GEOTHERMAL GREENHOUSE GAS EMISSIONS IN NEW ZEALAND IN 2020: LIFECYCLE AND OPERATIONAL EMISSIONS

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ABSTRACT

Greenhouse gas emissions from fourteen New Zealand (NZ) geothermal power stations in the calendar year 2020 are presented in this paper. Source data is given, verified against alternative sources, and used to calculate the overall geothermal emissions intensity for each power station as $gCO_2e/kWh(net)$. Statistical analysis of the results gives a representative emissions intensity for NZ geothermal electricity generation overall for 2020. Comparison of this to previous years shows a continuing decline in emissions intensity.

The emissions intensities presented in this paper are operational emissions only, those that are released directly during the operational phase of the plant life. This, however, only represents one portion of the total emissions over the full lifecycle of the plant. Life cycle analysis (LCA) "life-cycle emissions" take account of all emissions over the full life cycle of the plant, including materials and construction, operation and maintenance, and decommissioning. Accounting for the full life cycle will increase geothermal emissions intensity above the operational emissions by 20% on average for the NZ stations. Statistical comparison to life cycle emissions from other energy sources shows that NZ geothermal has the highest emissions intensity of the renewables, followed by solar PV, concentrating solar, hydro and then wind with the lowest. All renewables have life cycle emissions, an order of magnitude less than fossil fuel energy sources.

1. INTRODUCTION

The New Zealand Geothermal Association has recently led studies of NZ geothermal operational emissions (McLean and Richardson, 2019; McLean et al., 2020): where they come from, the positive impact they have had in decarbonising the NZ electricity supply, and decarbonising industrial process heat. Operational emissions are, however, only one part of the story: they do not include any upstream processes like construction or downstream processes like decommissioning. Life-cycle assessment (LCA) is necessary to analyse the entire lifecycle of a product 'from the cradle to the grave'.

When comparing between different energy sources, it is necessary to compare on a lifecycle emissions basis (rather than operational only) to appreciate the relative impact of each energy source. No source of energy is zero emissions. LCA is complex, and so work has been done by the World Bank to provide a reasonable estimate of plant cycle emissions to add to the operational emissions directly measured at a geothermal plant to give lifecycle emissions. This methodology is applied to the operational emissions data gathered for the 14 major geothermal power stations in New Zealand for CY2020. This provides an estimate of the lifecycle emissions of each plant and the NZ geothermal industry as a whole.

The international geothermal sector has been called upon by the World Bank to collect and publish as much data as possible to improve the global understanding of geothermal emissions (Fridriksson et al., 2017). Geothermal emissions certainly are more complex and variable than most other energy sources, and this paper aims to assist with this global effort.

2. BACKGROUND

2.1 What are "lifecycle" and "operational" emissions?

Life-cycle assessment (LCA) considers all emissions directly or indirectly related to a project over its lifetime. This is divided into two:

1. Plant Cycle
2. Fuel Cycle

The "Plant Cycle" emissions for geothermal power projects are those related to materials and construction for all surface plants, drilling and completion of wells, and eventual decommissioning, normalised over an assumed project life (Fridriksson et al., 2017).

The "Fuel Cycle" emissions are those that are brought to the surface in geothermal fluids and released during the energy conversion process, commonly referred to as "operational emissions" or "fugitive emissions" (Fridriksson et al., 2017). These are the emissions that are measured and reported in New Zealand under the 2009 Climate Change Regulations. These requirements are described by McLean and Richardson (2019) and the optional inclusion of reinjection by Mclean et al. (2020).

LCA is a non-trivial process that must make assumptions about the future. Otherwise, an LCA would only be possible retrospectively at the end of a project. An obvious assumption is the expected lifetime of a project, which is important as the longer the project life, the more years the lifecycle emissions are spread over, and the lower the emissions per year. It is also difficult to predict the maintenance requirements of different plants, and there are many other assumptions required.

The Plant Cycle emissions have been the missing piece for geothermal. Most publications of geothermal emissions focus on Fuel Cycle only (operational emissions) (Fridriksson et al., 2017).

2.2 Geothermal Plant Cycle emissions estimate

A World Bank review by Fridriksson et al. (2016) of studies on published geothermal plant cycle emissions in USA, Guadeloupe, Iceland, Japan, and NZ concludes the range is 2-19 gCO_2e/kWh, based on an assumed plant life of 30 years (6 estimates from 5 studies). The results are too sparse for statistical analysis and are not harmonised (no consistent set of assumptions). However, it is concluded that a value of 10 gCO_2e/kWh is a reasonable value to assume for the Plant Cycle of geothermal projects and that the difference between this number and reality will not be significant as geothermal lifecycle emissions are dominated by Fuel Cycle (operational) emissions (Fridriksson et al., 2017).

