GREENHOUSE GAS EMISSIONS FROM NEW ZEALAND GEOTHERMAL POWER GENERATION IN CONTEXT

Katie McLean[1,2*], Ian Richardson[1,3]

[1]New Zealand Geothermal Association

[2] Contact Energy Ltd, Private Bag 2001, Taupo 3352, New Zealand

[3] Mercury Ltd, 283 Vaughn Road, Rotorua 3010, New Zealand

* katie.mclean@contactenergy.co.nz

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ABSTRACT

Conventional geothermal systems are complex natural features, usually comprising a deep heat source such as a magma chamber, and above this a convecting system of hot water/steam. There are often natural features at the surface indicating the presence of these geothermal systems underground, including fumaroles, hot springs, geysers and steaming ground. There are many geothermal fields in New Zealand, mostly associated with volcanism within the extensional Taupo Volcanic Zone of the North Island.

From these geothermal surface features, there is a significant natural flux of CO_2 and methane (CH_4) through the ground surface and into the atmosphere. These gases are transported to the surface by hot geothermal fluids, though the original source of the gases is not yet known and is the subject of current research by GNS. When geothermal fields are developed for electricity generation, CO_2 and methane are released during the power generation process, while the natural flux of these gases is thought to diminish.

CO_2 and methane emissions data during plant operation (combined as CO_2-equivalent) are presented for the major geothermal plants in New Zealand. There is a focus on the most recent emissions for the calendar year 2018, followed by a review of how these emissions have changed over the period 2010-2018. The tendency of geothermal emissions intensity to decrease over time is shown, as well as the effect of plant/operational changes. The geothermal emissions intensity is compared to typical values for other clean energy sources, and also to fossil fuels.

1. INTRODUCTION

Greenhouse gases are emitted by most geothermal power stations during the power generation process. In the underground reservoir, the hot geothermal fluid contains carbon dioxide (CO_2) and methane (CH_4), which are then transported to the surface when the fluid is extracted. The gases separate into the steam phase which goes to the power plant where it is condensed in a heat exchanger (condenser). The greenhouse gases do not condense, and along with some others are referred to as non-condensable gases (NCGs) and would accumulate in the condenser where they would compromise efficiency if they were not removed. Removed gases are typically released to the atmosphere, though in a few cases are compressed and reinjected (Kaya and Zarrouk, 2017) or purified and used for industrial purposes such as production of methanol (Halper, 2011).

Significant fluxes of greenhouse gases are emitted via these natural surface features, and also as flux through the soil. The net effect of the power station development on all greenhouse gas emissions - from both power generation and the natural surface features - is arguably a more valid measure of the carbon impact of a geothermal development.

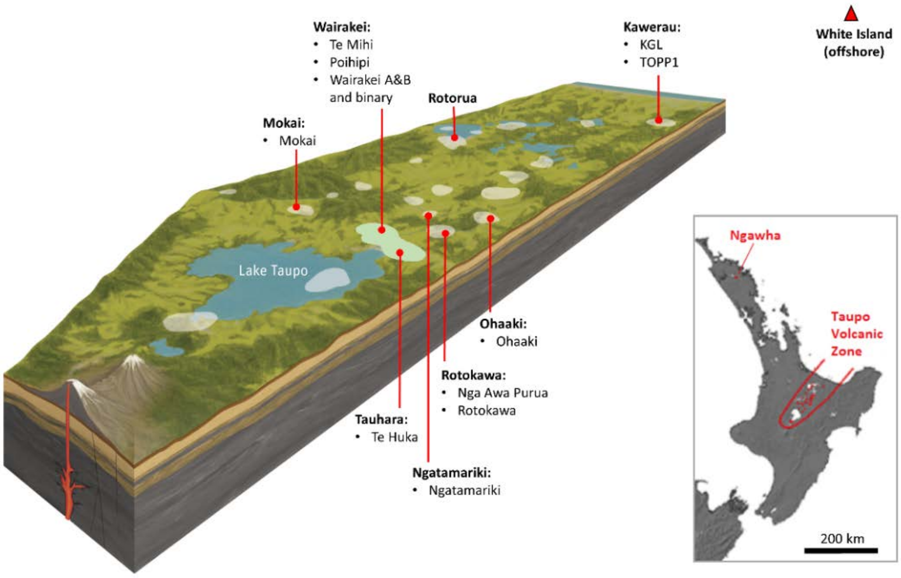

Figure 1: Map of the Taupo Volcanic Zone (TVZ) indicating the 23 known geothermal systems, associated power stations (bullet points), and other locations discussed in this paper. Inset: map of the north island, indicating the location of Ngawha geothermal field and TVZ.

To illustrate the full geothermal greenhouse gas emissions picture, available CO_2 and CH_4 emissions data have been collected from both natural surface features and from the 12 major power stations in New Zealand (Figure 1). These data are presented as CO_2-equivalent.

2. BACKGROUND

2.1 Major geothermal power stations in NZ

There are 12 major geothermal power stations in New Zealand, located at 8 geothermal fields (Figure 1). All but one are located within the Taupo Volcanic Zone, which is a wedge of volcanism through the north island resulting from crustal extension and melting associated with subduction of the Pacific tectonic plate under the Australian plate. The exception is Ngawha geothermal field, which is located in the far north (Figure 1).

2.2 Geothermal emissions: natural state vs development

In their natural state (pre-development) geothermal systems emit CO_2 and CH_4 (and also H_2S and other gases) via natural surface features which include fumaroles, steaming ground, hot pools, and flux through the soil (Figure 2).

