# Reducing greenhouse gas emissions from NZ geothermal power stations

Katie McLean[1,2], Ian Richardson[1,2], Fabian Hanik[1,3], Farrell Siega[1,4] and Ben Gibson[1,5]

[1] New Zealand Geothermal Association

[2] Contact Energy Ltd., Wairākei Power Station, Private Bag 001, Taupo 3352, New Zealand

[3] Ngāwhā Generation, PO Box 43, Kerikeri 0245, New Zealand

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

[5] Eastland Generation, 9 Manukorihi Drive, Kawerau 3127, New Zealand

katie.mclean@contactenergy.co.nz

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## ABSTRACT

Geothermal reservoirs contain naturally-occurring greenhouse gases, in the form of $CO_2$ and methane. In most cases the process of generating electricity using geothermal reservoir fluids results in the release of some greenhouse gases into the atmosphere. This means that the operational emissions intensity (scope 1 emissions) of geothermal power stations is not zero.

The operational emissions from the geothermal power stations in NZ have been collated and published each year since 2018 by the New Zealand Geothermal Association Emissions Working Group. The full lifecycle emissions are also estimated, to allow comparison to emissions from other renewable energy sources. The five previously published datasets are reviewed in this paper, along with the latest dataset from calendar year 2023. Changes and trends are identified, for the industry overall, and for individual power stations.

The change of most interest is the elimination or reduction of emissions from some power stations. This has been achieved by reinjection of the greenhouse gases back into the reservoir. This method effectively closes the loop on the gases and returns them to where they came from. This has so far been achieved at three geothermal power stations – Ngāwhā, Te Huka and Ngā Tamariki. This common and important emissions challenge has given rise to a cooperation between all the geothermal generators in New Zealand, enabling the decarbonisation effort to progress faster. The effect of this effort on the emissions can be seen in this paper.

## 1. INTRODUCTION

It is well-known that most geothermal power stations release emissions to the atmosphere as part of the generation process. The greenhouse gases involved ($CO_2$ and methane) are naturally-occurring underground in the reservoir. There is a wide range of emissions from different fields, ranging from very low to significant. It is not known why some fields are higher in gas, other than to say that the ultimate source of most of the gases is de-gassing from deep underground magma chambers, which must have a range of composition and gas content themselves.

It is useful to quantify geothermal emissions in NZ, for a number of reasons. Firstly, to compare to other energy types to put the numbers in context. Secondly, to track how the emissions are changing over time. Geothermal emissions change due to de-gassing of reservoirs, operational changes to plant, new wells accessing new parts of a reservoir, or most interestingly due to deliberate reductions from implementing $CO_2$ reinjection technology. Details of geothermal power station emissions have been published each year since 2018, with data in some cases going back to 2010. The purpose of this paper is to review these datasets and discuss trends over time.

## 2. BACKGROUND

### 2.1 Why do geothermal power stations have emissions?

Geothermal reservoirs in NZ are mostly liquid underground, containing dissolved gases. The geothermal reservoir is a convection cell which circulates underground, transporting the gases within the fluid. The ultimate source of dissolved gases in the fluid is de-gassing of magma deeper underground, and also fluid-rock interactions within the reservoir itself. Regardless of whether there is a power station present, all geothermal fields emit $CO_2$ (and methane) to the atmosphere via natural surface features such as fumaroles and hot pools (Figure 1). When a power station is present, fluid is produced from the reservoir and gases are released from the fluid during the power generation process. Usually, the gases are ejected from the condensers (of flash power stations) or vaporisers (of binary stations) and released to the atmosphere, which is necessary to keep the power stations running.

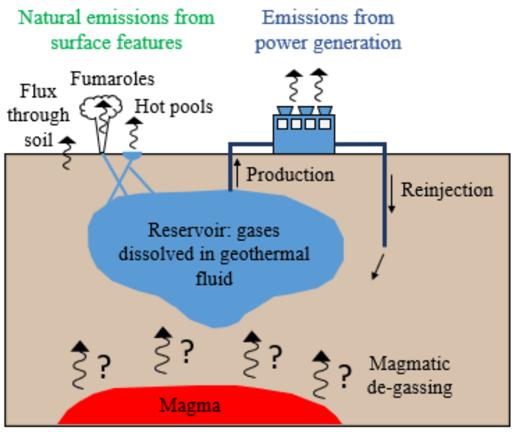


**Figure 1: Schematic of geothermal reservoir and primary source of gases – the magma chamber (modified from McLean and Richardson, 2019)**

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## 2.2 New Zealand ETS – reporting requirements

The NZ Emissions Trading Scheme (ETS) is a key tool for the government to meet emissions reduction targets (MFE, 2024). Amongst other things, the NZ ETS requires businesses to measure and report their emissions to the Ministry for the Environment (MFE). The legislation that governs this process is as follows:

- Climate Change (Stationary Energy and Industrial Processes) Regulations 2009 (SR 2009/285).
- Climate Change (Unique Emissions Factors) Regulations 2009 (SR 2009/286).

Both of these pieces of legislation are from September 2009, and are updated early each calendar year. At the time of writing, they were last updated in January and February 2023. The legislation requires that both $CO_2$ and methane are measured and reported as one $CO_2$-equivalent number ($CO_2$e). The current factor to convert methane numbers to $CO_2$ numbers is 28 (SR2009/286 Clause 16(1)d).

## 2.3 NZ Geothermal power stations

For the purposes of reporting under the NZ ETS, there are now 15 geothermal power stations (Table 1). Note that in some cases technically separate plants are grouped together, as this makes sense for emissions reporting. For example, the Wairākei A and B station are grouped as they are run on the same steam supply lines, and also grouped with Wairākei binary which is run on separated geothermal water (SGW) from the same steamfield.