The NZ Plant Cycle value comes from an LCA of Wairakei Power Station by Rule et al. (2009). This study concludes that the Plant Cycle emissions are 5.6 gCO_2e/kWh, based on 100-year plant life. Fridriksson et al. (2017) note that this converts to 18.6 gCO_2e/kWh if normal 30-year plant life is assumed. In reality, the Wairakei Power Station has been operational since 1958 (63 years) and counting, and so the true value will be somewhere in between.

2.3 Geothermal Fuel Cycle (operational) emissions

Operational emissions are those which are released during the operational phase of project life. In terms of fossil fuel electricity generation, these are the emissions created by burning fuel and then released to the atmosphere. For geothermal projects, operational emissions are naturally occurring CO_2 (and methane) from underground, which is brought to the surface and released during the power generation process. Depending on the plant configuration, some fraction of the emissions are returned to the underground reservoir by a process called reinjection. Geothermal power plants do not create CO_2 (there is any combustion). All geothermal emissions would have ended up in the atmosphere regardless of the presence of a power plant via natural emissions pathways such as fumaroles, gassy hot pools and steaming ground, though the rate of natural emissions can be altered by the power generation process (IPCC, 2011).

2.3.1 New Zealand

Statistics on Fuel Cycle emissions intensity for the major geothermal power stations in New Zealand is shown over the five years 2015-2019 in Table 1 and Figure 1.

Table 1: Statistics on Fuel Cycle emissions intensity 2015–2019 (see Figure 1, from McLean et al., 2020).

		Year				
		2015	2016	2017	2018	2019
	# Power plants	11	11	12	12	14
gCO_2e/kWh	MW-weighted av	91	89	78	76	73
	Minimum	15	15	24	21	24
	25th percentile	32	36	32	45	44
	Median	93	80	63	62	60
	75th percentile	139	122	91	94	85
	Maximum	376	463	375	341	312

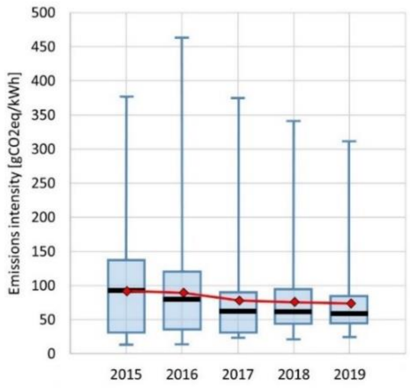

Figure 1: Fuel Cycle emissions intensity for NZ 2015 – 2019 (data from Table 1): box and whisker plots showing median values (black lines) and MW-weighted average (red data points).

There are 14 main geothermal power stations in New Zealand. Comprehensive data on operational emissions from these have been published by the New Zealand Geothermal Association (McLean and Richardson, 2019; McLean et al., 2020), with data from 2010 onwards. The last sizeable geothermal power station to be commissioned in NZ was Te Mihi in 2014. Over the five years since then, there has been a declining trend in emissions (Table 1, Figure 1).

A declining trend is usually expected in geothermal plants due primarily to degassing of the reservoir fluid over time. This is not always observed if there are operational changes to the plant or new wells drilled into previously untapped parts of the reservoir.

2.3.2 International

Other countries have different levels of geothermal emissions. What is relevant is the volcanic and geological setting, which controls the amount of naturally occurring CO_2 and CH_4 in the underground reservoir fluids. Most published studies account for CO_2 only. A review by Fridriksson et al. (2016) summarises these studies, giving an indication of variability across different countries. Weighted average values (gCO_2/kWh, CO_2 only, does not include CH_4) from Fridriksson et al. (2016) are given in Table 2.

Table 2: International Fuel Cycle geothermal emissions intensities (from Fridriksson et al., 2016).

