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Coupled Geothermal Reservoir and Process Simulation of a Binary Plant for Front End Engineering Design

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ABSTRACT

New Zealand generates around 18% of its total electrical capacity using geothermal sources and could benefit significantly from simulation for optimization (Ministry of Business, Innovation & Employment, 2017). Current geothermal reservoir and process simulations are conducted separately with data manually parsed between the different simulators. Delays in the modelling process and the inability to efficiently model effects that reservoir changes over the asset's lifetime have on the plant could lead to poor investment decisions and a lack of optimization. Integrating both reservoir and process simulators would enable accurate prediction of both reservoir and plant issues. In this paper, a proof of concept is developed. The reservoir simulator AUTOUGH is integrated with the process simulator VMGSim using Python and PyTOUGH. A demonstration based on a plant in New Zealand was built. The plant involves three producers and injectors which are used to feed brine to and inject brine from a binary geothermal plant. The aim of this study is to demonstrate and compare the effects of integrating reservoir and plant models in predicted reservoir and performance.

Geothermal fluid mass flow, pressure and temperature data is passed between AUTOUGH and VMGSim where both the wellbore and plant is simulated. Brine injection data is passed back to AUTOUGH. This cycle is run until either a simulated plant failure occurs or the simulation is terminated. In an ORC plant, typical failures relate to temperature drops in the geothermal fluid that lead to the inability to vapourize the working fluid used to power the turbines. As a result, plant changes are required to maintain production, which could reduce power generation or require drilling an additional production well.

by integrating the simulators, CO_2 depletion within the reservoir can be studied and the effects characterized. A reduction of CO_2 produced for a binary plant promotes heat transfer but at the cost of increased pressure drop within the wellbore, and, as a result, the power generation decline occurs much earlier than anticipated.

Coupling models adds additional benefits to the modelling process that supports the optimization of both reservoir and surface related activity. Addition of historical ambient air temperature allows for more accurate results but at the cost of increased simulation time, but, in turn, allows for more accurate economics when conducting FEED (Front End Engineering Design).

1. INTRODUCTION

The aim of this study is to demonstrate the ability to couple both subsurface with surface models for more accurate simulation. As the temperature of the geothermal fluid decreases, dissolved silica comes out of phase, resulting in the formation of scale. Scaling which occurs throughout the plant, reduces both flow and heat transfer coefficients, and as a result a decrease in both power output and efficiency can be observed (Zarrouk, Woodhurst, & Morris, 2014). A study conducted on the Wairakei binary plant in New Zealand, showed a reduction of power generation over a fouling life cycle of six months.

Previous work on a coupled geothermal model (Nandanwar & Anderson, 2014) does not accurately model the process plant, and as a result only benefits on the reservoir side are seen. The model developed by Nandanwar only removes an enthalpy which represents power generated. This technique cannot be used for plant design optimization and trouble shooting. Issues that may occur due to fouling cannot be modelled. Furthermore, ambient temperature has a large effect on power generation both in day/night and summer/winter cycles.

An advanced integrated software called Matatauria developed by Mercury in house (Franz, 2016), allows for sophisticated integrated models. Matatauria is private and thus does not allow for open use of the software. Matatauria also requires process models to be recreated within the software which leads to added time when trying to migrate existing models which sometimes can be very complex.

Typically, during forecasting or future prediction runs, injection rates and temperatures are kept constant. As a result, temperature and flow changes due to both fouling and natural decline are not accurately represented.Coupling both simulators allows for constantly updated injection parameters as both the reservoir and plant change over time.

2. SIMULATION TOOLS

2.1 AUTOUGH

AUTOUGH is a geothermal simulator based on a modified version of TOUGH2 by the University of Auckland. PyTOUGH (Croucher, 2011) is a Python script used to both generate a subsurface geothermal model and run AUTOUGH. In this paper a model is run constantly until simulated plant failure as a result of depleting reservoir temperature or other issues. The effect of ambient temperature is also demonstrated to show the large inaccuracies between simulating constant and variable temperatures within the binary plant.

2.2 VMGSim

VMGSim is a process simulator developed by Virtual Materials Group, which allows for steady-state and dynamic process simulation with integrated flowsheet design. VMGSim was used for simulating the binary geothermal power plant. A material and energy balance is conducted in steady state to obtain information such as power generated, temperature of brine leaving the plant and parasitic load on the plant. Input data for the process model is obtained from the coupled simulator and results are exported back.

2.3 COUPLER(Re2Pro)

The coupler (Re2Pro) built in python interacts with both PyTOUGH and VMGSim. The reservoir model is initially run for six simulated months. Bottomhole fluid flow and properties are parsed to VMGSim. The wellbore is then simulated to determine changes in temperature, pressure and vapour fraction of incoming fluid. The geothermal process plant is then simulated and injection temperatures and pressures at the bottom of the injection wells are calculated. This information is parsed back to AUTOUGH and injection information in the reservoir model is updated. Ambient air temperatures at a location close to the plant are obtained from NIWA (the National Institute of Water and Atmospheric Research) and are used in modelling the condensing air coolers. The above cycle is repeated until either the model stops at the user selected finish time or an issue/failure occurs in the plant that does not allow for the process simulation to complete.

