions from the T&D infrastructure. Barber (2011) used the same source of data[10] to estimate fuel emission factors but differed by using climate change potentials from the second IPCC (1995) assessment report. The present study used the CML 2001 – Apr. 2013 climate change potential values from the fourth assessment report (IPCC, 2007). It is unknown, due to the propriety nature of thinkstep’s dataset, which fossil fuel emission factors were used for their estimations. Coelho (2011), on the other hand, estimated the New Zealand carbon footprint at 360 g CO_2-eq per kWh considering the T&D infrastructure. However, her calculations are based on a thermal combustion efficiency of 30%.

Harmonization of carbon footprinting studies has led to a general consensus on expected GHG emissions from renewable and fossil fuel power generation systems. The National Renewable Energy Laboratory (NREL), has systematically reviewed hundreds of LCA studies published since 1970 (NREL, 2014). Using meta-analytical techniques, they managed to reduce the variability and uncertainty inherent in the LCA

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[10] The former Ministry for Economic Development (MED) is now the Ministry for Business, Innovation and Employment.

studies to reach statistical range of values for GHG emissions per unit of electricity produced. Their work resulted in a special issue on the Journal of Industrial Ecology (Lifset, 2012); several publications (O'Donoughue et al., 2014; Whitaker et al., 2012); and was used to support the IPCC report on Renewable Energy Sources and Climate Change Mitigation (Edenhofer et al., 2012).

The life cycle GHG emissions found in this study are in agreement with harmonized results found in the literature (Edenhofer et al., 2012). By looking at the carbon footprint of each individual LCI model in this study (Figure 19) it can be seen that the carbon footprint for natural gas is close to the harmonized median value of 450 g of CO_2-eq per kWh for combined cycle technologies (O'Donoughue et al., 2014).

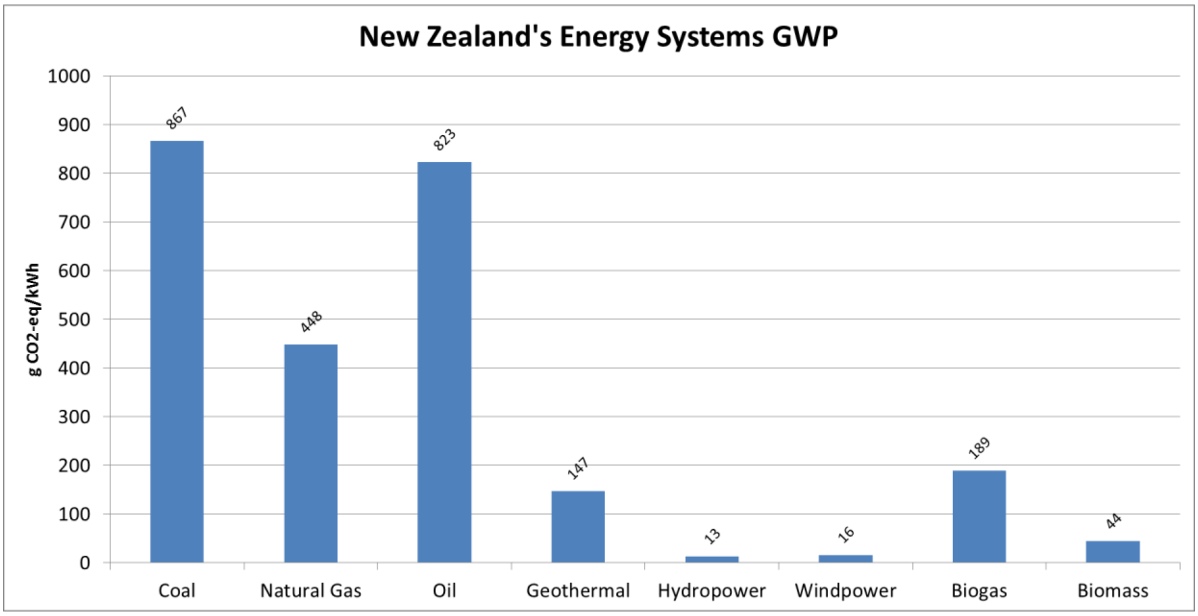

Figure 19 GWP of Individual Energy System Feeding Electricity into the Grid

The New Zealand LCI model for coal power, estimates a carbon footprint of 867 g CO_2-eq per kWh. This value falls well within published values for coal combustion (Masanet et al., 2013) but below the harmonized range of 870-1,120 g CO_2-eq per kWh found by Whitaker et al. (2012). In this study it was assumed that conventional boiler technology with an efficiency of 36% was used for coal combustion. Importantly, integrated gasification and supercritical coal combustion technologies have been found to have lower harmonized range values of life cycle GHG emissions (Whitaker et al., 2012). For oil power the value of 823 g

CO_2-eq per kWh is also well within the published harmonized range and close to the median value published by the IPCC report[11] (Sathaye et al., 2011).

For geothermal power generation, harmonization studies have not been undertaken although the IPCC Report provides a screening of published studies with values below 50 g CO_2-eq per kWh (Goldstein et al., 2011). In New Zealand, the work by Drysdale (2010) assessed the carbon footprint of Tauhara Stage II geothermal power plant. According to the author over a 35 year period 73,185 GWh are generated and 9.56 million tonnes of CO_2-eq are expected to be released. This gives a normalized carbon emission factor for geothermal of 131 g of CO_2-eq per kWh which is close to the value estimated in this study of 147 g CO_2-eq per kWh.

For hydropower, the present study estimated 13 g of CO_2-eq per kWh. This value falls well within the range of reservoir-dam LCA studies screened for consistency by the IPCC Report (Kumar et al., 2011). Rule and colleagues (2009) obtained a much lower value for Clyde reservoir-dam of 4.6 g CO_2-eq; because the authors did not considered emissions from the reservoir.

For wind power, the results in this study fall well within the range of harmonized LCA studies for onshore wind turbines (Dolan & Heath, 2012) although higher than the 3 g CO_2-eq reported by Rule and colleagues (2009). Since generic models were used for wind, biomass and biogas, the values obtained in this study for these power systems should be interpreted as approximations rather than accurate estimates.

7.3 Contribution of the T&D Network to Environmental Impacts

In the present study, the relative contribution of the T&D network infrastructure was found to be relatively high for the ADP Elements, TETP and HTP impact categories. The T&D network contributed to almost 90% of ADP Element impacts, 60% of TETP impacts and nearly 50% of HTP impacts. The low-voltage distribution network requires a high amount of copper (Figure 15, Chapter 6). The default ecoinvent value of copper used in this study is 2.1 tonnes of copper per km of power line. Copper and other metals like

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[11] Page 732 in Chapter 9, Renewable Energy in the Context of Sustainable Development,

aluminium and steel are required for masts, conductors and cables which dominate environmental impacts of the metal depletion category assessed in LCA studies of the T&D infrastructure (Jorge et al., 2011a). For HTP and TETP, the other impact categories where low-voltage distribution has a significant impact, the effects are derived from the emission of heavy metals. Atmospheric emissions of arsenic, selenium, thallium and cadmium contribute significantly to HTP. Emissions of chromium to soil contribute substantially to TETP. Because the aggregated infrastructure LCIs were used, it is hard to assess where these emissions occur. However, they might be associated with upstream activities, specifically for the production of switchgears and transformers, because production of raw materials has been found to make a significant contribution within infrastructure related impacts (Jorge et al., 2011b).

Although the literature on environmental impacts of T&D network is scarce, Jorge et al. (2011a) suggest that the effects of the T&D infrastructure could contribute up to 10% of total life cycle impacts of electricity grid systems. In the present study for New Zealand, inclusion of the T&D infrastructure increased environmental impacts more than 10% for all the 12 environmental impact categories. This is higher than the contribution effects described by Jorge and colleagues (2011a). However the high contribution of the T&D infrastructure was also found to dominate 18 environmental midpoint impact categories in Norway (Hauan, 2014). For example, the T&D network was found to contribute as high as 60% to climate change potential in the Norwegian[12] electricity production mix. In comparison with the NORDEL[13] and RER[14] production mixes which use a higher proportion of fossil fuels, the T&D contributed less than 10% to climate change. Importantly, Hauan (2014) concluded that in grids with a higher percentage of renewable energy technologies, the environmental impacts associated with the T&D network become more relevant (Hauan, 2014). The sensitivity analysis for the New Zealand Electricity LCI Model T&D infrastructure parameters used to adapt the Swiss T&D dataset shows that the most influential parameters are the infrastructure life-time and length. These parameters directly influence the quantity of infrastructure used per kWh of electricity.

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[12] Norway produces 98% of its energy from hydropower (Hauan, 2014)

[13] The NORDEL production mix consists of Swedish, Danish and Finish electricity production (Hauan, 2014)

[14] The RER is the regional European electricity production mix (Hauan, 2014)

7.4 Variability of the LCA Results over Different Time Scales

In this Section the variability of the New Zealand electricity LCA results over different time scales are discussed. In the very short term, there are hourly and seasonal changes in the electricity; for example Messagie et al. (2014) studied variability in the 2011 Belgian electricity grid over these time periods and reported an average of 184 g CO2-eq per KWh with a range of 102 to 262 g CO_2-eq per kWh. In the short-term LCA results for products using electricity in their life cycles may vary with annual changes in the electricity mix. In the longer term LCA results may vary with changes in power plant installed capacity. In this section, the short-term variability will be discussed first, followed by the long-term variability in LCA results.

In New Zealand annual changes in the electricity mix result from variation in rainfall patterns. Within each catchment where hydro dams are located, rainfall patterns change the water level and therefore, directly influence hydropower generation used as base load electricity. The variation in base load electricity supply is balanced using fossil fuelled power plants, geothermal, and to a lesser extent wind, biogas and biomass electricity. Table 43 in Appendix 4 shows annual mixes for 1990 to 2014 and Figure 20 shows the annual generation trend for the same period (MBIE, 2015a). Figure 20 shows hydropower annual fluctuation, and how natural gas is used to compensate for periods when hydropower generation is low. Geothermal and wind generation increase at the end of the analysed period.

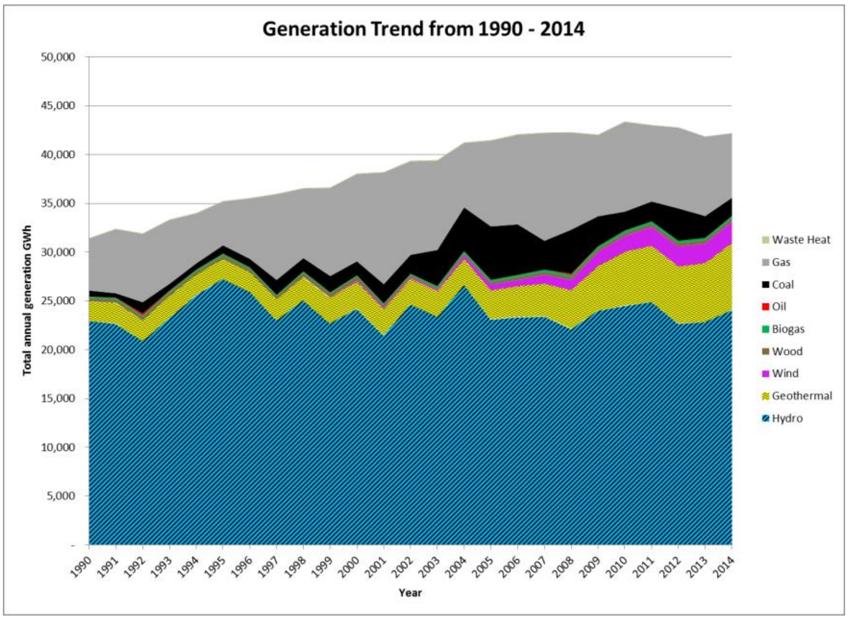


Figure 20 Total Annual Generation of New Zealand Electricity From Different Sources Between 1990 and 2014. Source: MBIE, 2015a

To explore how the LCA results for electricity may change over time, a scenario analysis was undertaken for the 1990-2014 period. The comprehensive LCA results for each annual electricity mix were calculated using the attributional model developed in this research. The results are shown on Figure 21 (Table 44 on Appendix 9) and it can be seen that they are quite variable over time. The most notable effect, comparing Figures 20 and 21, is the influence of coal on almost all environmental impacts. Three spikes can be seen in AP, ADP Fossil, EP, FAETP, HTP, MAETP and POCP. The first spike appears in 1992, the second in 2005 and the third in 2009. All of them coincide with an increase in coal power and a decrease in the share of electricity from renewables (see also the data in Table 43 in Appendix 9). The steady increase in ADP Elements and TETP towards the end of the analysed period is a result of the increase in geothermal and wind generation through time. The proportion of generation from geothermal power increased from 5% to 15%, and generation from wind increased from 1% to 5%, between 2005 and 2013. Previously, it was shown that atmospheric emissions of mercury from geothermal power made a 30% contribution to the TETP impact category (Section 6.1).

To reduce the variability of LCA results over a time period, the Moving Average Window (MAVG) technique was explored. Three, five and ten year MAVG were applied to the impact assessment results for each year (Table 45 in Appendix 9). Table 26 in this Section presents an analysis of the MAVG technique for all the impact category results. The variability of the three moving averages is presented as the range of values within the analysed period and the % change from the minimum to the maximum value. In other words, the table shows the variability of the data within each time period when applying a MAVG of three, five and ten years.

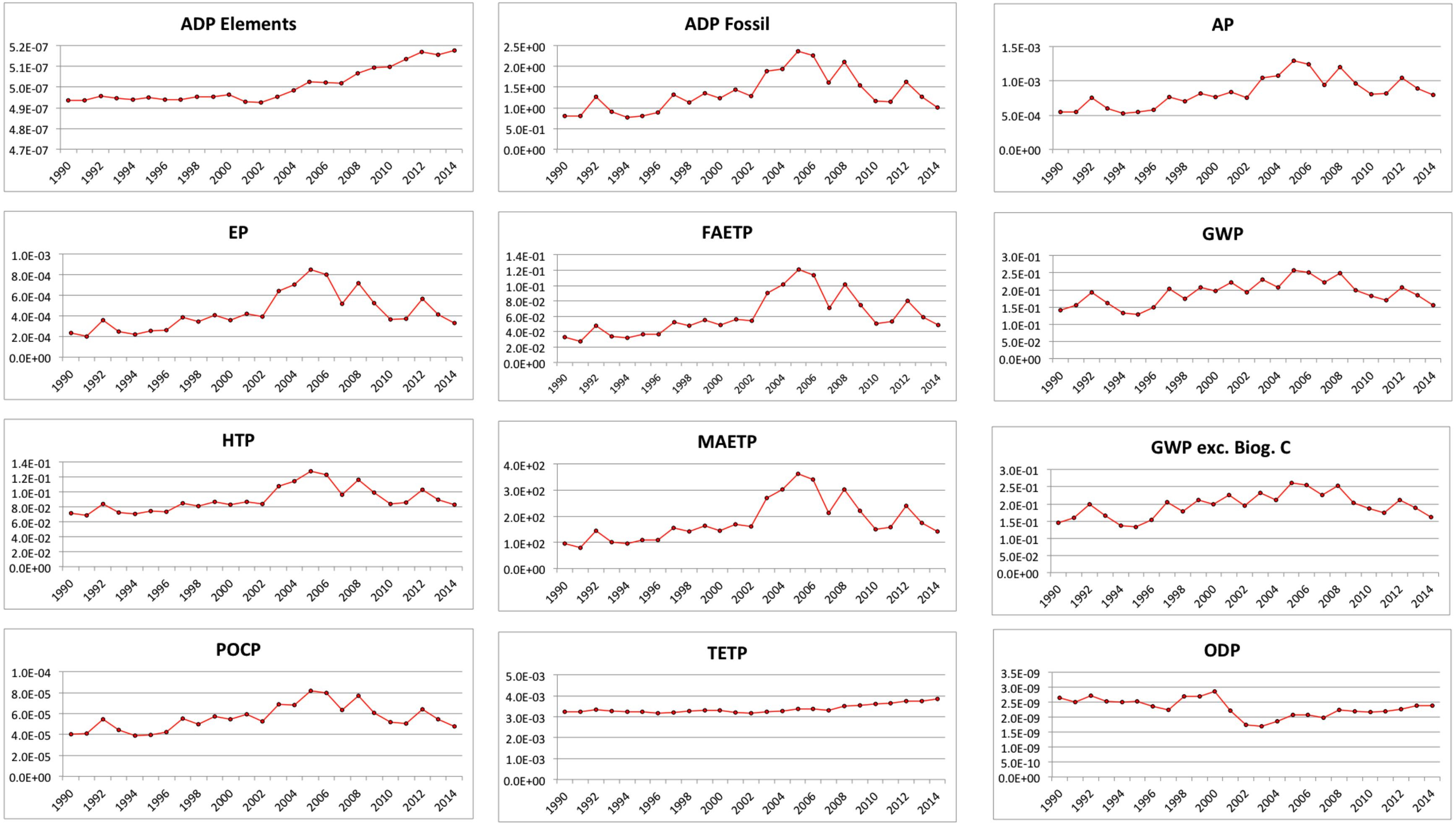


Figure 21 Variability in LCIA Results for Low-Voltage Electricity Supply due to Annual Changes in the Mix, Expected from Seasonal Weather Patterns and Plant Shut-downs for Maintenance and Upgrading, between 1990 and 2014

Table 26 Variability of LCA Results over 24 Year Period Using 3, 5 and 10 Year Moving Averages

	ADP Element [mg Sb-eq]			
	Min	**Max**	**Range**	***% Change***
Annual Mix	0.493	0.518	0.025	*5%*
3 Year MAVG	0.494	0.517	0.023	*5%*
5 Year MAVG	0.494	0.515	0.021	*4%*
10 Year MAVG	0.494	0.510	0.015	*3%*

ADP Fossilf [MJ]			
Min	**Max**	**Range**	**% Change**
0.76	2.38	1.61	*2.12*
0.82	2.19	1.38	*1.68*
0.90	2.06	1.16	*1.28*
1.00	1.77	0.77	*0.77*

AP [g SO2-eq]			
Min	**Max**	**Range**	**% Change**
0.526	1.295	0.768	*146%*
0.548	1.206	0.658	*120%*
0.593	1.151	0.558	*94%*
0.638	1.043	0.406	*64%*

	EP [g PO4-eq]			
	Min	**Max**	**Range**	**% Change**
Annual Mix	0.203	0.852	0.649	*319%*
3 Year MAVG	0.241	0.787	0.546	*226%*
5 Year MAVG	0.253	0.720	0.467	*185%*
10 Year MAVG	0.292	0.607	0.315	*108%*

FAETP [g DCB-eq]			
Min	**Max**	**Range**	**% Change**
27	121	94	*350%*
34	112	78	*229%*
35	102	67	*194%*
40	86	46	*114%*

GWP [g CO2-eq]			
Min	**Max**	**Range**	**% Change**
128	257	129	*101%*
137	244	107	*78%*
153	238	85	*55%*
164	224	59	*36%*

	HTP [g DCB-eq]			
	Min	**Max**	**Range**	**% Change**
Annual Mix	69	128	59	*87%*
3 Year MAVG	73	122	49	*67%*
5 Year MAVG	74	116	42	*57%*
10 Year MAVG	77	106	29	*38%*

MAETP [kg DCB-eq]			
Min	**Max**	**Range**	**% Change**
80	362	282	*351%*
102	336	234	*231%*
103	305	201	*195%*
120	256	136	*114%*

ODP [mg R11-eq]			
Min	**Max**	**Range**	**% Change**
0.0017	0.0029	0.0012	*69%*
0.0018	0.0028	0.0010	*56%*
0.0019	0.0026	0.0007	*37%*
0.0020	0.0026	0.0005	*27%*

	POCP [mg Ethene-eq]			
	Min	**Max**	**Range**	**% Change**
Annual Mix	39	82	44	*113%*
3 Year MAVG	40	77	37	*91%*
5 Year MAVG	44	74	30	*70%*
10 Year MAVG	46	67	20	*44%*

TETP [g DCB-eq]			
Min	**Max**	**Range**	**% Change**
3.17	3.85	0.67	*21%*
3.21	3.78	0.57	*18%*
3.23	3.72	0.50	*15%*
3.24	3.57	0.33	*10%*

As an example of interpretation, Table 26 shows that the three year MAVG results for GWP vary by up to 107 g CO_2-eq and this represents an increase of up to 78% over the minimum result when the MAVGs are calculated over a 24 year period. The five year MAVG will provide GWP results with a range of 85 g and this represents an increase up to 55% over the minimum results when the MAVGs are calculated over the 24 year period. The 10 year MAVG will provide GWP results with a range of 59 g CO_2-eq and this represents an increase of 36% over the minimum results when MAVGs are calculated over the 24 year period. By looking at Figure 22, it is evident that although the 10 year MAVG reduces the variability in LCA results it underestimates or overestimates the carbon footprint for years with a drastic changes in the mix.