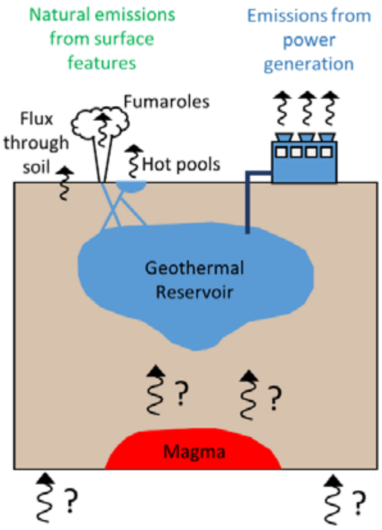

Figure 2: Schematic showing a geothermal reservoir with natural greenhouse gas emissions via surface features and from power generation.

These emissions are significant, and while this has not been studied extensively, or for all geothermal fields, some examples are (t/day of CO_2 only, does not include CH_4):

- Rotorua: at least 1000 (Werner and Cardellini, 2006)
- Rotokawa: 441 (Bloomberg et al., 2014)
- Crater floor of White Island volcano: 124 (Bloomberg et al., 2014)

When a geothermal field is developed, fluid is extracted from the reservoir and emissions of CO_2 and CH_4 are released from this fluid during the power generation process (Figure 2), along with other non-condensable gases which are removed from condensers in the power station and then released.

There is a lack of research into the effect that this geothermal fluid extraction has on the emissions from surface features. If it could be shown that the power generation resulted in a measureable decrease of the emissions from surface features then a case can be made to use this decrease to offset the power generation emissions (Bertani and Thain, 2002). In other words, it is the net effect of the development that is important (the balance of surface feature and power generation emissions).

There are few studies of CO_2 and CH_4 natural flux from geothermal systems in New Zealand, however this is the subject of a three-year Royal Society Te Aparangi Marsden project which commenced this year (led by Isabelle Chambefort, GNS, Chambefort et al., 2019, this volume). A goal of the project is to create a CO_2 flux map for the whole Taupo Volcanic Zone, including both inside and outside the known geothermal areas. Another goal is to identify the deep source of the CO_2 in geothermal reservoir fluids, which is not currently known (Figure 2).

2.3 Global geothermal emissions intensity survey

Bertani and Thain (2002) compiled CO_2 emission data from 85 geothermal power plants in 11 countries, representing 6643 MWe (net) of generation, which was 85% of the global generating capacity at the time. The global MW-weighted average emissions intensity was 122 gCO_2/kWh with a very wide range of 4 – 740 gCO_2/kWh. Also 73% of the plants had a MW-weighted emissions intensity of 55 gCO_2/kWh. This study does not mention CH_4.

2.4 Operational vs life-cycle emissions

To fully understand the impact of a development a life-cycle assessment is necessary, which includes all emissions from construction, operation and decommissioning. This paper examines the operational emissions from geothermal power stations: construction and decommissioning are beyond the scope of this paper. However, lifecycle analyses (LCAs) are examined for different energy sources by the Intergovernmental Panel on Climate Change (IPCC, 2011). Median values for emissions intensity in gCO_2/kWh are as follows: coal = 1001 and natural gas = 469, and the renewables: solar PV = 46, geothermal = 45, wind = 12 and hydro = 4 (IPCC, 2011).

2.5 Emissions measurement methodology

Under the Climate Change (Stationary Energy and Industrial Processes) Regulations 2009 (Schedule 2, Table 6), each site is allocated a default emissions factor (DF) which is the fraction of $CO_{2\text{-eq}}$ present in the steam ($tCO_{2\text{-eq}}$/t steam). An emissions factor (EF) is multiplied by the total annual mass of steam (t) to calculate the total annual mass of $CO_{2\text{-eq}}$. (t) (Equation 1).

$$mass\ CO_{2-eq}(t) = EF\left(\frac{tCO_{2-eq}}{t\ steam}\right) \times mass\ steam\ (t) \tag{1}$$

Geothermal power companies can also apply for a unique emissions factor (UEF) under the Climate Change (Unique Emissions Factors) Regulations 2009 (Clauses 14-17). Circumstances in which a UEF might be applied for/used includes if the emission factor drops below the default emissions factor (DF), and for all geothermal power stations built since the regulations, as the DF for new developments is very high. Hence the emissions factor “EF” in Equation 1 can be either the DF or the UEF. This is described in more detail in a letter from GNS Science to the NZGA (Carey, 2010). The UEF is usually a flow-weighted average of the sampled $CO_{2\text{-eq}}$ contents of the various steam lines supplying the power station, which is then verified by an auditor before reporting to government. Sampling for the UEF is completed by GNS Science. Some internal sampling also occurs.

In this paper all emissions factors are actual measured emissions factors (either UEF or internal sampling), not default emissions factors (DF). In some cases the emissions factors in this paper might correspond with the "official" UEF, though the UEF is only updated if the data shows a statistically significant change from the previous year, and so the finer details of the change with time are lost.

