A process model for geothermal power generation

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ABSTRACT

Geothermal power plants utilize the heat from geothermal reservoirs to generate electricity. Geothermal fluid has some non-condensable gases brought to the surface during electricity generation. These gases mainly consist of carbon dioxide. There is an impact of these gases present in the geothermal fluid on the production well productivity, the heat transfer efficiency of heat exchangers, etc.

Process models are considered powerful tools for understanding the working of geothermal power plants. The process models prepared are based on the specific components and given details of a geothermal system. The process model developed for this paper is a coupled wellbore and subsurface model of a geothermal power plant. Firstly, the wellbore model was developed using WELLFLOW, a wellbore simulator, and then the sub-surface model was developed using DWSIM, an open-source process modeling software. Both WELLFLOW and DWSIM can use Python scripting, which was utilized, and both models were coupled.

The paper demonstrates a coupled process model calculating the fluid flow from the production well and the output from the geothermal power plant. The wellbore model provides the flow rate from the wellbore based on the wellhead pressure. The composition of the geothermal fluid is obtained from the reservoir data. The process model shows that for a given wellhead pressure, we can estimate the flow rate from the wellbore and the pentane required for an Organic Rankine cycle. The process model then provides us with the output from the turbine and the desired temperature for the reinjection fluid.

1. INTRODUCTION

In the current era of renewable energy, geothermal energy is a prominent source for generating electricity. Climate change is a driving force towards using more renewable energy to generate electricity. The critical reason is to reduce emissions generated by generating electricity using other sources, such as coal, which produces high emissions. Under the Paris Agreement, 184 countries are committed to reducing emissions. New Zealand is one of them and has set two primary targets, namely:- generating 100% of its electricity using renewable energy by 2035 and net zero emissions by 2050 (Climate Change Commission 2021; He Pou a Rangi - Climate Change Commission 2021). New Zealand generates about 80% of its electricity from renewable energy. Geothermal energy is considered an essential component of New Zealand's electricity mix as it contributes to nearly 20% of the generation from renewables (Carey et al. 2015; Huttrer 2020). Besides cost-effectiveness, geothermal energy has many benefits because it is reliable, sustainable, and environmentally friendly (Rybach 2003).

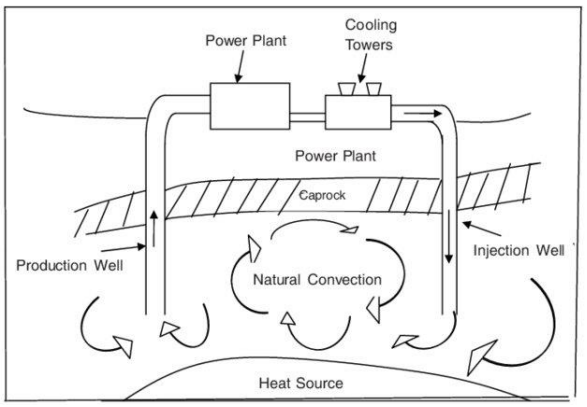

Figure 1: Schematic diagram of a geothermal system with a geothermal reservoir with production and reinjection well connected (Ganguly & Kumar, 2012).

The electricity generation process using the heat source available under the earth is an appropriate step towards creating a cleaner future. There is immense growth in the geothermal industry all over the globe due to it being a suitable and sustainable energy source. The geothermal fluid used for electricity generation contains CO_2 with other non-condensable gases (NCGs) and minerals that come with the fluid to the surface (McLean and Richardson 2016). The geothermal fluid typically includes minerals and gases of magmatic origin soluble in liquid due to the higher pressure found at depth. These gases can impact flow through the wellbore, pipeline, and power plant.

The size of these geothermal reservoirs is not strictly defined to any specific value. However, the typical dimensions of a small reservoir considered for some cases are 3x3x1km (Franco and Vaccaro 2014; Ganguly and Kumar 2012; Kane, Mishra, and Dutta 2016). A schematic representation of a geothermal system, shown in Figure 1, includes the reservoir, production well, reinjection well, powerplant, and cooling tower.