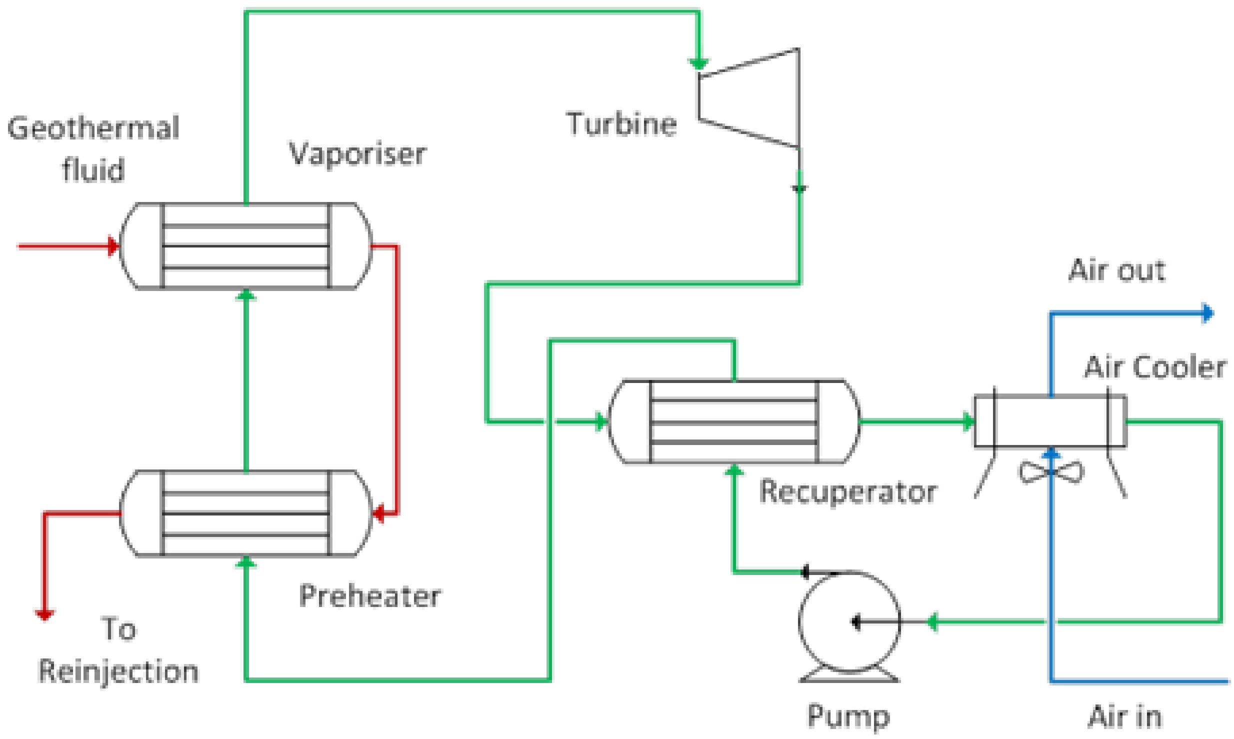

Figure 1: Simplified process flow diagram of a geothermal Organic Rankine Cycle

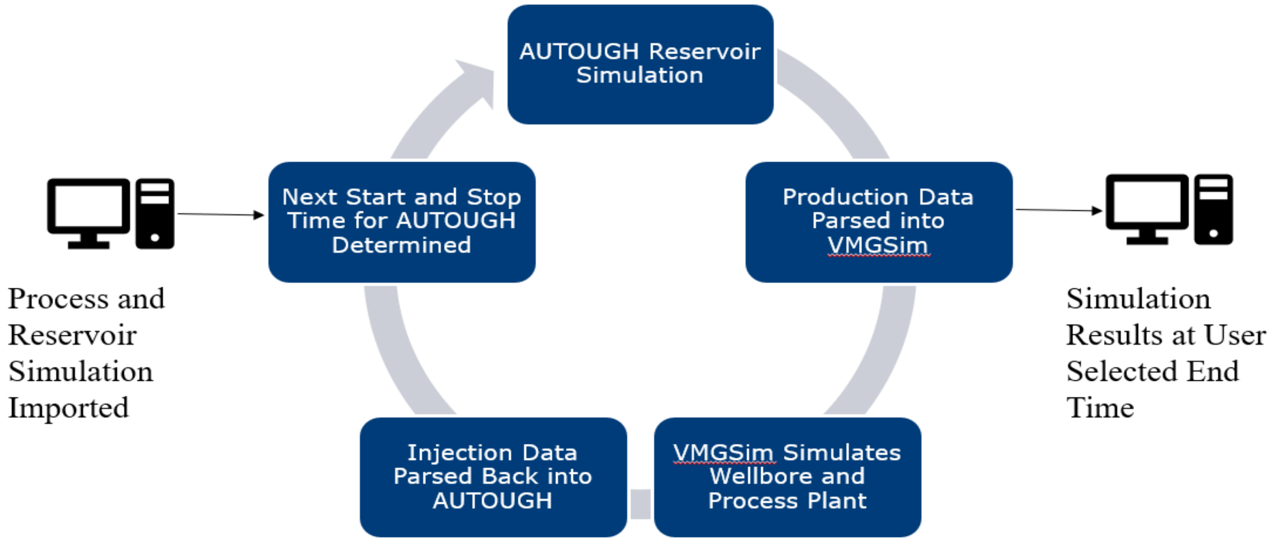

Figure 2: Data flow of integrated modelling

3. INTEGRATED MODEL

3.1 Reservoir Model

A model was built around an existing binary plant located in New Zealand to test the coupling capabilities. The model included three production and three injection wells. The model parameters are shown in Table 1. Two models were run, both starting with identical initial conditions, which were obtained from the natural state reservoir model. The first reservoir model is not integrated and continues to inject at a constant enthalpy. The second model which is integrated to VMGSim obtains injection temperatures from the process model which it cycles through every 90 days. The accuracy of the model depends on how often data is parsed between the reservoir and process model. Reducing the time between cycles increases run time.