Emissions intensity ($gCO_{2\text{-eq}}$/kWh, which is the same as $tCO_{2\text{-eq}}$ /GWh) is a measure of how much greenhouse gas is emitted per unit of electrical energy generated (Equation 2). It is useful for comparison between different types of power stations, as it is independent of the fuel source.

$$Emissions\ intensity\ \left(\frac{gCO_{2-eq}}{kWh}\right) = \frac{mass\ CO_{2-eq}(g)}{energy\ (kWh\ net)} \tag{2}$$

The effects of carbon dioxide (CO_2) and methane (CH_4) are combined into one value: carbon-dioxide-equivalent ($CO_{2\text{-eq}}$), which is the amount of actual CO_2 plus a calculated amount of CO_2 to represent the methane, which has 25 times more effect than carbon dioxide. For example, the emissions factor (EF) as measured at a particular sampling point on a steam line is calculated using Equation 3 (Climate Change (Unique Emissions Factors) Regulations 2009, Clause 15(1)(d)):

$$EF\ \left(\frac{tCO_{2-eq}}{t\ steam}\right) = MMF\ CO_2 + (25\ \times MMF\ CH_4) \tag{3}$$

Where: MMF CO_2 – mean mass fraction of CO_2 in the steam sample, and MMF CH_4 is the mean mass fraction of CH_4.

2.6 Emissions intensity from fossil fuel plants

Emissions factors for fossil fuel plants are expressed as $tCO_{2\text{-eq}}$/TJ, rather than geothermal emissions factors which are $tCO_{2\text{-eq}}$/t steam. Therefore an estimate of the emissions intensity of fossil fuel plants (used in Figure 4) can be calculated by multiplication with the heat rate (the inverse of efficiency) (Table 1).

Table 1: Calculation of estimated emissions intensity for fossil fuel power stations.

Fuel	Emissions factor*	Heat rate**		Emissions intensity
	$tCO_{2\text{-eq}}$/TJ	kJ/kWh		$gCO_{2\text{-eq}}$/kWh
Natural gas	53.64	OCGT	9,800	525
		CCGT	7,307	390
Coal	87.68	Coal	10,900	955

*Climate Change (Stationary Energy and Industrial Processes) Regulations 2009 (Schedule 2, Tables 1 and 4).

** PB Power (2009).

3. RECENT EMISSIONS INTENSITY (2018)

A recent snapshot of geothermal emissions for the calendar year 2018 is presented in Table 2 for the 12 major geothermal power stations in New Zealand, including emissions factor, total mass of steam, average generation and the calculated emissions intensity. There are various ways to calculate an overall number to represent this dataset:

- Not all power stations are the same size, and this is accounted for by calculating a MW-weighted average for the dataset of 76 $gCO_{2\text{-eq}}$/kWh (net).
- Standard median and inter-quartile range: median 61 and range 45-93 $gCO_{2\text{-eq}}$/kWh (net).

A straight average (unweighted) is not a valid representation of this skewed dataset due to the presence of significant outliers (Ohaaki and Ngawha). For example, in this case the average would be 103 $gCO_{2\text{-eq}}$/kWh (net), which is outside the inter-quartile range.

The dataset and statistical representations discussed above and in Table 2 are shown graphically in Figure 3, which clearly shows the skewed nature of the dataset with the two outliers of Ohaaki and Ngawha. When the geothermal numbers are compared to fossil fuels (Figure 4) it is clear that overall geothermal emissions are an order of magnitude less than emissions from fossil fuel plants.

Table 2: Geothermal power stations operational emissions intensity for 2018.

Power station	Geothermal field	Emissions factor	Total mass of steam	Average generation	Emissions Intensity	Annual emissions	Emissions rate
		t $CO_{2\text{-eq}}$ / t steam	t steam	MWe (net)	g $CO_{2\text{-eq}}$ / kWh (net)	t $CO_{2\text{-eq}}$	t $CO_{2\text{-eq}}$ / day
Wairakei A&B and binary	Wairakei	0.002300	9,287,157	116	21	21,360	58
Te Mihi	Wairakei	0.005100	11,703,800	157	43	59,689	163
Poihipi Road	Wairakei	0.004800	3,208,715	46	38	15,402	42
Ohaaki	Ohaaki	0.036300	2,552,176	31	341	92,644	254
Te Huka	Tauhara	0.007000	1,239,798	22	45	8,679	24
Rotokawa	Rotokawa	0.014540	1,683,626	33	84	24,480	67
Nga Awa Purua (NAP)	Rotokawa	0.009947	7,798,462	141	63	77,571	212
Mokai	Mokai	0.004600	5,615,613	56	52	25,832	71
Ngatamariki	Ngatamariki	0.013352	3,765,219	90	64	50,273	138
Kawerau (KGL)	Kawerau	0.017082	6,557,855	104	123	112,021	307
TOPP1	Kawerau	0.012100	929,196	21	60	11,243	31
Ngawha (all plants)	Ngawha	0.083950	735,127	23	304	61,714	169
MW-weighted average					**76**	**Σ 560,909**	**Σ 1536**
Median					**61**		
25th percentile					**45**		
75th percentile					**93**		

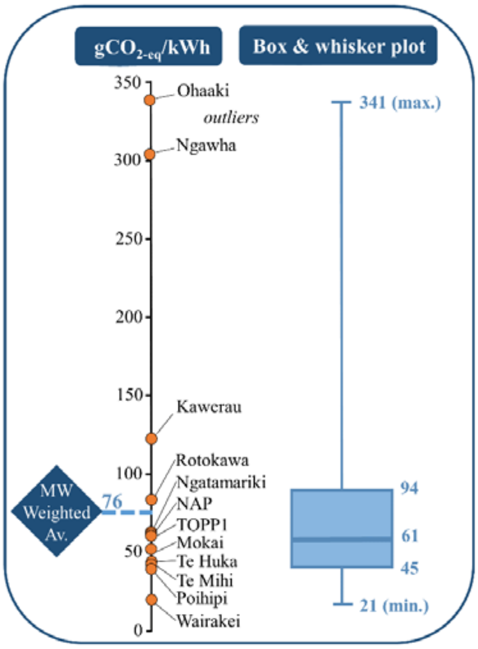

Figure 3: Graphical representation of operational emissions intensity from geothermal power stations data, and statistical representations of that dataset (Table 2).