2. BACKGROUND

Binary geothermal power plants are the most popular type of geothermal power plants as they allow the usage of low-temperature geothermal fluid for electricity generation (Tchanche et al. 2011). This study is focused on the binary geothermal power plants, and we have modeled the impact of gases (CO_2 considered for this study) on some parts of the geothermal system and parameters such as production wells, heat exchangers, and mass flow rate from the production wells. Analyzing the impact of NCG on these parameters could be beneficial for improvements in the existing power plants and the development of new geothermal power plants (Shengjun, Huaixin, and Tao 2011).

Figure 2 shows a simplified diagram of a binary geothermal powerplant, showing how the fluid flow takes place and how electricity is generated in this cycle. This paper demonstrates a wellbore and full process model of a geothermal power plant. The process model of the powerplant is driven by combining it with the wellbore model developed earlier through Python scripting. It includes all the significant parts of a binary geothermal powerplant.

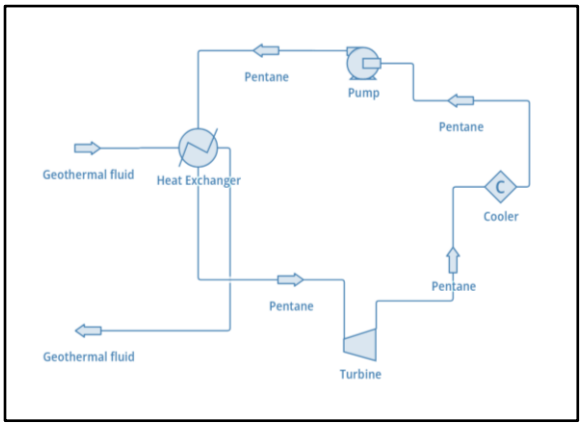

Figure 2: Simplified diagram of a binary geothermal powerplant.

3. SIMULATION TOOLS

We simulate the flow of geothermal fluid from a reservoir through a wellbore, into the heat exchanger, and back into the reservoir through the reinjection wells. We also simulated the pentane cycle in the power plant. Two simulation tools are used in the process: WELLFLOW (Hasan and Kabir 2007, 2010; Hasan, Kabir, and Sayarpour 2010) and DWSIM (Medeiros n.d.; Tangsriwong et al. 2020). WELLFLOW is used for simulating the flow of fluid from the geothermal reservoir to the wellbore. DWSIM is used to simulate the flow of geothermal fluid from the wellbore model travelling through the separator, heat exchangers, and to the reinjection well. The pentane cycle is also simulated in DWSIM.

3.1 WELL FLOW

WELLFLOW is a wellbore simulator developed by GNS Science and is used to solve the flow from the well. The wellbore simulator is a proprietary simulator that solves the equations for the conservation of mass, momentum, and energy (Hasan and Kabir 2007, 2010; Hasan, Kabir, and Sayarpour 2010). In this paper, the wellbore model connected to the above surface model was developed using WELLFLOW.

3.2 DWSIM

DWSIM is an open-source chemical process simulator with the functionality to work on steady-state mass and energy balances ((Medeiros n.d.; Tangsriwong et al. 2020). This software is used to simulate chemical processes using advanced thermodynamic models. This paper used DWSIM to generate a process flow diagram and a process model to solve for heat transfer, flow rates, and power output.

4. INTEGRATED MODEL

4.1 Wellbore Model

The wellbore model developed is a production well from a single-phase liquid-dominated geothermal field (1981 DSIR Ngawha - Sect 4 (Grant) & summary.pdf n.d.). This wellbore model is used to analyze the effect of carbon dioxide on the mass flow rate from the production well for the given wellhead pressure conditions. Both feeds to this well were in liquid phase conditions. The well specifications and reservoir properties are shown in Figure 3. The governing equations for fluid flow in the wellbore, between the feed zones, were represented as equations (1), (2) and (3) for mass, momentum and energy balance, respectively. The governing equations for the fluid flow at the feed zone were represented as equations (5) and (6) for mass and energy balance respectively.