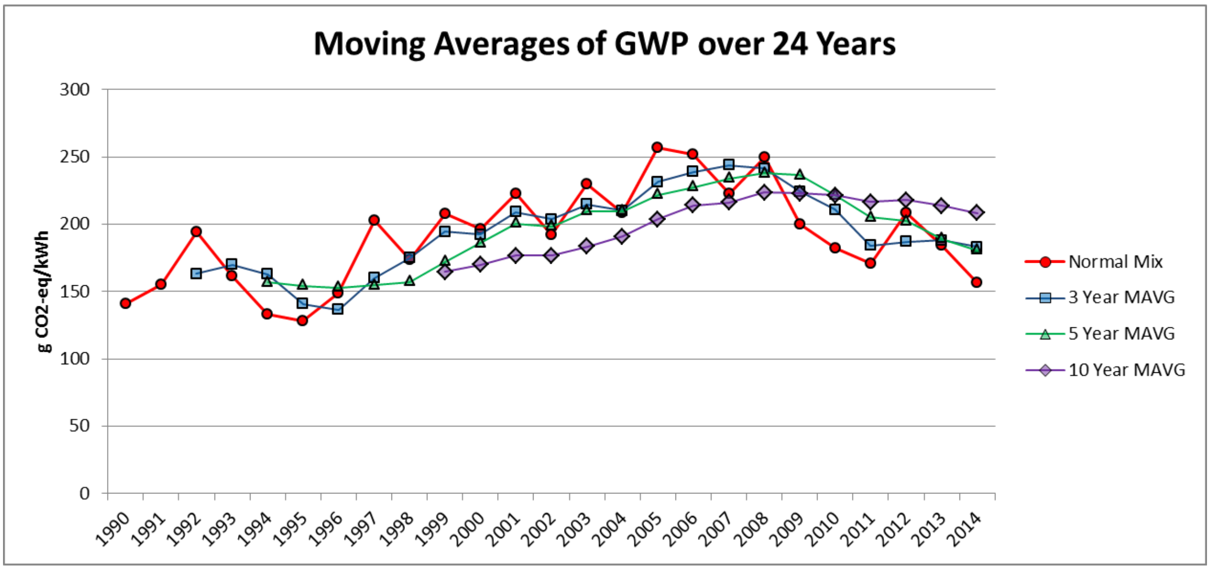


Figure 22 Moving Averages of the Global Warming Potential of 1 kWh Electricity Use over 24 years

In this study, an average case scenario of the New Zealand electricity grid mix was built for the year 2013 i.e. the LCI model is a snapshot of that year. Therefore, emissions for each technology contributing a percentage to the mix were estimated based on an average power plant in the reference year 2013. Due to the variable nature of the mix, over a short time frame (say less than five years); environmental impacts could reasonably be assessed based on this average case scenario by simply changing the percentage contribution of each technology to the grid to fit with the relevant time frame for the LCA study. That is, it can reasonably be assumed that all average technologies used to supply electricity to the grid are the same and will not change within these short time periods, and therefore environmental impacts can be calculated using the electricity LCI model.

However, over longer time periods, the variation in LCA results will be a consequence not only of weather patterns but also of technological changes in the average case scenario. For example, Figure 23 shows the change in power plant installed capacity operating in New Zealand since 1990. These technological changes, will change the average case scenario by an unknown degree and are not reflected in the attributional LCI model for the reference year 2013. This issue is introduced here as an aspect to be considered in LCA studies of products that use electricity over long periods of time.

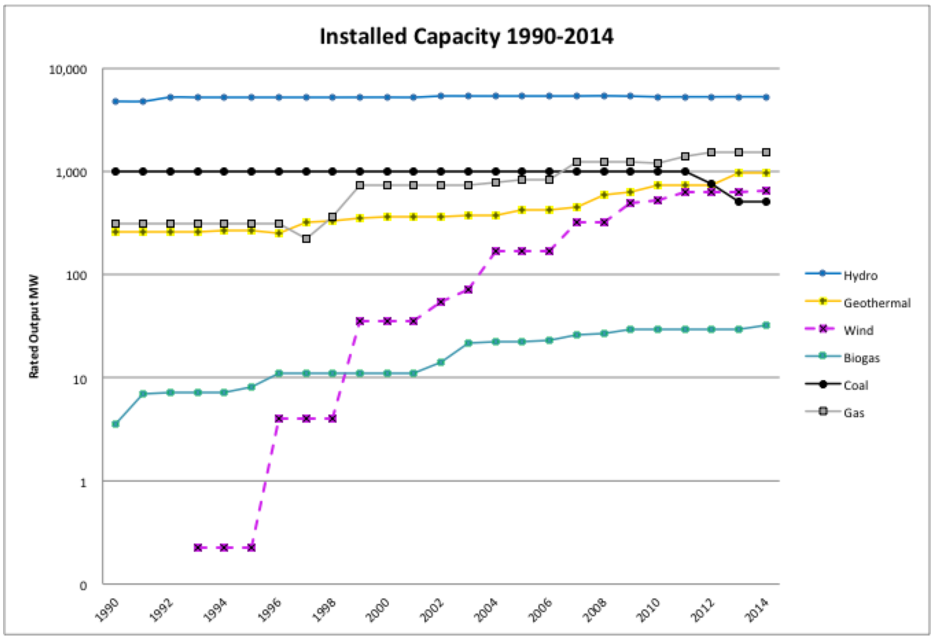


Figure 23 Change in Installed Capacity from 1990-2014. Source: MBIE, 2014b

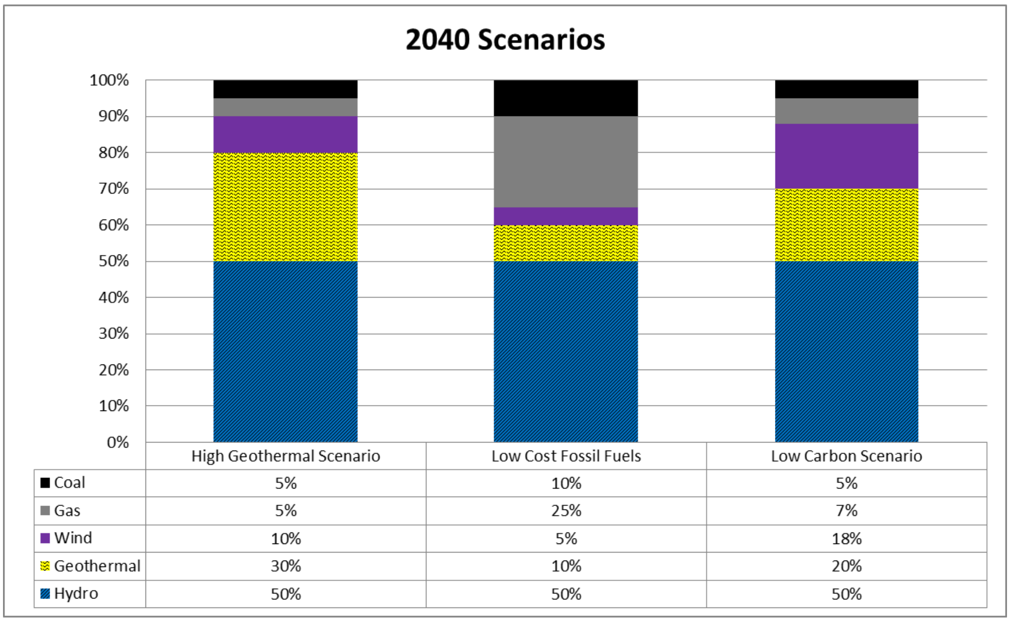
Therefore, for many LCA studies it may be more appropriate to use an average case scenario by calculating the average percentage contribution of each technology to the grid over a longer time period that is appropriate to the focus of the LCA study, and then calculating the associated environmental impacts. For LCA studies over longer time periods however, there are a number of additional modelling challenges related to the change in technologies and in particular, there is a high degree of uncertainty in estimating future environmental impacts associated with electricity generation (Soimakallio, Kiviluoma, & Saikku, 2011). Alternative approaches for such future-oriented LCA studies will be discussed in the following section.

7.5 Attributional vs Consequential Modelling Perspectives in LCA of Electricity

Consequential LCA addresses questions about how flows in a system change as a result of a change in demand over short or long-term time frames (Curran, Mann, & Norris, 2005); i.e. “What if?” scenarios. However, consequential modelling in LCA of energy systems has been argued to be problematic due to challenges in identifying the marginal technologies (Mathiesen, Münster, & Fruergaard, 2009). Marginal technologies are those which are affected by market constraints in the short or the long-term (Ekvall & Weidema, 2004). For example, short-term marginal technologies can be those that are used to meet peak power demands on an hourly basis, and have the highest operational costs (Ekvall & Weidema, 2004). The long-term marginal technologies are those that would most likely be installed due to their lowest long-term costs (Ekvall & Weidema, 2004). In New Zealand, short-term peak power demands are met with thermal generation (Parsons Brinckerhoff, 2012a); the fuels used include natural gas, coal and liquid fuels. However, geothermal power has been identified as the long-term marginal technology (MBIE, 2013a).

An alternative approach to undertaking consequential LCA using marginal technologies is to model future scenarios using an attributional approach (Zamagni, Guinée, Heijungs, Masoni, & Raggi, 2012). MBIE (2013a) presents four future scenarios modelled using energy system analysis: a mixed renewable scenario, a high geothermal access scenario, a low cost fossil fuels scenario, and a global low carbon scenario. Following this approach, a scenario analysis was undertaken using the attributional LCI electricity model developed in this research and based on the following scenarios (see Figure 24):

- High geothermal scenario: geothermal and wind increase generation to 30% and 10% of total capacity. Hydropower will continue to provide half of generation requirements.
- Low-cost fossil fuel scenario: there is increased oil and gas exploration and thus there is a price reduction and more fossil fuel resources. Hydropower continues to provide half of generation requirements.
- Low carbon scenario: wind power is cheaper and technology improvements make it easier to deploy while climate change policy reduces fossil fuels. Hydropower continues to provide half of generation requirements



	High Geothermal Scenario	Low Cost Fossil Fuels	Low Carbon Scenario
■ Coal	5%	10%	5%
■ Gas	5%	25%	7%
■ Wind	10%	5%	18%
▨ Geothermal	30%	10%	20%
▨ Hydro	50%	50%	50%

Figure 24 Scenario Analysis for the New Zealand Electricity Grid for the Year 2040 Considering Three Alternative Production Mixes

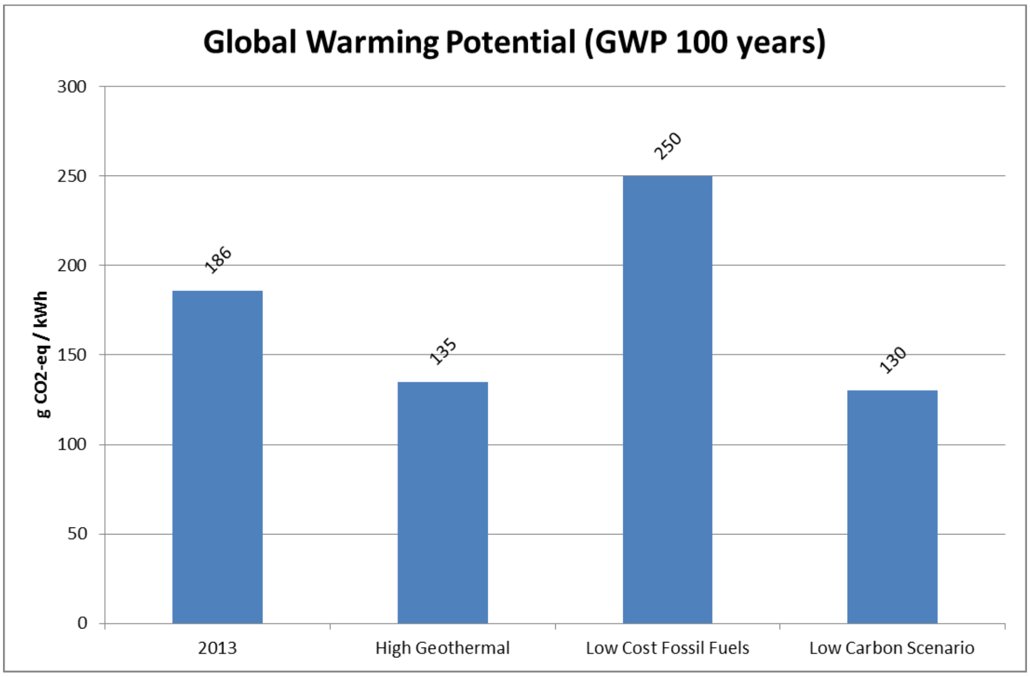


Figure 25 Carbon Footprint of the Scenario Analysis for the Year 2040

Using the LCA models of the different technologies, the carbon footprint of 1 kWh electricity delivered to a final consumer was calculated for the three scenarios. Figure 25 shows the low-cost fossil fuel scenario has the highest carbon footprint (250 g CO_2-eq per kWh which is 35% higher than the carbon footprint for electricity in 2013). The high geothermal scenario has a carbon footprint that is 27% lower than the 2013 value. The low-carbon scenario has a carbon footprint that is 30% lower than the 2013 value. Of course, these results are based on the simplifying assumption that the different generation technologies and associated environmental impacts are the same in 2040 as they are in 2013.

In this analysis, the short-term marginal technologies in the scenario analysis have a higher carbon footprint than the long-term marginal technologies and thus play a dominant role in the final carbon footprint results. Therefore, in future-oriented LCA studies the approach selected to model LCA impacts will highly influence LCA results.

Chapter 8 Conclusions and Recommendations

As discussed in Chapter 1, the aim of this research was to assess the life cycle-based-environmental impacts associated with the generation and use of 1 kWh New Zealand electricity. In addition, this research also aimed to understand the effects of: 1) the transmission and distribution of electricity; 2) temporal variability in LCA impact category results using 3, 5 and 10 year moving averages; and 3) attributional versus consequential modelling perspectives on the LCA results. The conclusions are discussed in the following sections.

8.1 Life Cycle Assessment of 1 kWh New Zealand Electricity

The LCA results show that fossil fuel generation technologies are the main contributors to most of the environmental impacts associated with New Zealand electricity. More specifically, electricity produced from coal contributes more than 70% of the total results for EP, FAETP and MAETP; between 50 and 69% of the total results for ADP; and between 30 and 49% of the total results for AP, HTP and POCP. The operation of the coal power station is the hotspot in four of the impact categories. Treatment of spoil from open cast mines is associated with emissions of a wide range of substances to water, soil and air. Other significant sources of environmental impacts derive from the transmission and distribution network; in particular, the low-voltage distribution network contributes 50 to 90% of the total results for ADP Fossil, HTP and TETP. Electricity produced from geothermal resources is associated with emissions of hydrogen sulphide and mercury that contribute approximately 30% of the total results for AP and TETP. The high contribution of electricity from biomass to ODP results is due to trichlorotrifluoroethane emissions. The carbon footprint (GWP) of 1 kWh low-voltage electricity is 186 g CO_2-eq per kWh.

8.2 Effects of Transmission and Associated Voltage Transformation

Stepping down high-voltage electricity to medium-voltage increases the results for all impact categories between 2% and 6%. Adding the medium-voltage infrastructure network increases impacts anywhere from 10 to 14%. The effects of stepping down electricity from medium to low-voltage increase environmental impacts from 10 to 41% with the exception of ADP Elements, HTP, and TETP whose results increase more than 100%. The consumption of copper, aluminium and steel to produce the transmission and distribution infrastructure is the leading cause of the T&D network's high contribution to ADP. Production of materials to produce switchgear and transformers might be the cause for upstream emissions of the T&D infrastructure that contribute to HTP and TETP.

8.3 Effects of temporal variability in LCA impact category results

The variability in the New Zealand electricity LCA results over short time frames are primarily due to changes in weather patterns (hourly, seasonal, annually). Weather patterns affect wind power on a daily basis, and hydropower on a seasonal basis. Fossil fuelled and geothermal power plants are used for base load and dispatchable electricity generation. Over longer time frames (5 to 10 years), variability in LCA impact categories would be related to changes in power plant installed capacity.

To investigate the variability in LCA results, 3, 5, and 10 year moving averages were analysed between 1990 and 2014. Not surprisingly, use of a 10 year moving average led to the greatest reduction in the variability in LCA results. Therefore, for near-term attributional LCA studies of products using electricity over short time frames, it is suggested to use a representative average of the electricity mix over that time period. For benchmarking LCA studies of products (i.e. where products are assessed year-on-year) within 3 year time frames a 3 year moving average could provide a reasonable reduction in variability.

For far-term prospective studies, i.e. 5 to 10 years, that will be affected by changes in installed capacity, a scenario analysis might provide an alternative approach to consequential LCA.

8.4 Attributional versus consequential modelling perspectives in the LCA results

The three scenarios assessed for the year 2040 using the attributional LCI model as an alternative approach to consequential LCA, provide insights into possible future electricity carbon footprint scenarios. The worst-case scenario, one with low-cost fossil fuels in the market, would increase the carbon footprint in 35% of the 2013 value. On the other hand, an increase of 30 % geothermal electricity or an increase to 18% of wind power in the grid mix could reduce the carbon footprint up to 30% of the 2013 base case. Importantly, the modelling approach used to identify the long and short-term marginal technologies play a crucial role in the outcome of carbon footprints results.

8.5 Recommendations for Future Areas of Research

Using European datasets that are easily accessed in the ecoinvent database is common practice in most LCA studies. This study used these datasets as a baseline and adapted them using New Zealand data. Use of more New Zealand-specific data would improve this dataset. For example, emission data from power stations could be collected from Monitoring Consent Reports held by New Zealand Regional Councils. This could be made easier by enhancing the accessibility of data in consent monitoring reports, and even developing reporting protocols for these consent reports based on life cycle principles. This could streamline LCA studies for upstream and downstream activities related to electricity generation (and other services).

In particular, based on the results of this study, it is a high priority to estimate site-specific emissions from coal mining activities in New Zealand. These were shown to have a significant effect on several life-cycle environmental impact categories for 1 kWh New Zealand electricity. Due to the high contribution of fossil fuelled power plants to overall environmental impacts, increasing the temporal resolution of electricity generation by fossil fuel type during an annual cycle would provide a better understanding of greenhouse gas emissions. Fossil fuelled power plants are used to compensate for weather variations and supply peak power demands and thus are variable throughout the year. There is also a percentage of cogeneration plant that switch from biomass to fossil fuels, and in this study this issues were not explored. However increasing temporal resolution would provide a clearer picture of how these issues affect overall life-cycle environmental impacts.

For the transmission and distribution infrastructure in New Zealand, the cumulative LCI Swiss datasets were used and adapted to New Zealand specific conditions using length and life time parameters. As shown by the work of Hahuan (2014) on electricity grid mixes with a higher share of renewables, the environmental impacts of the transmission and distribution become more relevant. Although total annual emission of CO_2 and SF_6 are reported by Transpower, It is unknown at which stage of the supply chain and voltage step these emissions occur. Therefore, in order to improve the New Zealand electricity life cycle inventory model, complete supply chain models for the T&D network could improve the accuracy and understanding of life-cycle environmental impacts of electricity transmission and distribution.

Finally, in this study, hydropower methane emissions were assumed based on the ecoinvent system model dataset of a Swiss hydropower plant at 6 g CO_2-eq per kWh. This value was chosen as a conservative approach because first, there are no studies reporting methane emissions from hydropower reservoirs in New Zealand. Second, the literature on methane emissions from hydropower reservoirs is under strong debate and report a wide range of values from mg to 10s of kg (Hertwich, 2013). An intensive literature review, on methane and carbon dioxide emissions from man-made reservoirs in similar latitudes as New Zealand could probably allow an estimation of a reasonable range of emission factor, until local studies could be conducted.

8.6 Conclusions

In this study 12 life cycle-based environmental impacts were assessed, expanding the scope from previous New Zealand carbon footprinting studies and building an improved version of the New Zealand electricity life cycle inventory dataset. This research is therefore, the first comprehensive LCA study made publicly available, that provides a better understanding of New Zealand's electricity supply chain. By using single-unit operation processes rather than aggregated inventory datasets it becomes easier to adapt models to site-specific conditions. It also allows identification of environmental hotspots that would be hard to identify in aggregated datasets. Specifically, the high contribution from fossil fuelled power plants to several impact categories reinforces the need to focus on these technologies when considering improvements. The results of this research are not only relevant to the LCA academic community, they are also a valuable benchmark for the electricity industry and policy makers that will support initiatives to improve the environmental performance of power plants and support New Zealand's energy sector greenhouse gas mitigation strategies.