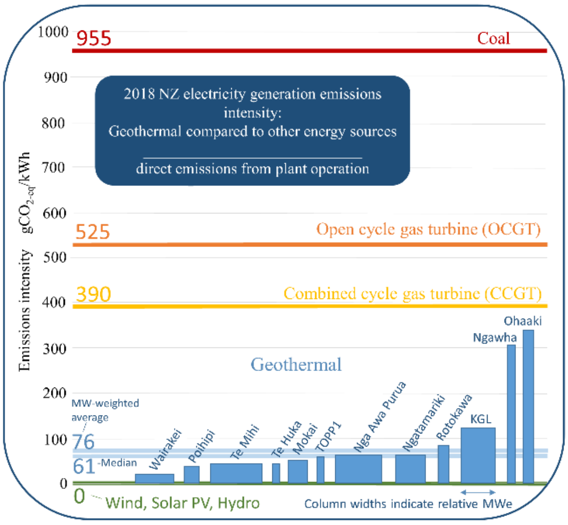

Figure 4: Graphical chart comparing the operational emissions intensity of geothermal power stations in New Zealand (Table 2) to other types of electricity generation (Table 1).

The emissions rate from each geothermal power station is also given in Table 2 as tonnes per day (t $CO_{2\text{-eq}}$ / day) for comparison with the emissions rates from three areas of natural surface features (Section 2.2). This comparison is shown graphically in Figure 5, and shows that total natural surface feature emissions exceed the total geothermal power station emissions, even though the three estimates represent only a small fraction of the total surface feature activity in the TVZ (23 known geothermal systems, Figure 1). Also CH_4 is not included in these estimates of natural surface feature emissions, if it was they would be greater.

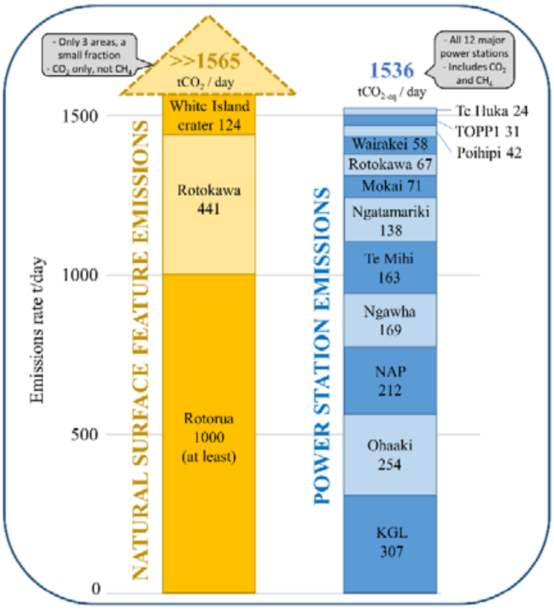

Figure 5: Comparison of emission rates from 3 areas of natural geothermal surface feature activity to the 12 major geothermal power stations.

4. CHANGES TO EMISSIONS INTENSITY 2010 – 2018

The previous section was a snapshot of geothermal emissions for the calendar year 2018. Geothermal emissions intensity is not constant through time, and while it generally declines over time due to degassing of the geothermal reservoir fluid, if there are operational changes to the steamfield or plant it can sharply increase or decrease. Emissions data is available for most geothermal power stations over the time period 2010 to 2018. Available emission data from Mercury operated power stations is given in Table 3, Ngawha and TOPP1 owned by Top Energy and NTGA, respectively in Table 4, and Contact Energy power stations in Table 5.

4.1 Decline due to degassing

4.1.1 Rotokawa

The Rotokawa field hosts both the Rotokawa and Nga Awa Purua power plants, where emissions intensity has been declining over time (Figure 6a).

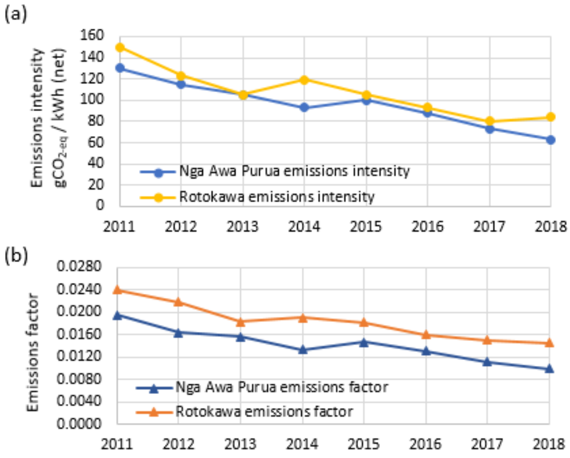

Figure 6: Rotokawa and Nga Awa Purua power stations 2011-2018: (a) emissions intensity; (b) emissions factor (Table 3).