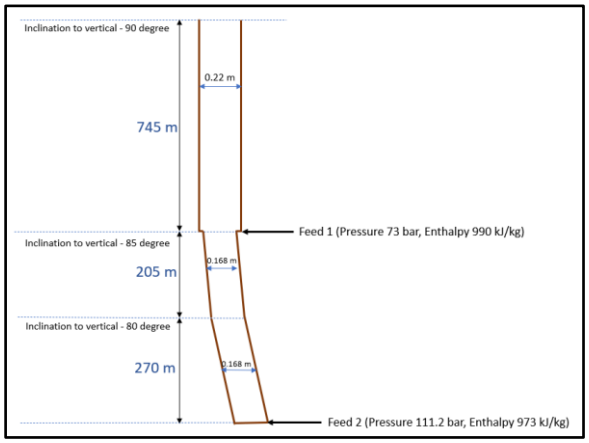

Figure 3: Well Specifications of the production well used for the analysis.

The mass and energy balance equation used for the flow between the feed zones are:

Mass balance,

$$dmy/dL = 0 \qquad (1)$$

where,

m= mass flow

L= length between feed zones

y = total fluid (CO_2, H_2O)

Momentum Balance,

$$\frac{dP}{dL} - \left[\frac{dP}{dL}\right]_{fri} - \left[\frac{dP}{dL}\right]_{\text{acc}} - \left[\frac{dP}{dL}\right]_{pot} = 0 \qquad (2)$$

where,

$$\left[\frac{dP}{dL}\right]_{fri} = \phi^2_{flo}\left[-\frac{dP}{dL}\right]_{LO}$$

$$\left[\frac{dP}{dL}\right]_{\text{acc}} = \frac{d(Gu_{m)}}{dL}$$

$$\left[\frac{dP}{dL}\right]_{pot} = pg\sin\emptyset$$

$[-\frac{dP}{dL}]_{LO}$ = pressure drop for a flowing single-phase liquid

ϕ^2_{flo} = two-phase multiplier

G = mass velocity

u_m = average fluid velocity

g = acceleration constant

$\emptyset$ = well deviation angle from horizontal

P = fluid density

$\emptyset$ = well inclination with horizontals, degrees

v_m = velocity of steam/liquid mixture, ft/s

Energy Balance,

$$\frac{dEt}{dL} + Qt = 0 \qquad (3)$$

Where,

Et = total energy in the well

Qt = ambient heat loss/gain over a unit distance

The total heat flux gradient, (dE-t)/dL is the sum of the discharge in the heat content of the fluid, kinetic and potential energy.

$$\frac{dE_t}{dL} = m\,\frac{d}{dL}\,[h_m + 0.5u_m^2 + g(L_w - D)] \qquad (4)$$

where,

m = total mass flow

h_m = enthalpy of the mixture

u_m = average fluid velocity

g = acceleration constant

L_w = total measured length of the well

D = measured depth

The mass and energy balance equation used for the flow at the feed zones are:

Mass balance,

$$\overrightarrow{m_m} = \overrightarrow{m_w} - \overrightarrow{m_f} \qquad (5)$$

where, m = mass flow

Subscripts m, w, and f are mixture, well, and feed zone, respectively.

Energy balance,

$$\overrightarrow{m_m}H_m = \overrightarrow{m_w}H_w - \overrightarrow{m_f}H_f \qquad (6)$$

where, H = fluid enthalpy

The mass flow in the well can have two possible directions: upward (when the well is producing) and downward (when the well is under reinjection). Similarly, the flow from the feed zone has two possible directions: towards the well (producing) and towards the reservoir (injecting).