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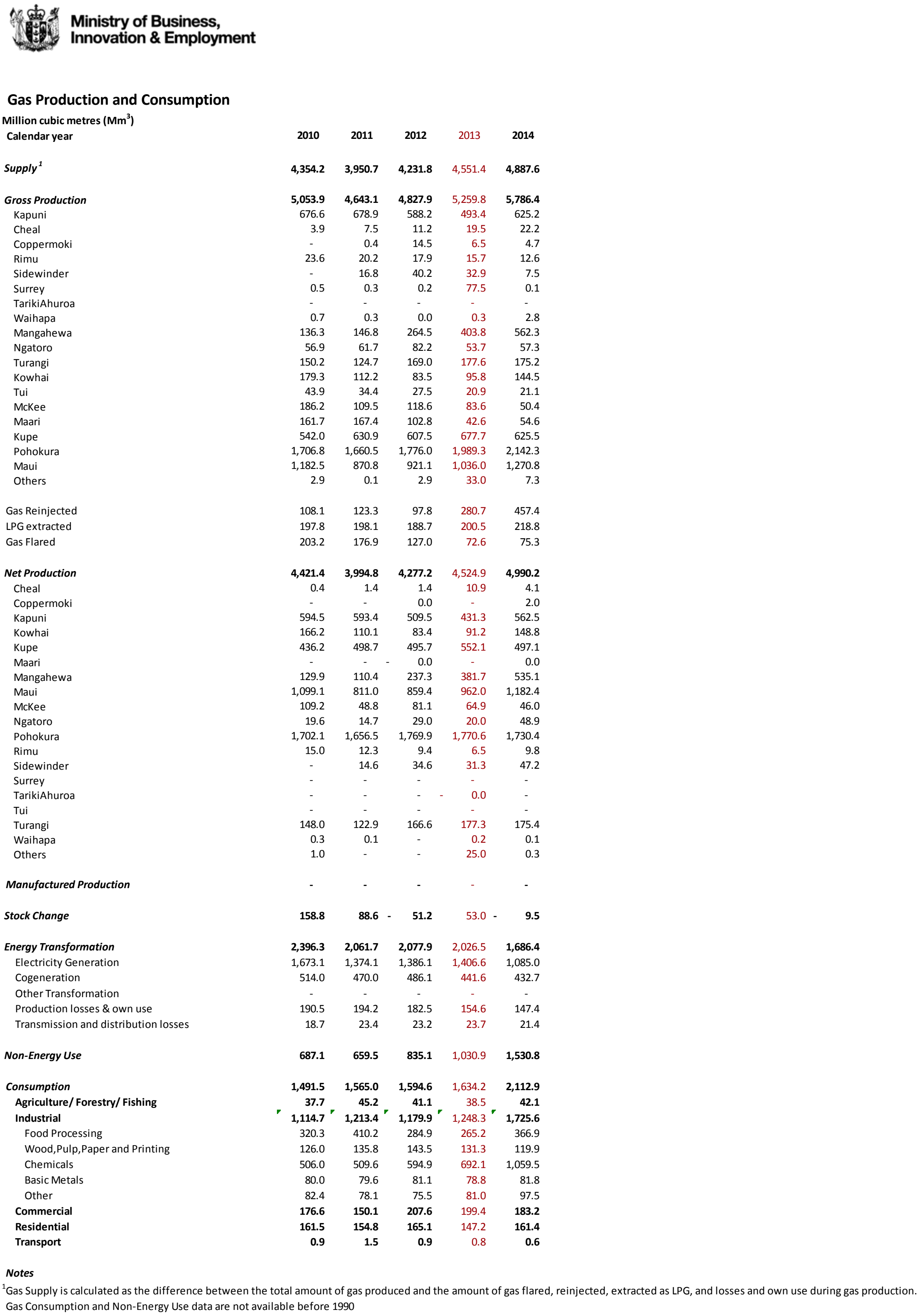
Appendix 1 MBIE Energy in New Zealand Annual Production Volumes

The Energy & Building Trends from the Ministry of Business, Innovation & Employment reports annual statistics which are available from the MBIE website: http://www.mbie.govt.nz/info-services/sectors-industries/energy/energy-data-modelling/statistics

Table 27 Annual Gas Production Volumes. Source MBIE Energy in New Zealand # 14 Web Tables http://www.mbie.govt.nz/info-services/sectors-industries/energy/energy-data-modelling/statistics/gas



Ministry of Business, Innovation & Employment

Gas Production and Consumption

Million cubic metres (Mm^3)

Calendar year	2010	2011	2012	2013	2014
Supply[1]	**4,354.2**	**3,950.7**	**4,231.8**	4,551.4	**4,887.6**
Gross Production	**5,053.9**	**4,643.1**	**4,827.9**	5,259.8	**5,786.4**
Kapuni	676.6	678.9	588.2	493.4	625.2
Cheal	3.9	7.5	11.2	19.5	22.2
Coppermoki	-	0.4	14.5	6.5	4.7
Rimu	23.6	20.2	17.9	15.7	12.6
Sidewinder	-	16.8	40.2	32.9	7.5
Surrey	0.5	0.3	0.2	77.5	0.1
TarikiAhuroa	-	-	-	-	-
Waihapa	0.7	0.3	0.0	0.3	2.8
Mangahewa	136.3	146.8	264.5	403.8	562.3
Ngatoro	56.9	61.7	82.2	53.7	57.3
Turangi	150.2	124.7	169.0	177.6	175.2
Kowhai	179.3	112.2	83.5	95.8	144.5
Tui	43.9	34.4	27.5	20.9	21.1
McKee	186.2	109.5	118.6	83.6	50.4
Maari	161.7	167.4	102.8	42.6	54.6
Kupe	542.0	630.9	607.5	677.7	625.5
Pohokura	1,706.8	1,660.5	1,776.0	1,989.3	2,142.3
Maui	1,182.5	870.8	921.1	1,036.0	1,270.8
Others	2.9	0.1	2.9	33.0	7.3
Gas Reinjected	108.1	123.3	97.8	280.7	457.4
LPG extracted	197.8	198.1	188.7	200.5	218.8
Gas Flared	203.2	176.9	127.0	72.6	75.3
Net Production	**4,421.4**	**3,994.8**	**4,277.2**	4,524.9	**4,990.2**
Cheal	0.4	1.4	1.4	10.9	4.1
Coppermoki	-	-	0.0	-	2.0
Kapuni	594.5	593.4	509.5	431.3	562.5
Kowhai	166.2	110.1	83.4	91.2	148.8
Kupe	436.2	498.7	495.7	552.1	497.1
Maari	-	-	- 0.0	-	0.0
Mangahewa	129.9	110.4	237.3	381.7	535.1
Maui	1,099.1	811.0	859.4	962.0	1,182.4
McKee	109.2	48.8	81.1	64.9	46.0
Ngatoro	19.6	14.7	29.0	20.0	48.9
Pohokura	1,702.1	1,656.5	1,769.9	1,770.6	1,730.4
Rimu	15.0	12.3	9.4	6.5	9.8
Sidewinder	-	14.6	34.6	31.3	47.2
Surrey	-	-	-	-	-
TarikiAhuroa	-	-	-	- 0.0	-
Tui	-	-	-	-	-
Turangi	148.0	122.9	166.6	177.3	175.4
Waihapa	0.3	0.1	-	0.2	0.1
Others	1.0	-	-	25.0	0.3
Manufactured Production	**-**	**-**	**-**	-	**-**
Stock Change	**158.8**	**88.6**	**- 51.2**	53.0	**- 9.5**
Energy Transformation	**2,396.3**	**2,061.7**	**2,077.9**	2,026.5	**1,686.4**
Electricity Generation	1,673.1	1,374.1	1,386.1	1,406.6	1,085.0
Cogeneration	514.0	470.0	486.1	441.6	432.7
Other Transformation	-	-	-	-	-
Production losses & own use	190.5	194.2	182.5	154.6	147.4
Transmission and distribution losses	18.7	23.4	23.2	23.7	21.4
Non-Energy Use	**687.1**	**659.5**	**835.1**	1,030.9	**1,530.8**
Consumption	**1,491.5**	**1,565.0**	**1,594.6**	1,634.2	**2,112.9**
Agriculture/ Forestry/ Fishing	**37.7**	**45.2**	**41.1**	38.5	**42.1**
Industrial	**1,114.7**	**1,213.4**	**1,179.9**	1,248.3	**1,725.6**
Food Processing	320.3	410.2	284.9	265.2	366.9
Wood,Pulp,Paper and Printing	126.0	135.8	143.5	131.3	119.9
Chemicals	506.0	509.6	594.9	692.1	1,059.5
Basic Metals	80.0	79.6	81.1	78.8	81.8
Other	82.4	78.1	75.5	81.0	97.5
Commercial	**176.6**	**150.1**	**207.6**	199.4	**183.2**
Residential	**161.5**	**154.8**	**165.1**	147.2	**161.4**
Transport	**0.9**	**1.5**	**0.9**	0.8	**0.6**

Notes

[1] Gas Supply is calculated as the difference between the total amount of gas produced and the amount of gas flared, reinjected, extracted as LPG, and losses and own use during gas production.

Gas Consumption and Non-Energy Use data are not available before 1990

Table 28 Annual Coal Supply, Transformation & Consumption. Source: MBIE Energy in New Zealand #14 Web Tables
http://www.mbie.govt.nz/info-services/sectors-industries/energy/energy-data-modelling/statistics/coal

Ministry of Business, Innovation & Employment

Annual Coal Supply, Transformation, & Consumption (Tonnes)

Year	**2010**	**2011**	**2012**	**2013**	**2014**
Supply	**2,644,603**	**2,831,604**	**3,250,080**	**2,914,553**	**2,434,717**
Production	**5,330,536**	**4,944,783**	**4,926,225**	**4,625,463**	**3,983,764**
Bituminous	**2,597,394**	**2,330,401**	**2,276,346**	**2,279,257**	**1,939,353**
Underground	956,826	572,195	245,873	154,525	189,577
Opencast	1,640,568	1,758,206	2,030,473	2,124,732	1,758,386
Sub-bituminous	**2,438,208**	**2,294,238**	**2,323,960**	**2,055,801**	**1,727,719**
Underground	394,610	345,289	349,878	176,992	106,922
Opencast	2,043,598	1,948,949	1,974,082	1,878,809	1,620,797
Lignite	**294,934**	**320,144**	**325,919**	**290,405**	**316,692**
Underground	0	0	0	0	0
Opencast	294,934	320,144	325,919	290,405	316,692
Imports	**251,151**	**171,406**	**1,380**	**519,490**	**30,585**
Bituminous	52,095	33,669	1,339	61,842	30,465
Sub-bituminous	198,952	137,717	0	457,628	0
Lignite	103	20	40	20	120
Exports	**2,420,196**	**2,159,835**	**2,210,341**	**2,095,644**	**1,741,314**
Bituminous	2,420,196	2,150,976	2,210,341	2,095,644	1,719,317
Sub-bituminous	0	8,859	0	0	21,997
Lignite	0	0	0	0	0
Stock Change	**516,888**	**124,750**	**-532,816**	**134,756**	**-161,682**
Transformation	**1,518,832**	**1,641,505**	**2,216,888**	**1,726,284**	**1,611,223**
Electricity Generation	637,386	760,810	1,347,162	811,638	610,776
Bituminous	0	0	0	0	0
Sub-bituminous	637,386	760,810	1,347,162	811,638	610,776
Lignite	0	0	0	0	0
Cogeneration	374,983	330,294	355,982	370,881	374,113
Bituminous	0	0	0	0	0
Sub-bituminous	358,510	314,973	343,063	358,657	361,422
Lignite	16,473	15,321	12,919	12,224	12,691
Other Transformation	484,932	525,550	508,054	533,541	545,615
Production Losses and Own Use	21,532	24,850	5,691	10,225	80,719
Consumption	**1,145,558**	**1,148,451**	**1,191,766**	**1,242,042**	**1,254,047**
Agriculture/ Forestry/ Fishing	87,709	127,514	169,880	146,814	76,930
Industrial	952,928	906,913	922,995	1,001,957	1,102,190
Commercial	72,392	71,793	75,180	74,023	54,548
Residential	30,407	40,388	22,933	17,805	19,774
Transport	2,122	1,843	779	1,444	604

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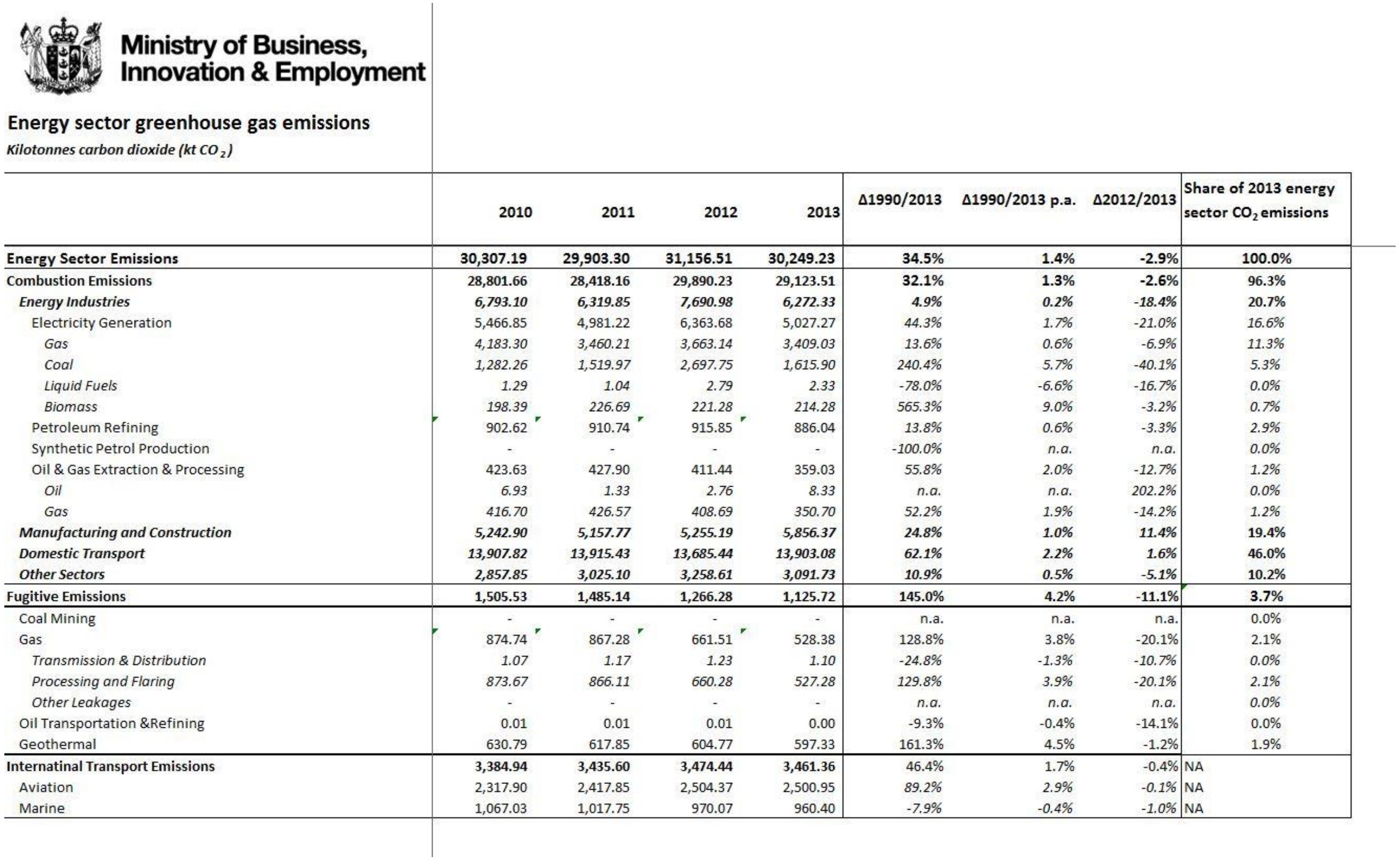
Notes:
1 Imports are bituminous and sub-bituminous coal.
2 Majority of coal exports are bituminous rank.
3 Stock change figures include coal at Huntly power station, NZ Steel and coal production sites.
4 Includes electricity generation, cogeneration, and losses and own use.

Appendix 2 MBIE Energy Sector Greenhouse Gas Emission Excel Web Tables

The Ministry of Business, Innovation and Employment is the entity in charge of statistical information for electricity greenhouse gas emissions. Excel tables can be downloaded from the following link: http://www.mbie.govt.nz/info-services/sectors-industries/energy/energy-data-modelling/statistics/greenhouse-gas-emissions

Table 29 Energy Sector Annual Carbon Dioxide Emissions. Source: MBIE, 2015



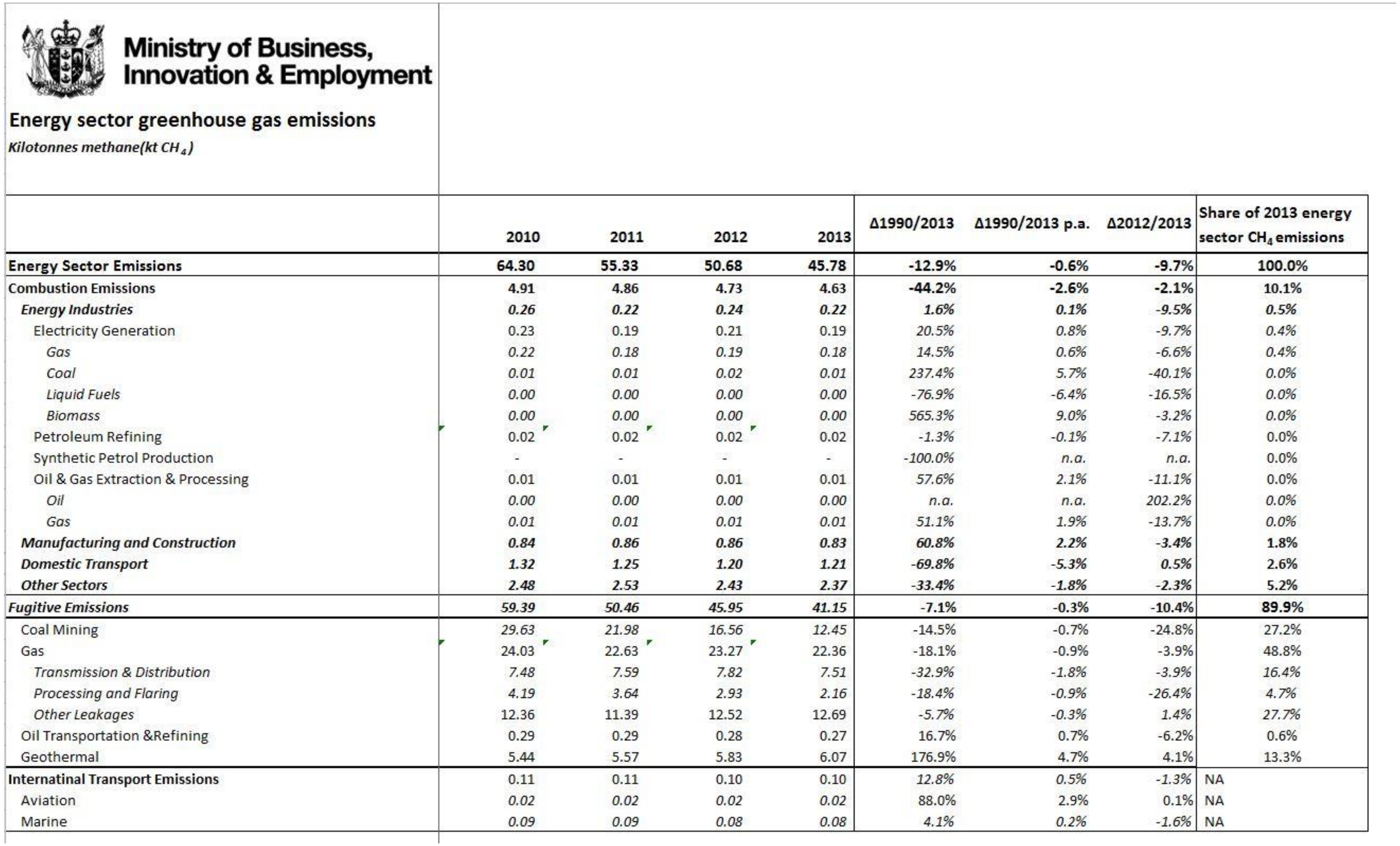
Ministry of Business, Innovation & Employment

Energy sector greenhouse gas emissions

Kilotonnes carbon dioxide (kt CO_2)

	2010	2011	2012	2013	Δ1990/2013	Δ1990/2013 p.a.	Δ2012/2013	Share of 2013 energy sector CO_2 emissions
Energy Sector Emissions	**30,307.19**	**29,903.30**	**31,156.51**	**30,249.23**	**34.5%**	**1.4%**	**-2.9%**	**100.0%**
Combustion Emissions	**28,801.66**	**28,418.16**	**29,890.23**	**29,123.51**	**32.1%**	**1.3%**	**-2.6%**	**96.3%**
Energy Industries	***6,793.10***	***6,319.85***	***7,690.98***	***6,272.33***	***4.9%***	***0.2%***	***-18.4%***	**20.7%**
Electricity Generation	5,466.85	4,981.22	6,363.68	5,027.27	*44.3%*	*1.7%*	*-21.0%*	*16.6%*
Gas	*4,183.30*	*3,460.21*	*3,663.14*	*3,409.03*	*13.6%*	*0.6%*	*-6.9%*	*11.3%*
Coal	*1,282.26*	*1,519.97*	*2,697.75*	*1,615.90*	*240.4%*	*5.7%*	*-40.1%*	*5.3%*
Liquid Fuels	*1.29*	*1.04*	*2.79*	*2.33*	*-78.0%*	*-6.6%*	*-16.7%*	*0.0%*
Biomass	*198.39*	*226.69*	*221.28*	*214.28*	*565.3%*	*9.0%*	*-3.2%*	*0.7%*
Petroleum Refining	902.62	910.74	915.85	886.04	*13.8%*	*0.6%*	*-3.3%*	*2.9%*
Synthetic Petrol Production	-	-	-	-	*-100.0%*	*n.a.*	*n.a.*	*0.0%*
Oil & Gas Extraction & Processing	423.63	427.90	411.44	359.03	*55.8%*	*2.0%*	*-12.7%*	*1.2%*
Oil	*6.93*	*1.33*	*2.76*	*8.33*	*n.a.*	*n.a.*	*202.2%*	*0.0%*
Gas	*416.70*	*426.57*	*408.69*	*350.70*	*52.2%*	*1.9%*	*-14.2%*	*1.2%*
Manufacturing and Construction	***5,242.90***	***5,157.77***	***5,255.19***	***5,856.37***	***24.8%***	***1.0%***	***11.4%***	**19.4%**
Domestic Transport	***13,907.82***	***13,915.43***	***13,685.44***	***13,903.08***	***62.1%***	***2.2%***	***1.6%***	**46.0%**
Other Sectors	***2,857.85***	***3,025.10***	***3,258.61***	***3,091.73***	***10.9%***	***0.5%***	***-5.1%***	**10.2%**
Fugitive Emissions	**1,505.53**	**1,485.14**	**1,266.28**	**1,125.72**	**145.0%**	**4.2%**	**-11.1%**	**3.7%**
Coal Mining	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Gas	874.74	867.28	661.51	528.38	128.8%	3.8%	-20.1%	2.1%
Transmission & Distribution	*1.07*	*1.17*	*1.23*	*1.10*	*-24.8%*	*-1.3%*	*-10.7%*	*0.0%*
Processing and Flaring	*873.67*	*866.11*	*660.28*	*527.28*	*129.8%*	*3.9%*	*-20.1%*	*2.1%*
Other Leakages	-	-	-	-	*n.a.*	*n.a.*	*n.a.*	*0.0%*
Oil Transportation &Refining	0.01	0.01	0.01	0.00	-9.3%	-0.4%	-14.1%	0.0%
Geothermal	630.79	617.85	604.77	597.33	161.3%	4.5%	-1.2%	1.9%
Internatinal Transport Emissions	**3,384.94**	**3,435.60**	**3,474.44**	**3,461.36**	46.4%	1.7%	-0.4%	NA
Aviation	2,317.90	2,417.85	2,504.37	2,500.95	*89.2%*	*2.9%*	*-0.1%*	NA
Marine	1,067.03	1,017.75	970.07	960.40	*-7.9%*	*-0.4%*	*-1.0%*	NA