This decline is predominantly a result of lower concentrations of CO2-eq in the steam at the two stations as shown in Figure 6b. There are some years where the emissions intensity has increased slightly from the previous year, this is typically a result of operational changes (well contributions). It is expected that the gas in steam concentrations at the Rotokawa field will continue to decline as the field degasses as a result of both development and natural surface feature emissions. It is interesting to note that Rotokawa is the only geothermal field in New Zealand for which emissions values for both power generation and natural surface feature emissions are available, and the total emissions from the two power stations in 2018 (67 + 212 = 279 $tCO_{2\text{-eq}}$/day, Table 2) are significantly exceeded by the natural surface feature emissions of 441 tCO_2/day (which does not include methane, Section 2.2). Continued degassing of the field is expected to further reduce the emissions intensity of these power plants.

4.1.2 Ngatamariki

The Ngatamariki power plant was commissioned in 2013, and the Ngatamariki geothermal field is one of the latest in New Zealand to be developed for power generation. The Ngatamariki field has shown early signs of decreasing emissions intensity due to decreasing gas in steam concentrations (emissions factor) (Figure 7).

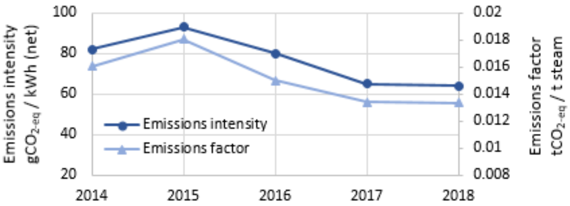

Figure 7: Ngatamariki power station 2014-2018: (a) emissions intensity; (b) emissions factor (Table 3).

Table 3: Emissions intensity and source data for Mercury power stations

Station	Year	Emissions factor [tCO_2(eq)/t steam]	# sample sets	Mass steam [kt]	Generation [GWh (net)]	Emissions intensity [gCO_2(eq)/ kWh(net)]
Mokai	2011	0.0058	*	*	*	35
	2013	0.004356	6	5,555	815	30
	2014	0.004033	6	5,722	876	26
	2015	0.0036	8	6,159	851	26
	2016	0.004599	8	6,215	852	34
	2017	0.004155	8	5,910	848	29
	2018	0.0046	12	5,616	492	52
Ngatamariki	2014	0.016062	8	3,220	629	82
	2015	0.01805	8	3,792	733	93
	2016	0.015	8	3,716	699	80
	2017	0.01342	10	3,873	801	65
	2018	0.013352	12	3,765	785	64
Nga Awa Purua (NAP)	2011	0.019449	*	*	*	130
	2012	0.016329	12	8,076	1145	115
	2013	0.015633	12	7,449	1106	105
	2014	0.013356	12	7,369	1063	93
	2015	0.014663	12	7,359	1083	100
	2016	0.01309	12	7,915	1170	88
	2017	0.011181	12	7,576	1170	73
	2018	0.009947	12	7,798	1239	63
Rotokawa	2011	0.024004	*	*	*	150
	2012	0.02174	6	1,614	284	123
	2013	0.01829	6	1,636	284	105
	2014	0.018994	6	1,603	256	119
	2015	0.018205	6	1,581	273	105
	2016	0.015991	8	1,620	280	93
	2017	0.014966	8	1,551	289	80
	2018	0.01454	12	1,684	292	84
Kawerau (KGL)	2011	0.017358	*	*	*	136
	2012	0.020443	12	6,647	842	161
	2013	0.018352	12	6,231	813	141
	2014	0.019471	10	6,857	901	123
	2015	0.02226	12	7,001	902	173
	2016	0.019153	12	6,676	853	150
	2017	0.017288	12	6,947	961	125
	2018	0.017082	12	6,558	912	123

*Source data for some of the Mercury power stations was not readily available for 2011, only the final results.

Table 4: Emissions intensity and source data for Top Energy (Ngawha) and NTGA (TOPP1) power stations.

Station	Year	Emissions factor [$tCO_2(eq)/t$ steam]	# sample sets	Mass steam [kt]	Generation [GWh (net)]	Emissions intensity [$gCO_2(eq)/$ kWh(net)]
TOPP1	2017	0.0122	15	920	187	60
	2018	0.0121	12	929	187	60
Ngawha	2010	0.09700	26	361	101	348
	2011	0.09252	4	683	193	328
	2012	0.08902	4	735	203	322
	2013	0.08839	6	769	197	345
	2014	0.08640	10	783	194	348
	2015	0.08119	4	784	192	332
	2016	0.08490	12	770	203	322
	2017	0.08314	6	726	198	306
	2018	0.08395	4	735	203	304