**Table 1: Details of the 15 NZ geothermal power stations: name, type and commissioning date.**

| # | Power station | Type | Commissioning date* |
|---|---|---|---|
| 1 | Wairākei A&B&binary | A&B: flash, and binary. | 1958-1963 (A&B), 2005 (binary) |
| 2 | Te Mihi | Flash | 2014 |
| 3 | Poihipi | Flash | 1997 |
| 4 | Ohaaki | Flash | 1989 |
| 5 | Te Huka | Binary | 2010 |
| 6 | Rotokawa | Flash-binary | 1997, 2003 |
| 7 | Ngā Awa Pūrua (NAP) | Flash | 2010 |
| 8 | Mokai | Flash-binary | 1999, 2005, 2007 |
| 9 | Ngā Tamariki | Binary | 2013 |
| 10 | Kawerau (KGL) | Flash | 2008 |
| 11 | TOPP1 | Binary | 2013 |
| 12 | TAOM | Binary | 2018 |
| 13 | GDL | Binary | 2008 |
| 14 | Ngāwhā (OEC1-3) | Binary | 1998, 2008 |
| 15 | Ngāwhā (OEC4) | Binary | 2021 |

*Some plants have multiple commissioning dates for different units.

## 2.4 Previously published datasets for NZ geothermal power stations

Emissions data for NZ geothermal power stations has been published by the New Zealand Geothermal Association each calendar year from 2018 onwards:

- CY2018: McLean and Richardson (2019) presented 2018 data but with data back to 2010 in some cases. Focus on comparison to other energy sources, and trends over time.
- CY2019: McLean et al. (2020) presented 2019 data and some direct use data. Focus on direct use and trends.
- CY2020: McLean and Richardson (2021) presented 2020 data. Focus on lifecycle vs operational emissions for better comparison with other energy types.
- CY2021: Montague et al. (2022) - 2021 emissions data incorporated into NZ annual geothermal review paper.
- CY2022: Montague et al. (2023) - 2022 emissions data incorporated into NZ annual geothermal review paper.

Relevant data from these papers is presented in Section 4 "Overall trends", from 2010 to 2023.

## 2.5 Non Condensable Gas (NCG) reinjection

2.5.1 Description and operational considerations

$CO_2$ and methane are not the only gases that do not condense and have to be ejected from power stations (Section 2.1). This group of gases is called non-condensable gases (NCG) and is primarily composed of $CO_2$, methane, and hydrogen sulfide, with other minor gases.

NCGs are usually separated from geothermal steam and condensate during the power generation process and released to the atmosphere via the cooling tower. NCG reinjection is a process that redirects the NCGs to the reinjection system where they are dissolved and carried back underground where they came from (Richardson and Webbison, 2024), see Figure 2 schematic.

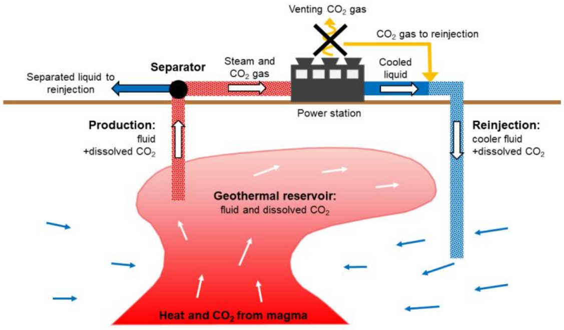


**Figure 2: Schematic showing how $CO_2$ moves through a geothermal system, above-ground plant, and reinjection.**

NCG reinjection as described here refers to deliberately routing the NCGs into the reinjection system ("active reinjection"). It does not refer to NCGs that dissolve in the condensate within the vaporiser during normal plant operation or those that remain in solution in the separated geothermal brine ("passive reinjection" - Ruiz et al., 2021)

NCG reinjection is applicable to both binary and flash plants. However, the operating conditions in binary plants are typically more favourable, including (Richardson and Webbison, 2024):

- Exclusion of oxygen from the NCGs - minimises corrosion.
- Higher NCG pressure - reduces or removes the need for compression.
- Lower reinjection fluid temperatures - improves the solubility of NCGs in that fluid.

For binary plants, the NCGs are usually routed from the vaporiser (or other heat exchanger where NCGs build up) to the reinjection line downstream of the preheaters – this is where the fluid temperature is lowest so the NCGs will be more soluble (Richardson and Webbison, 2024). The pressure of the NCGs as they leave the vaporiser can be sufficiently high that the NCGs flow to the reinjection line without the need for compression.

NCG reinjection is also applicable to flash plants with condensing steam turbines, though there are additional factors to consider, in particular the presence of oxygen in the NCGs which must be minimised to avoid corrosion of the reinjection line. Requirements for this (Richardson and Webbison, 2024):

- Surface condenser (such as shell-and-tube condenser at Poihipi where condensate does not contact the cooling fluid.
- Turbine gland steam system to minimise air ingress into systems that operate under vacuum. This must be adequately designed and maintained/operated.

In the case of a direct contact condenser, removal of oxygen from the NCGs will likely be required to avoid corrosion, and removal of nitrogen to avoid breakout pressure issues (presence of nitrogen makes it harder to keep the NCGs in solution).

Regardless of the type of condenser, the NCGs will be at vacuum pressure and so a gas compression system will be required to increase the NCG pressure to a suitable level for reinjection.

2.5.2 Overview of current NZ NCG reinjection projects

There are currently four geothermal power plants in New Zealand operating with NCG reinjection systems:

- Ngā Tamariki: 25% reinjection operational since October 2021.
- Ngāwhā OEC1-3: 100% reinjection operational since May 2022 (OEC1), August 2022 (OEC2) and January 2023 (OEC3).
- Te Huka: 100% reinjection operational since November 2022 (some outages/upgrades through 2023).
- Ngāwhā OEC4: 100% reinjection operational since September 2023.

All four of these plants are binary designs, and in each case the NCG reinjection system was retrofitted by the plant operators (Mercury, Ngāwhā Generation and Contact Energy respectively) with the plants previously operating without NCG reinjection systems.

2.5.3 Future NZ NCG reinjection projects

As a result of the success of these NCG reinjection projects, there are now several geothermal power plants in the planning, construction and commissioning phases that are having NCG reinjection systems designed and built as a part of the original plant design including Te Huka U3 (50 MW currently commissioning), Ngā Tamariki OEC Unit 5 (46 MW under construction) and TOPP2 (49 MW under construction). While there are also plans to add NCG reinjection systems to include the remaining Ngā Tamariki OEC units, the Te Ahi O Maui and TOPP1 power plants over time. The emissions avoided as a result of these NCG reinjection projects are discussed in Section 5.4 and 5.5.