The impacts of reinjecting gases are complex and vary for different reservoir conditions, and this work is carried out for single-phase liquid-dominated reservoir conditions. Gases impact the thermodynamic properties of the reservoir and the properties of the production fluid. Figure 4 shows the simulation results for a wellbore model with different reservoir fluid compositions. The compositions are taken as zero percent of gases present in the fluid from the geothermal reservoir up to 1.5% carbon dioxide present in the liquid from the geothermal reservoir (Choudhary et al. 2022; Choudhary, Rayudu, Burnell, et al. 2021; Choudhary, Rayudu, Hinkley, et al. 2021) . For example, the mass flow rate at a wellhead pressure of 12 bar was taken to assess the effect of the fluid composition. The curve demonstrates the difference in mass flow rate with and without CO_2 in the reservoir. Nearly 40% more mass flow rate is observed from the production well for the presence of around 1.5 % of gases in the reservoir.

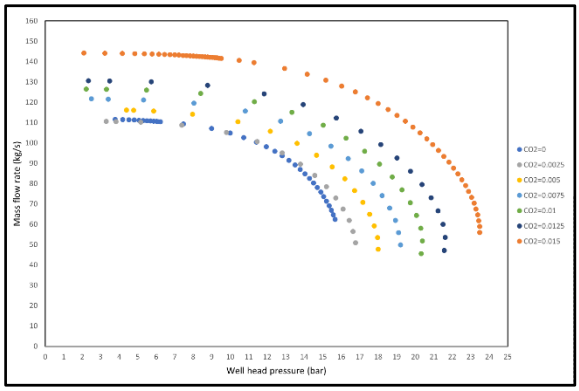

Figure 4: Simulated output for a well from case study.

4.2 Coupled Model

Figure 5 shows a process flow diagram (PFD) which shows the major components of a binary geothermal powerplant such as the separator, heat exchangers (vaporizer and evaporator), turbine, pump, cooler, and the production and reinjection wells. Figure 2 shows a simplified diagram of a binary geothermal system where the geothermal fluid flow and pentane flow in the process are shown. The process flow diagram is an expansion of the simplified diagram.

A separator (also known as flash drum) is a crucial system that separates the steam from the geothermal fluid (Lazalde-Crabtree 1984; Zarrouk and Purnanto 2015). During the calculation, the separator divides the inlet stream into two different streams. It runs on the input value of separation temperature and /or pressure. The calculation type used for this process model was to calculate the cold fluid outlet temperature type. In this mode, DWSIM needs the hot fluid outlet temperature and the exchange area to calculate the cold fluid temperature.

The heat exchanger in DWSIM is calculated using the simple convection heat equation:

$$Q = UA\Delta T_{ml} \qquad (7)$$

where, Q = heat transferred

A = heat transfer area

ΔT_{ml} = Logarithmic Mean Temperature Difference (LMTD)

Also,

$$Q = m\Delta H \qquad (8)$$

Where, Q= heat transferred from/to the fluid

ΔH= outlet-inlet enthalpy difference

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{\Delta T_2}} \quad (9)$$

where, ΔT_1 & ΔT_2 = Temperature differences for fluids at the inlet and outlet of the heat exchanger.

The mass and energy balance performed for the developed model gives us a correlation between the flow rate of geothermal fluid and the flow rate of pentane. However, it is limited to the given input temperature and pressure condition. The correlation is:

$$q_p = 0.857\ q_w \quad (10)$$

where,

q_p = mass flow rate of pentane (kg/s)

q_w = mass flow rate of geothermal fluid (kg/s)

The turbine or the expander is used to extract energy from a high-pressure vapor stream. The ideal process is isentropic, and the non-idealities are considered according to the efficiency of the turbine. The cooler simulates the cooling process of the stream. The pump provides energy to the liquid stream in the form of pressure. The process is isenthalpic, and the non-idealities are considered according to pump efficiency.