Table 5: Emissions intensity and source data for Contact Energy power stations

Station	Year	Emissions factor [$tCO_2(eq)/t$ steam]	# sample sets	Mass steam [kt]	Generation [GWh (net)]	Emissions intensity [$gCO_2(eq)/$ kWh(net)]
Wairakei	2010	0.0048	1	13,105	1,359	46
	2012	0.0065	2	13,202	1,324	65
	2013	0.0062	1	13,018	1,262	64
	2014	0.002	1	11,630	1,156	20
	2015	0.0022	1	11,540	1,113	23
	2016	0.0026	13	10,387	1,119	24
	2017	0.0026	12	9,581	1,045	24
	2018	0.0023	8	9,287	1,017	21
Te Mihi	2014	0.0059	12	6,107	756	48
	2015	0.005	8	10,627	1,262	42
	2016	0.0048	8	10,169	1,188	41
	2017	0.0052	10	12,121	1,410	45
	2018	0.0051	9	11,704	1,376	43
Poihipi	2010	0.006	1	3,208	385	50
	2012	0.0014	2	3,651	448	11
	2013	0.0013	1	3,471	450	10
	2014	0.0019	1	3,136	394	15
	2015	0.0020	1	2,464	322	15
	2016	0.0020	1	3,069	398	15
	2017	0.0041	3	3,215	413	32
	2018	0.0048	11	3,209	403	38
Te Huka	2010	0.0087	1	1,254	210	52
	2011	0.0079	1	779	133	46
	2012	0.0046	12	1,216	210	27
	2013	0.0047	6	1,020	176	27
	2014	0.0057	1	1,373	213	37
	2015	0.0059	10	1,221	195	37
	2016	0.0059	9	1,210	191	37
	2017	0.0055	10	1,188	207	32
	2018	0.007	8	1,240	193	45
Ohaaki	2010	0.0555	1	3,892	411	525
	2011	0.0493	1	3,480	392	438
	2012	0.04875	2	3,077	346	434
	2014	0.0463	1	2,597	272	443
	2015	0.0411	1	2,982	326	376
	2016	0.0494	12	3,103	331	463
	2017	0.0392	10	3,230	338	375
	2018	0.0363	9	2,552	272	341

4.1.3 Ngawha

A declining trend is observed in the emissions intensity from Ngawha due to decreasing emissions factor as the field degasses (Figure 8). The other factor affecting the emissions intensity is the efficiency of the plant which is higher at high utilisation, such as in 2012, accounting for the dip in emissions intensity at this time (Paul Doherty, Top Energy, personal communication). The efficiency of binary plants is a lot more variable than the larger power stations. However the plant efficiency does not affect the emissions factor, which is a simple fraction of greenhouse gas in the produced steam. By also plotting the emissions factor (Figure 8) the effect of efficiency is removed and the 2012 dip disappears.

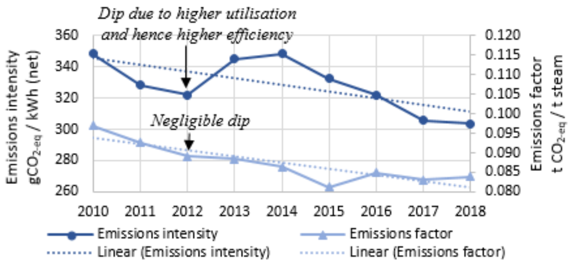

Figure 8: Ngawha binary station 2010-2018: (a) emissions intensity; (b) emissions factor (Table 4).

4.2 Operational changes

4.2.1 Wairakei/Te Mihi/Poihipi

The Wairakei A&B and binary, Te Mihi and Poihipi power stations are all owned by Contact Energy and are located in Wairakei geothermal field. They are interconnected via the above-ground steamfield and some wells can be switched between stations. If all wells in this field had the same emissions factor then the well switching would have no effect, the emissions factor of each station would be the same. The emissions intensity of each station would differ only slightly depending on the plant conversion efficiency between energy in the steam and electrical energy. However, some wells have a higher emissions factor than others, particularly some wells drilled into the shallow steam cap above the deeper liquid Wairakei reservoir.

The emissions intensity from these three stations must be considered in combination (Figure 9) as many of the sudden changes in the individual power stations emissions intensity are balanced by an opposite change in another station, as wells are switched between the two. This can be clearly seen as emissions at Wairakei rose in 2012, and dropped at Poihipi, when the higher-emitting dry-steam wells were switched to Wairakei as a new flash plant was completed (FP16) with liquid-fed lower-emissions wells, and the steam from this plant was used for Poihipi.

When Te Mihi started generating in 2014, the higher-emitting dry steam wells were switched there from Wairakei, causing the Wairakei emissions to drop (Figure 9). Those wells were priortised to Te Mihi as they are located near the station and transmission losses are minimised.

In 2017 there was an increase in emissions intensity at Poihipi and Te Mihi (Figure 9) due to two factors: fluid production increased (enabled by annual rather than quarterly accounting of fluid mass take), and also two new dry steam wells were connected.

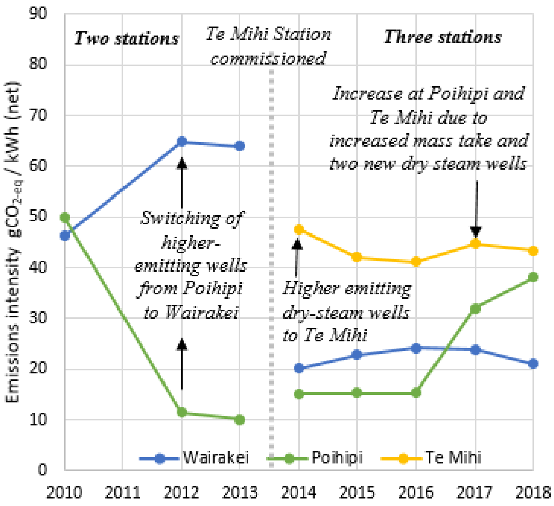

Figure 9: Wairakei A&B and binary, Poihipi, and Te Mihi power station emissions intensity 2010-2018.

4.2.2 Te Huka

There are only two wells supplying steam to Te Huka binary power station: TH14, which has higher enthalpy and higher emissions, and TH20 which has lower enthalpy and lower emissions, even though the wells are very close. The combined output of the wells is more than is required to run the plant. The proportion of steam coming from each of the two wells has been changed over time to maximise the electrical power output within the constraints of the plant control system TH14 and TH20 have different output characteristics, and so they are fed into different pressure reducing trains. The valve position of TH20 is fixed, while the valve position of TH14 automatically adjusts to the requirements of the plant, which vary throughout the day. The fixed valve position of TH20 is an indication of the proportion of flow coming from TH20 (Figure 10b).

