NUMERICAL MODELLING FOR CARBON ACCOUNTING FROM GEOTHERMAL POWER PLANTS

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ABSTRACT

Geothermal fields naturally emit greenhouse gasses through surface expression. When a geothermal power plant is installed on a geothermal field, the fluid extracted contains these gases, but generally, the reinjected fluid does not. For this reason, power companies producing from geothermal fields are considered an 'emitter' within the Emissions Trading Scheme (ETS) in New Zealand. They are hence liable to purchase carbon credits to offset emissions. At present, emissions are naively calculated from the emissions from production but do not consider the system as a whole.

When fluid is taken from a geothermal system, the pressure in the system is reduced, and some of the natural surface manifestations such as hot pools, fumaroles and steaming ground may decrease. This process lowers the natural emissions from the system, but this change is neglected in current emission calculations in the ETS. Numerical modelling of geothermal reservoirs provides a mechanism for more accurately accounting for total emissions provided the model has been well-calibrated to the emissions from the field. Numerical models solve conservation equations across the entire domain. Therefore, they can quantify emissions from geothermal wells and surface features to better explain total emissions from geothermal fields.

1. INTRODUCTION

As New Zealand transitions towards net zero carbon by 2050, examining emissions from all processes has become of interest. Geothermal fields naturally emit carbon dioxide and other non-condensible gases such as methane, whether they are being used for geothermal power production or not. This is mostly through surface features in the form of steaming ground, hot springs, fumaroles etc. When a geothermal power plant is installed on a geothermal field, the fluid extracted contains these emissions, but generally, the reinjected fluid does not. For this reason, power companies producing from geothermal fields are considered an emitter within the Emissions Trading Scheme (ETS) in New Zealand. They are hence liable to purchase carbon credits to offset emissions.

Under the Emissions Trading Scheme, a geothermal power plant is assigned an emissions factor, also known as emissions intensity. This is a standardised metric for comparison to other ways of generating electricity. It is measured as grams of CO_2-equivalent per kilo-watt hour ($gCO_2(eq)/kWh$), where CO_2-equivalent allows the combination of multiple greenhouse gasses into one number based on their warming effect on the climate (McLean and Richardson, 2019). This paper will focus on CO_2 but it is to be expected that the hypothesis and results presented will hold for other non-condensable gases. In terms of investment in green energy, a power plant is given a 'green label' which means it is suitable to be funded through 'green bonds' if it has a life-cycle emissions intensity of less than 100 $gCO_2(eq)/kWh$ (Abnett and Jessop, 2021). Most geothermal power plants in New Zealand meet this green label, with the megawatt weighted average for geothermal in New Zealand being 76 $gCO_2(eq)/kWh$ in 2018 (McLean and Richardson, 2019).

Under this system, the emissions factor naïvely only accounts for emissions from productions wells. However, that does not account for the full system dynamics at play. When fluid is taken from a geothermal system, the pressure in the system is reduced, and after some initial boiling, some of the natural surface manifestations such as hot pools, fumaroles and steaming ground decrease. This process lowers the natural emissions from the system, a change which is neglected in current emission calculations in the ETS. Numerical modelling of geothermal reservoirs provides a mechanism for total emissions to be more realistically accounted for, provided the model has been well-calibrated to the emissions from the field. This concept has been mentioned in previous studies looking at CO_2 output from geothermal fields, for example Bertani and Thain (2002) stating "Where there is a high natural release of CO_2 from the geothermal field prior to development any measurable decrease in this natural emission resulting from the power development should be subtracted from the measured plant emission rate". Others have suggested that as CO_2 content from wells varies over time, surface emissions may similarly vary (Fridriksson et al., 2017). There are sophisticated techniques available for measuring CO_2 from the surface (Werner and Cardellini, 2005; Chambefort et al., 2019) and in some cases estimates of total surface flux of CO_2 have been made (e.g. for Ohaaki (Rissmann et al., 2011) and Rotokawa (Bloomberg et al., 2012)). In these CO_2 flux was measured and sequential gaussian simulation was used to estimate total surface flux. In the study for Ohaaki, Rissmann et al., 2011 took measurements over 3 summers (2006-2008) only when conditions were suitable. This was a substantial undertaking to obtain one estimate of surface flux which does not consider the transient processes occurring. Also, measurements taken after production has started cannot infer the pre-production emission of CO_2 at the surface.