Country/comment	Weighted average gCO_2/kWh
Iceland (2013 values): very low emissions	34
Geysers, California in 2013	45
All USA Plants, including binary plants, 2003	91
Internationally representative value from Bertani and Thain (2002) IGA study, individual values not given, does not include binary plants:	122
Coso, California in 2013	245
Italy generally has high emissions, 2013 values	330

Mt Amiata, Italy, is an outlier, 2014 values. Very high due to carbonate reservoir and deep mantle degassing.	497
Turkey is an outlier with extreme emissions due to its carbonate reservoirs, 2014 values	1050

The most recent NZ value to compare to the international values in Table 2 is 73 gCO_2e/kWh (2020 value, Table 3). This is low compared to the international values in Table 2 especially considering that the NZ values also include CH_4.

As is the case for the outliers Ohaaki and Ngawha in New Zealand (McLean and Richardson, 2019), the outliers Mt Amiata and Turkey cannot be taken to be representative of the entire body of data.

2.4 Lifecycle emissions for all energy sources: IPCC and NREL

In 2011 the Intergovernmental Panel on Climate Change (IPCC) published lifecycle emissions data for a wide range of energy sources, compiled by the National Renewable Energy Laboratory (NREL) in the USA (IPCC, 2011). Statistical analysis of the results was published in the form of the median, inter-quartile range, minimum and maximum values for all energy types.

The IPCC (2011) study involved a review of thousands of published LCAs for all energy sources, with a rigorous screening process for inclusion. However, it was recognised that the assumptions made in the various studies were not consistent, and so this was followed up with further work by NREL to harmonise the results of these studies by adjusting the assumptions to be consistent. This was called the LCA Harmonisation Project (<https://www.nrel.gov/analysis/life-cycle-assessment.html>) and resulted in improved estimates of LCA emissions, with less variability in the results. These results are compared to NZ geothermal and discussed further in Section 4.1 (Table 4).

2.5 Threshold for being considered low emissions

With the differences in emissions intensities from different renewable energy technologies and the significant variations in emissions intensities within individual technologies, it can be difficult to assess what a suitable or threshold emissions intensity should be for a project to be considered low emission or sustainable from a climate change perspective.

In 2020 the European Union published the Sustainable Finance Taxonomy Regulation (Regulation (EU) 2020/852). The Taxonomy defines sustainable economic activities (sustainable from an environmental perspective, including climate change), including the generation of electricity and heat. The Regulation has calculated a technology-neutral total (lifecycle) emissions intensity threshold of 100 gCO_2e/kWh based on the targets for future sector emissions and the expected electricity demand. The threshold is planned to be reviewed (and reduced) every five years, with the threshold lowered to zero by 2050. The threshold value that applies to a given project is the threshold in place at the time of commissioning (i.e., 100 gCO_2e/kWh for projects commissioned between 2021-2025).

At the current threshold of 100 gCO_2e/kWh, 10 out of the 14 currently operating geothermal power plants in New Zealand meet the threshold as sustainable activities, and the MWh weighted average of all New Zealand's geothermal power plants meet the threshold.

New geothermal power plants consented and undergoing consenting for development in New Zealand include:

- The Tauhara development (under construction, due for commercial operation in 2023, 152MW) with an expected emissions intensity of ~50 gCO_2e/kWh (operational).
- Additional development at the Te Mihi geothermal power plant with a capacity of up to 180MWe (currently undergoing consenting). Based on the existing Te Mihi plant, the emissions intensity of the new plant is expected to be similar at ~40 gCO_2e/kWh (operational).

Both developments are expected to have lifecycle emissions well under the current threshold of 100 gCO_2e/kWh (given that Plant Cycle emissions are estimated around ten gCO_2e/kWh, see Section 2.2). While the future thresholds are unknown, the authors believe it reasonable that additional development at Te Mihi is likely to remain under the (reducing) threshold until at least the year 2030, given the low emissions intensities experienced at the Wairakei geothermal field.

3. EMISSIONS DATA FROM NZ GEOTHERMAL POWER STATIONS 2020

3.1 Data

Operational and lifecycle emissions data are presented in Table 3 for the 14 major geothermal power stations operational in New Zealand in CY2020. Details of these power stations, such as the owner/operator, commissioning date and rated generation capacity, can be found in McLean et al. (2020). Operational emissions intensities for the individual plants are calculated from the reported emissions factor for that plant in that year, the amount of steam used, and the GWh of energy generated (data provided by companies to NZGA). Generation data provided by the companies has been verified against publicly available data from the Electricity Authority Electricity Market Information website (EMI, 2020).