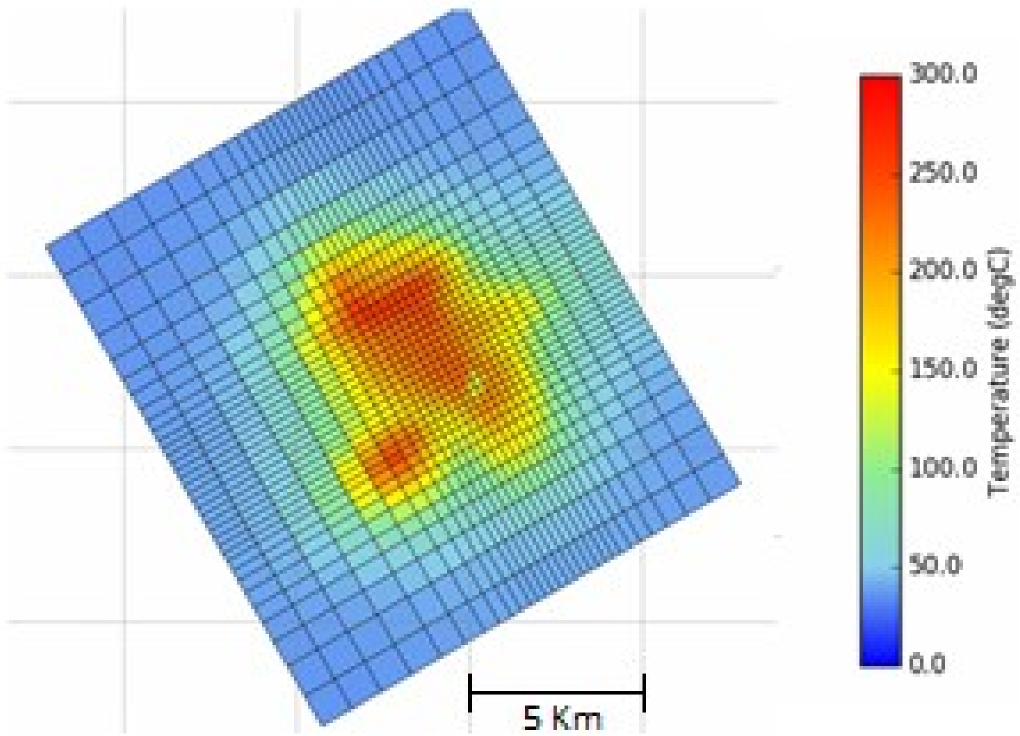

Figure 3: Reservoir model.

Table 1: Reservoir model properties

Initial temperature	227° C
Initial reservoir pressure	118 Bar
Production Wells	3
Injection Wells	3
Reservoir Temperature	225-230°C
Total Fluid Production Rate	~1,000,000 kg/hr
Composition	Water, CO_2

3.2 Process Model

The process model developed in VMGSim is based on a binary plant (Proctor, Yu, & Young, 2017) as shown on Figure 1. Geothermal fluid data obtained from AUTOUGH is passed to VMGSim, where the wellbore is modelled to allow for pressure drop and phase change. Fluid from the wellhead passes through a separator where separated fluid is passed through individual heat exchangers. Pentane, the working fluid selected, exchanges with steam and brine in vaporizer heat exchanger. Vaporized pentane is then passed through an expander to generate a constant power. This power is a function of both pentane flow rate and pressure. Expanded pentane is then passed through a recuperating heat exchanger and is then condensed using an air cooler. The condensed pentane is brought up to working pressure using a pump and is then preheated with cooled brine and CO_2. Cooled brine leaving the preheater is pumped and injection wellbores are then simulated. Injection flow rate, temperature and pressure is parsed back into the reservoir simulation. Figure 2 depicts a block flow diagram showing the movement of information through the integration process.

The process plant runs in essentially a closed-loop fashion, where pentane flowrate and pressure are determined by geothermal fluid coming into the plant.

4. RESULTS

4.1 Effects of Coupling

Figure 4 shows the simulated difference between plant power with and without integrating. The integrated model begins in year 15 in which the forecast of the reservoir begins (01 Jan 2012).

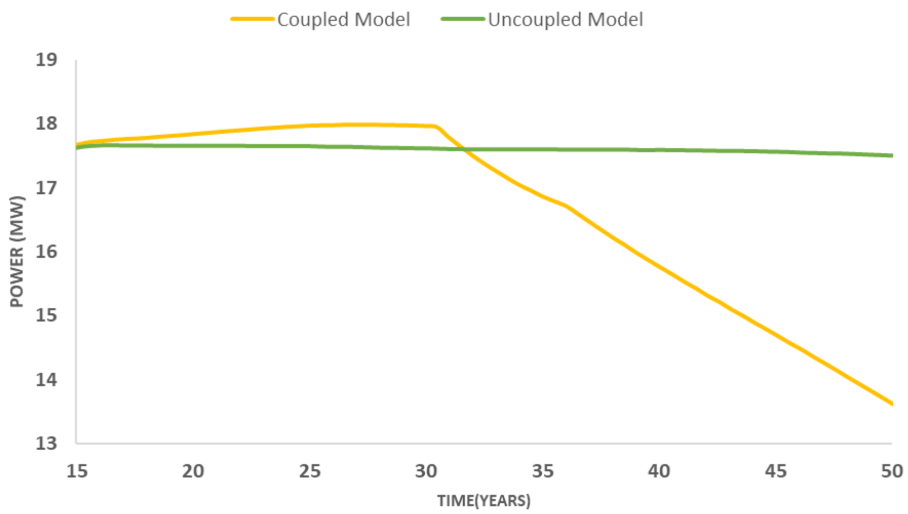

Figure 4: Plant production between coupled and uncoupled models with fixed ambient temperature.

Power in the coupled model initially increases due to decreasing CO_2 production as a result of reservoir depletion. This causes better heat transfer in the vapourizer leading to increased power generation. After excessive CO_2 production, plant power begins to decrease because CO_2 influences the formation of vapour in the wellbore. CO_2 increases the vapour pressure of the fluid therefore the mixture forms two phases deeper in the wellbore compared to when CO_2 is not present in the fluid. CO_2 also inhibits the formation of water vapour which reduces lost energy caused by forming steam which is not beneficial for a binary plant. Feed zone data such as mass flowrate, temperature, pressure and composition are sent for process simulation, with similar injection data generated and sent back to the reservoir simulation.

4.2 Effects of Ambient Temperature

Compared to Figure 4, the addition of ambient air temperature allows for much more accurate power predictions, as shown in Figure 5. The plant power rarely reaches the design temperature of 15°C, and as a result forecasted revenue during the design phase is lower than expected. A closer look into Figure 5 as shown in Figure 6 shows that winter and summer periods are both captured in the simulation. This is by using the assumption that the earth's temperatures behave in a cycle. Ten years of historical temperature datapoints were extracted from NIWA and are referenced during every simulation cycle for forecast runs.