Numerical reservoir models solve conservation equations across the entire domain. Therefore, they can quantify emissions from geothermal wells and surface features to better explain total emissions from geothermal fields. In this paper, we propose that a more accurate way to calculate the emissions factor is by considering the total extra CO_2 being extracted from the geothermal field:

$$Extra\ CO_2 = CO_2\ output\ from\ wells + CO_2\ output\ at\ the\ surface - Natural\ state\ CO_2\ output\ at\ surface. \quad (1)$$

Using a numerical model that has been well-calibrated to emissions data (from both production wells and available surface flux), a good estimate of the natural state surface emissions can be made. Hence if the CO_2 output at the surface at present day is less than the natural state emissions, then the overall extra CO_2 from production will be less than the CO_2 produced from wells.

In this paper, we discuss numerical modelling and the general assumptions made when modelling geothermal systems. We then use this methodology to show how the emissions are different on an example geothermal field, and we finish by showing how the emissions intensity of Ohaaki changes under this framework. This work is intended to provide a high-level overview of how numerical modelling can aid the assessment of CO_2 emissions rather than providing a discussion of the intricacies involved with numerical models.

2. NUMERICAL MODELS OF GEOTHERMAL SYSTEMS

Numerical modelling of a geothermal system has become a standard tool for assessing the sustainability of a geothermal field and aiding decision-makers who are managing the field (O'Sullivan et al., 2001; O'Sullivan and O'Sullivan, 2016). As computers have advanced over the years, models have become more complex, with more complicated rock structures included. In some cases uncertainty quantification of results has been carried out providing statistically more meaningful predictions for the field (e.g., McDowell et al., 2018a). However, over time the fundamentals of geothermal modelling have remained the same. In this section, we will briefly discuss the fundamentals of numerical modelling and discuss how it can be used to investigate CO_2 emissions.

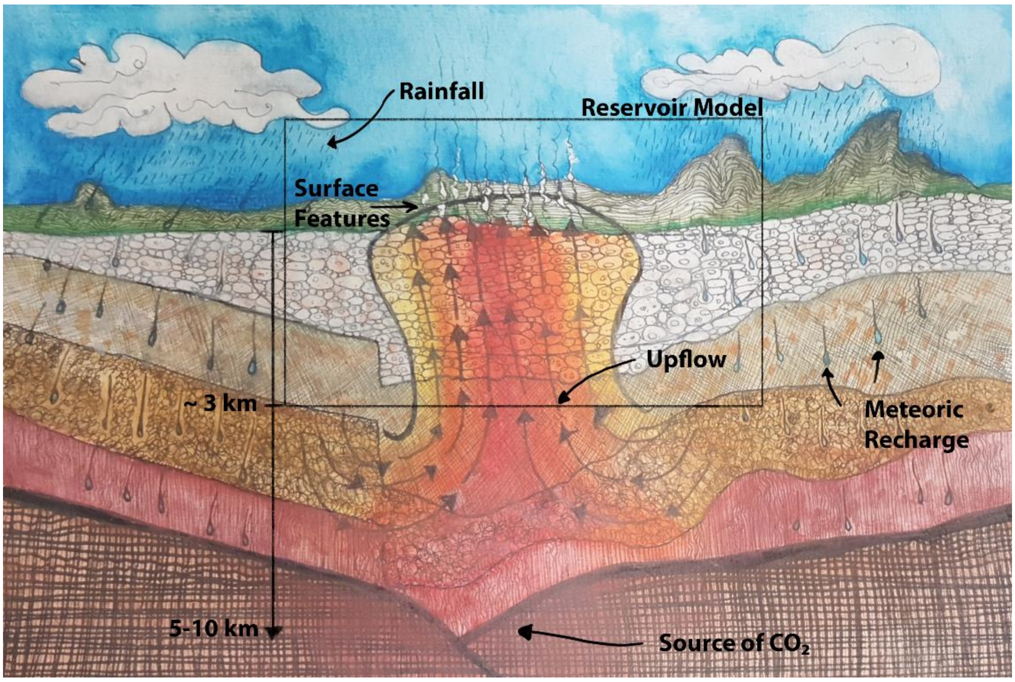

Figure 1: Illustration showing a geothermal system. The rectangle shows the extent of the reservoir model and it is assumed that the source of CO_2 is deeper and part of the carbon cycle (lithosphere melting in magma). CO_2 enters the model through the upflow at the base of the model.