The emissions factors include both CO_2 and methane to produce one CO_2-equivalent (CO_2e) number. The calculations are performed as required by the NZ regulations currently in force (Climate Change Stationary Energy and Industrial Processes Regulations 2009, and Climate Change Unique Emissions Factors Regulations 2009). The conversion for methane to CO_2-equivalent is a factor 25, as per the regulations. The methodology is described in more detail in McLean et al. (2020).

The lifecycle emissions intensities are then estimated by adding the recommended value for geothermal of 10 gCO_2e/kWh (Fridriksson et al., 2017, Section 2.2).

4. DISCUSSION

4.1 Comparison to other energy sources (NREL lifecycle emissions)

The lifecycle emissions intensity data for different energy sources have been compared in Table 4 as median, interquartile range and maximum/minimum, which is a standard statistical analysis that can be graphically represented as a box-and-whisker plot. This has been the practice of IPCC and NREL (Section 2.4) and facilitates comparison between energy sources. The statistics of Table 4 have been represented graphically in Figure 2. Also shown in Figure 2 is the lifecycle emissions data for individual NZ geothermal power stations (from Table 3). Emissions from renewable energy sources are much lower than for fossil fuels and are challenging to see on the scale of Figure 2, and so a zoomed-in version is shown in Figure 3. It can be seen in Figure 2 and Figure 3 that the renewable energy sources have Lifecycle emissions intensities that are a least an order of magnitude less than for fossil fuels. This is the same as the conclusion drawn by McLean et al. (2020) based on Fuel Cycle emissions only, which is not surprising as for geothermal, Fuel Cycle emissions dominate Lifecycle emissions (Section 2.2).

While most renewable energy Lifecycle emissions are under the threshold of 100 gCO_2e/kWh (Figure 3), as represented by the median and inter-quartile range, there are interesting very-high emitting outliers for 3 out of 5 renewable energy types. The highest is 1694 gCO_2e/kWh for hydro, then 323 gCO_2e/kWh for geothermal, and then 183 gCO_2e/kWh for solar photovoltaics. As a side note, if a full international geothermal dataset was available and represented in this figure, then the outlier for geothermal would be higher (>1000 gCO_2e/kWh for Turkey). It is clear that outliers (for any dataset) are not representative of the body of that data. It is true that Ohaaki and Ngawha have high emissions, almost within the range of gas combined-cycle plants (Figure 2). However, it is also true that the low-emissions outlier for NZ geothermal, Wairakei, has emissions lower than the median and even the interquartile range of solar photovoltaics. It is not valid to pick any outlier and use it to describe the body of the dataset. The best statistical indication of the central tendency of a dataset is the median (as it is less skewed by outliers), combined with the interquartile range. By this measure, all renewable energy types fall under the 100 gCO_2e/kWh threshold (Figure 3).

Table 3: NZ geothermal power stations: operational (Fuel Cycle) and lifecycle emissions intensities for CY2020.

					Operational (Fuel Cycle)			Lifecycle (=Fuel Cycle +10)
		Emission factor	Total mass of steam	Net generation	Emission intensity	Annual emission	Emission rate	Emissions intensity
Power Station	Geothermal Field	$t\ CO_2e$ / t steam	t steam	GWh	gCO_2e / kWh	$t\ CO_2e$	$t\ CO_2e$ / day	$g\ CO_2e$ / kWh
Wairakei A&B&binary	Wairakei	0.00200	9,889,705	1,119	18	19,779	54	28
Te Mihi	Wairakei	0.00480	9,995,170	1,265	38	47,977	131	48
Poihipi	Wairakei	0.00490	2,498,278	319	38	12,242	34	48
Ohaaki	Ohaaki	0.03330	2,720,613	297	305	90,596	248	315
Te Huka	Tauhara	0.00780	1,374,041	209	51	10,718	29	61
Rotokawa	Rotokawa	0.01465	1,784,039	265	99	26,136	72	109
Nga Awa Purua (NAP)	Rotokawa	0.00823	7,841,465	1,180	55	64,535	177	65
Mokai	Mokai	0.00460	5,163,703	752	32	23,753	65	42
Ngatamariki	Ngatamariki	0.00960	3,914,410	721	52	37,578	103	62
Kawerau (KGL)	Kawerau	0.01578	7,024,449	931	119	110,846	303	129
TOPP1	Kawerau	0.01060	964,505	179	57	10,224	28	67
TAOM	Kawerau	0.01000	1,023,524	211	49	10,235	28	59
GDL	Kawerau	0.01300	224,733	69	42	2,922	8	52
Ngawha (all)	Ngawha	0.08469	756,846	205	313	64,097	175	323
MW-weighted average					69	Σ 531,638	Σ 1,456	79
Median					52			62
25th percentile					39			49
75th percentile					88			98

Table 4: Summary of lifecycle emissions statistics for a range of energy types.