## 3. NEW DATASET – CY2023

The raw data as reported by the geothermal operators (UEF, mass of steam, net generation) for CY2023 is given in Table 2, along with the calculated total emissions for that year, the operational emissions intensity and an estimate of the lifecycle emissions intensity. For 2023 the MW-weighted average operational emissions intensity is 58 $gCO_2/kWh$ and median is 50 $gCO_2/kWh$. Long term trends in the data from Table 2 are given in Section 4 (overall industry trends) and Section 5 (trends for individual plants).

## 4. OVERALL TRENDS

All available emissions intensity numbers are summarised in Table 3, with references from the papers described in Section 2.4. While there is data available back to 2010, the dataset is patchy in those early years and not reliable for overall statistics and long-term trending. The dataset since 2014 is considered to be reliable for this purpose as data is less patchy and any new plants commissioned during this time are small and quite average in terms of emissions so will not alter the median or weighted average much.

All available emissions numbers are summarised in Table 4, with references. The dataset since 2017 is considered to be sufficiently complete to calculate a valid total tonnes of $CO_2e$ for those years, as only GDL is missing from the dataset and the emissions from that plant are negligible in the big picture.

The trends in both emissions intensity and total emissions for individual plants are given in Section 5.

### 4.1 Overall geothermal emissions intensity trend

The best indication of the overall emissions intensity trend of the industry is the MW-weighted average (Figure 3, data from Table 3). This is the best measure to use as it takes account the size of the plant (by weighting the emissions intensity values using the generation volumes) and so large plants which emit more tonnes of $CO_2$ have more weight than small plants. It can be seen from Figure 3 that there is a long-term declining trend which is approximately linear and decreasing the emissions intensity by approximately 5 $gCO_2e/kWh$ each year.

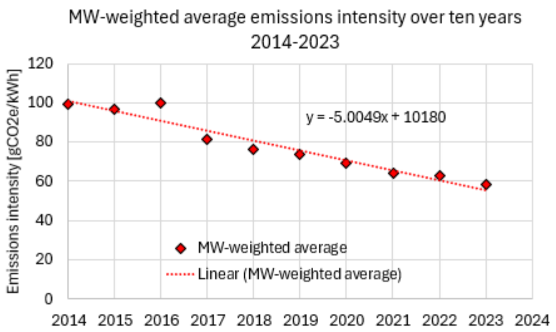


**Figure 3: MW-weighted average operational emissions intensity over ten years 2014-2023 (from Table 3).**

**Table 2: NZ geothermal power stations operational and lifecycle emissions intensity for CY2023.**

| | | | | | 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 $CO_2$e / t steam | t steam | GWh | g $CO_2$e / kWh | t $CO_2$e | t $CO_2$e / day | g $CO_2$e / kWh |
| Wairākei A&B&binary | Wairākei | 0.0023 | 9,199,769 | 1,027 | 21 | 21,159 | 58 | 31 |
| Te Mihi | Wairākei | 0.0041 | 11,759,826 | 1,405 | 34 | 48,215 | 132 | 44 |
| Poihipi | Wairākei | 0.0049 | 2,506,087 | 315 | 39 | 12,280 | 34 | 49 |
| Ohaaki | Ohaaki | 0.0333 | 2,862,059 | 316 | 302 | 95,307 | 261 | 312 |
| Te Huka | Tauhara | 0.00358 | 1,116,893 | 170 | 24 | 3,998 | 11 | 34 |
| Rotokawa | Rotokawa | 0.0121 | 1,164,330 | 241 | 58 | 14,088 | 39 | 68 |
| Ngā Awa Pūrua (NAP) | Rotokawa | 0.00901 | 7,854,274 | 1,198 | 59 | 70,767 | 194 | 69 |
| Mokai | Mokai | 0.00382 | 4,972,399 | 698 | 27 | 18,995 | 52 | 37 |
| Ngā Tamariki | Ngā Tamariki | 0.00746 | 3,999,434 | 692 | 43 | 29,836 | 82 | 53 |
| Kawerau (KGL) | Kawerau | 0.0156 | 5,148,336 | 661 | 122 | 80,314 | 220 | 132 |
| TOPP1 | Kawerau | 0.0088 | 1,193,047 | 187 | 56 | 10,499 | 29 | 66 |
| TAOM | Kawerau | 0.0113 | 1,097,984 | 202 | 61 | 12,407 | 34 | 71 |
| GDL | Kawerau | 0.0119 | 268,901 | 57 | 56 | 3,200 | 9 | 66 |
| Ngāwhā (OEC1-3) | Ngāwhā | 0 | 713,857 | 196 | 0 | 0 | 0 | 10 |
| Ngāwhā (OEC4) | Ngāwhā | 0.03 | 775,100 | 245 | 95 | 23,253 | 64 | 105 |
| MW-weighted average | | | | | 58 | Σ 444,318 | Σ 1,216 | 70 |
| Median | | | | | 50 | | | 60 |
| 25th percentile | | | | | 29 | | | 39 |
| 75th percentile | | | | | 59 | | | 69 |