Table 30 Energy Sector Annual Methane Emissions. Source: MBIE, 2015



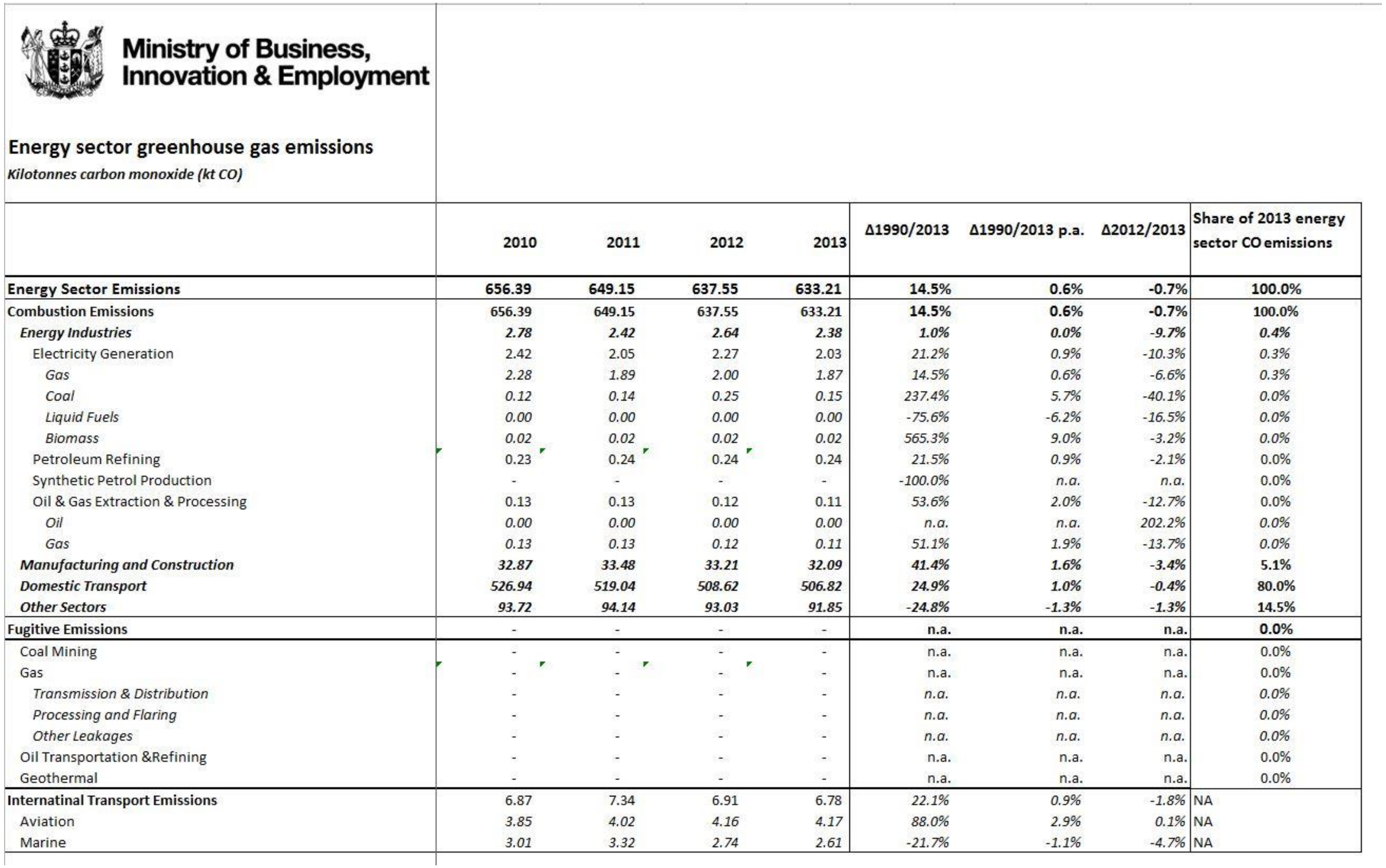
Ministry of Business, Innovation & Employment

Energy sector greenhouse gas emissions

Kilotonnes methane(kt CH_4)

	2010	2011	2012	2013	Δ1990/2013	Δ1990/2013 p.a.	Δ2012/2013	Share of 2013 energy sector CH_4 emissions
Energy Sector Emissions	64.30	55.33	50.68	45.78	-12.9%	-0.6%	-9.7%	100.0%
Combustion Emissions	4.91	4.86	4.73	4.63	-44.2%	-2.6%	-2.1%	10.1%
Energy Industries	0.26	0.22	0.24	0.22	1.6%	0.1%	-9.5%	0.5%
Electricity Generation	0.23	0.19	0.21	0.19	20.5%	0.8%	-9.7%	0.4%
Gas	0.22	0.18	0.19	0.18	14.5%	0.6%	-6.6%	0.4%
Coal	0.01	0.01	0.02	0.01	237.4%	5.7%	-40.1%	0.0%
Liquid Fuels	0.00	0.00	0.00	0.00	-76.9%	-6.4%	-16.5%	0.0%
Biomass	0.00	0.00	0.00	0.00	565.3%	9.0%	-3.2%	0.0%
Petroleum Refining	0.02	0.02	0.02	0.02	-1.3%	-0.1%	-7.1%	0.0%
Synthetic Petrol Production	-	-	-	-	-100.0%	n.a.	n.a.	0.0%
Oil & Gas Extraction & Processing	0.01	0.01	0.01	0.01	57.6%	2.1%	-11.1%	0.0%
Oil	0.00	0.00	0.00	0.00	n.a.	n.a.	202.2%	0.0%
Gas	0.01	0.01	0.01	0.01	51.1%	1.9%	-13.7%	0.0%
Manufacturing and Construction	0.84	0.86	0.86	0.83	60.8%	2.2%	-3.4%	1.8%
Domestic Transport	1.32	1.25	1.20	1.21	-69.8%	-5.3%	0.5%	2.6%
Other Sectors	2.48	2.53	2.43	2.37	-33.4%	-1.8%	-2.3%	5.2%
Fugitive Emissions	59.39	50.46	45.95	41.15	-7.1%	-0.3%	-10.4%	89.9%
Coal Mining	29.63	21.98	16.56	12.45	-14.5%	-0.7%	-24.8%	27.2%
Gas	24.03	22.63	23.27	22.36	-18.1%	-0.9%	-3.9%	48.8%
Transmission & Distribution	7.48	7.59	7.82	7.51	-32.9%	-1.8%	-3.9%	16.4%
Processing and Flaring	4.19	3.64	2.93	2.16	-18.4%	-0.9%	-26.4%	4.7%
Other Leakages	12.36	11.39	12.52	12.69	-5.7%	-0.3%	1.4%	27.7%
Oil Transportation &Refining	0.29	0.29	0.28	0.27	16.7%	0.7%	-6.2%	0.6%
Geothermal	5.44	5.57	5.83	6.07	176.9%	4.7%	4.1%	13.3%
Internatinal Transport Emissions	0.11	0.11	0.10	0.10	12.8%	0.5%	-1.3%	NA
Aviation	0.02	0.02	0.02	0.02	88.0%	2.9%	0.1%	NA
Marine	0.09	0.09	0.08	0.08	4.1%	0.2%	-1.6%	NA

Table 31 Energy Sector Annual Carbon Monoxide Emissions. Source: MBIE, 2015



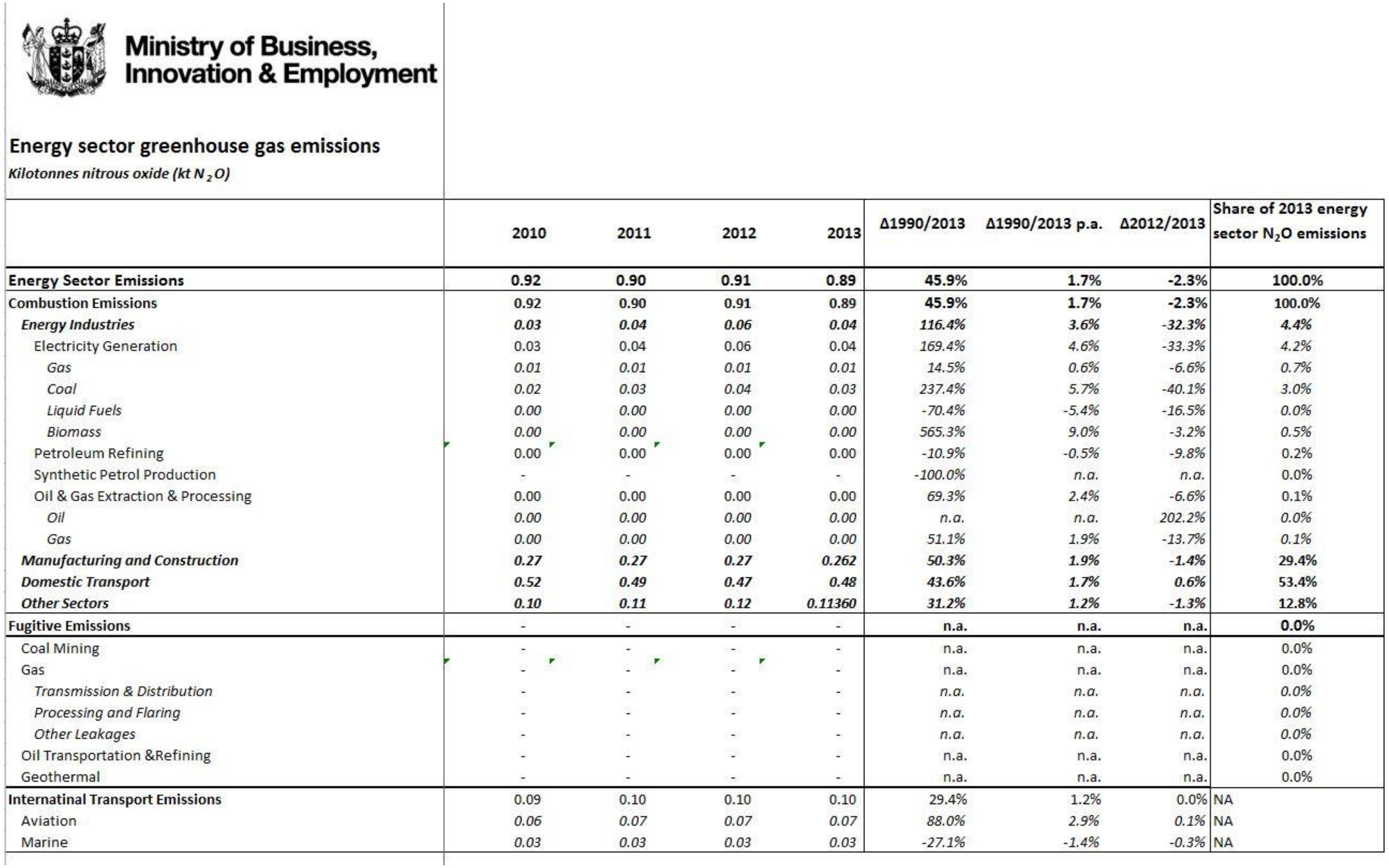
Ministry of Business, Innovation & Employment

Energy sector greenhouse gas emissions

Kilotonnes carbon monoxide (kt CO)

	2010	2011	2012	2013	Δ1990/2013	Δ1990/2013 p.a.	Δ2012/2013	Share of 2013 energy sector CO emissions
Energy Sector Emissions	**656.39**	**649.15**	**637.55**	**633.21**	**14.5%**	**0.6%**	**-0.7%**	**100.0%**
Combustion Emissions	656.39	649.15	637.55	633.21	**14.5%**	**0.6%**	**-0.7%**	100.0%
Energy Industries	***2.78***	***2.42***	***2.64***	***2.38***	***1.0%***	***0.0%***	*-9.7%*	***0.4%***
Electricity Generation	2.42	2.05	2.27	2.03	*21.2%*	*0.9%*	*-10.3%*	*0.3%*
Gas	*2.28*	*1.89*	*2.00*	*1.87*	*14.5%*	*0.6%*	*-6.6%*	*0.3%*
Coal	*0.12*	*0.14*	*0.25*	*0.15*	*237.4%*	*5.7%*	*-40.1%*	*0.0%*
Liquid Fuels	*0.00*	*0.00*	*0.00*	*0.00*	*-75.6%*	*-6.2%*	*-16.5%*	*0.0%*
Biomass	*0.02*	*0.02*	*0.02*	*0.02*	*565.3%*	*9.0%*	*-3.2%*	*0.0%*
Petroleum Refining	0.23	0.24	0.24	0.24	*21.5%*	*0.9%*	*-2.1%*	0.0%
Synthetic Petrol Production	-	-	-	-	*-100.0%*	*n.a.*	*n.a.*	0.0%
Oil & Gas Extraction & Processing	0.13	0.13	0.12	0.11	*53.6%*	*2.0%*	*-12.7%*	0.0%
Oil	*0.00*	*0.00*	*0.00*	*0.00*	*n.a.*	*n.a.*	*202.2%*	*0.0%*
Gas	*0.13*	*0.13*	*0.12*	*0.11*	*51.1%*	*1.9%*	*-13.7%*	*0.0%*
Manufacturing and Construction	***32.87***	***33.48***	***33.21***	***32.09***	***41.4%***	***1.6%***	*-3.4%*	**5.1%**
Domestic Transport	***526.94***	***519.04***	***508.62***	***506.82***	***24.9%***	***1.0%***	*-0.4%*	**80.0%**
Other Sectors	***93.72***	***94.14***	***93.03***	***91.85***	***-24.8%***	*-1.3%*	*-1.3%*	**14.5%**
Fugitive Emissions	-	-	-	-	**n.a.**	**n.a.**	**n.a.**	**0.0%**
Coal Mining	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Gas	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Transmission & Distribution	-	-	-	-	*n.a.*	*n.a.*	*n.a.*	*0.0%*
Processing and Flaring	-	-	-	-	*n.a.*	*n.a.*	*n.a.*	*0.0%*
Other Leakages	-	-	-	-	*n.a.*	*n.a.*	*n.a.*	*0.0%*
Oil Transportation &Refining	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Geothermal	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Internatinal Transport Emissions	6.87	7.34	6.91	6.78	*22.1%*	*0.9%*	*-1.8%*	NA
Aviation	*3.85*	*4.02*	*4.16*	*4.17*	*88.0%*	*2.9%*	*0.1%*	NA
Marine	*3.01*	*3.32*	*2.74*	*2.61*	*-21.7%*	*-1.1%*	*-4.7%*	NA

Table 32 Energy Sector Annual Nitrous Oxide Emissions. Source: MBIE, 2015



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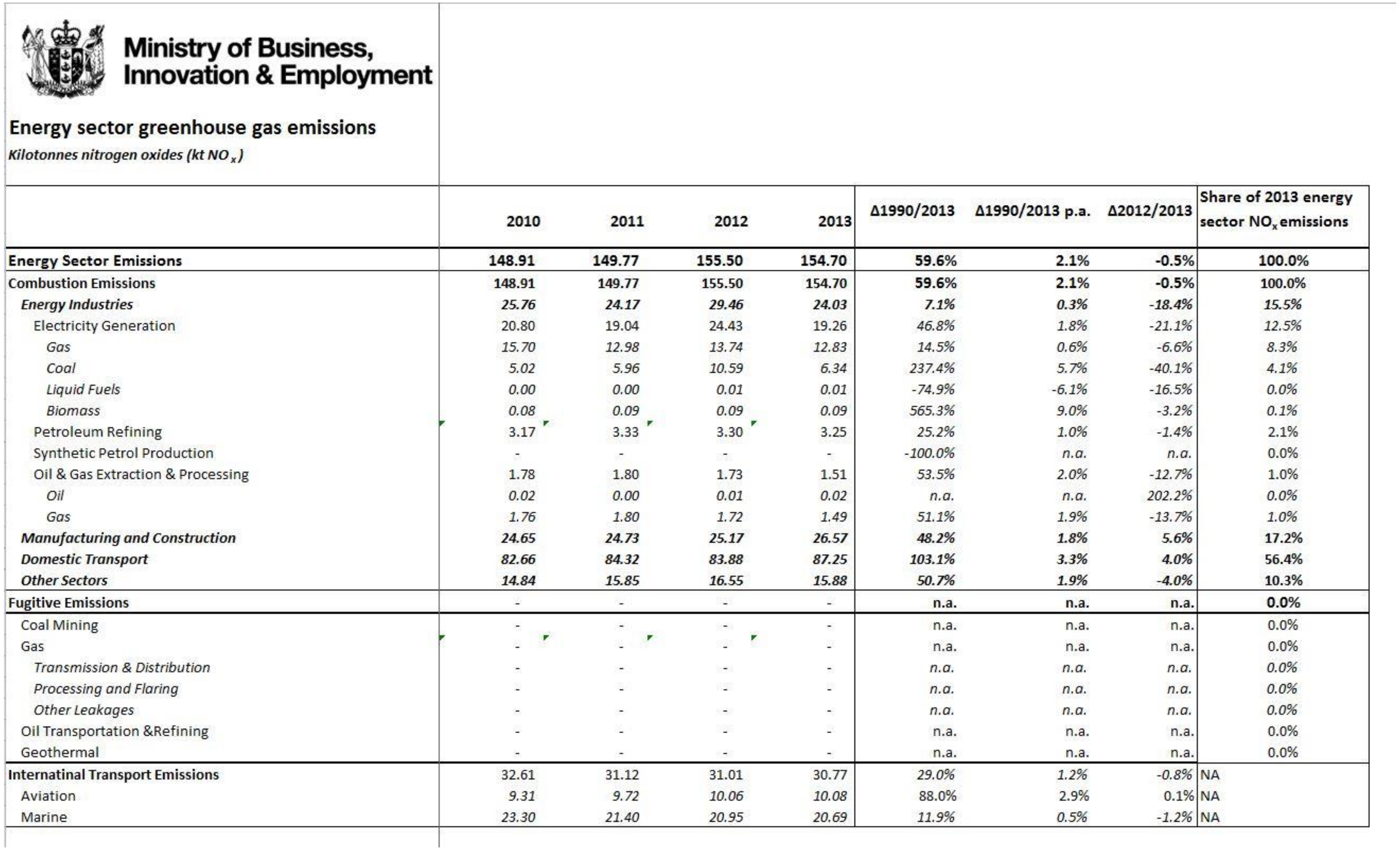
Energy sector greenhouse gas emissions

Kilotonnes nitrous oxide (kt N_2O)

	2010	2011	2012	2013	Δ1990/2013	Δ1990/2013 p.a.	Δ2012/2013	Share of 2013 energy sector N_2O emissions
Energy Sector Emissions	**0.92**	**0.90**	**0.91**	**0.89**	**45.9%**	**1.7%**	**-2.3%**	**100.0%**
Combustion Emissions	**0.92**	**0.90**	**0.91**	**0.89**	**45.9%**	**1.7%**	**-2.3%**	**100.0%**
Energy Industries	*0.03*	*0.04*	*0.06*	*0.04*	*116.4%*	*3.6%*	*-32.3%*	*4.4%*
Electricity Generation	0.03	0.04	0.06	0.04	*169.4%*	*4.6%*	*-33.3%*	*4.2%*
Gas	*0.01*	*0.01*	*0.01*	*0.01*	*14.5%*	*0.6%*	*-6.6%*	*0.7%*
Coal	*0.02*	*0.03*	*0.04*	*0.03*	*237.4%*	*5.7%*	*-40.1%*	*3.0%*
Liquid Fuels	*0.00*	*0.00*	*0.00*	*0.00*	*-70.4%*	*-5.4%*	*-16.5%*	*0.0%*
Biomass	*0.00*	*0.00*	*0.00*	*0.00*	*565.3%*	*9.0%*	*-3.2%*	*0.5%*
Petroleum Refining	0.00	0.00	0.00	0.00	*-10.9%*	*-0.5%*	*-9.8%*	0.2%
Synthetic Petrol Production	-	-	-	-	*-100.0%*	*n.a.*	*n.a.*	0.0%
Oil & Gas Extraction & Processing	0.00	0.00	0.00	0.00	*69.3%*	*2.4%*	*-6.6%*	0.1%
Oil	*0.00*	*0.00*	*0.00*	*0.00*	*n.a.*	*n.a.*	*202.2%*	*0.0%*
Gas	*0.00*	*0.00*	*0.00*	*0.00*	*51.1%*	*1.9%*	*-13.7%*	*0.1%*
Manufacturing and Construction	*0.27*	*0.27*	*0.27*	*0.262*	*50.3%*	*1.9%*	*-1.4%*	29.4%
Domestic Transport	*0.52*	*0.49*	*0.47*	*0.48*	*43.6%*	*1.7%*	*0.6%*	53.4%
Other Sectors	*0.10*	*0.11*	*0.12*	*0.11360*	*31.2%*	*1.2%*	*-1.3%*	12.8%
Fugitive Emissions	-	-	-	-	**n.a.**	**n.a.**	**n.a.**	**0.0%**
Coal Mining	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Gas	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Transmission & Distribution	-	-	-	-	*n.a.*	*n.a.*	*n.a.*	*0.0%*
Processing and Flaring	-	-	-	-	*n.a.*	*n.a.*	*n.a.*	*0.0%*
Other Leakages	-	-	-	-	*n.a.*	*n.a.*	*n.a.*	*0.0%*
Oil Transportation &Refining	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Geothermal	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Internatinal Transport Emissions	0.09	0.10	0.10	0.10	29.4%	1.2%	0.0%	NA
Aviation	*0.06*	*0.07*	*0.07*	*0.07*	*88.0%*	*2.9%*	*0.1%*	NA
Marine	*0.03*	*0.03*	*0.03*	*0.03*	*-27.1%*	*-1.4%*	*-0.3%*	NA