Energy type		Lifecycle emissions [gCO_2e /kWh]					Reference
		Min	25th	Median	75th	Max	
Fossil fuels	Coal	750	930	**980**	1050	1370	Whitaker et al. (2012)
	Gas - combustion turbine	535	570	**670**	750	855	O'Donoughue et al. (2014)
	Gas - combined cycle	330	420	**450**	480	695	O'Donoughue et al. (2014)
Renewables	Geothermal NZ	28	49	**62**	98	323	Table 3

	Solar PV	18	37	**44**	49	183	NREL Solar Fact Sheet (2012)
	Solar concentrator	9	15	**28**	35	82	NREL Concentrating Solar Fact Sheet 2012)
	Hydro	0.1	6	**19**	59	1694	International Hydropower Association (2018)
	Wind	0	8	**11**	19	45	NREL Wind Fact Sheet (2013)

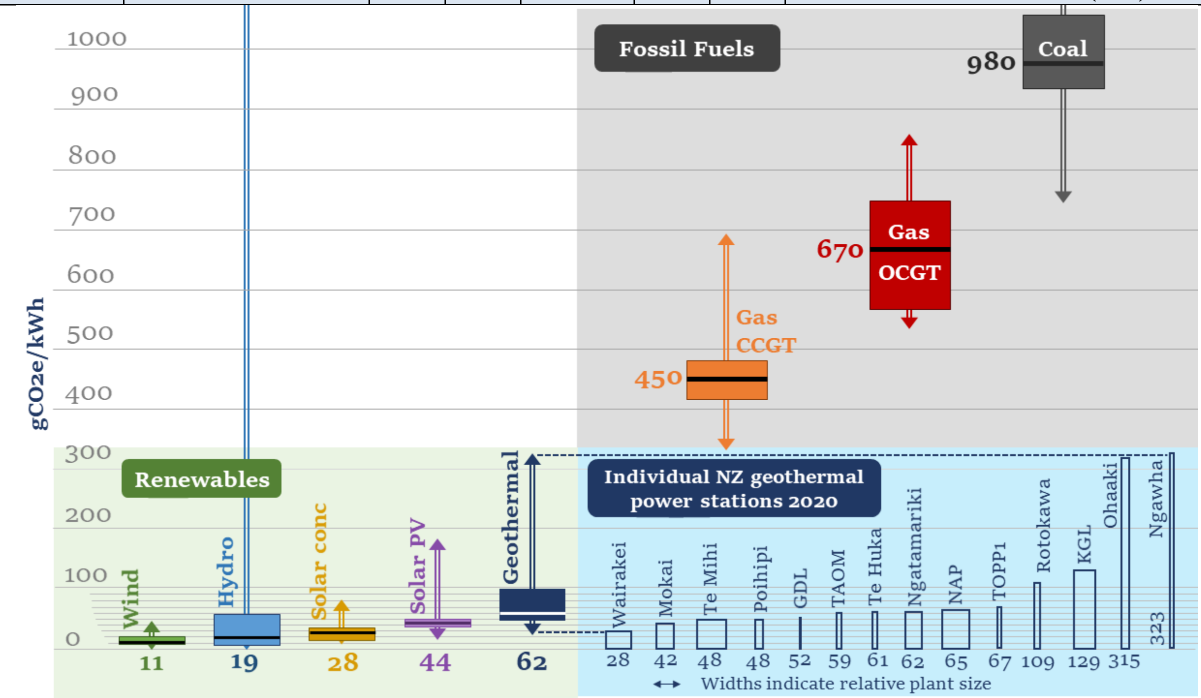

Figure 2: Graphical comparison of lifecycle emissions intensity (gCO_2e/kWh) across renewable and fossil fuel energy types.