**Table 3: Summary of emissions intensity trends over time for NZ geothermal power stations CY2010-2023.**

| Operational emissions intensity [g $CO_2$e / kWh] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Data set patchy, 8 data points or less each year | | | | All major power stations present, 11 data points or more each year | | | | | | | | | |
| | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018[1] | 2019 | 2020 | 2021 | 2022 | 2023 |
| Wairākei A&B &binary | 46 | | 65 | 64 | 20 | 23 | 24 | 24 | 21 | 24 | 18 | 19 | 19 | 21 |
| Te Mihi | | | | | 48 | 42 | 41 | 45 | 43 | 38 | 38 | 39 | 37 | 34 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Poihipi | 50 | | 11 | 10 | 15 | 15 | 15 | 32 | 39 | 41 | 38 | 38 | 38 | 39 |
| Ohaaki | 525 | 438 | 434 | | 443 | 376 | 463 | 375 | 341 | 299 | 305 | 264 | 282 | 302 |
| Te Huka | 52 | 46 | 27 | 27 | 37 | 37 | 37 | 32 | 45 | 51 | 51 | 52 | 49 | 24 |
| Rotokawa | | 150 | 123 | 105 | 119 | 105 | 93 | 80 | 98 | 88 | 99 | 80 | 57 | 58 |
| Ngā Awa Pūrua (NAP) | | 130 | 115 | 105 | 93 | 100 | 88 | 73 | 65 | 59 | 55 | 51 | 56 | 59 |
| Mokai | | 35 | | 30 | 26 | 26 | 34 | 29 | 36 | 30 | 32 | 31 | 25 | 27 |
| Ngā Tamariki | | | | | 82 | 93 | 80 | 65 | 72 | 61 | 52 | 50 | 40 | 43 |
| Kawerau (KGL) | | 136 | 161 | 141 | 123 | 173 | 150 | 125 | 130 | 130 | 119 | 97 | 126 | 122 |
| TOPP1 | | | | | | | | 60 | 60 | 53 | 57 | 58 | 74 | 56 |
| TAOM | | | | | | | | | | 75 | 49 | 57 | 60 | 61 |
| GDL | | | | | | | | | | 70 | 42 | 45 | 53 | 56 |
| Ngāwhā (OEC1-3) | 348 | 328 | 322 | 345 | 348 | 332 | 322 | 306 | 307 | 312 | 313 | 315 | 162 | 0 |
| Ngāwhā (OEC4) | | | | | | | | | | | | | | 95 |
| | | | | | | | | | | | | | | |
| # stations data available | 5 | 7 | 8 | 8 | 11 | 11 | 11 | 12 | 12 | 14 | 14 | 14 | 14 | 15 |
| MW-weighted average | 172 | 342 | 145 | 94 | 99 | 96 | 100 | 82 | 76 | 73 | 69 | 64 | 63 | 58 |
| Median | 52 | 136 | 119 | 85 | 82 | 93 | 80 | 63 | 63 | 60 | 52 | 52 | 55 | 56 |
| 25th percentile | 50 | 88 | 56 | 29 | 32 | 32 | 36 | 32 | 42 | 44 | 39 | 41 | 39 | 31 |
| 75th percentile | 348 | 239 | 201 | 114 | 121 | 139 | 122 | 91 | 106 | 85 | 89 | 75 | 71 | 60 |
| Maximum | 525 | 438 | 434 | 345 | 443 | 376 | 463 | 375 | 341 | 312 | 313 | 315 | 282 | 302 |
| Minimum | 46 | 35 | 11 | 10 | 15 | 15 | 15 | 24 | 21 | 24 | 18 | 19 | 19 | 0 |
| **Reference:** | **2** | **2** | **2** | **2** | **2** | **2** | **2** | **2** | **2** | **3** | **4** | **5** | **6** | **Table 2** |

[1] Some of the 2018 numbers have been corrected slightly since the McLean and Richardson (2019) publication, due to revision of the generation volumes (GWh). Grey shading means data is unavailable for this plant for this year.

[2] McLean and Richardson, 2019; [3] McLean et al., 2020; [4] McLean and Richardson, 2021; [5] Montague et al., 2022; [6] Montague et al., 2023.

**Table 4: Summary of emissions trends over time for NZ geothermal power stations CY2010-2023.**

| $CO_2e$ emissions per year [kilo tonnes $CO_2e$] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Not enough power stations present for sum to be valid[1] | | | | | | | Dataset complete enough for sum to be valid [1] | | | | | | |
| | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018[1] | 2019 | 2020 | 2021 | 2022 | 2023 |
| Wairākei A&B &binary | 63 | | 86 | 81 | 23 | 25 | 27 | 25 | 21 | 22 | 20 | 19 | 19 | 21 |
| Te Mihi | | | | | 36 | 53 | 49 | 63 | 60 | 52 | 48 | 54 | 51 | 48 |
| Poihipi | 19 | | 5 | 5 | 6 | 5 | 6 | 13 | 15 | 15 | 12 | 13 | 12 | 12 |
| Ohaaki | 216 | 172 | 150 | | 120 | 123 | 153 | 127 | 93 | 98 | 91 | 89 | 89 | 95 |
| Te Huka | 11 | 6 | 6 | 5 | 8 | 7 | 7 | 7 | 9 | 10 | 11 | 8 | 10 | 4 |
| Rotokawa | | 35 | 30 | 30 | 29 | 26 | 23 | 25 | 24 | 26 | 17 | 14 | 14 | 35 |
| Ngā Awa Pūrua (NAP) | | 132 | 117 | 98 | 108 | 104 | 85 | 78 | 66 | 65 | 60 | 62 | 71 | 132 |
| Mokai | | | | 24 | 23 | 22 | 29 | 25 | 26 | 25 | 24 | 24 | 20 | 19 |
| Ngā Tamariki | | | | | 52 | 68 | 56 | 52 | 50 | 45 | 38 | 37 | 30 | 30 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kawerau (KGL) | | | 136 | 114 | 134 | 156 | 128 | 120 | 112 | 116 | 111 | 78 | 113 | 80 |
| TOPP1 | | | | | | | | 11 | 11 | 10 | 10 | 12 | 9 | 11 |
| TAOM | | | | | | | | | | 14 | 10 | 11 | 12 | 12 |
| GDL | | | | | | | | | | 4 | 3 | 3 | 4 | 3 |
| Ngāwhā (OEC1-3) | 35 | 63 | 65 | 68 | 68 | 64 | 65 | 60 | 62 | 60 | 64 | 61 | 31 | 0 |
| Ngāwhā (OEC4) | | | | | | | | | | | | | | 23 |
| | | | | | | | | | | | | | | |
| Σ Total | | | | | | | | 610 | 561 | 560 | 532 | 485 | 474 | 444 |
| # stations data available | 5 | 5 | 8 | 8 | 11 | 11 | 11 | 12 | 12 | 14 | 14 | 14 | 14 | 15 |
| **Reference:** | **2** | **2** | **2** | **2** | **2** | **2** | **2** | **2** | **2** | **3** | **4** | **5** | **6** | **Table 2** |