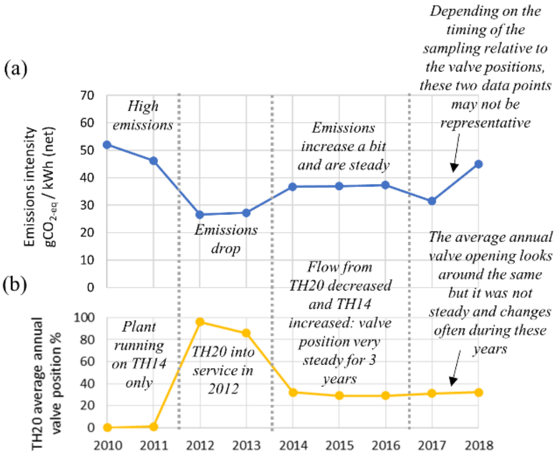

Figure 10: Te Huka binary station 2010 – 2018: (a) emissions intensity; (b) TH20 estimated average annual valve position.

When Te Huka first started generating, during 2010 and 2011, the plant was run on TH14 only (TH20 valve position is zero, Figure 10b), and emissions were relatively high (Figure 10a). TH20 was brought into service in 2012 and supplied the majority of steam to the plant for two years, and so emissions dropped. The valve opening of TH20 was increased to ~30% in 2014 (Figure 10b) for two reasons: the highly throttled state of TH14 during 2012-2013 caused operational issues that could trip the plant, and also calcite scaling in TH20 let to installation of a calcite inhibition system which required the well to be operated at a higher pressure. The result was that emissions increased in 2014 (Figure 10a). The valve opening of TH20 was then steady during 2014-2016, very rarely changing from 30%, and emissions were also steady. For the final two years (2017 and 2018) the valve opening data (which is an annual average) looks unchanged, but actually was quite variable over the year. Hence the emissions sampling could have been unwittingly biased depending on the timing of the sampling relative to the timing of the valve changes, which could explain the change in the 2017 and 2018 emissions compared to 2014-2016 (Figure 10a).

4.2.3 Ohaaki

Multiple factors are influencing the emissions intensity from Ohaaki power station over the 2010-2018 period (Figure 11).

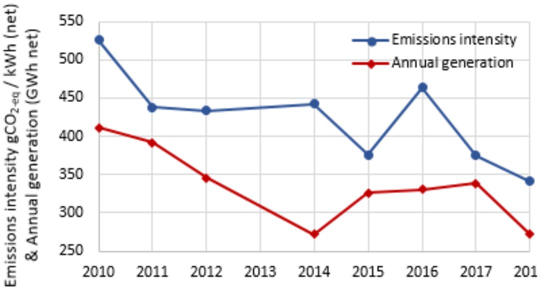

Figure 11: Ohaaki power station 2010-2018: (a) emissions intensity; (b) annual generation.

The generation has decreased as fluid production has been cut back to the long-term sustainable levels indicated by numerical modelling. There has also been a new focus on production from the previously-untapped deep reservoir under the West Bank (starting in 2007/2008). This new production initially caused a large spike in emissions (which were still high in 2010) as pressure dropped significantly in the deep reservoir. However now the pressures have partially recovered and stabilised, there is less pressure drawdown and therefore less boiling and degassing, so emissions are lower.

5. MBIE EMISSIONS DATA

Commencing in 2008, with the commissioning of Mercury's (then Mighty River Power) Kawerau geothermal power plant (KGL) the New Zealand electricity market has seen a significant addition of geothermal capacity over the last 10 years. During this period the Kawerau geothermal power plant, Te Huka, Nga Awa Purua, Ngatamariki, Te Mihi and Te Ahi O Maui geothermal plants have been commissioned. Together these power plants have added over 500 MW of renewable generation capacity to the New Zealand electricity system.

If this increased geothermal generation capacity is used to supply electricity that otherwise would have been generated from fossil fuels, an estimate of the corresponding reduction in CO$_{2eq}$ emissions can be made. Since 2007, annual geothermal electricity generation has increased by over 4000 GWh. An assessment of the expected CO$_{2eq}$ emissions of this increased generation is shown in Table 6.

Table 6: Estimated CO$_{2eq}$ emissions for 4000 GWh generated by: coal, gas and geothermal.

Fuel	Emissions Intensity (gCO$_{2eq}$/kWh)	Annual Emissions (tCO$_{2eq}$)
Coal	955	3,820,000
Gas OCGT	525	2,100,000
Gas CCGT	390	1,560,000
Geothermal	76	304,000
Δ Emissions (coal – geothermal)		3,516,000
Δ Emissions (CCGT – geothermal)		1,256,000

As can be seen in Table 6, displacing 4000 GWh of coal fired generation with geothermal is estimated to reduce CO$_{2eq}$ emissions by approximately 3,500,000 tonnes per year. If geothermal displaced CCGT gas generation this would reduce emissions by more than 1,250,000 tonnes per year.