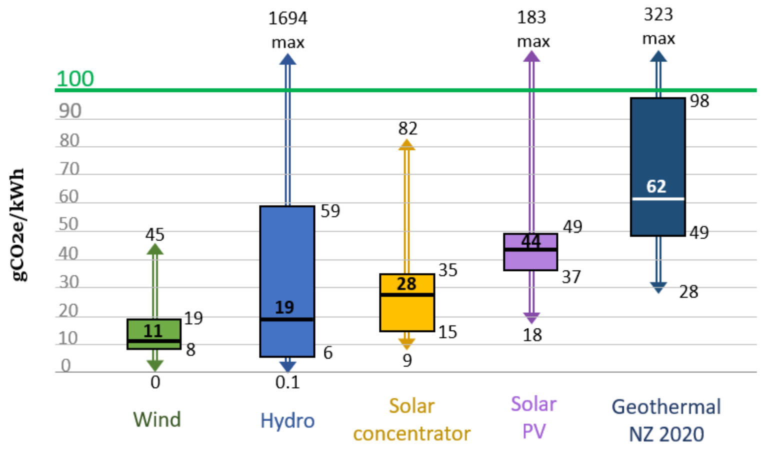

Figure 3: Zoom in of renewable energy sources in Figure 2, compared to the EU Sustainable Finance Threshold (Section 2.5).

4.2 Source of emissions for different energy types

A summary of different energy types, their median lifecycle emissions, and the primary source of these emissions is given in Table 5. It is interesting to note where the emissions mostly come from in each case, whether it be Fuel Cycle or Plant Cycle.

All fossil fuel energy types are dominated by Fuel Cycle emissions from the combustion of coal or gas. Solar (PV and concentrating) and wind are dominated by Plant Cycle emissions from upstream processes related to materials extraction, production, manufacturing, and construction. In the case of wind power, these emissions do not add up to much, and the overall lifecycle emissions from wind are the lowest of the renewables (11 gCO_2e/kWh). In the case of solar, these emissions are relatively significant, with a median of 44 gCO_2e/kWh for solar PV. This is not surprising because while silica (Si) is one of the most abundant elements on Earth (sand is mostly Si), the processing and energy requirements to produce solar cell-grade silicon wafers are enormous (must be very pure and have good crystal structure).

Geothermal is dominated by Fuel Cycle emissions, which are naturally occurring CO_2e from underground which are released during the power generation process (Section 2.3) and are typically much higher than the standard ten gCO_2e/kWh for geothermal Plant Cycle (Section 2.2).

Hydro can be dominated by either Fuel Cycle or Plant Cycle. Hydro Plant Cycle emissions can be significant and come from materials like concrete and steel and plant construction. These, however, can be dwarfed by emissions from land-use change, which are classified as Fuel Cycle emissions, and vary greatly between hydro projects. The relevant biochemical processes are very complex and are very specific to individual projects, as they depend on factors such as reservoir depth, shape, solar irradiance, depth of the thermocline, average wind speed and type of vegetation flooded in the creation of the reservoir (International Hydropower Association, 2018).

4.3 Declining trend over time

The overall emissions intensity of the NZ geothermal power stations continued to decline in 2020 (Figure 4).

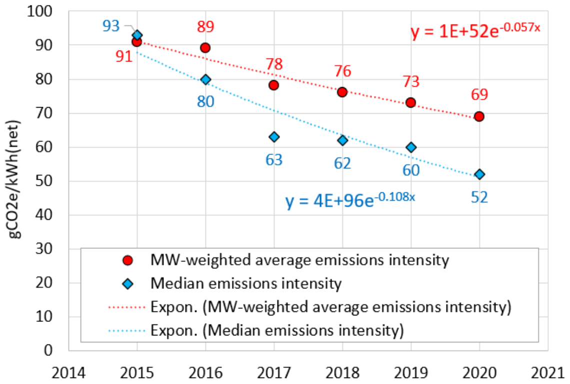

Figure 4: Declining operational emissions intensity of NZ geothermal power stations 2015 – 2020 (data from Table 1 and Table 3).

The exponential decline rate is between 6 and 11 %, depending on whether the median or MW-weighted average values are used. This declining trend is likely to continue as the only new geothermal power station announced to date is Tauhara II, on the Tauhara Geothermal Field, and this is predicted to have low emissions similar to Te Huka, the other plant on the same field (50 gCO_2e/kWh).

4.4 Improvements to UEF methodology for binary stations

In recent years the emissions intensities from a few geothermal power stations have apparently dropped suddenly. This is not due to an actual change in the CO_2e content of the fluid in these reservoirs or emissions from these plants. Rather, it is because the methodology for assessing the UEF has been reviewed and improved and now accounts for the CO_2e that remains in the reinjection fluid and goes back underground. This option is specified in the 2009 NZ regulations (Climate Change (Unique Emissions Factors) Regulations 2009 (SR 2009/286), Regulation 16, sub-clause 2) and is described in Mclean et al. (2020). So, it is not that the CO_2e content/emissions have dropped at these stations, but rather that they were never as high as they appeared to be.