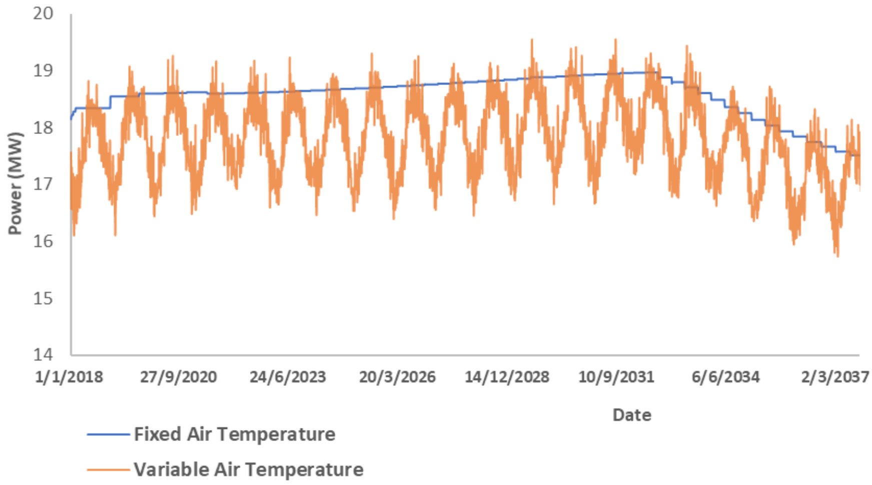

Figure 5: Effects of fixed vs. variable air temperature in power generation simulation.

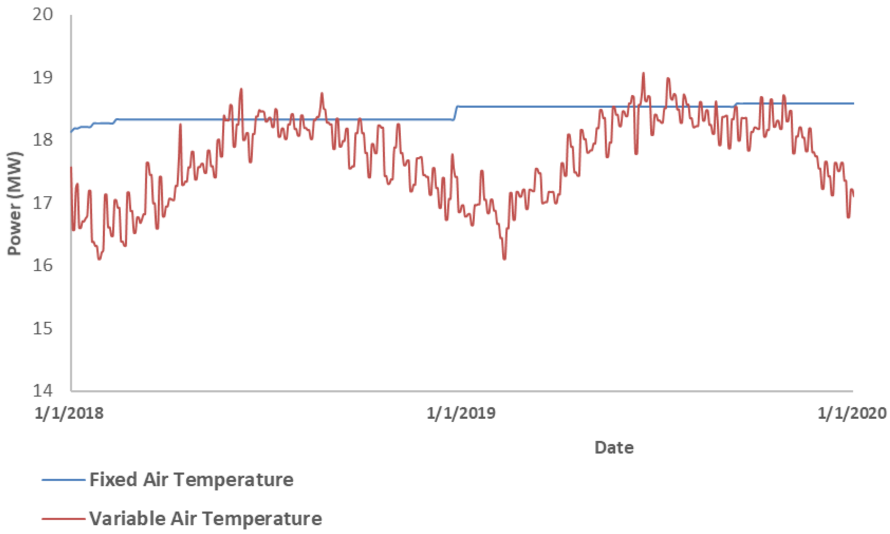

Figure 6: Seasonal effects on power generation.

4.3 Economic Analysis of Condensing Banks

An economics analysis of the condenser banks was performed to ascertain whether investing in more cooling capacity was feasible. Runs were performed using 14, 16 and 18 banks using both fixed air temperature and variable. A discount factor of 10% over 10 years was used to calculate NPV, with an initial investment of 1 million $ per bank. Table 2 shows the results of upgrading the plant from 14 banks to 16 banks using both variable and fixed air temperatures in forecasting. As a result, earnings are largely overestimated. In table 3 two more banks are added resulting in an 18 bank condenser configuration. Using variable air temperature 18 banks is no longer economically feasible.

Table 2: Economics of 14 banks to 16 banks using variable vs fixed ambient temperature.

PROJECT COST ($)	**2000000**			**DISCOUNT RATE**	**10%**
LIFE OF PROJECT(YEARS)	10				
	Year	NPV Value (Variable) ($)	NPV Value (Fixed) ($)		
ANNUAL COST SAVINGS	1	$395,873.64	$643,355.91		
	2	$359,885.13	$584,869.01		
	3	$327,168.30	$531,699.10		
	4	$297,425.73	$483,362.82		
	5	$270,387.02	$439,420.75		
	6	$245,806.39	$399,473.41		
	7	$223,460.35	$363,157.64		
	8	$203,145.77	$330,143.31		
	9	$184,677.98	$300,130.28		
	10	$167,889.07	$272,845.71		
	NPV	2,675,719.37	4,348,457.94		
INITIAL INVESTMENT	Now	(2,000,000.00)	(2,000,000.00)		
		675,719.37	2,348,457.94		

Table 3: Economics of 16 banks to 18 banks using variable vs fixed ambient temperature.

PROJECT COST ($)	**2000000**			**DISCOUNT RATE**	**10%**
LIFE OF PROJECT (YEARS)	10				
	Year	NPV Value (Variable) ($)	NPV Value (Fixed) ($)		
ANNUAL COST SAVINGS	1	280,516.47	502,071.65		
	2	255,014.98	456,428.77		
	3	231,831.80	414,935.24		
	4	210,756.18	377,213.86		
	5	191,596.53	342,921.69		
	6	174,178.66	311,746.99		
	7	158,344.24	283,406.36		
	8	143,949.31	257,642.14		
	9	130,863.01	234,220.13		
	10	118,966.37	212,927.39		
	NPV	1,896,017.53	3,393,514.21		
INITIAL INVESTMENT	Now	(2,000,000.00)	(2,000,000.00)		
		(103,982.47)	1,393,514.21		

5. MODEL VALIDATION AND PERFORMANCE

The model was validated across two one-month periods: one period being during summer and the other during winter. This allowed the model to be validated against large temperature changes that occur during seasons and during different times of the day and the effects it has on power validation. Figures 7 and 8 show the months of January 2018 and July 2018. There is a very close match in January showing the cycling of power during steady state, but the model does not capture plant upsets that may occur. In July the model shows a flat line with a close match but is unable to capture very small changes in temperature as the plant is at maximum capacity. The absolute residual error for power prediction for the month of January and July are 3.6% and 1.49%, respectively.