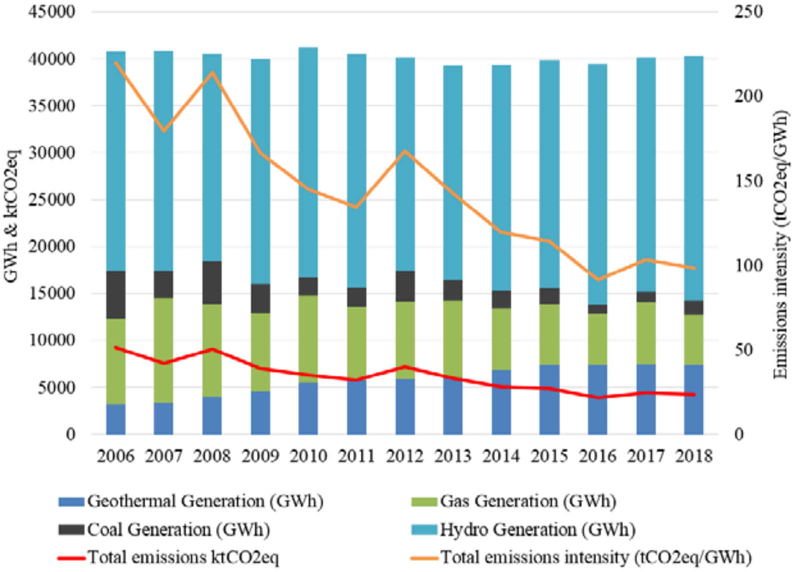

Figure 12: New Zealand electricity generation and CO$_{2eq}$ emissions data (MBIE Electricity statistics, 2019 and MBIE New Zealand energy sector greenhouse gas emissions, 2019).

The impact of the increase in geothermal generation on New Zealand's electricity generation emissions is illustrated in Figure 12. It can be seen that as geothermal generation has increased and fossil fuel based generation has decreased over the last 10 years, the overall emissions intensity of the electricity generation sector has approximately halved, along with the total emissions.

6. CONCLUSIONS

- For the 12 major geothermal power stations in New Zealand in 2018:
  - The MW-weighted average operational emissions intensity is 76 $gCO_{2\text{-eq}}$/kWh (net).
  - The median and interquartile range for operational emissions intensity is: median 61 and range 45-93 $gCO_{2\text{-eq}}$/kWh (net).
- Operational geothermal emissions are higher than many other renewable energy sources, but much lower than fossil fuel plants.
- Emissions from geothermal power stations are outweighed by emissions from natural surface features. The effect of development on this natural flux of greenhouse gases is not known, and is required in order to know the net effect of development on emissions.
- Decline in emissions intensity due to degassing has been shown at several New Zealand geothermal fields, with Rotokawa perhaps showing the most dramatic decline in emissions intensity over the last 10 years.
- It has been shown that emissions intensity is variable at several New Zealand geothermal power stations due to operational reasons. These increases and decreases are due to well switching between stations, new wells being connected, and changes in the proportion of flow from existing wells.
- The increase in electricity generated from geothermal sources has made a significant contribution to major reductions in emissions from New Zealand's electricity industry over the last 10 years.

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REFERENCES

Bertani, R. & Thain, I. (2002): Geothermal power generating plant CO_2 emission survey; *IGA Newsletter*, 49, July-Sept 2002.

Bloomberg, S.; Werner, C.; Rissmann, C.; Mazot, A.; Horton, T.; Gravley, D.; Kennedy, B. & Oze, C. (2014): Soil CO_2 emissions as a proxy for heat and mass flow assessment, Taupo Volcanic Zone, New Zealand, *Geochemistry, Geophysics, Geosystems*, 15.

Carey, B. (2010), letter from GNS Science to NZGA, 23 September 2010 < https://nzgeothermal.org.nz/app/uploads/2019/08/Letter-Emissions-Trading-Scheme/NZGA-Commentary-FINAL.pdf >.

Chambefort, I., Rowe, M., Mazot, A., Yang, T-H., and Farsky, D. (2019): Superhot fluids: The origin and flux of natural greenhouse gases in volcanic areas. *Proceedings 41st New Zealand Geothermal Workshop*, Auckland 25-27 November, 2019.

Climate Change (Stationary Energy and Industrial Processes) Regulations 2009 (SR 2009/285), 28 September 2009 <http://legislation.govt.nz/regulation/public/2009/0285/latest/DLM2394207.html>.

Climate Change (Unique Emissions Factors) Regulations 2009 (SR 2009/286), 28 September 2009 <http://legislation.govt.nz/regulation/public/2009/0286/latest/DLM2378401.html>.

Halper, M. (2011): Forget storing carbon; re-use it: A company in Iceland is turning CO_2 into methanol to power cars, *Renewable Energy Focus*, 12(1), 56-58.

IPCC (2011): Special report: Renewable Energy Sources and Climate Change Mitigation.

Kaya, E. and Zarrouk, S. (2017): Reinjection of greenhouse gases into geothermal reservoirs, *International Journal of Greenhouse Gas Control*, 67, 111-129.

MBIE Electricity statistics (updated 13 June 2019): <https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-statistics-and-modelling/energy-statistics/electricity-statistics/>

MBIE New Zealand energy sector greenhouse gas emissions (updated 13 June 2019): <https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-statistics-and-modelling/energy-statistics/new-zealand-energy-sector-greenhouse-gas-emissions/>.

PB Power (2009): Thermal Power Station Advice, a report to the NZ Electricity Commission, Wellington.

Werner, C. & Cardellini, C. (2006): Comparison of carbon dioxide emissions with fluid upflow, chemistry, and geologic structures at the Rotorua geothermal system, New Zealand, *Geothermics*, 35, 221-238.