Reservoir models solve conservation of mass and energy over a three-dimensional domain by splitting the domain into blocks and discretising the governing equations. The numerical method then solves how fluid moves between blocks (generally the finite volume method is used as it naturally conserves quantities). Each block in the model is assigned a rock type informed by a geological model of the field which generally includes faults and alterations. In reservoir modelling, the rock type of a particular zone is characterised by properties related to faulting and alterations (i.e., how fluid can flow through it) as well as its geological classification. The properties of the rocks in the sub-surface are inferred by calibrating (changing the properties) the model to match available measured data from the reservoir. The other parameters that are calibrated are mass and CO_2 inflow at the base of the model. This represents the upflow of hot water and CO_2 coming from deeper than the base of the model (as shown in Figure 1).

Reservoir models are run in three stages: natural state, production history and future scenarios. The natural state and production history simulations are used to calibrate parameters of the model so that the last stage, future scenarios, can be run to predict quantities of interest in the future with good accuracy. The first stage natural state simulation is used to estimate the pressure and temperature distribution in the reservoir prior to development. Calibration of the natural state model involves changing permeabilities and upflows to match the early temperature and pressure data. The aim is to estimate how much hot fluid needs to be put into the base of the model and to infer from the observed temperature distribution what the permeability distribution must look like. The pressure and temperature distribution from the natural state is used as the initial state for the production history simulation. The model is further calibrated by adjusting permeabilities, deep upflows and porosities to match the transient data trends for the reservoir. We simulate production from the start of the project until present day, imposing measured production and reinjection rates in the model. The transient data that has been collected typically includes transient pressure trends, enthalpy from production wells and transient CO_2 trends. Once the model shows a good match to data in the natural state and production history, it can be used to estimate the future state of the reservoir.

In models of gassy geothermal fields, we simulate the pressure, temperature, mass flow and CO_2 flow through the entire domain through time, and hence from the model the CO_2 being emitted from the surface can be derived. This quantity is not constant in time and depends on the production that is occurring. We suggest that if a model has been well calibrated to CO_2 data, it could be used to account for the CO_2 being produced from the field more accurately than just by measuring CO_2 from wells.

In all mathematical modelling, assumptions are made to capture reality in a mathematical form. Here are some of the assumptions made in reservoir modelling that are pertinent to the modelling of CO_2 in geothermal reservoirs:

- Standard reservoir simulators solve conservation equations without chemical reactions being included. This means that all the CO_2 entering the base of the model in the natural state will come out the top of the model in the form of surface features. No CO_2 will be captured by chemical reaction with the rock in the model.
- There are two ways of representing mass (and CO_2) upflows at the base of the model. In the simplest approach they are considered to be constant in time and in this case the effects of production and injection will not induce transient effects in the bottom boundary conditions. Sometimes a more complex approach is used where extra deep recharge can be induced if the pressure at the base of the model declines. For geothermal fields where close to full reinjection is used little change in deep pressures is expected and the simple approach is adequate.
- Only CO_2 is considered at present in the model. Methane and other greenhouse gasses are not included in estimating emissions intensity with the model.

3. EXAMPLES

The emissions from two models are presented in this paper. Firstly we introduce a synthetic model, which represents the type of liquid dominated geothermal fields generally present in the Taupo Volcanic Zone in New Zealand. This model will be used to demonstrate the concept. Secondly, use a model of Ohaaki to demonstrate this methodology of accounting for CO_2 emissions. Ohaaki is one of two production geothermal fields in New Zealand responsible for producing uncharacteristically high CO_2 emissions (with the other being Ngawha). Here we show that the emissions based on (1) are significantly less than the emissions from production alone. For all simulations, the simulator AUTOUGH2 is used together with the EOS2 equation of state for water-CO_2 mixtures. AUTOUGH2 (Yeh et al., 2012) is the modified version of TOUGH2 (Pruess et al., 1999) used at the University of Auckland.