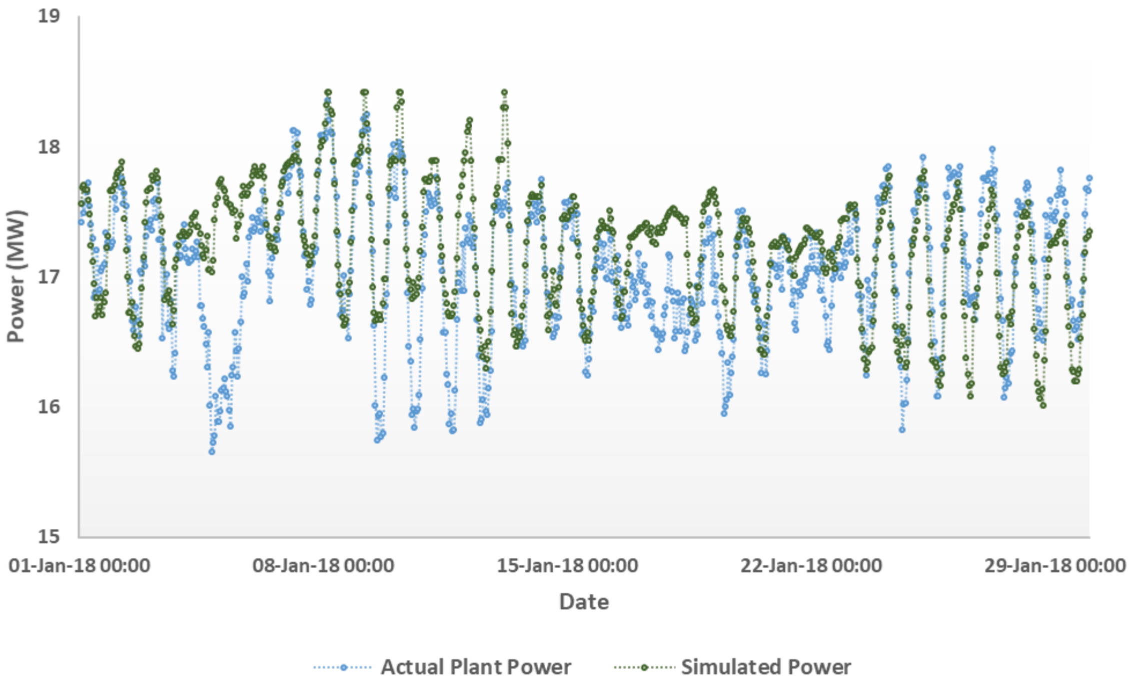

Figure 7: Plant power simulated vs. actual for January 2018.

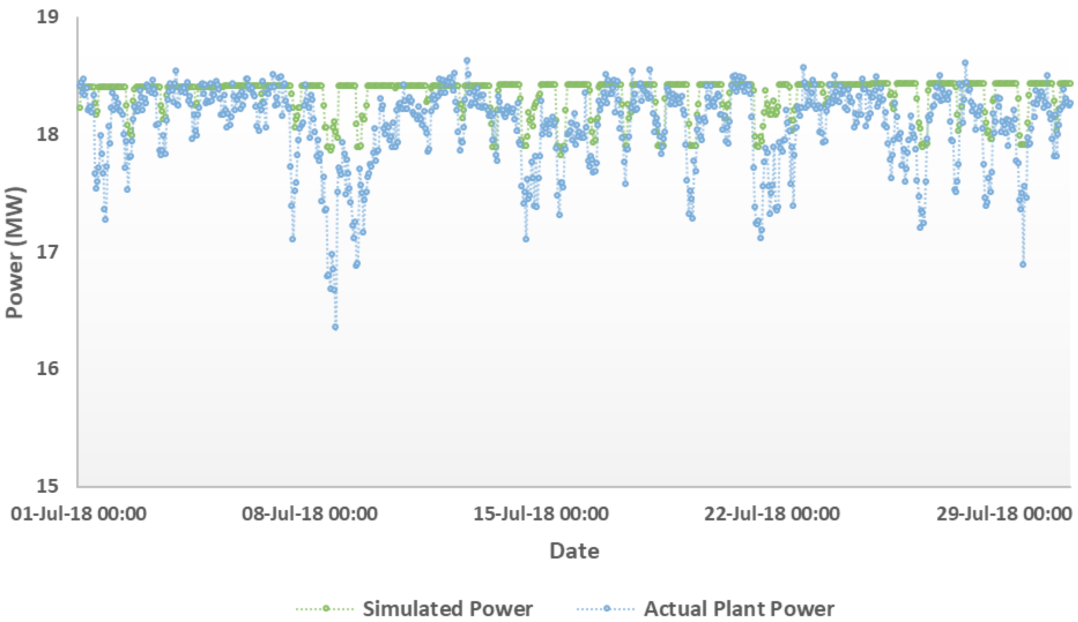

Figure 8: Plant power simulated vs. actual for July 2018

Table 4 shows the performance of the runs. As the process simulation is run serially the run times are highly impacted by the complexity of the process model. Factors such as the number of segments in a heat exchanger or wellbore increase the run time significantly. CPU core clock speed also largely impacts the run performance.

Table 4: Performance comparison of runs.

Cycle length	Real time to complete one simulated month	CPU Core clock speed
1 Hour	44 Hours	3.7 GHz
1 Hour	30 Hours	4.7 GHz
12 Hours	3.5 Hours	3.7 GHz
12 Hours	2.5 Hours	4.7 GHz

The type of investigation will determine cycle length. When investigating CO_2 depletion large integrated timestep sizes of several years are enough. Smaller timesteps such as 12 hours or even bi-weekly can be used for investigating process plant performance for Front End Engineering Design. This may include heat exchanger sizing, and condenser design.