Table 33 Energy Sector Annual Nitrogen Oxides Emissions. Source: MBIE, 2015



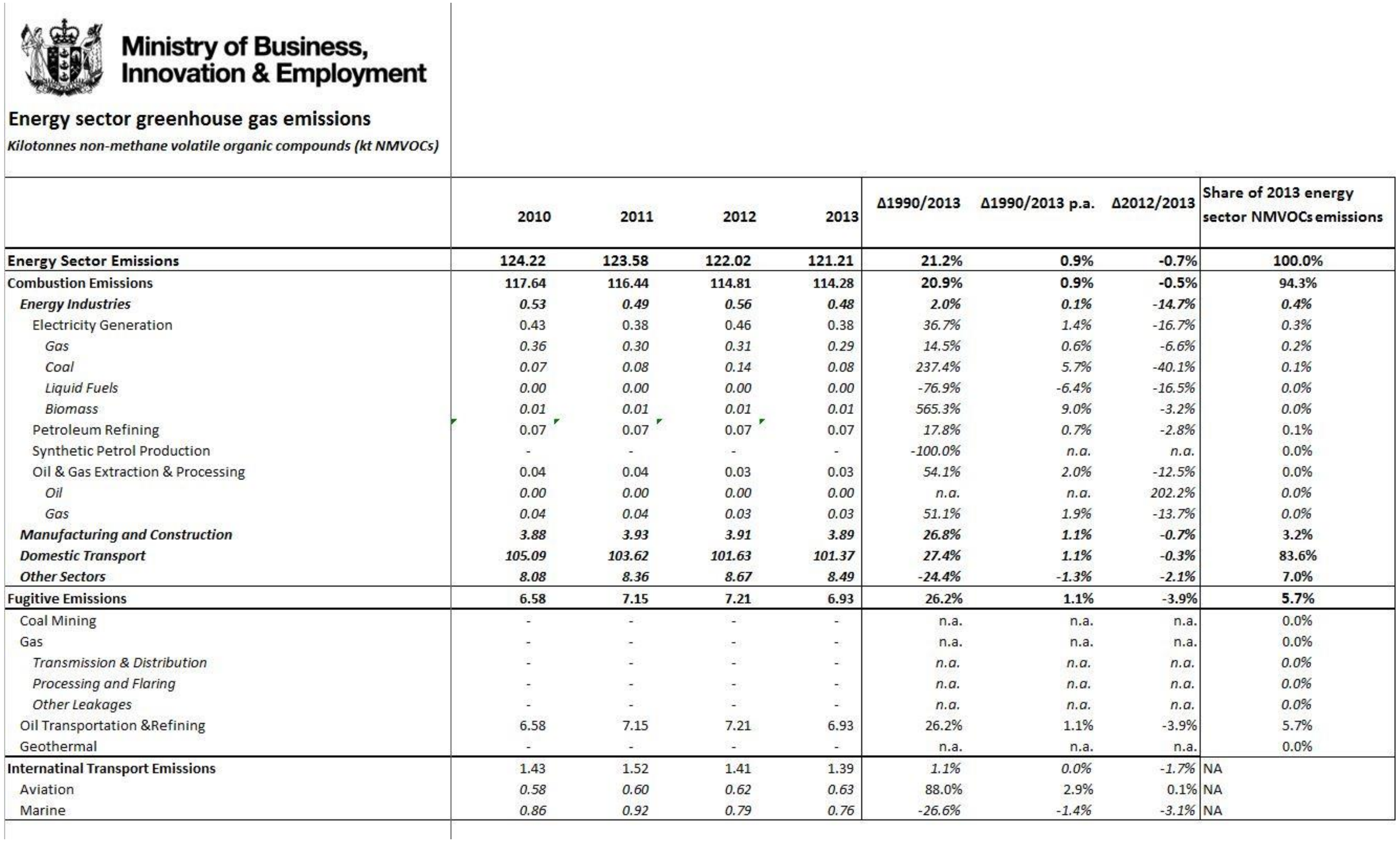
Ministry of Business, Innovation & Employment

Energy sector greenhouse gas emissions

Kilotonnes nitrogen oxides (kt NO_x)

	2010	2011	2012	2013	Δ1990/2013	Δ1990/2013 p.a.	Δ2012/2013	Share of 2013 energy sector NO_x emissions
Energy Sector Emissions	**148.91**	**149.77**	**155.50**	**154.70**	**59.6%**	**2.1%**	**-0.5%**	**100.0%**
Combustion Emissions	**148.91**	**149.77**	**155.50**	**154.70**	**59.6%**	**2.1%**	**-0.5%**	**100.0%**
Energy Industries	***25.76***	***24.17***	***29.46***	***24.03***	***7.1%***	***0.3%***	***-18.4%***	***15.5%***
Electricity Generation	20.80	19.04	24.43	19.26	*46.8%*	*1.8%*	*-21.1%*	*12.5%*
Gas	*15.70*	*12.98*	*13.74*	*12.83*	*14.5%*	*0.6%*	*-6.6%*	*8.3%*
Coal	*5.02*	*5.96*	*10.59*	*6.34*	*237.4%*	*5.7%*	*-40.1%*	*4.1%*
Liquid Fuels	*0.00*	*0.00*	*0.01*	*0.01*	*-74.9%*	*-6.1%*	*-16.5%*	*0.0%*
Biomass	*0.08*	*0.09*	*0.09*	*0.09*	*565.3%*	*9.0%*	*-3.2%*	*0.1%*
Petroleum Refining	3.17	3.33	3.30	3.25	*25.2%*	*1.0%*	*-1.4%*	2.1%
Synthetic Petrol Production	-	-	-	-	*-100.0%*	*n.a.*	*n.a.*	0.0%
Oil & Gas Extraction & Processing	1.78	1.80	1.73	1.51	*53.5%*	*2.0%*	*-12.7%*	1.0%
Oil	*0.02*	*0.00*	*0.01*	*0.02*	*n.a.*	*n.a.*	*202.2%*	*0.0%*
Gas	*1.76*	*1.80*	*1.72*	*1.49*	*51.1%*	*1.9%*	*-13.7%*	*1.0%*
Manufacturing and Construction	***24.65***	***24.73***	***25.17***	***26.57***	***48.2%***	***1.8%***	***5.6%***	**17.2%**
Domestic Transport	***82.66***	***84.32***	***83.88***	***87.25***	***103.1%***	***3.3%***	***4.0%***	**56.4%**
Other Sectors	***14.84***	***15.85***	***16.55***	***15.88***	***50.7%***	***1.9%***	***-4.0%***	**10.3%**
Fugitive Emissions	-	-	-	-	**n.a.**	**n.a.**	**n.a.**	**0.0%**
Coal Mining	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Gas	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Transmission & Distribution	-	-	-	-	*n.a.*	*n.a.*	*n.a.*	*0.0%*
Processing and Flaring	-	-	-	-	*n.a.*	*n.a.*	*n.a.*	*0.0%*
Other Leakages	-	-	-	-	*n.a.*	*n.a.*	*n.a.*	*0.0%*
Oil Transportation &Refining	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Geothermal	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Internatinal Transport Emissions	32.61	31.12	31.01	30.77	*29.0%*	*1.2%*	*-0.8%*	NA
Aviation	*9.31*	*9.72*	*10.06*	*10.08*	88.0%	2.9%	0.1%	NA
Marine	*23.30*	*21.40*	*20.95*	*20.69*	*11.9%*	*0.5%*	*-1.2%*	NA

Table 34 Energy Sector Annual Non-Methane Volatile Organic Compounds Emissions. Source: MBIE, 2015



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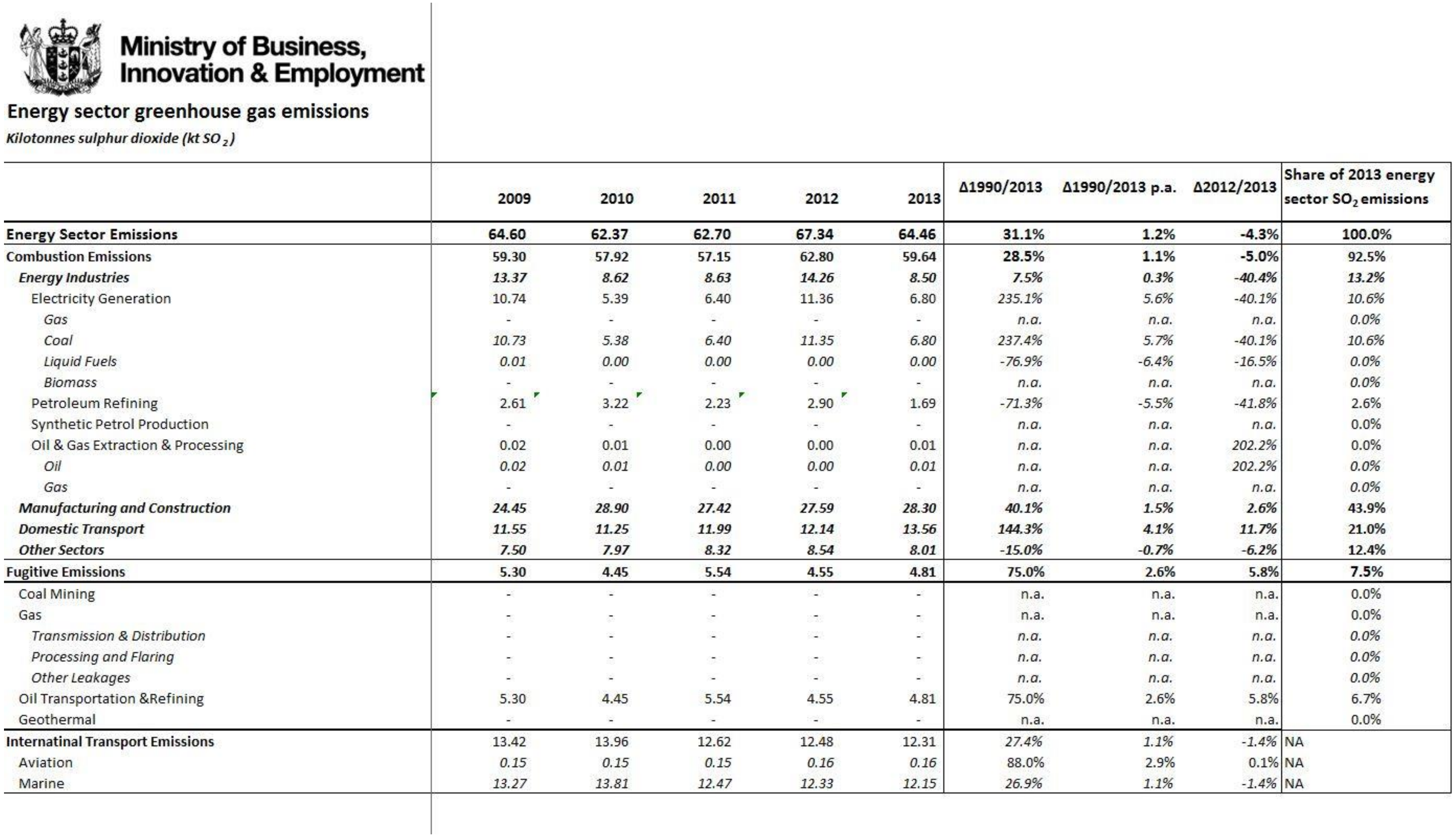
Energy sector greenhouse gas emissions

Kilotonnes non-methane volatile organic compounds (kt NMVOCs)

	2010	2011	2012	2013	Δ1990/2013	Δ1990/2013 p.a.	Δ2012/2013	Share of 2013 energy sector NMVOCs emissions
Energy Sector Emissions	**124.22**	**123.58**	**122.02**	**121.21**	**21.2%**	**0.9%**	**-0.7%**	**100.0%**
Combustion Emissions	**117.64**	**116.44**	**114.81**	**114.28**	**20.9%**	**0.9%**	**-0.5%**	**94.3%**
Energy Industries	***0.53***	***0.49***	***0.56***	***0.48***	***2.0%***	***0.1%***	***-14.7%***	***0.4%***
Electricity Generation	0.43	0.38	0.46	0.38	*36.7%*	*1.4%*	*-16.7%*	*0.3%*
Gas	*0.36*	*0.30*	*0.31*	*0.29*	*14.5%*	*0.6%*	*-6.6%*	*0.2%*
Coal	*0.07*	*0.08*	*0.14*	*0.08*	*237.4%*	*5.7%*	*-40.1%*	*0.1%*
Liquid Fuels	*0.00*	*0.00*	*0.00*	*0.00*	*-76.9%*	*-6.4%*	*-16.5%*	*0.0%*
Biomass	*0.01*	*0.01*	*0.01*	*0.01*	*565.3%*	*9.0%*	*-3.2%*	*0.0%*
Petroleum Refining	0.07	0.07	0.07	0.07	*17.8%*	*0.7%*	*-2.8%*	0.1%
Synthetic Petrol Production	-	-	-	-	*-100.0%*	*n.a.*	*n.a.*	0.0%
Oil & Gas Extraction & Processing	0.04	0.04	0.03	0.03	*54.1%*	*2.0%*	*-12.5%*	0.0%
Oil	*0.00*	*0.00*	*0.00*	*0.00*	*n.a.*	*n.a.*	*202.2%*	*0.0%*
Gas	*0.04*	*0.04*	*0.03*	*0.03*	*51.1%*	*1.9%*	*-13.7%*	*0.0%*
Manufacturing and Construction	***3.88***	***3.93***	***3.91***	***3.89***	***26.8%***	***1.1%***	***-0.7%***	**3.2%**
Domestic Transport	***105.09***	***103.62***	***101.63***	***101.37***	***27.4%***	***1.1%***	***-0.3%***	**83.6%**
Other Sectors	***8.08***	***8.36***	***8.67***	***8.49***	***-24.4%***	***-1.3%***	***-2.1%***	**7.0%**
Fugitive Emissions	**6.58**	**7.15**	**7.21**	**6.93**	**26.2%**	**1.1%**	**-3.9%**	**5.7%**
Coal Mining	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Gas	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Transmission & Distribution	-	-	-	-	*n.a.*	*n.a.*	*n.a.*	*0.0%*
Processing and Flaring	-	-	-	-	*n.a.*	*n.a.*	*n.a.*	*0.0%*
Other Leakages	-	-	-	-	*n.a.*	*n.a.*	*n.a.*	*0.0%*
Oil Transportation &Refining	6.58	7.15	7.21	6.93	26.2%	1.1%	-3.9%	5.7%
Geothermal	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Internatinal Transport Emissions	1.43	1.52	1.41	1.39	*1.1%*	*0.0%*	*-1.7%*	NA
Aviation	*0.58*	*0.60*	*0.62*	*0.63*	88.0%	2.9%	0.1%	NA
Marine	*0.86*	*0.92*	*0.79*	*0.76*	*-26.6%*	*-1.4%*	*-3.1%*	NA

Table 35 Energy Sector Annual Sulphur Dioxide Emissions. Source: MBIE, 2015



Ministry of Business, Innovation & Employment

Energy sector greenhouse gas emissions

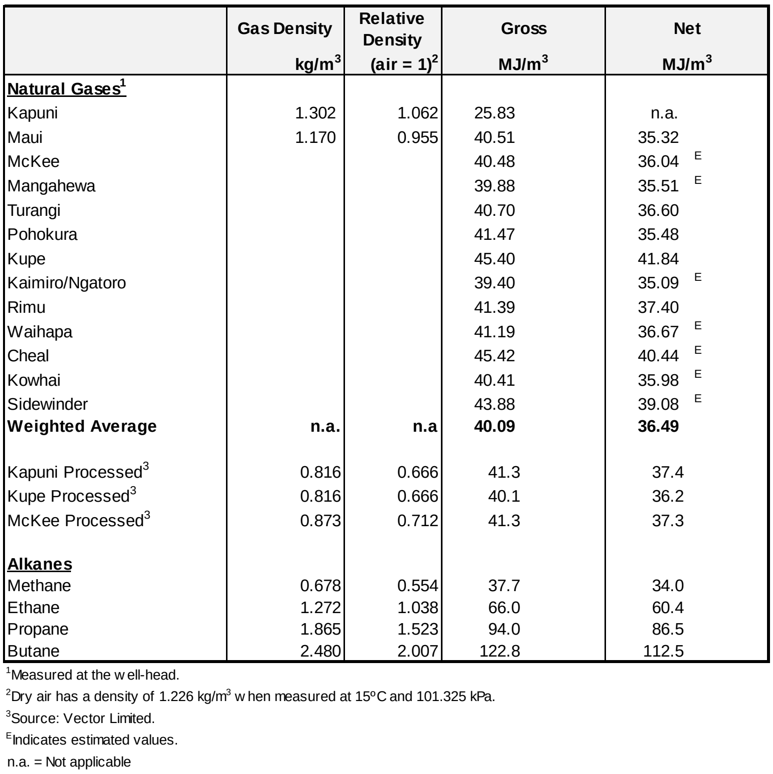
Kilotonnes sulphur dioxide (kt SO_2)

	2009	2010	2011	2012	2013	Δ1990/2013	Δ1990/2013 p.a.	Δ2012/2013	Share of 2013 energy sector SO_2 emissions
Energy Sector Emissions	64.60	62.37	62.70	67.34	64.46	31.1%	1.2%	-4.3%	100.0%
Combustion Emissions	59.30	57.92	57.15	62.80	59.64	28.5%	1.1%	-5.0%	92.5%
Energy Industries	13.37	8.62	8.63	14.26	8.50	7.5%	0.3%	-40.4%	13.2%
Electricity Generation	10.74	5.39	6.40	11.36	6.80	235.1%	5.6%	-40.1%	10.6%
Gas	-	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Coal	10.73	5.38	6.40	11.35	6.80	237.4%	5.7%	-40.1%	10.6%
Liquid Fuels	0.01	0.00	0.00	0.00	0.00	-76.9%	-6.4%	-16.5%	0.0%
Biomass	-	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Petroleum Refining	2.61	3.22	2.23	2.90	1.69	-71.3%	-5.5%	-41.8%	2.6%
Synthetic Petrol Production	-	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Oil & Gas Extraction & Processing	0.02	0.01	0.00	0.00	0.01	n.a.	n.a.	202.2%	0.0%
Oil	0.02	0.01	0.00	0.00	0.01	n.a.	n.a.	202.2%	0.0%
Gas	-	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Manufacturing and Construction	24.45	28.90	27.42	27.59	28.30	40.1%	1.5%	2.6%	43.9%
Domestic Transport	11.55	11.25	11.99	12.14	13.56	144.3%	4.1%	11.7%	21.0%
Other Sectors	7.50	7.97	8.32	8.54	8.01	-15.0%	-0.7%	-6.2%	12.4%
Fugitive Emissions	5.30	4.45	5.54	4.55	4.81	75.0%	2.6%	5.8%	7.5%
Coal Mining	-	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Gas	-	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Transmission & Distribution	-	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Processing and Flaring	-	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Other Leakages	-	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Oil Transportation &Refining	5.30	4.45	5.54	4.55	4.81	75.0%	2.6%	5.8%	6.7%
Geothermal	-	-	-	-	-	n.a.	n.a.	n.a.	0.0%
Internatinal Transport Emissions	13.42	13.96	12.62	12.48	12.31	27.4%	1.1%	-1.4%	NA
Aviation	0.15	0.15	0.15	0.16	0.16	88.0%	2.9%	0.1%	NA
Marine	13.27	13.81	12.47	12.33	12.15	26.9%	1.1%	-1.4%	NA

Appendix 3 MBIE Fossil Fuels Calorific Values

The Ministry of Business, Innovation and Employment reports annually energy production volumes. Although it is not included on the print and web version of the annual report, the web site provides web tables for New Zealand fossil fuel physical properties in the following link http://www.mbie.govt.nz/info-services/sectors-industries/energy/energy-data-modelling/publications/energy-in-new-zealand

Table 36 New Zealand Natural Gas Physical Properties. Source: MBIE Energy in New Zealand #14 Web Tables



	Gas Density kg/m^3	Relative Density (air = 1)[2]	Gross MJ/m^3	Net MJ/m^3
Natural Gases[1]				
Kapuni	1.302	1.062	25.83	n.a.
Maui	1.170	0.955	40.51	35.32
McKee			40.48	36.04 ^{E}
Mangahewa			39.88	35.51 ^{E}
Turangi			40.70	36.60
Pohokura			41.47	35.48
Kupe			45.40	41.84
Kaimiro/Ngatoro			39.40	35.09 ^{E}
Rimu			41.39	37.40
Waihapa			41.19	36.67 ^{E}
Cheal			45.42	40.44 ^{E}
Kowhai			40.41	35.98 ^{E}
Sidewinder			43.88	39.08 ^{E}
Weighted Average	**n.a.**	**n.a**	**40.09**	**36.49**
Kapuni Processed[3]	0.816	0.666	41.3	37.4
Kupe Processed[3]	0.816	0.666	40.1	36.2
McKee Processed[3]	0.873	0.712	41.3	37.3
Alkanes				
Methane	0.678	0.554	37.7	34.0
Ethane	1.272	1.038	66.0	60.4
Propane	1.865	1.523	94.0	86.5
Butane	2.480	2.007	122.8	112.5

[1] Measured at the well-head.

[2] Dry air has a density of 1.226 kg/m^3 when measured at 15ºC and 101.325 kPa.

[3] Source: Vector Limited.