3.1 Synthetic geothermal field

The synthetic model used here is the same as that preneted in our accompanying paper (Renaud et al., 2021); for more detail on the geothermal model and the methodology of solving reservoir models, we refer the reader there. The synthetic model is based on a geological model produced by GNS, which represents a typical liquid-dominated geothermal systems in New Zealand. The geological model, alteration model and faults structures are shown in **Error! Reference source not found.**. The conceptual model used to guide the design of the reservoir model is as follows. The geothermal system is a mature system in which nine wells have been drilled. Temperatures of up to 270°C have been measured. The system has three primary structural faults, two trending South to North and one trending from South-West to North-East. Based on the location of the faults and the location of the alteration and the presence of some chloride-rich hot springs aligning with the faults, we deduced that the main upflow in the model occurs at the intersection of the faults. We align the input of CO_2 at the base of the model with the upflow location (shown in Figure 2). This assumes that the meteoric fluid has been heated by the magma at a depth greater than the extent of the numerical model (as shown in Figure 1) and assumes that CO_2 is generated by the lithosphere melting in the magma as part of the carbon cycle. Hence, the CO_2 and meteoric fluid share the same pathway into the base of the model, most likely the fault structures. Since this is a synthetic model, we will present results from a synthetic production case, and the CO_2 content in the base of the model is chosen as a constant proportion of the upflow (1.0%). This CO_2 content is high for a geothermal field and represents fields like Ohaaki and Ngawha rather than fields such as Wairakei or Ngatamariki. In practice, the proportion of CO_2 across the base of the models may not be a constant proportion of upflow. It is a parameter that is calibrated by matching model results to transient CO_2 trends (this is shown in Figure 6 for Ohaaki).

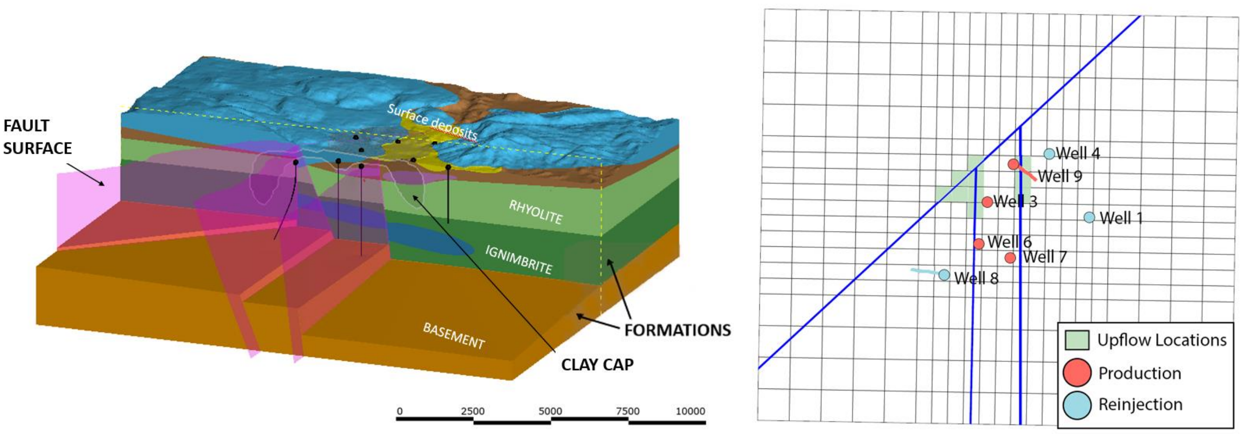

Figure 2: Geological model, alteration model and fault structures included in setting up the synthetic model.

For this synthetic model we calibrated the natural state (NS) to a set of synthetic data. The match for the NS calibration is shown in Figure 3 for a selection of wells. To simplify the results, we keep production and reinjection constant over 40 years, extracting 300 kg/s from four production wells and reinjecting 80% of production evenly across three reinjection wells. The location of the production and reinjection wells are shown in Figure 2 and the details of the wells are presented in **Error! Reference source not found.**.

Well name	Type	Proportion
Well 3	Production	40%
Well 6	Production	10%
Well 7	Production	10%
Well 9	Production	40%
Well 1	Reinjection	33%
Well 4	Reinjection	33%
Well 8	Reinjection	34%

Table 1: Well type and proportions of production and reinjection used in simulating 40 years in the synthetic geothermal field. Fixed production of 300 kg/s was used and 80% of this was reinjected.