6. CO_2 DEPLETION

Two runs where preformed to compare the effect of incorporating changing fluid chemistry regarding forecast predictions. Figure 9 and 10 show CO_2 dissolved in the brine simulated in the wellbore model. The wellbore model uses Duns and Ros pressure drop correlation as that gave the best fit compared to actual data. As CO_2 is depleted from the reservoir heat transfer in the vaporizer is improved resulting in increased power. As CO_2 is a heavier molecule the average velocity is slower than that of water vapor and a result causes a lower pressure to drop due to friction. This can be compared to Figure 11 and 12 in which the initial CO2 concentration was kept during the forecast. As a result, make up wells are required much earlier than expected impacting plant economics. Similar results where shown in Tanaka and Nishi. (1988).

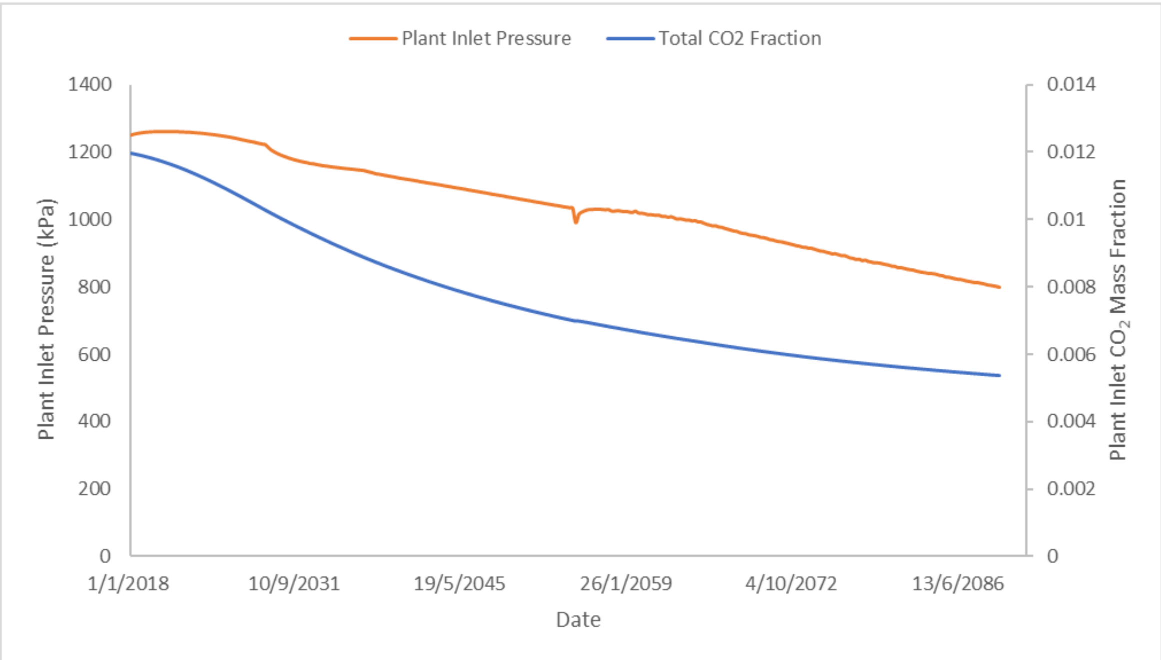

Figure 9: Plant inlet pressure with changing dissolved CO_2.

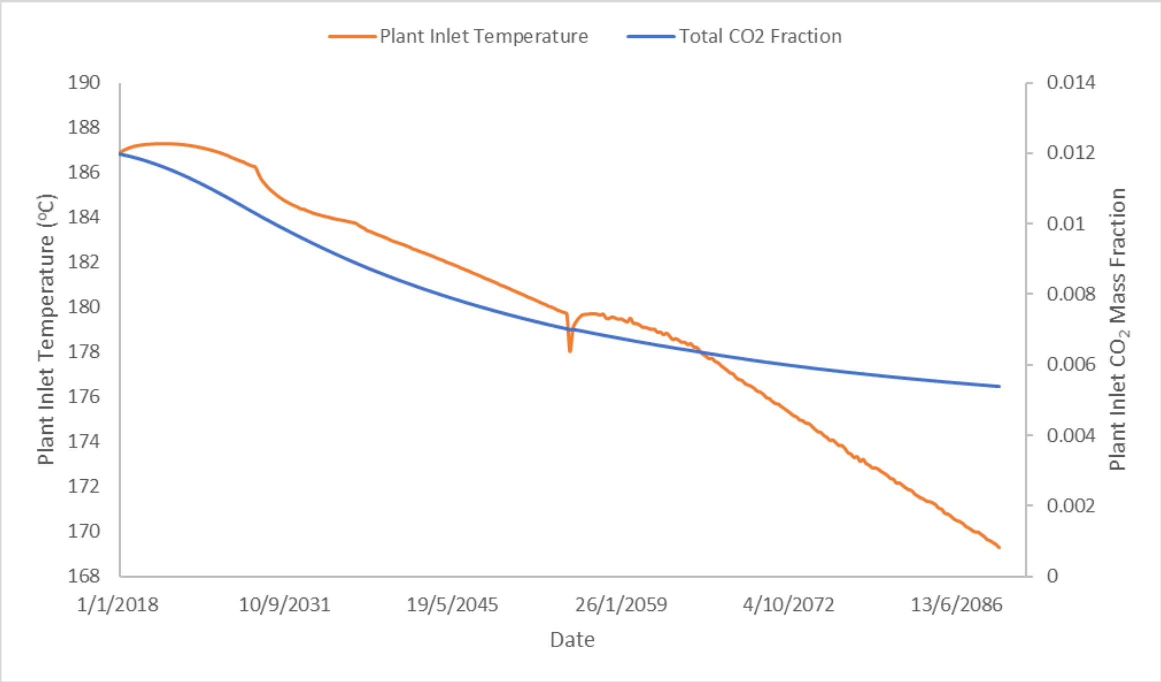

Figure 10:Plant inlet temperature with changing dissolved CO_2.