^{E}Indicates estimated values.

n.a. = Not applicable

Table 37 Solid Fuel Calorific Values. Source: MBIE, Energy in New Zealand # 14 Web Tables

Region	Mine Name	Coal Field	Coal Rank	Mining Method	Gross		Net	
					Mbtu/tonne	MJ/kg	Mbtu/tonne	MJ/kg
Waikato	Awaroa	Rotowaro	Sub-bituminous	Opencast	21.08	22.24	19.79	20.88
	Kimihia	Huntly	Sub-bituminous	Opencast	21.73	22.93	20.43	21.55
	Kopako	Maramarua	Sub-bituminous	Opencast	18.56	19.58	17.44	18.40
	O'Reillys	Huntly	Sub-bituminous	Opencast	21.77	22.97	20.69	21.83
	East Mine	Huntly	Sub-bituminous	Underground	21.73	22.93	20.43	21.55
West Coast	Berlins Creek	Inangahua	Sub-bituminous	Opencast	17.85	18.83	16.85	17.78
	Burkes Creek	Reefton	Sub-bituminous	Opencast	23.70	25.00	22.46	23.70
	Cascade	Buller	Bituminous	Opencast	29.38	31.00	27.37	28.87
	Giles Creek	Inangahua	Sub-bituminous	Opencast	17.61	18.58	16.29	17.19
	New Creek	Buller	Sub-bituminous	Opencast	22.68	23.93	21.39	22.57
	Rockies	Buller	Bituminous	Opencast	26.54	28.00	25.49	26.89
	Stockton	Buller	Bituminous	Opencast	30.00	31.65	28.81	30.40
	Echo	Garvey Creek	Bituminous	Underground	29.16	30.77	28.00	29.54
	Roa	Greymouth	Bituminous	Underground	31.52	33.26	30.38	32.05
	Spring Creek	Greymouth	Bituminous	Underground	28.27	29.83	27.04	28.53
Canterbury	Canterbury Coal	Canterbury	Sub-bituminous	Opencast	18.48	19.50	17.37	18.33
Otago	Castle Hill	Kaitangata	Sub-bituminous	Opencast	18.64	19.67	17.24	18.19
	Harliwich	Roxburgh	Lignite	Opencast	17.72	18.70	16.40	17.30
Southland	Newvale	Waimumu	Lignite	Opencast	14.45	15.25	12.95	13.66
	Nightcaps	Ohai	Sub-Bituminous	Opencast	19.70	20.78	18.43	19.44
Average Coal Figures (weighted for 2013 production)								
Bituminous (export)					29.77	31.41	28.58	30.15
Bituminous (used in New Zealand)					28.00	29.54	26.84	28.32
Sub-bituminous					20.58	21.72	19.32	20.39
Lignite					14.51	15.31	13.01	13.72

Type of Wood	% Moisture Content of Wet	Gross		Net	
		Mbtu/tonne	MJ/kg	Mbtu/tonne	MJ/kg
Oven-dried Wood	0	19.47	20.55	18.20	19.20
Fresh Harvested	50–55	8.84	9.33	7.01	7.40
Bark	60-70	8.59	9.06	6.63	7.00
Fuel Wood	38–41	11.45	12.08	9.76	10.30
Wooden Containers	23–29	14.15	14.94	12.60	13.30
Furniture Residues	12–14	16.86	17.79	15.45	16.30
Black Liquor	50	9.95	10.5	8.15	8.60

[1] Coal values are at point of sale

Table 38 Petroleum Calorific Values. Source: MBIE Energy in New Zealand #14 Web Tables

				Gross			Net		
		kg/l	bbl/tonne	MJ/bbl	MJ/kg	MJ/litre	MJ/bbl	MJ/kg	MJ/litre
Indigenous Crudes in 2013									
Kaimiro Crude		0.794	7.92	5,854.0	46.37	36.82	5,480.3	43.41	34.47
Kapuni Condensate		0.769	8.18	5,763.6	47.17	36.25	5,391.3	44.12	33.91
Kupe Condensate		0.753	8.35	5,641.7	47.12	35.48	5,256.2	43.90	33.06
Maari Crude		0.840	7.49	6,354.8	47.60	39.97	5,941.8	44.50	37.37
Mangahewa Crude		0.773	8.14	6,121.7	49.83	38.50	5,531.1	45.02	34.79
Maui Condensate		0.743	8.47	5,563.7	47.12	34.99	5,195.3	44.00	32.68
McKee Crude		0.795	7.91	5,791.2	45.83	36.42	5,436.1	43.02	34.19
Ngatoro Crude		0.852	7.39	5,015.8	37.04	31.55	4,714.5	34.82	29.65
Pohokura Crude		0.761	8.26	5,636.8	46.56	35.45	5,271.2	43.54	33.15
Tui Crude		0.810	7.76	6,133.6	47.60	38.58	5,567.5	43.21	35.02
Waihapa Crude		0.862	7.29	6,142.0	44.80	38.63	5,826.7	42.50	36.65
Kowhai Condensate		0.760	8.28	6,021.8	49.83	37.87	5,440.9	45.03	34.22
Turangi Condensate		0.760	8.27	4,797.5	39.69	30.17	4,537.8	37.54	28.54
Rimu Crude		0.896	7.02	6,608.1	46.37	41.56	6,186.3	43.41	38.91
Sidewinder Condensate		0.757	8.31	5,514.6	45.83	34.68	5,156.1	42.85	32.43
Cheal Crude		0.833	7.55	5,255.7	39.69	33.05	4,971.2	37.54	31.27
Surrey Crude		0.880	7.15	5,480.8	39.17	34.47	5,184.2	37.05	32.60
Copper Moki Crude		0.818	7.69	6,480.0	49.83	40.76	6,082.7	46.78	38.26
Top Ten Crudes/Residues used at the New Zealand Refinery in 2013 (Country of Origin)									
Kikeh	(Indonesia)	0.883	7.12	6,301.6	44.88	39.63	5,923.2	42.19	37.25
Abu Safah	(Saudi Arabia)	0.870	7.23	6,260.8	45.26	39.38	5,873.5	42.46	36.94
ESPO Blend	(Russia)	0.851	7.39	6,147.1	45.43	38.66	5,770.9	42.65	36.30
Umm Shaif	(Dubai)	0.841	7.48	6,101.3	45.63	38.37	5,722.2	42.79	35.99
Labuan	(Malaysia)	0.867	7.25	6,237.8	45.25	39.23	6,229.0	45.19	39.18
Ratawi	(Kuwait)	0.910	6.91	6,716.5	46.42	42.24	6,288.2	43.46	39.55
Arab Medium Crude	(Saudi Arabia)	0.869	7.24	6,256.4	45.28	39.35	5,873.6	42.51	36.94
Upper Zakum	(Dubai)	0.855	7.36	6,171.2	45.40	38.81	5,786.0	42.56	36.39
Okono	(Nigeria)	0.816	7.71	5,998.3	46.23	37.73	5,630.5	43.40	35.41
Seria Light Export Blend	(Brunei)	0.848	7.42	6,145.6	45.58	38.65	5,766.1	42.77	36.26
Refinery Feedstocks									
Naphtha		0.750	8.39	5,601.2	46.97	35.23	5,218.4	43.76	32.82
Middle Distillate		0.820	7.67	5,997.5	46.00	37.72	5,623.3	43.13	35.37
Lgo/Kero Ex Naphtha		0.810	7.76	5,943.7	46.15	37.38	5,570.2	43.25	35.03
Intermediate Variation		0.767	8.20	5,700.1	46.74	35.85	5,328.1	43.69	33.51
Intermediate Residue		0.899	7.00	6,405.2	44.81	40.28	5,999.2	41.97	37.73
Blendstock		0.840	7.49	6,105.0	45.71	38.40	5,729.7	42.90	36.04
Petroleum Products[1]									
Premium Unleaded Gasoline		0.749	8.40	5,594.3	46.99	35.18	5,222.2	43.86	32.84
Regular Unleaded Gasoline		0.744	8.45	5,566.6	47.05	35.01	5,194.5	43.90	32.67
Automotive Gas Oil - 10 ppm Sulphur		0.840	7.49	6,105.9	45.71	38.40	5,722.6	42.84	35.99
Light Fuel Oil		0.922	6.82	6,429.4	43.84	40.44	6,044.0	41.21	38.01
Heavy Fuel Oil		0.948	6.63	6,488.2	43.05	40.81	6,122.1	40.62	38.50
Bunker Fuel Oil		0.959	6.56	6,517.0	42.72	40.99	6,155.2	40.35	38.71
Power Station Fuel Oil		0.890	7.07	6,360.9	44.95	40.01	5,717.0	40.40	35.96
Export Fuel Oil		0.940	6.69	6,598.7	44.15	41.50	6,174.2	41.31	38.83
Lighting Kerosene		0.788	7.98	5,813.5	46.40	36.56	5,462.7	43.60	34.36
Jet Fuel		0.803	7.83	5,906.2	46.23	37.15	5,524.3	43.24	34.74
Aviation Gasoline		0.716	8.78	5,384.8	47.30	33.87	5,066.1	44.50	31.86
Blended Heating Oil		0.824	7.63	6,079.1	46.40	38.23	5,686.1	43.40	35.76
Bitumen		1.030	6.11	6,757.3	41.26	42.50	6,408.3	39.13	40.30
Natural Gasoline		0.668	9.42	5,130.0	48.30	32.26	4,812.5	45.31	30.27
Liquid Petroleum Gas[2]									
LPG 60/40		0.534	11.78	4,203.8	49.51	26.44	3,876.3	45.65	24.38
General Product LPG		0.536	11.73	4,219.6	49.51	26.54	3,890.9	45.66	24.47
Commercial Propane		0.508	12.38	4,027.5	49.86	25.33	3,713.5	45.98	23.36
Commercial Butane		0.572	11.00	4,465.5	49.10	28.09	4,118.2	45.28	25.90

[1] The calorific values of petroleum products are based on the New Zealand Refinery Company's update for 2013.

[2] Source: Vector Limited.

Appendix 4 MBIE New Zealand Annual Electricity Generation Web Tables

Historical electricity information is published and updated annually by the Energy and Data Modelling Team from the Ministry of Business, Innovation and Employment, from their website: http://www.mbie.govt.nz/info-services/sectors-industries/energy/energy-data-modelling/statistics/electricity

Table 39 Annual Electricity Generation for the Years 1990 – 2013. Source: MBIE, 2015

Ministry of Business, Innovation & Employment

Annual electricity generation and consumption

Calendar year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Net Generation (GWh)[1,2]	31,459	32,410	31,936	33,358	34,026	35,250	35,560	35,993	36,579	36,643	38,069	38,218
Hydro	22,953	22,666	20,882	23,258	25,579	27,259	25,921	23,026	25,066	22,690	24,191	21,464
Geothermal	2,011	2,158	2,131	2,247	2,101	2,039	2,038	2,130	2,386	2,636	2,756	2,678
Biogas	131	151	156	156	162	172	146	139	137	116	103	101
Wood	336	336	336	336	336	336	310	312	409	392	447	361
Wind	-	-	1	1	1	1	8	13	22	39	119	138
Solar[3]	-	-	-	-	-	-	-	-	-	-	-	-
Oil	9	24	192	59	20	48	15	-	1	0	0	-
Coal	620	451	1,171	696	647	842	876	1,535	1,365	1,678	1,445	1,980
Gas	5,336	6,561	7,006	6,543	5,117	4,489	6,183	8,775	7,131	9,030	8,946	11,450
Waste Heat[4]	63	63	63	63	63	63	63	63	63	63	63	47
Renewable Share (%)	80.8%	78.1%	73.6%	77.9%	82.8%	84.6%	79.9%	71.2%	76.6%	70.6%	72.5%	64.7%
Total Line Losses (GWh)	2,409	2,405	2,401	2,457	2,538	2,614	2,612	2,737	2,798	2,769	3,044	3,028
Losses - Transmission	1,191	1,210	1,189	1,232	1,263	1,288	1,249	1,338	1,378	1,355	1,547	1,467
Losses - Distribution	1,218	1,195	1,212	1,225	1,275	1,326	1,363	1,399	1,420	1,414	1,498	1,561

Calendar year	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Net Generation (GWh)[1,2]	39,386	39,454	41,466	41,452	41,979	42,332	42,307	42,067	43,409	43,046	42,802	41,874
Hydro	24,624	23,387	26,968	23,094	23,337	23,404	22,124	23,976	24,493	24,868	22,674	22,815
Geothermal	2,655	2,595	2,631	2,981	3,177	3,354	3,966	4,589	5,546	5,777	5,843	6,053
Biogas	131	178	199	194	218	214	203	215	218	234	229	223
Wood	231	192	236	277	299	314	324	344	346	350	361	369
Wind	154	145	358	608	616	921	1,048	1,462	1,618	1,932	2,055	2,000
Solar[3]	-	-	-	-	-	3	3	4	4	4	5	7
Oil	0	19	23	4	22	1	123	8	2	2	3	3
Coal	1,925	3,707	4,474	5,481	5,176	2,956	4,515	3,082	1,929	2,028	3,317	2,238
Gas	9,572	9,148	6,494	8,739	9,062	11,112	9,943	8,335	9,197	7,804	8,281	8,134
Waste Heat[4]	93	84	83	76	71	53	56	53	57	46	35	33
Renewable Share (%)	70.6%	67.2%	73.3%	65.5%	65.9%	66.6%	65.4%	72.7%	74.2%	77.0%	72.8%	75.1%
Total Line Losses (GWh)	3,013	2,893	2,994	2,978	3,011	3,029	3,130	2,992	3,102	2,999	2,996	2,888
Losses - Transmission	1,444	1,304	1,328	1,273	1,346	1,338	1,451	1,350	1,359	1,310	1,387	1,303
Losses - Distribution	1,569	1,589	1,666	1,705	1,664	1,690	1,679	1,642	1,743	1,689	1,610	1,585

Notes:

1. These fuels include generation from cogeneration plants.
2. 1 Gigawatt Hour (GWh) = 0.0036 Petajoules (PJ).

3. Distributed Solar PV Generation has been estimated using Electricity Authority data.
4. Waste heat includes heat from chemical processes - e.g. fertiliser industry.

5. Revised due to updated company returns

6. Solar PV demand has not been broken down into subheadings within Industrial, therefore subtotals do not exactly sum to Industrial total for 2014.

Appendix 5 Waikato Regional Council Consent Monitoring Reports

Table 40 Waikato Regional Council Consent Monitoring Reports for H_2S and Hg Annual Total Emissions Since 1998 and Annual Emissions per kWh electricity generated. Source: Contact Energy, 2014a 2014b; Contact Energy/GNS Science, 2014a, 2014b.

Wairakei	**Output**	**970**	**GWh**																	
		9.7E+08	**kWh**																	
		1998	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**Average**	**Total Kg/year**	**Kg per kWh**
H2S	kg/hr	60	40	50	35	38	40	25	30	35	30	32	30	55	30	29	27	36.6	320,835	**3.31E-04**
Hg	g/hr			3		2		2	2			2		1			1	1.83	16	**1.65E-08**
Isopentane	ton/year																7	7	7,240	**7.46E-06**

Te Huka	**Output**	**200**	**GWh**																	
		2E+08	**kWh**																	
		1998	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**Average**	**Total Kg/year**	**Kg per kWh**
H2S	kg/hr																24	24.0	210,240	**1.05E-03**
Hg	g/hr																0.31	0.31	3	**1.36E-08**

Mokai	**Output**	**930**	**GWh**																	
		9.3E+08	**kWh**																	
		1999	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**Average**	**Total Kg/year**	**Kg per kWh**
H2S	kg/hr										175	225	240	175	250	175	100	191	1,676,914	**1.80E-03**
Hg	g/hr										3	5	6	5	10	10	6.00	6.43	56	**6.06E-08**
NCG	ton/day										100	95	75	110	125	75	50	90.0		
Pentane	ton/year																	18.0	18,000	**1.94E-05**

Rotokawa	**Output**	**270**	**GWh**																	
		2.7E+08	**kWh**																	
		1999	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**Average**	**Total Kg/year**	**Kg per kWh**
H2S	kg/hr													0.12	0.12	0.10	0.10	0.11	964	**3.57E-06**
Hg	g/hr													65	5	35	3.00	27.0	237	**8.76E-07**

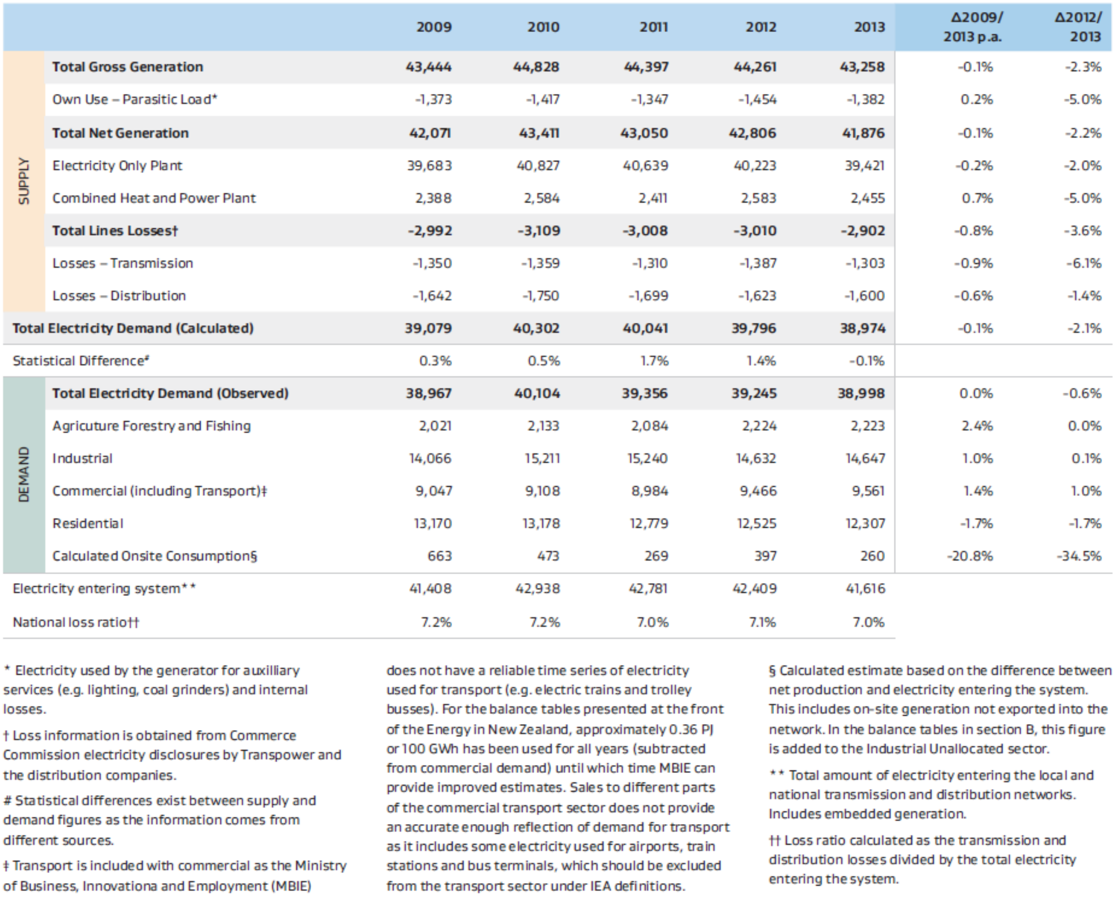
Nga Awa Purua	**Output**	**1000**	**GWh**																	
		1E+09	**kWh**																	
		1999	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**Average**	**Total Kg/year**	**Kg per kWh**
H2S	kg/hr													0.60	0.50	0.50	0.35	0.49	4,271	**4.27E-06**
Hg	g/hr													20	15	10		15.0	131	**1.31E-07**

Ngatamariki	**Outupu**	**650**	**GWh**																	
		6.5E+08	**kWh**																	
		1999	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2014**	**2014**	**Average**	**Total Kg/year**	**Kg per kWh**
H2S	kg/hr																125.06	125.06	1,095,526	**1.69E-03**
Hg	kg/hr															0.007	0.014	0.01	90	**1.39E-07**
N-Pentane	tonnes																25	25	25000	**3.85E-05**

Note: The average kg/h H_2S and Hg emission value was multiplied by 8760 hours in a year to give the total Kg emissions per year. The total emission value was divided by the total kWh of electricity produced in each geothermal field (based on their rated output), to produce the emission factor in kg per kWh.

Appendix 6 New Zealand Electricity Balances and Transmission Losses

Table 41 Electricity Supply and Demand Energy Balance, Annual Values in GWh. Source: MBIE, 2014b; Page 55



		2009	2010	2011	2012	2013	Δ2009/ 2013 p.a.	Δ2012/ 2013
SUPPLY	**Total Gross Generation**	**43,444**	**44,828**	**44,397**	**44,261**	**43,258**	-0.1%	-2.3%
	Own Use – Parasitic Load*	-1,373	-1,417	-1,347	-1,454	-1,382	0.2%	-5.0%
	Total Net Generation	**42,071**	**43,411**	**43,050**	**42,806**	**41,876**	-0.1%	-2.2%
	Electricity Only Plant	39,683	40,827	40,639	40,223	39,421	-0.2%	-2.0%
	Combined Heat and Power Plant	2,388	2,584	2,411	2,583	2,455	0.7%	-5.0%
	Total Lines Losses†	**-2,992**	**-3,109**	**-3,008**	**-3,010**	**-2,902**	-0.8%	-3.6%
	Losses – Transmission	-1,350	-1,359	-1,310	-1,387	-1,303	-0.9%	-6.1%
	Losses – Distribution	-1,642	-1,750	-1,699	-1,623	-1,600	-0.6%	-1.4%
Total Electricity Demand (Calculated)		**39,079**	**40,302**	**40,041**	**39,796**	**38,974**	-0.1%	-2.1%
Statistical Difference#		0.3%	0.5%	1.7%	1.4%	-0.1%		
DEMAND	**Total Electricity Demand (Observed)**	**38,967**	**40,104**	**39,356**	**39,245**	**38,998**	0.0%	-0.6%
	Agricuture Forestry and Fishing	2,021	2,133	2,084	2,224	2,223	2.4%	0.0%
	Industrial	14,066	15,211	15,240	14,632	14,647	1.0%	0.1%
	Commercial (including Transport)‡	9,047	9,108	8,984	9,466	9,561	1.4%	1.0%
	Residential	13,170	13,178	12,779	12,525	12,307	-1.7%	-1.7%
	Calculated Onsite Consumption§	663	473	269	397	260	-20.8%	-34.5%
Electricity entering system**		41,408	42,938	42,781	42,409	41,616		
National loss ratio††		7.2%	7.2%	7.0%	7.1%	7.0%		

* Electricity used by the generator for auxilliary services (e.g. lighting, coal grinders) and internal losses.

† Loss information is obtained from Commerce Commission electricity disclosures by Transpower and the distribution companies.

\# Statistical differences exist between supply and demand figures as the information comes from different sources.

‡ Transport is included with commercial as the Ministry of Business, Innovationa and Employment (MBIE) does not have a reliable time series of electricity used for transport (e.g. electric trains and trolley busses). For the balance tables presented at the front of the Energy in New Zealand, approximately 0.36 PJ or 100 GWh has been used for all years (subtracted from commercial demand) until which time MBIE can provide improved estimates. Sales to different parts of the commercial transport sector does not provide an accurate enough reflection of demand for transport as it includes some electricity used for airports, train stations and bus terminals, which should be excluded from the transport sector under IEA definitions.

§ Calculated estimate based on the difference between net production and electricity entering the system. This includes on-site generation not exported into the network. In the balance tables in section B, this figure is added to the Industrial Unallocated sector.

** Total amount of electricity entering the local and national transmission and distribution networks. Includes embedded generation.

†† Loss ratio calculated as the transmission and distribution losses divided by the total electricity entering the system.