This provision is significant for binary power stations, where the geothermal steam is condensed at an elevated pressure which results in a portion of the non-condensable gases (NCGs) dissolving into the condensate. The steam condensate is then typically mixed with the separated geothermal water for further use in the plan (preheaters) before being injected back into the geothermal reservoir. The CO_2e that dissolves into the condensate and is then reinjected back underground is referred to in the geothermal industry as "passive CO_2 reinjection". All other geothermal power stations (non-binary) are called "flash" power stations and work by flashing (boiling) the geothermal fluid, where the steam and separated and the steam is sent to a steam turbine. In these plants, the steam is typically condensed at very low pressures (often ~0.1bara) to maximise plant efficiency. In these plants, it is usually the case that very little CO_2e remains in the reinjection fluid.

Table 5: Summary of energy types, lifecycle emissions, and their sources (Fuel Cycle vs Plant Cycle).

Energy type	Lifecycle emissions median (Table 4) gCO_2e/kWh	Dominated by: Fuel or Plant Cycle	Description
Coal	980	Fuel Cycle	> 98% operational: mostly from extraction, transport, and combustion of fuel (Whitaker et al., 2012)
Gas - combustion turbine	670	Fuel Cycle	Like coal, dominated by operational emissions from extraction, transport, and combustion of fuel (IPCC, 2011)
Gas - combined cycle	450	Fuel Cycle	Like coal, dominated by operational emissions from extraction, transport, and combustion of fuel (IPCC, 2011)
Geothermal NZ	62	Fuel Cycle	Majority operational: release of natural CO_2 from underground during power generation (Fridriksson et al., 2016).
Solar PV	44	Plant Cycle	Upstream and downstream processes: majority upstream (60-70%) from raw materials (Si) extraction and production, manufacturing, construction (NREL Solar Fact Sheet, 2012).
Solar concentrator	28	Plant Cycle	Upstream and downstream processes: majority upstream (60-70%) from raw materials (Si) extraction and production, manufacturing, construction (NREL Concentrating Solar Fact Sheet, 2012).
Hydro	19	Plant or Fuel Cycle	Plant Cycle: materials production and transport (particularly concrete and steel), installation/ plant construction. Fuel Cycle: land-use change can be significant

			for some operations as some freshwater bodies are significant emitters of CO_2e. (International Hydropower Association, 2018)
Wind	11	Plant Cycle	~86% upstream processes: raw materials extraction, manufacturing, construction (NREL Wind Fact Sheet, 2013).

* McLean and Richardson (2019), Table 1.
** See Table 3, this paper.

Until recently, this provision was not used at any power stations, as the extra sampling required was rigorous and expensive. In many cases, the additional cost of the sampling (and verification by external parties) outweighed the potential savings that could be made in the Emissions Trading Scheme (ETS). However, the recent increases in the price of carbon emissions in New Zealand and increased scrutiny of geothermal emissions have prompted a review of some UEFs, especially where the financial benefits of a lower UEF outweigh the additional sampling, analysis and verification costs.

4.4.1 Ngatamariki

The 82 MW Ngatamariki power station was commissioned in 2013 and is owned and operated by Mercury (McLean et al., 2020). UEFs from 2014 to 2020 are presented in Table 6 and Figure 5.

After an initial small increase, the UEF has been steadily declining as the field degasses (McLean and Richardson, 2019). The step-change in UEF in 2019 was due to the inclusion of CO_2e reinjection in the methodology. The numbers in Table 6 show the old method overestimates the actual emissions by 14% (UEF = 0.0127 instead of 0.0111).

Table 6: UEFs for Ngatamariki 2014-2020, see Figure 5 (McLean and Richardson, 2019; McLean et al., 2020).