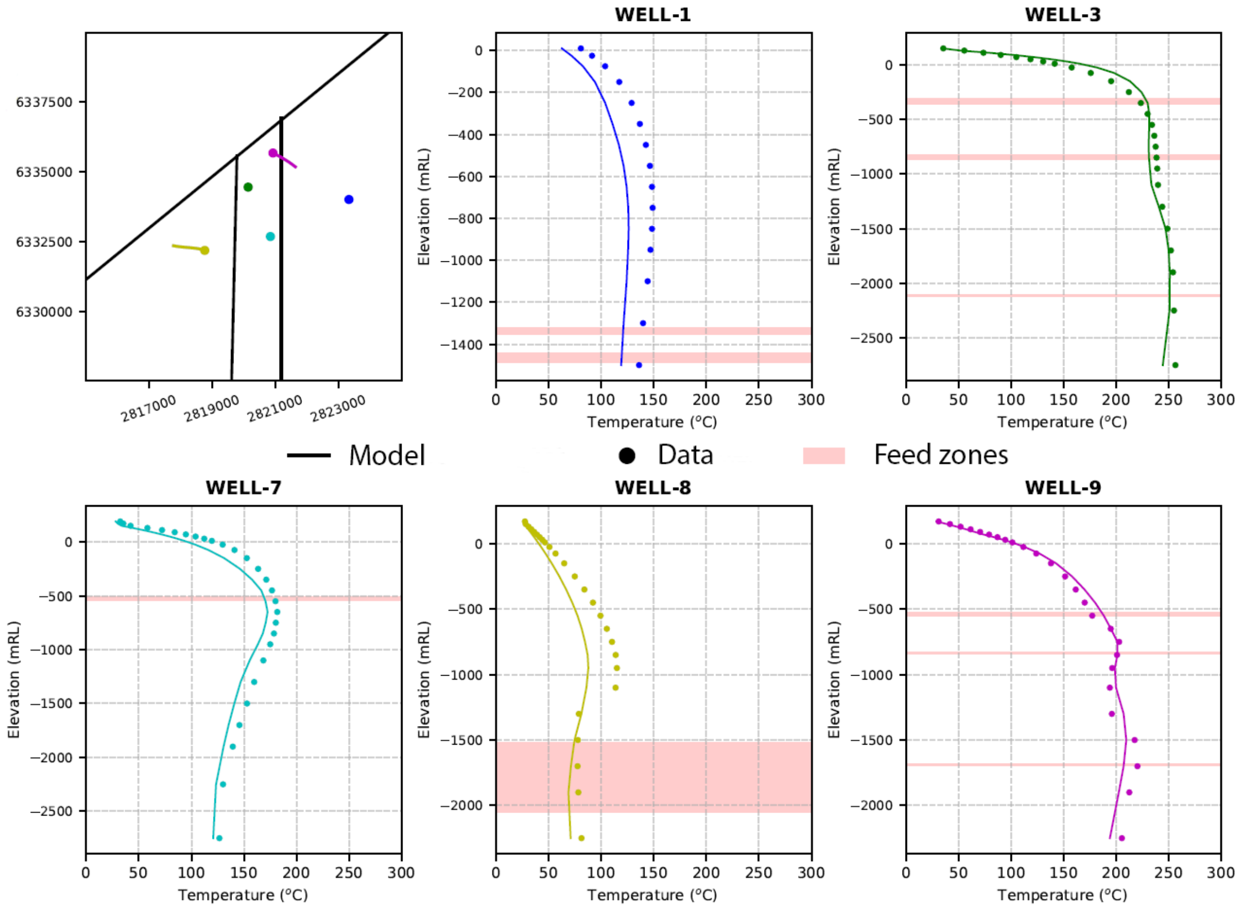

Figure 3: Natural state temperature match between model and data. Part of the model calibration process used to ensure reservoir model temperatures broadly represent reservoir temperatures.

In this model we assume a single-flash process and a separator pressure of 4.5 bara and then calculate the steam flow based on the enthalpy and pressure in the model. This is done using PyTOUGH (Croucher, 2011). In Figure 4 we show the steam flow over the 40 years (left) and the reinjection (right). We convert steam flow into power by assuming a conversion factor of 2.3 kg/s per MW. This conversion factor is power plant specific and calculated based on empirical data. By using a power output based on steam we can calculate of emissions intensity, as it is the grams of CO_2 (equivalent) produced, divided by the kWh produced. Surface CO_2 emissions from the geothermal model were calculated by summing flow of CO_2 from the surface blocks to the atmosphere. Figure 5 5 on the left shows the CO_2 rate from surface emissions (green), natural state surface emissions (black), from production wells (red) and nett CO_2 as per Equation 1. In Figure 5 on the right, the emission intensities are shown for when only production is considered (red) and for when production and change in surface features are also considered (blue) as per Equation 1. In Figure 5, we can see there is a brief period where the surface emissions increase at the start of production. This is due to a drop in pressure which induces boiling, and therefore there is a brief period of degassing of CO_2. After this, the pressure stabilises, and the surface emissions reduce below what would have been emitted if no power plant was present. This means that the emission intensity, calculated by including CO_2 flow to the surface, is slightly higher when production first starts but is significantly lower over a large period of the life cycle of the power plant (after 40 years, 265.7 gCO_2/kWh from production alone compared to 210.9 g CO_2/kWh including surface features). The purpose of these results is to demonstrate the physical processes governing emissions of CO_2 from geothermal fields. In the next section, we demonstrate this framework applied to Ohaaki and using real production data.