A recycle block is added to the pentane cycle, which allows pentane to be continuously circulated within the process without being sent to the waste stream. Adding a recycling block is helpful in a process where it is necessary to maintain continuity of the streams. The state of the recycled stream can be adjusted to set required conditions such as temperature, pressure, composition, and flow rate.

The process models use geothermal fluid as the primary fluid and secondary fluid as n-pentane (Choudhary et al. 2022; Nurhilal et al. 2016). The production well was operated at a

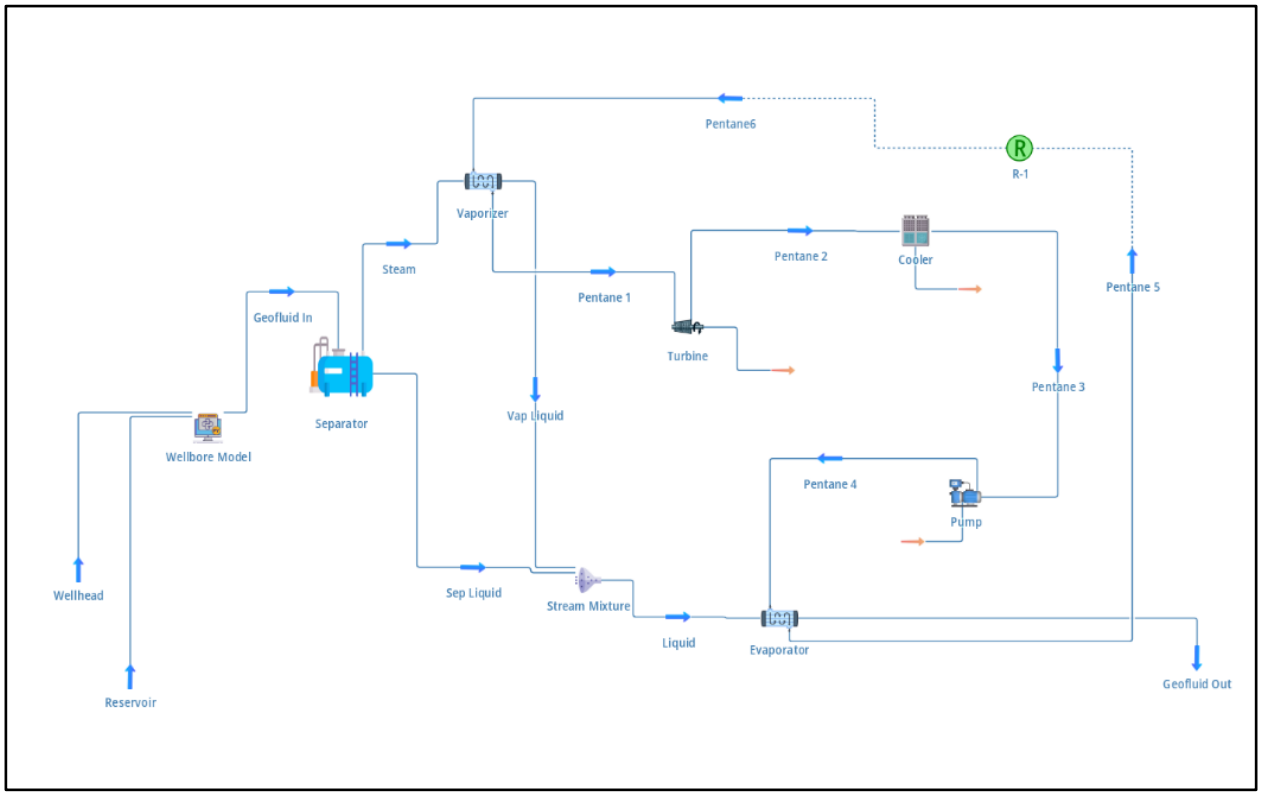

Figure 5: The Process Flow Diagram (PFD) of a Binary geothermal powerplant.

The separated steam is passed through the vaporizer, transferring heat to the pentane, and sending the separate liquid to the evaporator. The vaporizer and the evaporator are the heat exchangers. The heat exchangers in DWSIM have seven different calculation modes.