[1] In the 2017-2023 time window, the dataset is almost fully complete. Grey boxes in this time period - TAOM and Ngāwhā OEC4 have not yet been commissioned. Only GDL is missing and the 3-4 kt$CO_2$e per year is negligible compared to the sum total of several hundred kt$CO_2$e

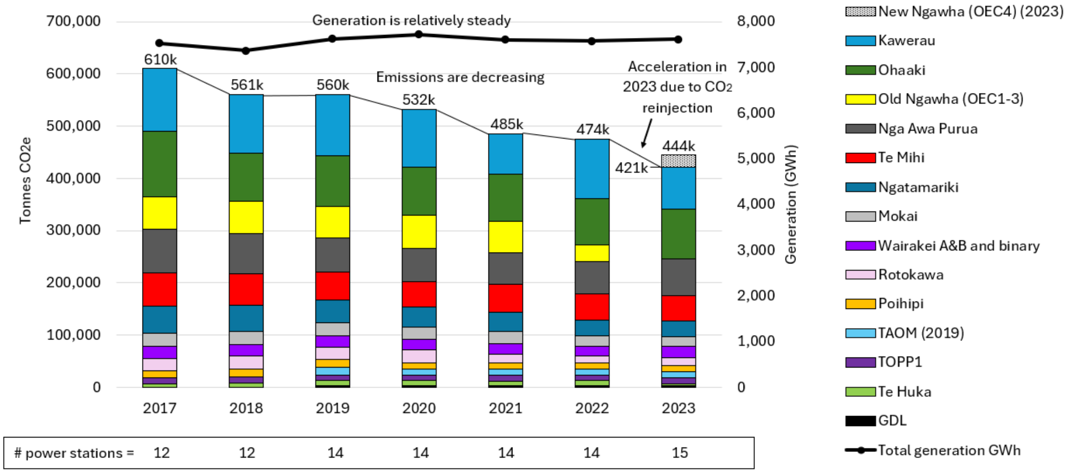


**Figure 4: Annual $CO_2$e emissions stacked from each plant 2017-2023 (data from Table 4).**

### 4.2 Overall geothermal emissions volumes trend

The tonnes of $CO_2$e emitted by each plant are stacked in Figure 4 to reveal the total for each year 2017-2023. This allows the contributions to the total industry emissions from individual plants to be seen easily. It is also clear when those emissions are decreasing, as is the case for Ngāwhā OEC1-3 which disappears from the stack completely in 2023.

Note that TAOM appears in the stack in 2019 as it was commissioned in 2018. Ngāwhā OEC4 appears in the stack in 2023 as this in the first year for which data is available since commissioning. Only data from GDL in 2017 and 2018 is missing, and this is negligible for this big picture, as GDL typically emits 3-4 kt$CO_2$e each year.

$CO_2$e reinjection projects have been in progress starting in 2021 and throughout 2022 and 2023. The full effect of these is visible by comparing the data stack from the 14 plants available throughout that time, in order to observe the changes. The addition of a fifteenth station (Ngāwhā OEC4) in 2023 adds a whole new set of emissions (23 kt$CO_2$e) and would mask the reductions achieved at the other plants. Thus, it is valid to observe the reductions along the line in Figure 4, from 485k in 2021, to 474k in 2022 and then an acceleration down to 421kt$CO_2$e in 2023.

Emissions volumes data are vulnerable to changes in generation – less generation means less steam used, which means less emissions. For this reason, the total generation volumes are included in Figure 4, to show that the generation is steady, or even slightly increasing throughout the dataset.

### 4.3 Geothermal contribution to reduction in NZ electricity generation emissions

The NZ Ministry of Business, Innovation and Employment (MBIE) publishes data on electricity generation and associated emissions (MBIE, 2024). This data provides less detail on geothermal than this paper for example, however, provides useful big-picture data across all electricity generation types including the main ones: hydro, coal, gas, geothermal, wind and solar. Figure 5 shows a stacked plot of generation from these sources from 2006 to 2023 (very minor types are excluded for simplicity, including biogas, wood, oil, and waste heat).

It can be seen that hydro has been steady overall with the usual fluctuations due to wet vs dry years. It can be seen that despite some fluctuations, the amount of coal and gas generation has been steadily reducing. The fossil fuel generation has been replaced primarily by geothermal, and to a lesser extent wind and solar.

In particular, over the ten years 2006-2015 a significant number of new geothermal power stations were built in NZ (Kawerau – KGL, GDL, Ngāwhā - OEC3, Ngā Awa Pūrua, Te Huka, Ngā Tamariki, TOPP1, Te Mihi), enabling the closure of some thermal plants. This is reflected in the geothermal data in Figure 5 and also resulted in the overall emissions from the NZ electricity industry approximately halving over the same time period. The total emissions halve from 9,220 kt$CO_2$e in 2006 to less than 4,852 kt$CO_2$e from 2015 onwards. The emissions intensity halves from 222 g$CO_2$e/kWh in 2006 to 112 g$CO_2$e/kWh in 2015.

The downward trend in emissions intensity is interrupted in 2019-2021, due to an increase in coal and gas generation offsetting lower hydro generation.

Emissions and emissions intensity in 2022-2023 are lower than ever before. Emissions in 2023 were 3,054 kt$CO_2$e and emissions intensity was 70 g$CO_2$e/kWh, less than one third of the 2006 value.

## 5. TRENDS FOR INDIVIDUAL PLANTS – NCG REINJECTION PLANTS

The trends for individual power stations are discussed in this section, with the data from Section 4 (Table 3 and Table 4). First the power stations with NCG reinjection projects are shown, followed by all other power stations. Long term trends and the factors at play are discussed. The total emissions numbers show the scale of the emissions and therefore the reductions from a plant. However, they can be misleading, as a drop in emissions may be simply due to a reduction in generation that year (less generation means less steam use which means less emissions). The true indicator of a change at that plant is the emissions intensity.