Year	Reinjection included in methodology?	UEF
2014	No	0.016062
2015	No	0.01805
2016	No	0.015
2017	No	0.01342
2018	No	0.013352
2019	No	0.0127
2019	Yes	0.0111
2020	Yes	0.0096

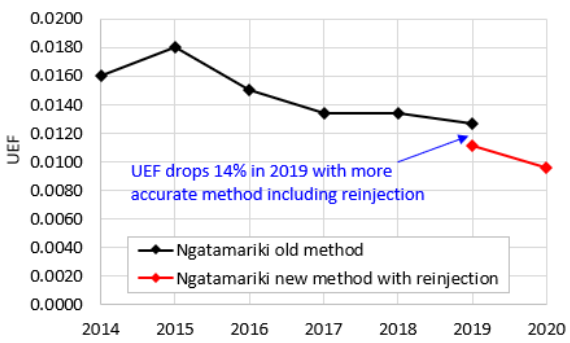

Figure 5: UEFs for Ngatamariki 2014-2020 (Table 6).

A point of technical interest: the initial slight increase in UEF (2014-2015, Figure 5) is not unexpected in new fields, as the reservoir response to production stabilises. Early production from geothermal wells tends to stimulate "extra boiling" (referred to as "excess enthalpy") in the reservoir, particularly in higher-enthalpy fields, which are generally lower-permeability systems (Zarrouk and McLean, 2019).

4.4.2 Te Ahi O Maui

The 24 MWe Te Ahi O Maui (TAOM) power station was commissioned in 2018 and is joint owned by Eastland Generation and the Kawerau A8D Ahu Whenua Trust, operated by Eastland Generation. UEFs from 2019 and 2020 are presented in Table 7 and Figure 6.

At TAOM the UEF methodology was reviewed in 2020 to optimise sampling methodology and include reinjection, hence the observed drop in UEF in 2020. The numbers show that the old method overestimates the actual emissions by 20% (UEF = 0.012 instead of 0.01).

The dataset is too small to draw any conclusions on whether the field is degassing like Ngatamariki. However, the 2020 UEF is 39% lower than the 2019 UEF, approximately half of which is due to the improvement in methodology, and half is due to an actual decrease in emissions.

Table 7: UEFs for Te Ahi O Maui-2019-2020.

Year	Reinjection included in methodology?	UEF
2019	No	0.0139
2020	No	0.0120
2020	Yes	0.0100

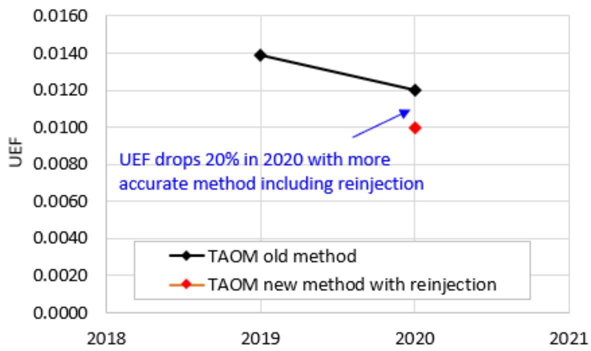

Figure 6: UEFs for TAOM 2019-2020 (Table 7).

5. CONCLUSIONS

- NZ geothermal is a low emissions industry.
- There are outliers and variability as geothermal systems are natural systems; geothermal plants just harness them.
- Statistics for the 14 NZ geothermal power stations CY2020 operational emissions intensity (“fuel cycle”) are:
    - Median: 52 gCO_2e/kWh
    - IQR: 39-88 gCO_2e/kWh
    - MW-weighted average: 69 gCO_2e/kWh
- A reasonable estimate of “plant cycle” emissions for geothermal power stations is 10 gCO_2e/kWh, (from the World Bank).
- Adding “plant cycle” to “fuel cycle” gives full lifecycle emissions intensity, which for NZ in CY2020 are:
    - Median: 62 gCO_2e/kWh
    - IQR: 49-98 gCO_2e/kWh
    - MW-weighted average: 79 gCO_2e/kWh
- The overall emissions intensity for NZ has been declining since 2015 (after the last major power station, Te Mihi, was commissioned), and this trend continued in 2020. The decline rate is between 6 and 11%.
- Comparison of lifecycle emissions between energy sources shows that geothermal has the highest emissions of the renewables, followed by solar, concentrating solar, hydro and then wind with the lowest.
- All the renewables, including geothermal, have median and inter-quartile range lifecycle emissions less than the current EU Sustainable Finance Threshold of 100 gCO_2e/kWh.
- Accounting for reinjected gases in the assessment of UEF has resulted in significant reductions in UEF (13-20%) for binary stations.
- This is only “passive” CO_2 reinjection – it has always been happening. Trials of “active” (deliberate) CO_2 reinjection are starting in NZ in 2021, with the potential to significantly decrease emissions for all plant types.

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