Next, the vaporized liquid from the vaporizer is passed through the evaporator, transferring energy to the pentane, and is then reinjected into the reservoir. In the pentane cycle, the pentane coming out of the turbine is passed through the cooler to provide cooling. After that, pentane is passed through the pump, which increases the pressure of pentane before it enters the vaporizer.

well head pressure (WHP) of 12 bars, which is used for calculations in the model using the wellhead stream. The stream from the reservoir provided the concentration of gases in the geothermal fluid. Therefore, the process model ran for different concentrations of gases in the geothermal fluid. The separator pressure was given as 14 bar. The heat exchanger's cold and hot pressure drop was set at 0 bar. The adiabatic efficiency of the turbine was set to 84%, and the outlet pressure to 1 bar. The cooler and pump efficiencies were 100% and 75 %, respectively.

To estimate the total energy extracted from the geothermal reservoir, this process model was developed by considering the feeds to the production well from the reservoir. In the coupled process model, the wellbore model was coupled

with the process model in which the output from the wellbore model was passed from a custom component of the wellbore model. Finally, a Python script connects the wellbore model to the flowsheet.

5. RESULTS AND CONCLUSION

The results of this experiment were calculated based on the changing concentration of gases in the reservoir, keeping the other parameters unchanged. The wellhead stream provided the wellhead pressure, and the reservoir stream provided the reservoir conditions. The model was run using a set of concentrations of gas in a range of 0 to 1.5 %.

Section 5.1 shows the impact of varying concentrations of gas in the reservoir on the mass flow rate from the production well and the power output generated from the turbine. Section 5.2 below shows process model calibration with the approximate data point from the Ngawha geothermal field.

5.1 Change in Power output and Mass flow rate from Production wells

For this experiment, the concentration of CO_2 in the reservoir varied from 0-1.5%. This experiment is limited to geothermal fields with a single-phase liquid-dominated reservoir. The flow rate from the production well was observed to increase due to an increase in the concentration of CO_2 in the reservoir.

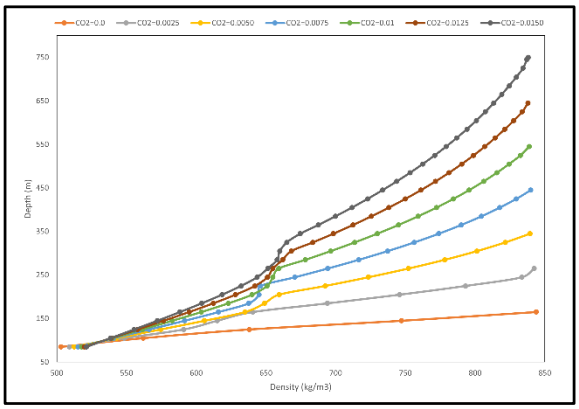

Figure 6: Change in density of the fluid from the production well.

The mass flow nearly doubles as the concentration of CO_2 increases from 0 to 1.5% in the reservoir. The more fluid produced from the production well, the more megawatts are generated from the turbine. Figure 6 shows the change in density of the geothermal fluid as the concentration of gas changes in the wellbore. This finding results from boiling occurring at a deeper level in the wellbore when more gas is present. As the fluid moves upward from feed one, which was at the bottom of the well, to feed two, 475m from the bottom, the flashing occurs deeper, and we have a smaller column of dense liquid.

Figure 7 shows output from three identical production wells, giving a total flow rate like the Ngawha geothermal field. The power output was 13.97 MW for no CO_2 present in the reservoir, while for the composition of 1.5 % CO2 in the reservoir, the power output obtained was 28.02 MW, almost doubled. One of the reasons for the increasing flow rate is that boiling occurs at a deeper level in the production well with more gas present.