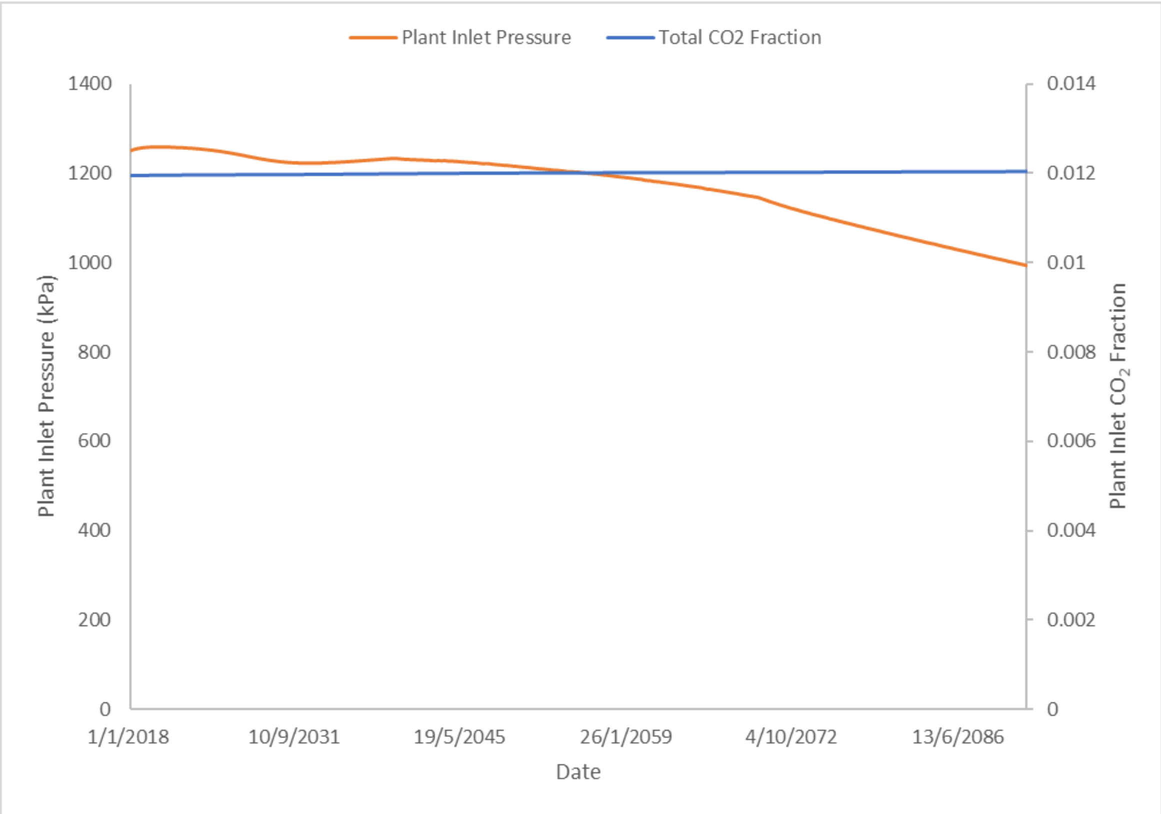

Figure 11: Plant inlet pressure with fixed dissolved CO_2

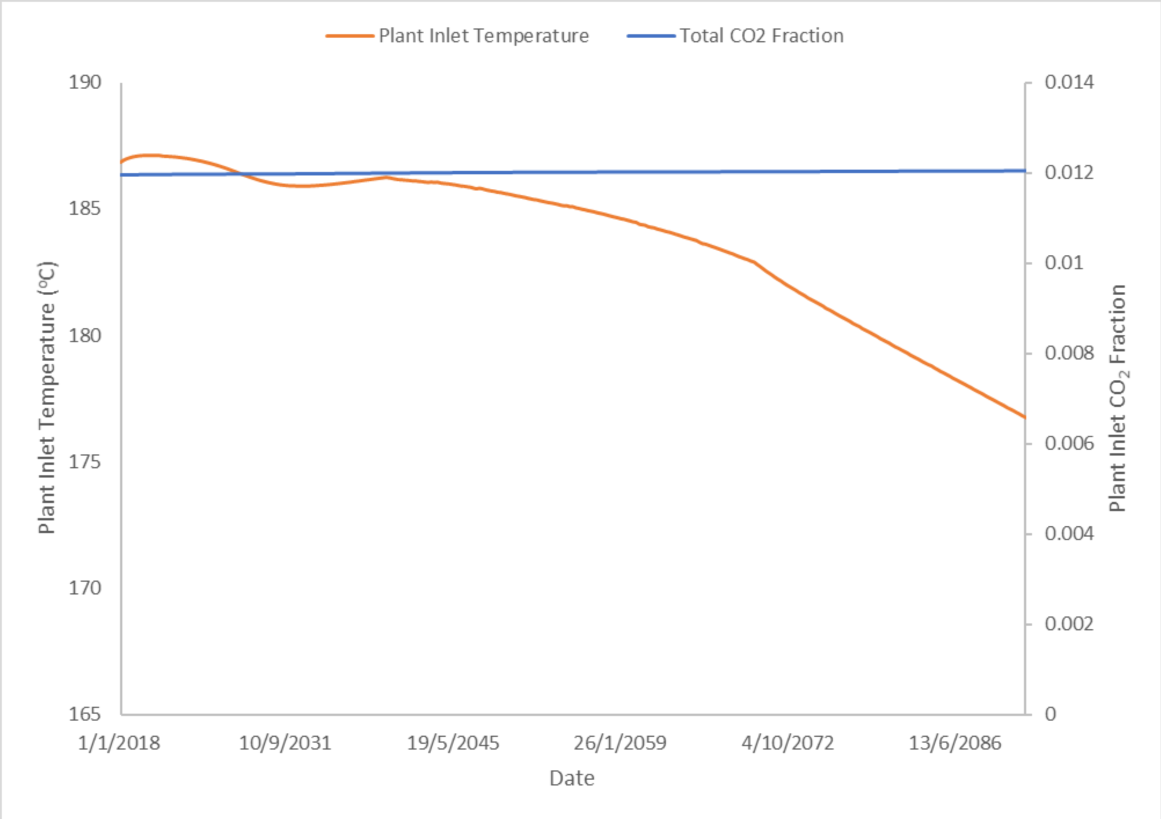

Figure 12: Plant inlet temperature with fixed dissolved CO_2.