Appendix 7 Hot Spot Analysis Substance Quantities

Table 42 Substance Quantities Contributing More than 1% to CML 2001 – Apr. 2013 Impact Categories from the Production of 1kWh New Zealand Electricity

Abiotic Depletion Potential Elements	**kg Sb-Equiv.**									
	Biogas	**Coal**	**Geotherm**	**Hydro**	**Gas**	**Wind**	**Wood**	**HV**	**LV**	**MV**
Non renewable elements										
Cadmium	0.00E+00	5.34E-10	4.29E-09	6.55E-10	0.00E+00	3.32E-09	0.00E+00	1.56E-09	2.73E-08	3.68E-09
Chromium	0.00E+00	0.00E+00	1.11E-09	6.39E-09	9.10E-10	2.20E-09	0.00E+00	0.00E+00	1.09E-09	0.00E+00
Copper	0.00E+00	1.79E-09	1.03E-09	2.29E-09	2.45E-09	4.58E-09	0.00E+00	3.64E-09	2.22E-07	2.03E-08
Gold	0.00E+00	9.40E-10	5.39E-10	0.00E+00	0.00E+00	3.18E-09	0.00E+00	0.00E+00	2.56E-08	2.36E-09
Lead	0.00E+00	0.00E+00	2.98E-09	0.00E+00	0.00E+00	2.51E-09	0.00E+00	1.31E-09	3.37E-08	3.89E-09
Molybdenum	0.00E+00	0.00E+00	0.00E+00	1.09E-09	6.75E-10	1.45E-09	0.00E+00	8.70E-10	5.27E-08	4.80E-09
Nickel	0.00E+00	0.00E+00	1.01E-09	2.25E-09	0.00E+00	8.02E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Silver	0.00E+00	0.00E+00	9.66E-10	0.00E+00	0.00E+00	1.23E-09	0.00E+00	7.79E-10	3.43E-08	3.36E-09
Zinc	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.50E-09	5.35E-10
Non renewable resources										
Colemanite, in ground	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.37E-10	0.00E+00
Gypsum (natural gypsum)	0.00E+00	0.00E+00	8.79E-10	3.10E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sodium chloride (rock salt)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.03E-10	0.00E+00

Abiotic Depletion Potential Fossil	**MJ**									
	Biogas	**Coal**	**Geotherm**	**Hydro**	**Gas**	**Wind**	**Wood**	**HV**	**LV**	**MV**
Crude oil	0.00	0.01	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Hard coal	0.00	0.86	0.02	0.01	0.00	0.00	0.00	0.00	0.01	0.00
Lignite	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural gas	0.00	0.01	0.00	0.01	0.41	0.00	0.00	0.00	0.00	0.00

Acidification Potential	**kg SO2-Equiv.**									
	Biogas	**Coal**	**Geotherm**	**Hydro**	**Gas**	**Wind**	**Wood**	**HV**	**LV**	**MV**
Inorganic emissions to air										
Ammonia	1.37E-06	8.38E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.22E-06	0.00E+00
Hydrogen chloride	0.00E+00	1.14E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hydrogen fluoride	0.00E+00	1.09E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hydrogen sulphide	0.00E+00	9.37E-07	2.08E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nitrogen oxides - Operation	0.00E+00	1.02E-04	2.98E-05	6.15E-06	1.72E-04	1.25E-06	9.91E-06	1.14E-06	3.45E-06	0.00E+00
Sulphur dioxide	3.08E-06	2.50E-04	1.56E-05	1.10E-05	3.58E-06	3.89E-06	1.20E-06	4.23E-06	4.63E-05	4.68E-06

Eutrophication Potentials	**kg Phosphate-Equiv.**									
	Biogas	**Coal**	**Geotherm**	**Hydro**	**Gas**	**Wind**	**Wood**	**HV**	**LV**	**MV**
Ammonia (air)	0.0E+00	1.8E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Nitrogen oxides (air)	0.0E+00	2.6E-05	7.7E-06	1.6E-06	4.5E-05	0.0E+00	2.6E-06	0.0E+00	9.0E-07	0.0E+00
Nitrous oxide (air)	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.4E-06	0.0E+00	0.0E+00
Nitrate (long-term water)	0.0E+00	9.3E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	8.4E-07	0.0E+00
Phosphate (long-term water)- Spoil from	0.0E+00	2.7E-04	2.9E-06	2.2E-06	6.8E-07	1.2E-06	0.0E+00	8.4E-07	2.2E-05	2.1E-06
Inorganic Nitrate (water)	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Phosphate (water) - Spoil from Mining	0.0E+00	3.9E-05	0.0E+00	4.8E-07	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.4E-05	1.3E-06
Phosphorus (soil)	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.2E-06	0.0E+00	0.0E+00	0.0E+00

Freshwater Aquatic Ecotoxicity Potential	**kg DCB-Equiv.**									
	Biogas	**Coal**	**Geotherm**	**Hydro**	**Gas**	**Wind**	**Wood**	**HV**	**LV**	**MV**
Arsenic (+V)	0.00E+00	7.10E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Barium	0.00E+00	5.24E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Beryllium	0.00E+00	1.26E-02	1.24E-04	1.41E-04	0.00E+00	1.16E-04	0.00E+00	7.36E-05	3.14E-03	2.88E-04
Cadmium (+II)	0.00E+00	9.27E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.55E-04	0.00E+00
Cobalt	0.00E+00	6.01E-03	1.33E-04	2.47E-04	0.00E+00	1.17E-04	0.00E+00	0.00E+00	1.58E-03	1.44E-04
Molybdenum	0.00E+00	2.02E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.70E-05	0.00E+00
Nickel (+II)	0.00E+00	2.64E-02	4.92E-04	1.78E-03	1.75E-04	8.46E-04	7.83E-05	7.55E-05	1.04E-03	9.73E-05
Selenium	0.00E+00	8.32E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.66E-04	0.00E+00
Thallium	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.25E-04	0.00E+00
Vanadium (+III)	0.00E+00	3.57E-03	1.07E-04	2.94E-04	7.21E-05	2.08E-04	0.00E+00	1.70E-04	7.79E-04	9.57E-05
Zinc (+II)	0.00E+00	9.23E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.11E-04	7.40E-05

Global Warming Potential	**kg CO2-Equiv.**									
	Biogas	**Coal**	**Geotherm**	**Hydro**	**Gas**	**Wind**	**Wood**	**HV**	**LV**	**MV**
Carbon dioxide	3.38E-04	4.66E-02	1.92E-02	4.02E-03	9.36E-02	7.70E-04	3.18E-04	8.08E-04	1.18E-03	0.00E+00
Carbon dioxide (biotic)	3.20E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.16E-02	0.00E+00	2.32E-04	0.00E+00
Nitrous oxide (laughing gas)	0.00E+00	3.91E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.60E-03	0.00E+00	0.00E+00
Methane	0.00E+00	5.21E-03	4.24E-03	0.00E+00	2.25E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Methane (biotic)	6.85E-04	0.00E+00	0.00E+00	4.04E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table 42 Substance Quantities Contributing More than 1% to CML 2001 – Apr. 2013 Impact Categories from the Production of 1kWh New Zealand Electricity

Human Toxicity Potential	**kg DCB-Equiv.**									
	Biogas	**Coal**	**Geotherm**	**Hydro**	**Gas**	**Wind**	**Wood**	**HV**	**LV**	**MV**
Antimony (air)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Arsenic (air)	0.00E+00	4.42E-04	1.49E-04	2.15E-04	2.14E-04	3.27E-04	0.00E+00	2.95E-04	1.73E-02	1.57E-03
Cadmium (air)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.51E-03	2.29E-04
Chromium (+VI) (air)	0.00E+00	4.35E-04	7.36E-04	4.28E-03	6.09E-04	1.46E-03	1.26E-04	0.00E+00	5.33E-04	0.00E+00
Copper (air)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.10E-04	0.00E+00
Mercury (air)	0.00E+00	0.00E+00	1.99E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nickel (air)	0.00E+00	1.31E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.43E-03	3.13E-04
Selenium (air)	0.00E+00	1.60E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.41E-04	0.00E+00
Hydrogen fluoride (air)	0.00E+00	2.29E-03	1.02E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.00E-04	0.00E+00	0.00E+00
Nitrogen oxides (air)	0.00E+00	2.45E-04	0.00E+00	0.00E+00	4.14E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Antimony (freshwater)	0.00E+00	1.78E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.36E-04	0.00E+00
Arsenic (+V) (freshwater)	0.00E+00	3.26E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.48E-04	0.00E+00
Barium (freshwater)	0.00E+00	1.45E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Beryllium (freshwater)	0.00E+00	1.92E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.80E-04	0.00E+00
Cobalt (freshwater)	0.00E+00	1.70E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Molybdenum (freshwater)	0.00E+00	2.34E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.92E-04	0.00E+00
Nickel (+II) (freshwater)	0.00E+00	2.70E-03	0.00E+00	1.82E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.06E-04	0.00E+00
Selenium (freshwater)	0.00E+00	1.60E-02	1.70E-04	2.30E-04	1.07E-04	2.31E-04	0.00E+00	1.48E-04	7.01E-03	6.43E-04
Thallium (freshwater)	0.00E+00	1.83E-03	0.00E+00	1.45E-04	0.00E+00	1.08E-04	0.00E+00	0.00E+00	3.51E-03	3.20E-04
Vanadium (+III) (freshwater)	0.00E+00	1.26E-03	0.00E+00	1.04E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.75E-04	0.00E+00

Marine Aquatic Ecotoxicity Potential	**kg DCB-Equiv.**									
	Biogas	**Coal**	**Geotherm**	**Hydro**	**Gas**	**Wind**	**Wood**	**HV**	**LV**	**MV**
Nickel (air)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.37	0.00
Selenium (air)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydrogen fluoride (air)	0.00	32.75	1.46	1.09	0.32	0.41	0.00	2.86	0.85	0.61
Barium (freshwater)	0.00	1.92	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Beryllium (freshwater)	0.00	74.22	0.73	0.83	0.35	0.69	0.00	0.43	18.52	1.70
Cobalt (freshwater)	0.00	7.73	0.00	0.32	0.00	0.00	0.00	0.00	2.03	0.00
Molybdenum (freshwater)	0.00	0.89	0.00	0.00	0.00	0.00	0.00	0.00	0.34	0.00
Nickel (+II) (freshwater)	0.00	18.35	0.34	1.24	0.00	0.59	0.00	0.00	0.72	0.00
Selenium (freshwater)	0.00	7.23	0.00	0.00	0.00	0.00	0.00	0.00	3.17	0.29
Thallium (freshwater)	0.00	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.41	0.00
Vanadium (+III) (freshwater)	0.00	3.42	0.00	0.28	0.00	0.20	0.00	0.00	0.74	0.00
Zinc (+II) (freshwater)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Ozone Layer Depletion Potential	**kg R11-Equiv.**									
	Biogas	**Coal**	**Geotherm**	**Hydro**	**Gas**	**Wind**	**Wood**	**HV**	**LV**	**MV**
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	0.00E+00	0.00E+00	7.49E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Carbon tetrachloride (tetrachloromethane)	5.49E-12	9.61E-12	2.41E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.87E-12	0.00E+00
Halon (1211)	0.00E+00	4.59E-12	9.22E-12	1.37E-11	5.46E-12	4.50E-12	0.00E+00	4.30E-12	8.14E-12	0.00E+00
Halon (1301)	1.21E-11	1.20E-10	2.15E-10	2.16E-10	2.66E-11	4.42E-11	4.97E-11	3.30E-11	5.42E-11	6.95E-12
R 113 (trichlorotrifluoroethane)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.26E-09	0.00E+00	0.00E+00	0.00E+00
R 114 (dichlorotetrafluoroethane)	0.00E+00	5.04E-12	9.63E-12	1.82E-11	3.33E-12	5.42E-12	0.00E+00	0.00E+00	8.29E-12	0.00E+00
R 12 (dichlorodifluoromethane)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.24E-12	0.00E+00	2.05E-11	0.00E+00	0.00E+00	0.00E+00
R 124 (chlorotetrafluoroethane)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.52E-11	0.00E+00	0.00E+00	0.00E+00
R 22 (chlorodifluoromethane)	0.00E+00	2.96E-12	4.87E-11	9.46E-12	5.06E-11	6.05E-12	0.00E+00	2.85E-12	9.08E-12	0.00E+00

POCP	**kg Ethene-Equiv.**									
	Biogas	**Coal**	**Geotherm**	**Hydro**	**Gas**	**Wind**	**Wood**	**HV**	**LV**	**MV**
Carbon monoxide	4E-07	5E-07	1E-06	3E-07	1E-06	1E-07	7E-08	1E-07	2E-07	0E+00
Carbon monoxide (biotic)	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00	1E-06	0E+00	0E+00	0E+00
Nitrogen oxides	0E+00	6E-06	2E-06	3E-07	1E-05	7E-08	6E-07	6E-08	2E-07	0E+00
Sulphur dioxide	1E-07	1E-05	6E-07	4E-07	1E-07	2E-07	0E+00	2E-07	2E-06	2E-07
NMVOC (unspecified)	7E-08	3E-06	2E-06	8E-07	3E-06	4E-07	5E-07	1E-07	7E-07	0E+00
Pentane (n-pentane)	0E+00	0E+00	0E+00	0E+00	7E-07	0E+00	0E+00	0E+00	0E+00	0E+00
Xylene (dimethyl benzene)	0E+00	6E-07	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00
Methane	0E+00	1E-06	1E-06	0E+00	5E-07	0E+00	0E+00	0E+00	0E+00	0E+00
Methane (biotic)	2E-07	0E+00	0E+00	1E-06	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00

Terrestrial Ecotoxicity Potential	**kg DCB-Equiv.**									
	Biogas	**Coal**	**Geotherm**	**Hydro**	**Gas**	**Wind**	**Wood**	**HV**	**LV**	**MV**
Arsenic (air)	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	8.0E-05	7.3E-06
Chromium (+VI) (air)	0.0E+00	0.0E+00	0.0E+00	3.8E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Chromium (unspecified) (air)	0.0E+00	9.6E-06	2.6E-05	1.5E-04	2.3E-05	5.2E-05	5.3E-06	0.0E+00	2.0E-05	0.0E+00
Mercury (air)	0.0E+00	7.0E-05	9.4E-04	1.0E-05	4.8E-06	6.0E-06	0.0E+00	0.0E+00	4.7E-06	0.0E+00
Mercury (long-term freshwater)	0.0E+00	2.3E-05	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Chromium (+VI) (industrial soil)	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.0E-03	2.3E-04

Appendix 8 MBIE Combustion Emission Factors

Ministry of Business,
Innovation & Employment

Combustion carbon dioxide emission factors

Kilotonnes carbon dioxide per petajoule (kt CO_2/PJ)

	2009	2010	2011	2012	2013
Liquid Fuels					
Premium Petrol	66.82	66.79	66.79	66.74	66.72
Regular Petrol	66.57	66.59	66.55	66.56	66.51
Diesel	69.55	69.64	69.64	69.73	69.57
Light Fuel Oil	72.78	72.91	72.85	72.88	72.50
Heavy Fuel Oil	73.84	73.68	73.84	73.49	73.46
Bunker Fuel Oil	74.23	74.09	74.12	73.82	73.83
Jet Kerosene	68.59	68.57	68.53	68.56	68.38
Aviation Gasoline	65.89	65.89	65.89	65.89	65.89
LPG	60.43	59.24	58.10	57.01	55.95
Bitumen	76.90	76.90	76.98	76.97	77.00
Exported Naphtha	63.51	63.36	63.36	63.33	63.35
Bioethanol	64.20	64.20	64.20	64.20	64.20
Biodiesel	62.40	62.40	62.40	62.40	62.40
Natural Gas					
National weighted average	53.17	53.29	53.46	53.47	53.24
Coal					
Bituminous	89.10	89.10	89.10	89.10	89.10
Sub-bituminous	92.00	92.00	92.00	92.00	92.00
Lignite	93.10	93.10	93.10	93.10	93.10
Biomass					
Wood	104.15	104.15	104.15	104.15	104.15
Biogas	100.98	100.98	100.98	100.98	100.98

Sources:

- Refining New Zealand
- New Zealand Energy Statistics (MBIE)
- New Zealand Emissions Trading Scheme (EPA)
- New Zealand Energy Handbook (1993)
- IPCC (2006) default emission factors

Combustion non-carbon dioxide emission factors

Tonnes emission per petajoule (t/PJ)

	Methane CH_4	Nitrous Oxide N_2O	Carbon monoxide CO	Nitrogen oxides NO_x	Non-methane volatile organic compounds NMVOCs	Sulphur dioxide SO_2
Liquid Fuel						
Stationary						
Agriculture - Stationary	0.19	0.38	351.50	114.00	161.50	NA
Industry - Distillate Fuel Oil Boilers (Petrol, Diesel)	0.19	0.38	15.20	61.75	4.75	NA
Industry - Residual Fuel Oil Boilers	2.85	0.29	14.25	161.50	4.75	NA
Industry - LPG	1.05	0.57	15.68	91.68	4.75	NA
Commercial - Distillate Fuel Oil (Petrol, Diesel)	0.67	0.38	15.20	61.75	4.75	NA
Commercial - Residual Fuel Oil	1.33	0.29	14.25	161.50	4.75	NA
Commercial - LPG	1.05	0.57	9.69	66.98	4.75	NA
Residential - Distillate Fuel Oil	0.67	0.19	15.20	61.75	4.75	NA
Residential - Residual Fuel Oil	1.33	0.19	14.25	161.50	4.75	NA
Residential - LPG	1.05	0.57	9.50	44.65	4.75	NA
Electricity - Distillate Fuel Oil	0.86	0.38	15.20	209.00	4.75	NA
Electricity - Residual Fuel Oil	0.86	0.29	14.25	190.00	4.75	NA
Refinery	2.85	0.29	14.25	161.50	4.75	NA
Crude Oil	3.00	0.60	15.00	200.00	5.00	104.39
Mobile						
Petrol	18.53	1.43	4,591.35	210.90	884.93	2.13
Diesel (road)	3.80	3.71	303.05	643.15	101.65	104.39
Diesel (rail)	3.80	3.71	303.05	643.15	101.65	104.39
Fuel Oil (heavy fuel oil)	6.65	1.90	171.00	1,710.00	49.40	1,044.03
Fuel Oil (light fuel oil)	6.65	1.90	171.00	1,710.00	49.40	787.22
Av Fuel/Kerosene	0.48	1.90	114.00	275.50	17.10	4.31
LPG	28.50	0.57	1,377.50	361.00	608.00	-
Bunkers - Diesel + Fuel Oil	6.65	1.90	171.00	1,710.00	49.40	-
Bunkers - Av Fuel	0.48	1.90	114.00	275.50	17.10	-
Gas						
Industry - Natural Gas Boilers	1.26	0.09	16.20	225.00	4.50	-
Commercial - Natural Gas Boilers	1.08	2.07	8.46	40.50	4.50	-
Residential - Natural Gas Heaters	0.90	0.09	9.00	42.30	4.50	-
Transport - CNG	567.00	0.09	648.00	342.00	81.00	-
Electricity - Large Gas-fired turbines	5.40	0.09	41.40	171.00	4.50	-
Electricity - Natural Gas Boilers	0.09	0.09	16.20	225.00	4.50	-
Own Use	1.26	0.09	16.20	225.00	4.50	-
Coal						
Agriculture	9.50	1.33	190.00	228.00	190.00	-
Industrial (Cement and Lime)	0.95	1.33	75.05	500.65	19.00	-
Industry (Excl Cement and Lime)	0.67	1.52	8.55	361.00	19.00	-
Commercial	9.50	1.33	190.00	228.00	190.00	-
Residential	285.00	1.33	3,420.00	171.00	190.00	-
Electricity	0.67	1.52	8.55	361.00	4.75	-
Transport - Railways	9.38	1.31	140.66	281.31	18.75	-
Bituminous	-	-	-	-	-	668.22
Sub-Bituminous	-	-	-	-	-	387.17
Lignite	-	-	-	-	-	350.00
Biomass						
Biogas	1.08	2.07	8.46	40.50	4.50	-
Wood (Industrial)	14.25	3.80	560.50	61.75	47.50	331.13
Wood (residential)	285.00	3.80	10,450.00	104.50	570.00	331.13
Bioethanol	18.00	-	4,591.35	210.90	884.93	2.13
Biodiesel	18.00	-	303.05	643.15	101.65	104.39

Sources
IPCC (2006) default emission factor

Appendix 9 Grid Mix Analysis 1990 – 2014

Table 43 Electricity Mix for the period 1990 – 2014 based on Annual Net Generation. Source: New Zealand Energy Balance Web Tables 2015.