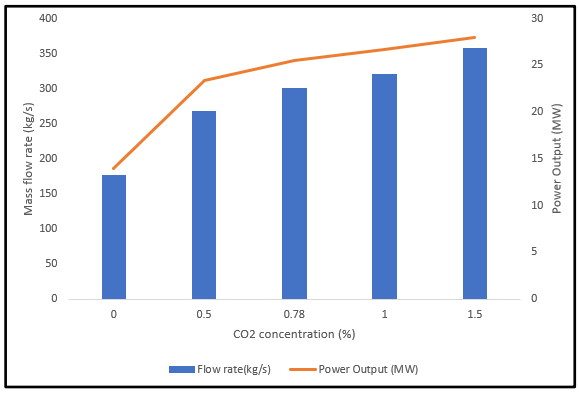

Figure 7:Change in Power output and mass flow rate from a stream of three identical Production wells to the wellhead for varying concentrations of gases in the reservoir.

5.2 Model Calibration

The process model was developed, and analyses were calibrated with approximate data points from the Ngawha Geothermal power plant in New Zealand. The data set of a single data point where the fluid of mass flow rate of about 300 kg/s generates 25 MW of output with a concentration of almost 0.75 % of gases in that reservoir was considered for the study. The reservoir conditions were similar to those in the Ngawha Geothermal field.

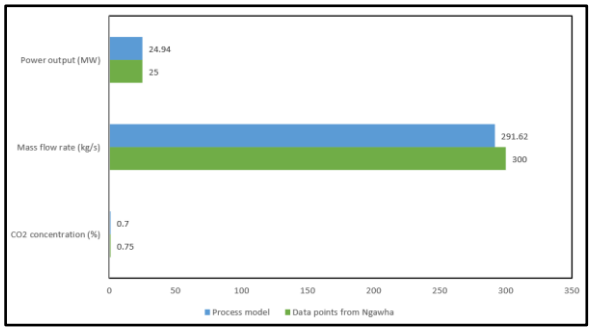

Figure 8 shows the process model calibrated with the data point from the Ngawha geothermal field.

The following conclusions have been derived from the work:

- The changes due to the impact of gas in the reservoir cannot be predicted and hence need to be analyzed for different concentrations.
- A liquid-dominated reservoir with a high concentration of CO2 considered for this study shows that the useful output increases as the CO2 concentration increases.
- The model developed captures the primary process and approximately matches the measured data. It allows us to test the response of a system to changes in its conditions.

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REFERENCES

"1981 DSIR Ngawha - Sect 4 (Grant) & Summary.Pdf."

Carey, Brian et al. 2015. "2015 New Zealand Country Update." *World Geothermal Congress* (April): 19–25.

Choudhary, Anu, Ramesh Rayudu, John Burnell, et al. 2021. "Reinjection as a Solution to Greenhouse Gas Emissions from High Emitting Geothermal Powerplants in New Zealand." *Eea2021* (figure 3): 6.

Choudhary, Anu, Ramesh Rayudu, Jim Hinkley, and John Burnell. 2021. "Analysis of the Impact of the Reinjection of Gases on the Mass Flow Rate from Production Wells at Varying Reservoir Conditions." *New Zealand Geothermal Workshop Proceedings* (November).

———. 2022. "Estimation for Heat Loss to the Working Fluid in the Heat Exchanger of an Organic Rankine Cycle for a given Concentration of Gases."

Climate Change Commission. 2021. "2021 Draft Advice for Consultation." : 1–188. https://www.climatecommission.govt.nz/get-involved/our-advice-and-evidence/.

Franco, Alessandro, and Maurizio Vaccaro. 2014. "Numerical Simulation of Geothermal Reservoirs for the Sustainable Design of Energy Plants: A Review." *Renewable and Sustainable Energy Reviews* 30: 987–1002.

Ganguly, Sayantan, and M. S.Mohan Kumar. 2012. "Geothermal Reservoirs - A Brief Review." *Journal of the Geological Society of India* 79(6): 589–602.