### 5.1 Ngāwhā

Ngāwhā OEC1-3 data is plotted in Figure 6. Only one data point is available for Ngāwhā OEC4, so no long-term trends can be identified. Ngāwhā OEC1-3 data shows a long-term slight decline due to the field de-gassing.

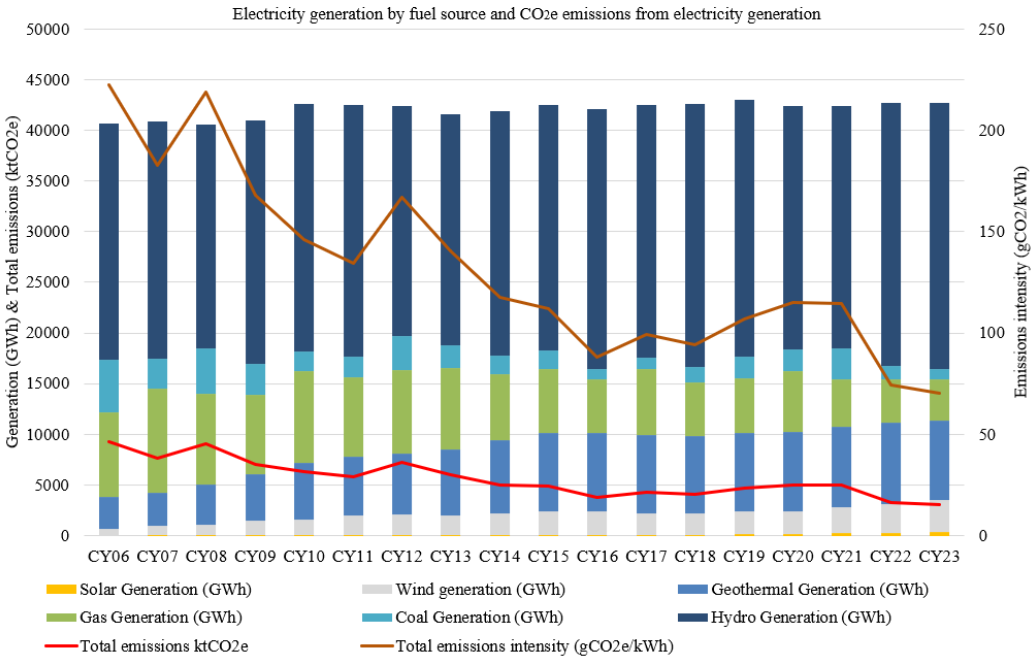


**Figure 5: MBIE data 2006-2023: Hydro, coal, gas, geothermal, wind and solar generation, and overall total emissions and total emissions intensity for NZ electricity (MBIE, 2024).**

This is the usual response to long-term production, which tends to drop the levels of gas dissolved in the reservoir fluid from the pre-development state (no power station) to a lower level. With sufficient time, this is expected to level off at a new equilibrium, in a manner analogous to reservoir pressure.

The effect of NCG reinjection is clearly seen as emissions approximately halve during 2022 as the 100% reinjection projects are implemented throughout that year (and very early 2023) and are then zero during 2023. The pre-NCG reinjection emissions are around 60,000 tonnes $CO_2$e at OEC1-3. For OEC4 this was around 68,000 tonnes $CO_2$e, and so with 100% reinjection at OEC1-3 and OEC4 combined, the emissions reductions per year are around 128,000 tonnes $CO_2$e.

### 5.2 Te Huka

Te Huka data is plotted in Figure 7. The emissions and emissions intensity are quite variable in the long-term, as this plant is supplied by only two wells, with different levels of emissions, and the proportion of fluid utilised from the two wells changes over time (McLean and Richardson, 2019). The effect of the 100% NCG reinjection is clearly seen as the emissions approximately halve in 2023, down from a pre-NCG-reinjection level of around 9,000 tonnes $CO_2$e to around 4,000 tonnes $CO_2$e. The emissions are not zero as the NCG reinjection system was not operational for about half of 2023, undergoing important safety upgrades. The 100% system has been operational again throughout 2024 and emissions are predicted to be zero.

### 5.3 Ngā Tamariki

Ngā Tamariki data is plotted in Figure 8. Data is available from 2014 onwards as the plant was commissioned in 2013. The emissions and intensity initially increase after a change in well utilisation, shifting production closer to the centre of the field with higher enthalpy and fluid gas content. After this the trend is a rapid decline as the field de-gasses as described for Ngāwhā (longer-term more subtle decline there). The effect of the 25% NCG reinjection system (commissioned October 2021) is seen in 2022, with the emissions dropping from the pre-NCG-reinjection level of around 38,000 tonnes $CO_2$e to around 30,000 tonnes $CO_2$e.

### 5.4 Summary of emissions reductions due to current NCG reinjection projects

The estimated emissions reductions from the current NCG reinjection projects as currently operating are as follows: 60,000 tonnes $CO_2$e from Ngāwhā OEC1-3, 68,000 tonnes $CO_2$e from Ngāwhā OEC4, 9,000 tonnes $CO_2$e from Te Huka and 8,000 tonnes $CO_2$e from Ngā Tamariki, giving a total of 145,000 tonnes $CO_2$e.

### 5.5 Estimated emissions reductions for future NCG reinjection projects

Future NCG reinjection projects are described in Section 2.5.3. These include plants that are not yet built, and retrofitting old plants.

For the three new plants the emissions and emissions intensity have been estimated during the design process (Table 5). Modern plants tend to be more efficient than older plants, and so the emissions intensity may be lower for the new plants than older nearby plants (Table 3), as there is more generation for the same amount of steam use/emissions. The total emissions reductions for new plants are anticipated to be 63,500 $tCO_2$e.

For retrofitting old plants there are also plans to expand NCG reinjection to the remaining existing OEC units at Ngā Tamariki, which would mean an emissions reduction of 30,000 tonnes $CO_2$e, and both TAOM and TOPP1, which would mean a reduction of 23,000 tonnes $CO_2$e (2023 numbers from Table 4). The total emissions reductions for retrofitting are anticipated to be 53,000 tonnes $CO_2$e.