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Hydro	73%	70%	65%	70%	75%	77%	73%	64%	69%	62%	64%	56%	63%	59%	65%	56%	55%	55%	52%	57%	56%	58%	53%	54%	57%
Geothermal	6%	7%	7%	7%	6%	6%	6%	6%	7%	7%	7%	7%	7%	7%	6%	7%	8%	8%	9%	11%	13%	13%	14%	14%	16%
Biogas	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	0%	1%	1%	1%	1%	1%	1%
Wood	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
Wind	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	2%	2%	3%	4%	4%	5%	5%	5%
Oil	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Coal	2%	1%	4%	2%	2%	2%	2%	4%	4%	5%	4%	5%	5%	9%	11%	13%	12%	7%	11%	7%	4%	5%	8%	5%	4%
Gas	17%	20%	22%	20%	15%	13%	17%	24%	19%	25%	23%	30%	24%	23%	16%	21%	22%	26%	24%	20%	21%	18%	19%	19%	16%
Waste Heat[3]	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Percentage Renewable	80.8%	78.1%	73.6%	77.9%	82.8%	84.6%	79.9%	71.2%	76.6%	70.6%	72.5%	64.7%	70.6%	67.2%	72.9%	65.4%	65.7%	66.7%	65.4%	72.7%	74.2%	77.0%	72.8%	75.1%	79.9%
Percentage Fossil Fuel	19.0%	21.7%	26.2%	21.9%	17.0%	15.3%	19.9%	28.6%	23.2%	29.2%	27.3%	35.1%	29.2%	32.6%	26.9%	34.4%	34.2%	33.1%	34.5%	27.2%	25.6%	22.8%	27.1%	24.8%	20.0%

Table 44 LCIA Results for the Electricity Mix 1990 -2014

		1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
ADP Elements	**[kg Sb-Equiv.]**	4.9E-07	4.9E-07	5.0E-07	4.9E-07	4.9E-07	4.9E-07	4.9E-07	4.9E-07	5.0E-07	5.0E-07	5.0E-07	4.9E-07	4.9E-07	5.0E-07	5.0E-07	5.0E-07	5.0E-07	5.0E-07	5.1E-07	5.1E-07	5.1E-07	5.1E-07	5.2E-07	5.2E-07	5.2E-07
ADP Fossil	**[MJ]**	8.0E-01	8.0E-01	1.3E+00	9.1E-01	7.6E-01	8.1E-01	8.8E-01	1.3E+00	1.1E+00	1.4E+00	1.2E+00	1.4E+00	1.3E+00	1.9E+00	1.9E+00	2.4E+00	2.3E+00	1.6E+00	2.1E+00	1.5E+00	1.2E+00	1.2E+00	1.6E+00	1.3E+00	1.0E+00
AP	**[kg SO2-Equiv.]**	5.5E-04	5.4E-04	7.5E-04	6.0E-04	5.3E-04	5.4E-04	5.8E-04	7.7E-04	7.0E-04	8.2E-04	7.6E-04	8.4E-04	7.6E-04	1.0E-03	1.1E-03	1.3E-03	1.2E-03	9.4E-04	1.2E-03	9.6E-04	8.1E-04	8.1E-04	1.0E-03	8.9E-04	8.0E-04
EP	**[kg Phosphate-Equiv.]**	2.3E-04	2.0E-04	3.6E-04	2.5E-04	2.2E-04	2.5E-04	2.6E-04	3.9E-04	3.5E-04	4.1E-04	3.6E-04	4.2E-04	3.9E-04	6.4E-04	7.0E-04	8.5E-04	8.0E-04	5.2E-04	7.2E-04	5.2E-04	3.7E-04	3.8E-04	5.6E-04	4.1E-04	3.3E-04
FAETP	**[kg DCB-Equiv.]**	3.3E-02	2.7E-02	4.8E-02	3.3E-02	3.2E-02	3.7E-02	3.7E-02	5.2E-02	4.8E-02	5.5E-02	4.9E-02	5.6E-02	5.4E-02	9.0E-02	1.0E-01	1.2E-01	1.1E-01	7.1E-02	1.0E-01	7.4E-02	5.1E-02	5.4E-02	8.0E-02	5.8E-02	4.8E-02
GWP	**[kg CO2-Equiv.]**	1.5E-01	1.6E-01	2.0E-01	1.7E-01	1.4E-01	1.3E-01	1.5E-01	2.1E-01	1.8E-01	2.1E-01	2.0E-01	2.3E-01	1.9E-01	2.3E-01	2.1E-01	2.6E-01	2.6E-01	2.3E-01	2.5E-01	2.0E-01	1.9E-01	1.8E-01	2.1E-01	1.9E-01	1.6E-01
GWP excl Biog. (	**[kg CO2-Equiv.]**	1.4E-01	1.5E-01	1.9E-01	1.6E-01	1.3E-01	1.3E-01	1.5E-01	2.0E-01	1.7E-01	2.1E-01	2.0E-01	2.2E-01	1.9E-01	2.3E-01	2.1E-01	2.6E-01	2.5E-01	2.2E-01	2.5E-01	2.0E-01	1.8E-01	1.7E-01	2.1E-01	1.8E-01	1.6E-01
HTP	**[kg DCB-Equiv.]**	7.1E-02	6.9E-02	8.4E-02	7.3E-02	7.1E-02	7.4E-02	7.4E-02	8.5E-02	8.2E-02	8.7E-02	8.3E-02	8.7E-02	8.4E-02	1.1E-01	1.1E-01	1.3E-01	1.2E-01	9.7E-02	1.2E-01	9.9E-02	8.4E-02	8.6E-02	1.0E-01	9.0E-02	8.3E-02
MAETP	**[kg DCB-Equiv.]**	9.7E+01	8.0E+01	1.4E+02	1.0E+02	9.5E+01	1.1E+02	1.1E+02	1.6E+02	1.4E+02	1.6E+02	1.5E+02	1.7E+02	1.6E+02	2.7E+02	3.0E+02	3.6E+02	3.4E+02	2.1E+02	3.0E+02	2.2E+02	1.5E+02	1.6E+02	2.4E+02	1.7E+02	1.4E+02
ODP	**[kg R11-Equiv.]**	2.7E-09	2.5E-09	2.7E-09	2.5E-09	2.5E-09	2.5E-09	2.4E-09	2.2E-09	2.7E-09	2.7E-09	2.9E-09	2.2E-09	1.7E-09	1.7E-09	1.9E-09	2.1E-09	2.1E-09	2.0E-09	2.2E-09	2.2E-09	2.2E-09	2.2E-09	2.3E-09	2.4E-09	2.4E-09
POCP	**[kg Ethene-Equiv.]**	4.0E-05	4.1E-05	5.5E-05	4.4E-05	3.9E-05	3.9E-05	4.2E-05	5.5E-05	5.0E-05	5.8E-05	5.4E-05	6.0E-05	5.3E-05	6.9E-05	6.8E-05	8.2E-05	8.0E-05	6.3E-05	7.7E-05	6.1E-05	5.2E-05	5.1E-05	6.4E-05	5.5E-05	4.8E-05
TETP	**[kg DCB-Equiv.]**	3.2E-03	3.2E-03	3.3E-03	3.3E-03	3.2E-03	3.2E-03	3.2E-03	3.2E-03	3.3E-03	3.3E-03	3.3E-03	3.2E-03	3.2E-03	3.2E-03	3.3E-03	3.4E-03	3.4E-03	3.3E-03	3.5E-03	3.5E-03	3.6E-03	3.7E-03	3.7E-03	3.8E-03	3.8E-03

Table 45 Moving Averages of LCA Results over 1990-2014

ADP Elements	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Normal Mix	4.9E-07	4.9E-07	5.0E-07	4.9E-07	4.9E-07	4.9E-07	4.9E-07	4.9E-07	5.0E-07	5.0E-07	5.0E-07	4.9E-07	4.9E-07	5.0E-07	5.0E-07	5.0E-07	5.0E-07	5.0E-07	5.1E-07	5.1E-07	5.1E-07	5.1E-07	5.2E-07	5.2E-07	5.2E-07
3 Year MAVG	#N/A	#N/A	4.9E-07	4.9E-07	4.9E-07	4.9E-07	4.9E-07	4.9E-07	4.9E-07	4.9E-07	5.0E-07	4.9E-07	4.9E-07	4.9E-07	5.0E-07	5.0E-07	5.0E-07	5.0E-07	5.0E-07	5.1E-07	5.1E-07	5.1E-07	5.1E-07	5.2E-07	5.2E-07
5 Year MAVG	#N/A	#N/A	#N/A	#N/A	4.9E-07	4.9E-07	4.9E-07	4.9E-07	4.9E-07	4.9E-07	4.9E-07	4.9E-07	4.9E-07	4.9E-07	5.0E-07	5.0E-07	5.0E-07	5.0E-07	5.0E-07	5.0E-07	5.1E-07	5.1E-07	5.1E-07	5.1E-07	5.1E-07
10 Year MAVG	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	4.9E-07	4.9E-07	4.9E-07	4.9E-07	4.9E-07	4.9E-07	5.0E-07	5.0E-07	5.0E-07	5.0E-07	5.0E-07	5.0E-07	5.0E-07	5.1E-07	5.1E-07	5.1E-07
ADP Fossil	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Normal Mix	8.0E-01	8.0E-01	1.3E+00	9.1E-01	7.6E-01	8.1E-01	8.8E-01	1.3E+00	1.1E+00	1.4E+00	1.2E+00	1.4E+00	1.3E+00	1.9E+00	1.9E+00	2.4E+00	2.3E+00	1.6E+00	2.1E+00	1.5E+00	1.2E+00	1.2E+00	1.6E+00	1.3E+00	1.0E+00
3 Year MAVG	#N/A	#N/A	9.5E-01	9.9E-01	9.8E-01	8.3E-01	8.2E-01	1.0E+00	1.1E+00	1.3E+00	1.2E+00	1.3E+00	1.3E+00	1.5E+00	1.7E+00	2.1E+00	2.2E+00	2.1E+00	2.0E+00	1.8E+00	1.6E+00	1.3E+00	1.3E+00	1.3E+00	1.3E+00
5 Year MAVG	#N/A	#N/A	#N/A	#N/A	9.0E-01	9.1E-01	9.2E-01	9.3E-01	9.8E-01	1.1E+00	1.2E+00	1.3E+00	1.3E+00	1.4E+00	1.6E+00	1.8E+00	2.0E+00	2.0E+00	2.1E+00	2.0E+00	1.7E+00	1.5E+00	1.5E+00	1.4E+00	1.2E+00
10 Year MAVG	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	1.0E+00	1.0E+00	1.1E+00	1.1E+00	1.2E+00	1.3E+00	1.5E+00	1.6E+00	1.7E+00	1.8E+00	1.8E+00	1.8E+00	1.7E+00	1.8E+00	1.7E+00	1.6E+00
AP	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Normal Mix	5.5E-04	5.4E-04	7.5E-04	6.0E-04	5.3E-04	5.4E-04	5.8E-04	7.7E-04	7.0E-04	8.2E-04	7.6E-04	8.4E-04	7.6E-04	1.0E-03	1.1E-03	1.3E-03	1.2E-03	9.4E-04	1.2E-03	9.6E-04	8.1E-04	8.1E-04	1.0E-03	8.9E-04	8.0E-04
3 Year MAVG	#N/A	#N/A	6.1E-04	6.3E-04	6.3E-04	5.6E-04	5.5E-04	6.3E-04	6.8E-04	7.6E-04	7.6E-04	8.0E-04	7.9E-04	8.8E-04	9.6E-04	1.1E-03	1.2E-03	1.2E-03	1.1E-03	1.0E-03	9.9E-04	8.6E-04	8.9E-04	9.2E-04	9.1E-04
5 Year MAVG	#N/A	#N/A	#N/A	#N/A	5.9E-04	5.9E-04	6.0E-04	6.0E-04	6.2E-04	6.8E-04	7.2E-04	7.8E-04	7.8E-04	8.4E-04	9.0E-04	1.0E-03	1.1E-03	1.1E-03	1.2E-03	1.1E-03	1.0E-03	9.4E-04	9.7E-04	9.0E-04	8.7E-04
10 Year MAVG	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	6.4E-04	6.6E-04	6.9E-04	6.9E-04	7.3E-04	7.9E-04	8.6E-04	9.3E-04	9.5E-04	1.0E-03	1.0E-03	1.0E-03	1.0E-03	1.0E-03	1.0E-03	1.0E-03
EP	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Normal Mix	2.3E-04	2.0E-04	3.6E-04	2.5E-04	2.2E-04	2.5E-04	2.6E-04	3.9E-04	3.5E-04	4.1E-04	3.6E-04	4.2E-04	3.9E-04	6.4E-04	7.0E-04	8.5E-04	8.0E-04	5.2E-04	7.2E-04	5.2E-04	3.7E-04	3.8E-04	5.6E-04	4.1E-04	3.3E-04
3 Year MAVG	#N/A	#N/A	2.6E-04	2.7E-04	2.8E-04	2.4E-04	2.5E-04	3.0E-04	3.3E-04	3.8E-04	3.7E-04	4.0E-04	3.9E-04	4.9E-04	5.8E-04	7.3E-04	7.9E-04	7.2E-04	6.8E-04	5.9E-04	5.4E-04	4.2E-04	4.4E-04	4.5E-04	4.4E-04
5 Year MAVG	#N/A	#N/A	#N/A	#N/A	2.5E-04	2.6E-04	2.7E-04	2.7E-04	2.9E-04	3.3E-04	3.5E-04	3.9E-04	3.9E-04	4.5E-04	5.1E-04	6.0E-04	6.8E-04	7.0E-04	7.2E-04	6.8E-04	5.9E-04	5.0E-04	5.1E-04	4.5E-04	4.1E-04
10 Year MAVG	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	2.9E-04	3.1E-04	3.3E-04	3.3E-04	3.7E-04	4.2E-04	4.8E-04	5.3E-04	5.5E-04	5.8E-04	5.9E-04	5.9E-04	5.9E-04	6.1E-04	5.8E-04	5.5E-04
FAETP	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Normal Mix	3.3E-02	2.7E-02	4.8E-02	3.3E-02	3.2E-02	3.7E-02	3.7E-02	5.2E-02	4.8E-02	5.5E-02	4.9E-02	5.6E-02	5.4E-02	9.0E-02	1.0E-01	1.2E-01	1.1E-01	7.1E-02	1.0E-01	7.4E-02	5.1E-02	5.4E-02	8.0E-02	5.8E-02	4.8E-02
3 Year MAVG	#N/A	#N/A	3.6E-02	3.6E-02	3.8E-02	3.4E-02	3.5E-02	4.2E-02	4.6E-02	5.2E-02	5.0E-02	5.3E-02	5.3E-02	6.7E-02	8.2E-02	1.0E-01	1.1E-01	1.0E-01	9.5E-02	8.2E-02	7.5E-02	6.0E-02	6.2E-02	6.4E-02	6.2E-02
5 Year MAVG	#N/A	#N/A	#N/A	#N/A	3.5E-02	3.5E-02	3.7E-02	3.8E-02	4.1E-02	4.6E-02	4.8E-02	5.2E-02	5.2E-02	6.1E-02	7.0E-02	8.5E-02	9.6E-02	1.0E-01	1.0E-01	9.6E-02	8.2E-02	7.0E-02	7.2E-02	6.3E-02	5.8E-02
10 Year MAVG	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	4.0E-02	4.2E-02	4.5E-02	4.5E-02	5.1E-02	5.8E-02	6.6E-02	7.4E-02	7.6E-02	8.1E-02	8.3E-02	8.3E-02	8.3E-02	8.6E-02	8.3E-02	7.7E-02
GWP	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Normal Mix	1.4E-01	1.5E-01	1.9E-01	1.6E-01	1.3E-01	1.3E-01	1.5E-01	2.0E-01	1.7E-01	2.1E-01	2.0E-01	2.2E-01	1.9E-01	2.3E-01	2.1E-01	2.6E-01	2.5E-01	2.2E-01	2.5E-01	2.0E-01	1.8E-01	1.7E-01	2.1E-01	1.8E-01	1.6E-01
3 Year MAVG	#N/A	#N/A	1.6E-01	1.7E-01	1.6E-01	1.4E-01	1.4E-01	1.6E-01	1.8E-01	1.9E-01	1.9E-01	2.1E-01	2.0E-01	2.1E-01	2.1E-01	2.3E-01	2.4E-01	2.4E-01	2.4E-01	2.2E-01	2.1E-01	1.8E-01	1.9E-01	1.9E-01	1.8E-01
5 Year MAVG	#N/A	#N/A	#N/A	#N/A	1.6E-01	1.5E-01	1.5E-01	1.5E-01	1.6E-01	1.7E-01	1.9E-01	2.0E-01	2.0E-01	2.1E-01	2.1E-01	2.2E-01	2.3E-01	2.3E-01	2.4E-01	2.4E-01	2.2E-01	2.1E-01	2.0E-01	1.9E-01	1.8E-01
10 Year MAVG	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	1.6E-01	1.7E-01	1.8E-01	1.8E-01	1.8E-01	1.9E-01	2.0E-01	2.1E-01	2.2E-01	2.2E-01	2.2E-01	2.2E-01	2.2E-01	2.2E-01	2.1E-01	2.1E-01
HTP	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Normal Mix	7.1E-02	6.9E-02	8.4E-02	7.3E-02	7.1E-02	7.4E-02	7.4E-02	8.5E-02	8.2E-02	8.7E-02	8.3E-02	8.7E-02	8.4E-02	1.1E-01	1.1E-01	1.3E-01	1.2E-01	9.7E-02	1.2E-01	9.9E-02	8.4E-02	8.6E-02	1.0E-01	9.0E-02	8.3E-02
3 Year MAVG	#N/A	#N/A	7.5E-02	7.5E-02	7.6E-02	7.3E-02	7.3E-02	7.8E-02	8.0E-02	8.4E-02	8.4E-02	8.6E-02	8.5E-02	9.3E-02	1.0E-01	1.2E-01	1.2E-01	1.2E-01	1.1E-01	1.0E-01	1.0E-01	9.0E-02	9.1E-02	9.3E-02	9.2E-02
5 Year MAVG	#N/A	#N/A	#N/A	#N/A	7.4E-02	7.4E-02	7.5E-02	7.5E-02	7.7E-02	8.0E-02	8.2E-02	8.5E-02	8.5E-02	9.0E-02	9.5E-02	1.0E-01	1.1E-01	1.1E-01	1.2E-01	1.1E-01	1.0E-01	9.7E-02	9.8E-02	9.3E-02	8.9E-02
10 Year MAVG	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	7.7E-02	7.8E-02	8.0E-02	8.0E-02	8.3E-02	8.8E-02	9.3E-02	9.8E-02	9.9E-02	1.0E-01	1.0E-01	1.0E-01	1.0E-01	1.1E-01	1.0E-01	1.0E-01
MAETP	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Normal Mix	9.7E+01	8.0E+01	1.4E+02	1.0E+02	9.5E+01	1.1E+02	1.1E+02	1.6E+02	1.4E+02	1.6E+02	1.5E+02	1.7E+02	1.6E+02	2.7E+02	3.0E+02	3.6E+02	3.4E+02	2.1E+02	3.0E+02	2.2E+02	1.5E+02	1.6E+02	2.4E+02	1.7E+02	1.4E+02
3 Year MAVG	#N/A	#N/A	1.1E+02	1.1E+02	1.1E+02	1.0E+02	1.0E+02	1.3E+02	1.4E+02	1.5E+02	1.5E+02	1.6E+02	1.6E+02	2.0E+02	2.5E+02	3.1E+02	3.4E+02	3.1E+02	2.9E+02	2.5E+02	2.3E+02	1.8E+02	1.8E+02	1.9E+02	1.9E+02
5 Year MAVG	#N/A	#N/A	#N/A	#N/A	1.0E+02	1.1E+02	1.1E+02	1.1E+02	1.2E+02	1.4E+02	1.4E+02	1.6E+02	1.6E+02	1.8E+02	2.1E+02	2.5E+02	2.9E+02	3.0E+02	3.0E+02	2.9E+02	2.5E+02	2.1E+02	2.1E+02	1.9E+02	1.7E+02
10 Year MAVG	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	1.2E+02	1.2E+02	1.3E+02	1.4E+02	1.5E+02	1.7E+02	2.0E+02	2.2E+02	2.3E+02	2.4E+02	2.5E+02	2.5E+02	2.5E+02	2.6E+02	2.5E+02	2.3E+02
ODP	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Normal Mix	2.7E-09	2.5E-09	2.7E-09	2.5E-09	2.5E-09	2.5E-09	2.4E-09	2.2E-09	2.7E-09	2.7E-09	2.9E-09	2.2E-09	1.7E-09	1.7E-09	1.9E-09	2.1E-09	2.1E-09	2.0E-09	2.2E-09	2.2E-09	2.2E-09	2.2E-09	2.3E-09	2.4E-09	2.4E-09
3 Year MAVG	#N/A	#N/A	2.6E-09	2.6E-09	2.6E-09	2.5E-09	2.5E-09	2.4E-09	2.4E-09	2.5E-09	2.8E-09	2.6E-09	2.3E-09	1.9E-09	1.8E-09	1.9E-09	2.0E-09	2.0E-09	2.1E-09	2.1E-09	2.2E-09	2.2E-09	2.2E-09	2.3E-09	2.3E-09
5 Year MAVG	#N/A	#N/A	#N/A	#N/A	2.6E-09	2.6E-09	2.5E-09	2.4E-09	2.5E-09	2.5E-09	2.6E-09	2.5E-09	2.4E-09	2.2E-09	2.1E-09	1.9E-09	1.9E-09	1.9E-09	2.0E-09	2.1E-09	2.1E-09	2.2E-09	2.2E-09	2.2E-09	2.3E-09
10 Year MAVG	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	2.5E-09	2.6E-09	2.5E-09	2.4E-09	2.4E-09	2.3E-09	2.2E-09	2.2E-09	2.2E-09	2.1E-09	2.1E-09	2.0E-09	2.0E-09	2.1E-09	2.1E-09	2.2E-09
POCP	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Normal Mix	4.0E-05	4.1E-05	5.5E-05	4.4E-05	3.9E-05	3.9E-05	4.2E-05	5.5E-05	5.0E-05	5.8E-05	5.4E-05	6.0E-05	5.3E-05	6.9E-05	6.8E-05	8.2E-05	8.0E-05	6.3E-05	7.7E-05	6.1E-05	5.2E-05	5.1E-05	6.4E-05	5.5E-05	4.8E-05
3 Year MAVG	#N/A	#N/A	4.5E-05	4.7E-05	4.6E-05	4.1E-05	4.0E-05	4.6E-05	4.9E-05	5.4E-05	5.4E-05	5.7E-05	5.6E-05	6.0E-05	6.3E-05	7.3E-05	7.7E-05	7.5E-05	7.3E-05	6.7E-05	6.3E-05	5.5E-05	5.6E-05	5.7E-05	5.6E-05
5 Year MAVG	#N/A	#N/A	#N/A	#N/A	4.4E-05	4.4E-05	4.4E-05	4.4E-05	4.5E-05	4.9E-05	5.2E-05	5.5E-05	5.5E-05	5.9E-05	6.1E-05	6.6E-05	7.0E-05	7.2E-05	7.4E-05	7.3E-05	6.7E-05	6.1E-05	6.1E-05	5.7E-05	5.4E-05
10 Year MAVG	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	4.6E-05	4.8E-05	5.0E-05	4.9E-05	5.2E-05	5.5E-05	5.9E-05	6.3E-05	6.4E-05	6.6E-05	6.7E-05	6.6E-05	6.6E-05	6.7E-05	6.5E-05	6.3E-05
TETP	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Normal Mix	3.2E-03	3.2E-03	3.3E-03	3.3E-03	3.2E-03	3.2E-03	3.2E-03	3.2E-03	3.3E-03	3.3E-03	3.3E-03	3.2E-03	3.2E-03	3.2E-03	3.3E-03	3.4E-03	3.4E-03	3.3E-03	3.5E-03	3.5E-03	3.6E-03	3.7E-03	3.7E-03	3.8E-03	3.8E-03
3 Year MAVG	#N/A	#N/A	3.3E-03	3.3E-03	3.3E-03	3.2E-03	3.2E-03	3.2E-03	3.2E-03	3.3E-03	3.3E-03	3.3E-03	3.2E-03	3.2E-03	3.2E-03	3.3E-03	3.3E-03	3.4E-03	3.4E-03	3.5E-03	3.6E-03	3.6E-03	3.7E-03	3.7E-03	3.8E-03
5 Year MAVG	#N/A	#N/A	#N/A	#N/A	3.3E-03	3.3E-03	3.3E-03	3.2E-03	3.2E-03	3.2E-03	3.3E-03	3.3E-03	3.3E-03	3.3E-03	3.2E-03	3.3E-03	3.3E-03	3.3E-03	3.4E-03	3.4E-03	3.5E-03	3.5E-03	3.6E-03	3.7E-03	3.7E-03
10 Year MAVG	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	3.3E-03	3.3E-03	3.3E-03	3.2E-03	3.2E-03	3.2E-03	3.3E-03	3.3E-03	3.3E-03	3.3E-03	3.3E-03	3.4E-03	3.4E-03	3.5E-03	3.5E-03	3.6E-03