Hasan, A. R., and C. S. Kabir. 2010. "Modeling Two-Phase Fluid and Heat Flows in Geothermal Wells." *Journal of Petroleum Science and Engineering* 71(1–2): 77–86.

Hasan, A. R., C. S. Kabir, and M. Sayarpour. 2010. "Simplified Two-Phase Flow Modeling in Wellbores." *Journal of Petroleum Science and Engineering* 72(1–2): 42–49.

Hasan, A R, and C S Kabir. 2007. "A Simple Model for Annular Two-Phase Flow in Wellbores." *SPE Production & Operations* 22(02): 168–75. https://doi.org/10.2118/95523-PA.

He Pou a Rangi - Climate Change Commission. 2021. "Ināia Tonu Nei: A Low Emissions Future for Aotearoa Advice to the New Zealand Government on Its First Three Emissions Budgets and Direction for Its Emissions Reduction Plan 2022 – 2025." : 418.

Huttrer, Gerald W. 2020. "Geothermal Power Generation in the World 2015-2020 Update Report." *Proceedings World Geothermal Congress 2020*: 1–17. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwi6573kuozrAhU88uAKHSFQCCcQFjAKegQICRAB&url=https%3A%2F%2Fwww.geothermal-energy.org%2Fpdf%2FIGAstandard%2FWGC%2F2020%2F01017.pdf&usg=AOvVaw3emXGVb2ZcY0of5dlloOhk.

Kane, Shashank N., Ashutosh Mishra, and Anup K. Dutta. 2016. "Preface: International Conference on Recent Trends in Physics (ICRTP 2016)." *Journal of Physics: Conference Series* 755(1).

Lazalde-Crabtree, Hugo. 1984. "Design Approach of Steam-Water Separators and Steam Dryers Dor Geothermal Applications." *Geothermal Resources Council Bulletin*: 11–20. papers3://publication/uuid/C44B5C53-E615-40D0-8D54-4883EFC61386.

McLean, Katie, and Ian Richardson. 2016. "Greenhouse Gas Emissions from New Zealand Geothermal Power Generation in Context." *New Zealand Geothermal Workshop* 23: 1–9. https://www.geothermal-energy.org/pdf/IGAstandard/NZGW/2019/101.pdf.

Medeiros, Daniel. "DWSIM." https://dwsim.org/.

Nurhilal, Otong, Cukup Mulyana, Nendi Suhendi, and Didi Sapdiana. 2016. "The Simulation of Organic Rankine Cycle Power Plant with N-Pentane Working Fluid." *AIP Conference Proceedings* 1712(February 2016).

Rybach, Ladislaus. 2003. "Geothermal Energy: Sustainability and the Environment." *Geothermics* 32(4): 463–70.

Shengjun, Zhang, Wang Huaixin, and Guo Tao. 2011. "Performance Comparison and Parametric Optimization of Subcritical Organic Rankine Cycle (ORC) and Transcritical Power Cycle System for Low-Temperature Geothermal Power Generation." *Applied Energy* 88(8): 2740–54. http://dx.doi.org/10.1016/j.apenergy.2011.02.034.

Tangsriwong, Kwanchanok et al. 2020. "Modeling of Chemical Processes Using Commercial and Open-Source Software: A Comparison between Aspen plus and DWSIM." *IOP Conference Series: Earth and Environmental Science* 463(1).

Tchanche, Bertrand F., Gr Lambrinos, A. Frangoudakis, and G. Papadakis. 2011. "Low-Grade Heat Conversion into Power Using Organic Rankine Cycles - A Review of Various Applications." *Renewable and Sustainable Energy Reviews* 15(8): 3963–79. http://dx.doi.org/10.1016/j.rser.2011.07.024.

Zarrouk, Sadiq J., and Munggang H. Purnanto. 2015. "Geothermal Steam-Water Separators: Design Overview." *Geothermics* 53: 236–54. http://dx.doi.org/10.1016/j.geothermics.2014.05.009.