**Table 5: Estimated emissions to be mitigated from new power stations NCG reinjection projects.**

| New plant | Design MW/GWh | Estimated unmitigated emissions ($tCO_2e$) | Expected emissions intensity ($gCO_2e/kWh$) |
|---|---|---|---|
| Te Huka U3 | 50/438 | 14,000 | 32 |
| Ngā Tamariki OEC5 | 46/403 | 24,500 | 61 |
| TOPP2 | 49/430 | 25,000 | 58 |
| | **Total** | 63,500 | |

The total reductions for all these future projects would be 116,500 tonnes $CO_2$e (new plants and retrofitting old plants).

It is worth noting that while NCG reinjection is not currently planned for Ohaaki due to technical challenges, a $CO_2$ capture/utilisation project is underway and preparing for front end engineering design. While this will not be recognised as a change to Ohaaki emissions under the current NZ ETS, it would provide high purity $CO_2$ to commercial and industrial customers that would otherwise be imported from overseas.

## 6. TRENDS FOR INDIVIDUAL PLANTS – OTHER

Data trends from other plants illustrate typical reasons for changes in geothermal emissions over time (Figure 9 to Figure 14, data from Table 3 and Table 4).

### 6.1 Wairākei, Te Mihi, Poihipi

The Wairākei A&B&binary and Te Mihi and Poihipi stations are considered as a group because they are interconnected to the same steamfield and operate under the same total annual mass take limit (Figure 9). The Wairākei reservoir has been under production since the 1950s and therefore has de-gassed and reached its new equilibrium, so no long-term declining trend is visible in the data. The emissions data is stable (and low) despite some noise due to operational changes, also discussed in McLean and Richardson, 2019.

### 6.2 Ohaaki

The Ohaaki emissions and emissions intensity are shown in Figure 10. The Ohaaki reservoir is low-permeability and not well-interconnected. This means that any new parts of the reservoir are accessed, new pockets of fluid which have not yet de-gassed may be encountered. A significant deep drilling campaign of ten wells into the previously-untapped "deep reservoir" at Ohaaki resulted in the 2009 spike in emissions seen in Figure 10. Another smaller deep drilling campaign of two wells into a different part of the deep reservoir resulted in the smaller emissions spike in 2016. No new wells have been drilled since, and emissions appear stable for the past six years at a new equilibrium level.

### 6.3 Rotokawa and NAP

These plants on the Rotokawa field show a steep early de-gassing trend similar to that for Ngā Tamariki.

### 6.4 TOPP1

TOPP1 shows a much higher emissions intensity (though not emissions) in 2022. This is because the plant efficiency was significantly lower due to an extended pre-heater outage.