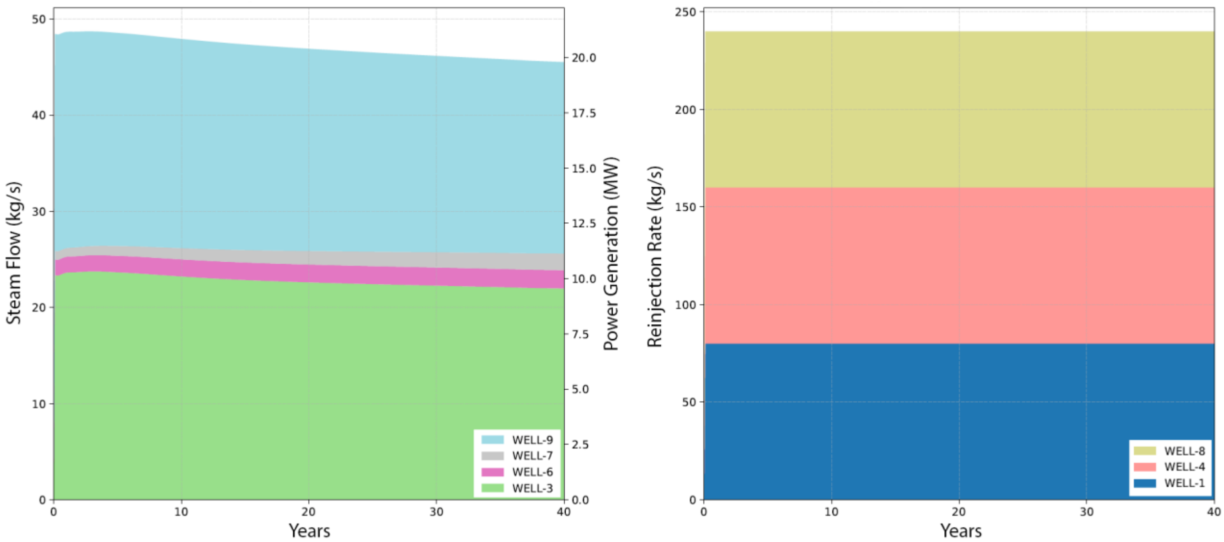

Figure 4: The left production results show the steam flow from the geothermal field calculated assuming a single separation pressure of 4.5 bara. Power generation was calculated using a constant conversion factor of 2.3 kg/s per MW. Right shows reinjection rate in the three reinjection wells, 80% of the 300 kg/s produced for 40 years.

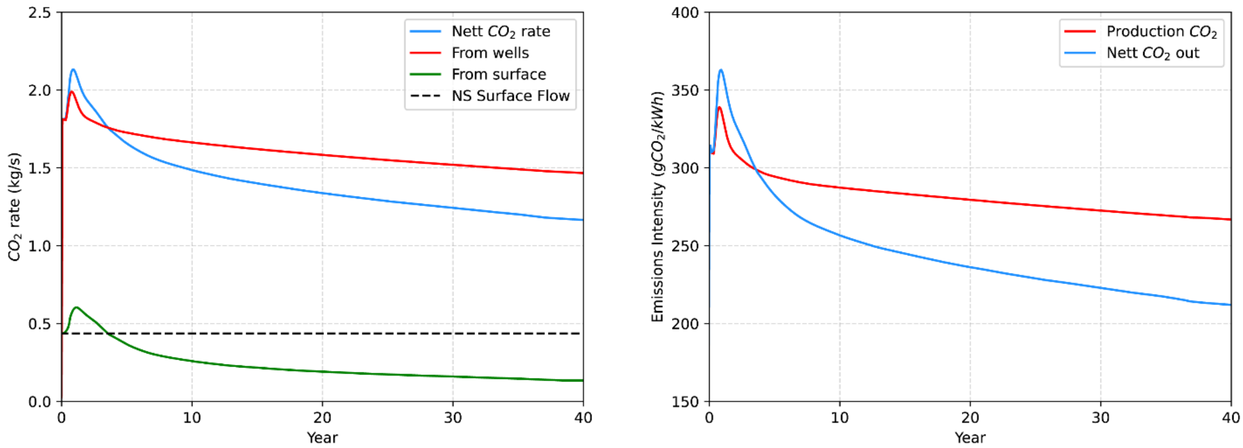

Figure 5: Left shows CO_2 rate from the surface (green), production wells (red) and nett CO_2 (blue). Right shows emissions intensity calculated traditionally from production (red) and by considering the change in surface emissions (blue).