Figure 13 shows a plot of pressure and temperature vs depth for Well 1 at the beginning of the run (1/1/2018). As CO2 begins to decrease from 1.18% mass fraction the temperature loss as a result of friction becomes more apparent. Figure 14 shows the results after 35 years of production, where CO2 has reduced to 0.31% by mass. As a result, the vaporizer struggles with such a small temperature difference between the brine and the required temperature to vaporize the working fluid, therefore increased sizing of the heat exchangers should be acknowledged prior to plant design to reduce the impact this causes on future plant power. Is it possible to choke the well to increase the well head pressure but at a cost of flow rate. Run conversion issues might have occurred resulting in a sharp spike as shown around the year 2050.

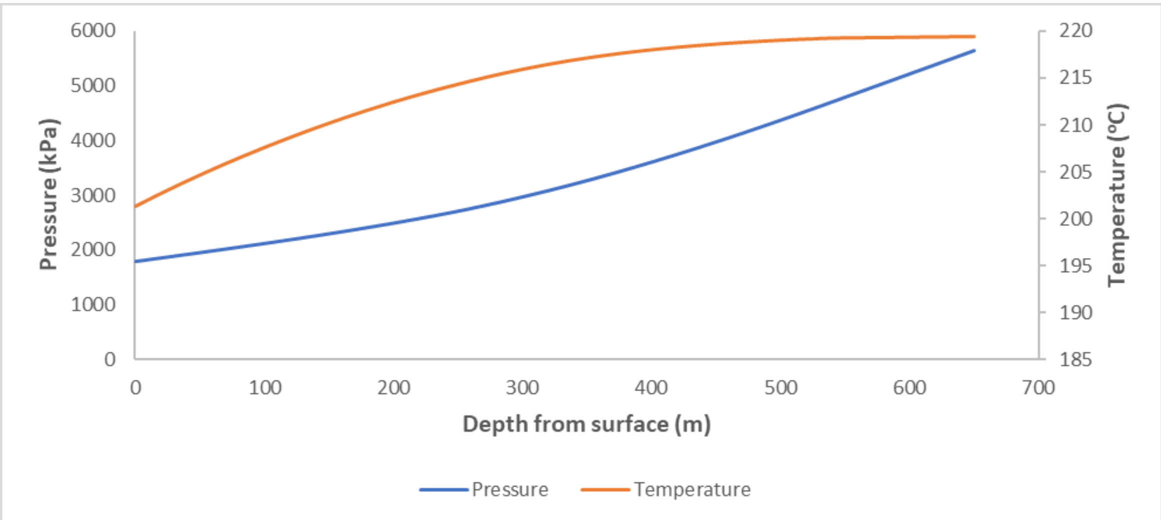

Figure 13: Well 1 Pressure and Temperature vs Depth at 01/01/2018 with 1.18% Mass CO_2.

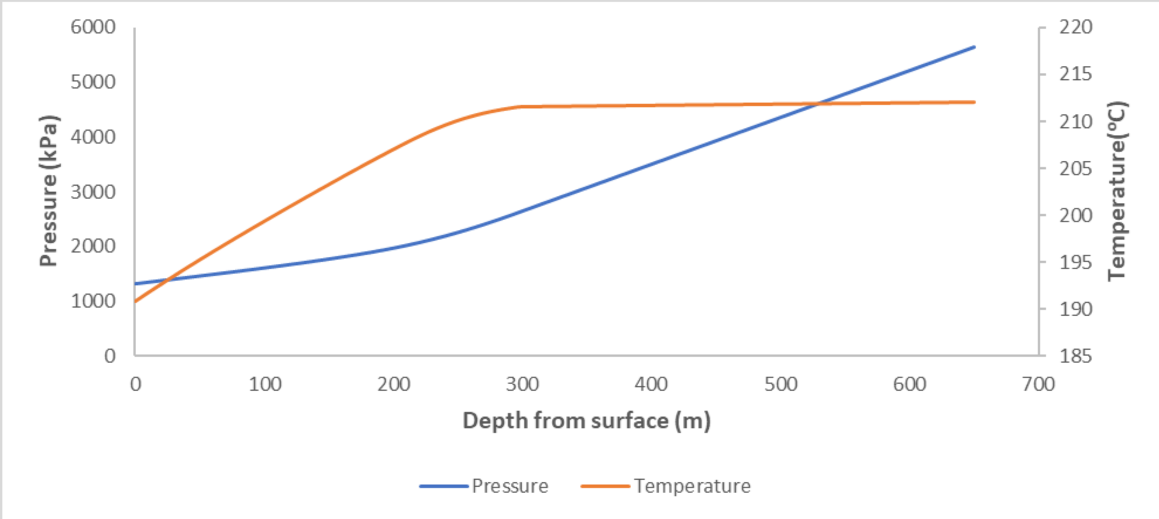

Figure 14: Well 1 Pressure and Temperature vs Depth at 01/01/2053 with 0.31% Mass CO2.

7. CONCLUSIONS

Typically, during forecasting or future prediction runs, injection rates and temperatures are kept constant. As a result, temperature and flow changes due to both fouling and natural decline are not accurately represented. The study conducted on both integrated and standard models shows that there is a difference between both methods as a result of both ambient temperature and reservoir chemical changes. Detailed analysis is required when investigating plant changes where day/night and seasonal effects are considered. In the case study it was shown that the condensing fans were under-designed and maximum plant capacity was rarely ever reached, an issue which would have been addressed during the design phase if integrated modelling was used and as a result a loss in power revenue of 3% per year was estimated. CO_2 depletion poses a significant threat in moderate temperature, CO2-rich geothermal reservoirs that leads to over-estimating power reserves in a plant which can only be shown in through an integrated model. Results show that make up wells must be drilled earlier than expected to maintain power output of the plant.

There are multiple different scenarios that occur in real life which could test further the benefits of integrated modelling such as integrated to assets that use multiple formations to power their plant.

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