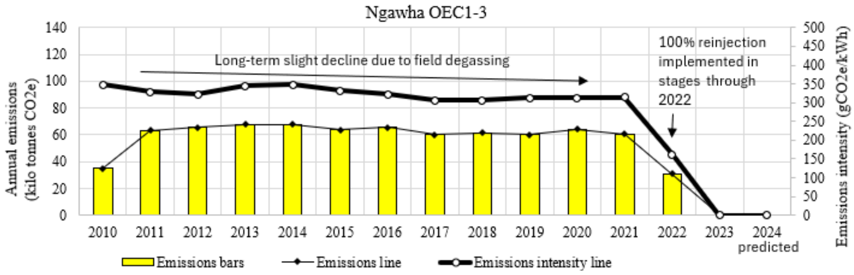


**Figure 6: Ngāwhā OEC1-3 total emissions and emissions intensity 2010-2023.**

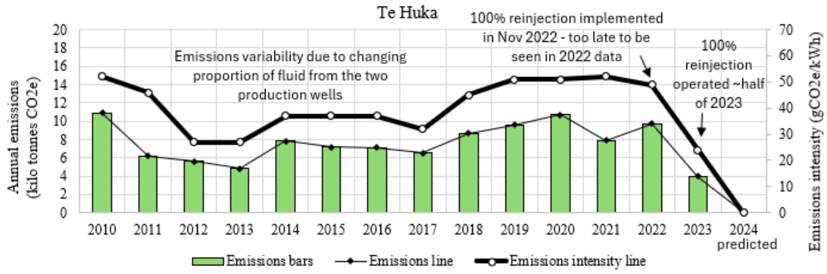


**Figure 7: Te Huka total emissions and emissions intensity 2010-2023.**

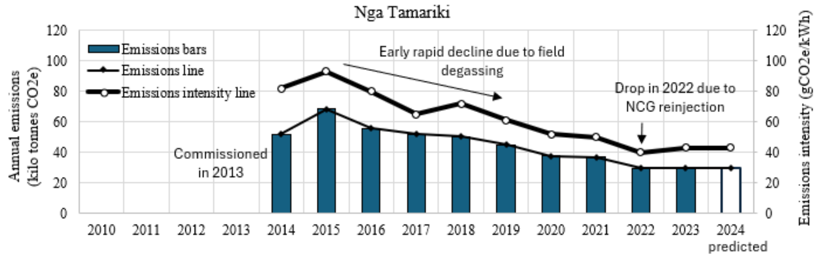


**Figure 8: Ngā Tamariki total emissions and emissions intensity 2014-2023**

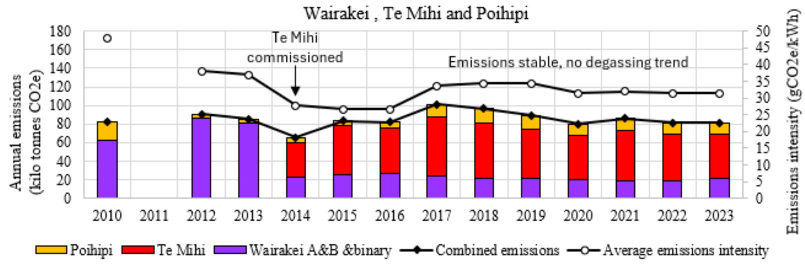


**Figure 9: Wairākei A&B&binary, Te Mihi and Poihipi emissions 2010-2023.**

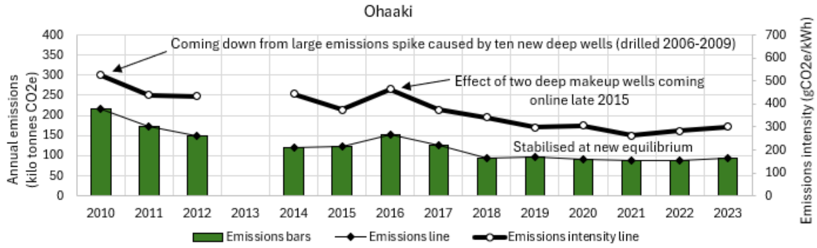


**Figure 10: Ohaaki emissions 2010-2023.**

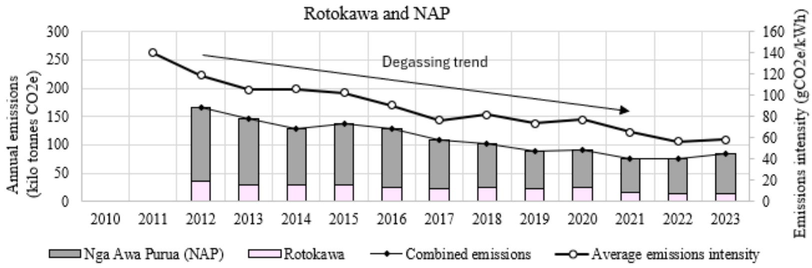


**Figure 11: Rotokawa and NAP emissions 2011-2023.**

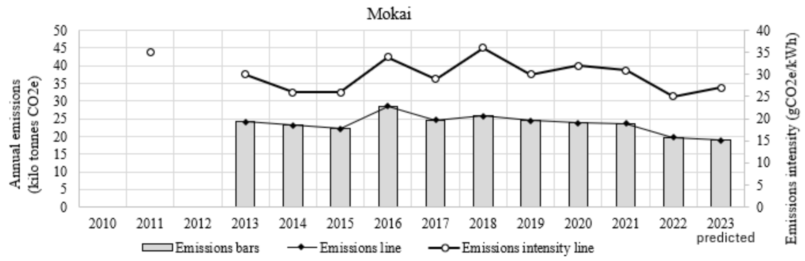


**Figure 12: Mokai emissions 2011-2023.**

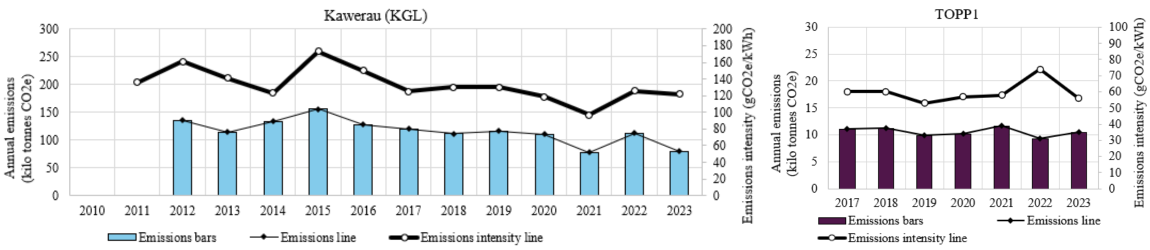


**Figure 13: (a) Kawerau (KGL) emissions 2011-2023; (b) TOPP1 emissions 2017-2023.**

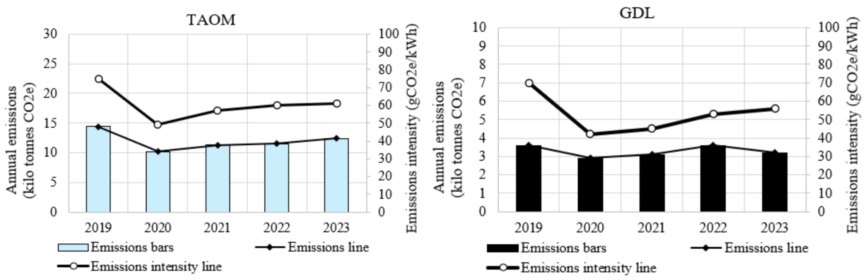


**Figure 14: (a) TAOM emissions 2019-2023; (b) GDL emissions 2019-2023.**

## 6. SUMMARY AND CONCLUSIONS

- For 2023 the MW-weighted average and median operational emissions intensities are 58 and 50 $gCO_2/kWh$, respectively.
- The past ten years have shown a long-term declining trend in MW-weighted average emissions intensity, which is approximately linear and decreasing by approximately 5 $gCO_2e/kWh$ each year.
- The minimum value in the emissions intensity dataset is now zero, with 100% NCG reinjection at Ngāwhā OEC1-3 throughout 2023.
- NCG reinjection projects are active at four NZ geothermal binary power stations: Ngā Tamariki, Ngāwhā OEC1-3, Te Huka and Ngāwhā OEC4.
- Total annual emissions reductions from these current NCG reinjection projects are 145,000 tonnes $CO_2e$.
- The predicted annual emissions reductions from future NCG reinjection projects are 116,500 tonnes $CO_2e$, including retrofitting additional old plants, and building new plants with NCG reinjection.
- The disappearance of Ngāwhā from the emissions stack along with other NCG reinjection projects has accelerated the reduction in emissions from geothermal.
- Over the ten years 2006-2015 emissions and emissions intensity for NZ electricity generation approximately halved, due primarily to new geothermal power stations. After a temporary increase in 2019-2021 due

to dry years and increased fossil fuel use, the reduction in emissions continued in 2022-2023.
- Long-term trends in emissions show a variety of behaviour including steep early decline (Ngā Tamariki and Rotokawa/NAP), later subtle decline (Ngāwhā OEC1-3) and late stabilisation (Wairākei/Te Mihi/Poihipi).
- Changes in emissions due to new wells and operational changes to plant are also observed.

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