3.2 Ohaaki geothermal field

The Ohaaki geothermal field is located in the Taupo volcanic zone. It is a mature geothermal field as it has been producing power since the 31st of October 1989. The first well was drilled in 1965 and large scale testing was carried out until mid-1971 (Clotworthy et al. 1995). The production and reinjection history of Ohaaki are shown in Figure 6 (left). Ohaaki has a CO_2 content higher than most geothermal fields in New Zealand with a reported operational emissions intensity of 299 gCO_2 eq/kWh in 2019 (McClean et al., 2020). Reservoir models of Ohaaki have been under development as a collaboration between the University of Auckland and Contact Energy Ltd. for many years to aid decision making and consent applications (O'Sullivan et al., 2012; Clearwater et al., 2014;

Ratouis et al., 2017; McDowell et al., 2018a,b). These numerical models have been calibrated extensively using data such as; downhole temperature data, transient temperature and pressure data, production enthalpy data, surface feature information and transient CO_2 data (with an example match shown in Figure 6 (right)). The production and reinjection data for a real geothermal field has more noise than the synthetic case above, but the physics remains the same. This example has been published (O'Sullivan et al, 2021), focusing on emissions over time if the power plant was shut down. Here we focus specifically on how modelling can be used to quantify and account for surface emissions.

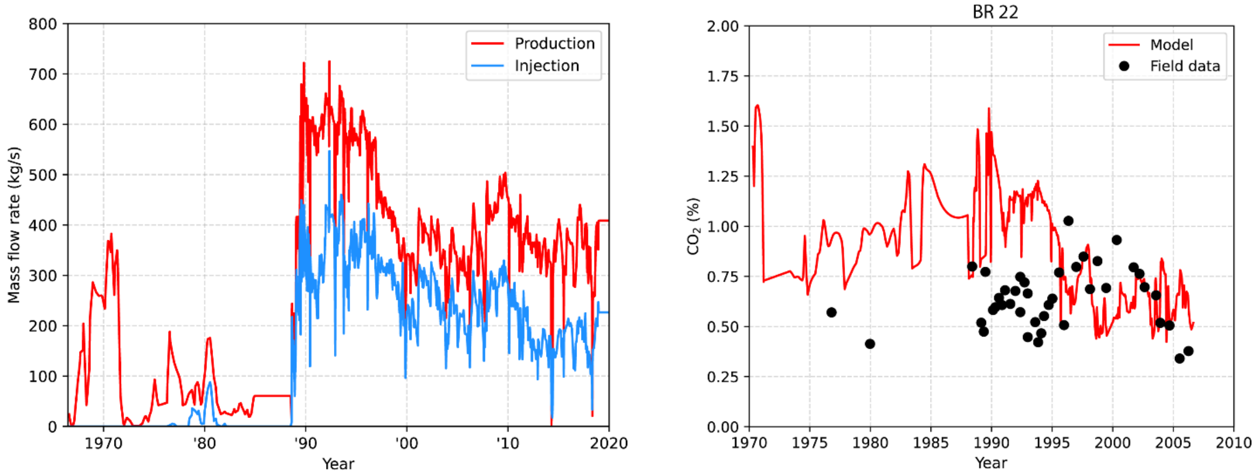

Figure 6: Left shows production and reinjection for Ohaaki over its lifespan and right shows an example match between model results and transient CO_2 data for BR 22.

In Figure 7 we show the modelled rate of emissions from the surface (green), production (red) and nett as per Equation 1 (blue). There are two distinct periods of degassing of CO_2 in the history of Ohaaki, the first is when exploration and large scale testing happened between 1965 and 1971. This again is due to pressure drop due to production (as no rejection occurred over this period). The second was when production began in 1989, and lasted for approximately 5 years. Since then, the model predicts a reduction in surface CO_2 emissions which will in turn reduce the emissions intensity (as shown in Figure 8). The mean emissions intensity over the last 10 years (2010 - 2020), just considering production is 476.5 gCO_2/kWh, compared to 96.6 gCO_2/kWh when considering the change in surface emissions. Note that the field data presented in Figure 8 is calculated from production emissions.

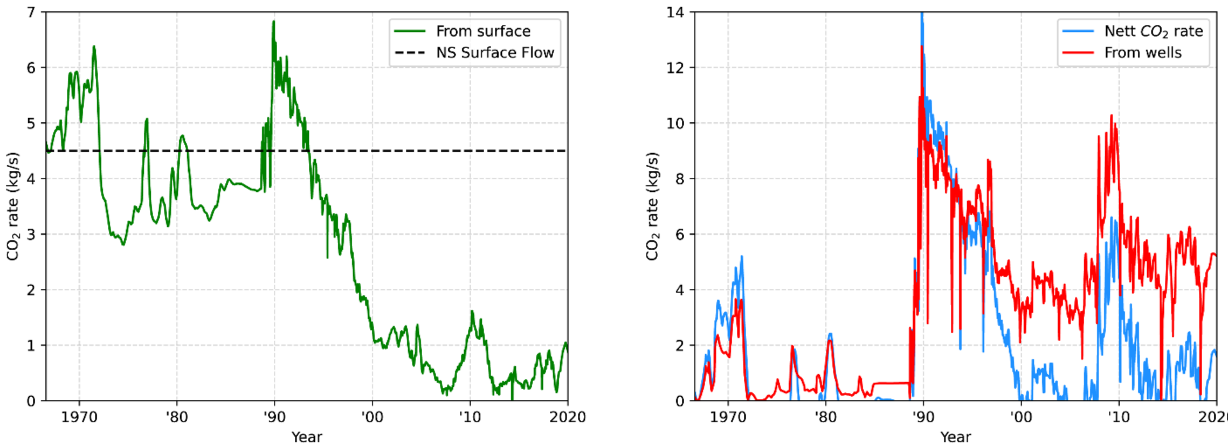

Figure 7: Rate of CO_2 from the Ohaaki geothermal field over time. Left shows the change in surface CO_2 (green) compared to natural state and right shows the CO_2 from production (red) and the nett extra CO_2 (blue) caused by production when reduction in surface emissions is accounted for.

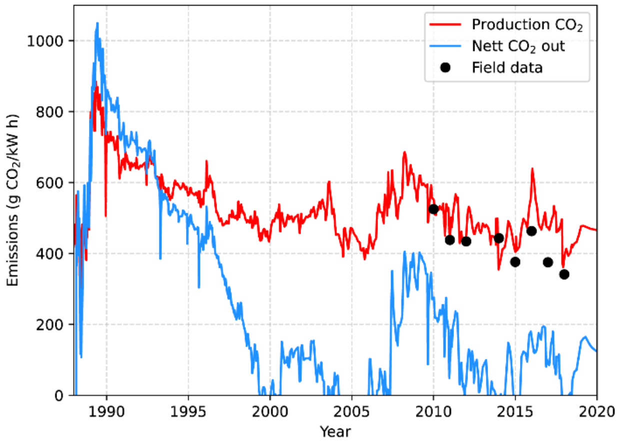

Figure 8: Emissions intensity from Ohaaki, red shows just emissions from production and blue shows production and change in surface emissions. Field data shown is calculated from production emissions.

4. CONCLUSIONS

In this paper, we propose that to calculate emissions from geothermal fields, one needs to consider the change in surface emissions due to production. Numerical modelling of the reservoir is a tool that could be used to quantify net emissions of CO_2 when reservoir models have been well-calibrated to emissions data and surface features. This includes all available production CO_2 and surface CO_2 flux data available. In practice, due to financial implications, if numerical models were adopted for calculating emissions, we would recommend an independent peer review focused on the quality of the emissions calibration. Two examples are shown, one of a synthetic geothermal model and one of the Ohaaki geothermal system. Both show that after an initial degassing period due to an increase in boiling caused by a pressure drop from initial production, we see a reduction in surface emissions compared to the natural state. For the Ohaaki model, we show an estimated emission intensity over the last 10 year period of 96.6 gCO_2/kWh if surface features are included instead of 476.5 gCO_2/kWh predicted by the model when only considering production. These predictions depend on the quality of the calibration to emissions data. We note that for Ohaaki more focused calibration on the behaviour of surface features, particularly the sparse data on CO_2 emissions, is needed to improve the accuracy of the results presented above. Matching the behaviour of surface features is not normally the highest priority for model calibration and representing surface features accurately in a reservoir model is well known to be a difficult problem, and one that needs to be solved in order to achieve implementation of our modelling based approach for calculation of CO_2 emissions from geothermal fields. Usually the data required to well calibrate model performance in representing CO_2 emissions at surface features are not available. So the results above should be taken as indicative rather than absolute.

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