Geothermal Strategy Optimisation: A Summary

ENGSCI 700 Preliminary Literature Review and Statement of Research Intent

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*Abstract*—The Wairakei geothermal field is one of the oldest geothermal electricity producers in the world, and it has been instrumental in advancing the utilisation of lower enthalpy fluids. Contact Energy Ltd. is the current operator, and they wish to find ways to increase the productivity of their assets and staff.

The optimisation of geothermal well operation is not well-studied; it is often done on a case-by-case basis for each steamfield. However, there are many advanced techniques such as non-linear analysis, mixed-integer programming and Bayesian inference that could improve the current workflow applied by Contact. This document contains a review of previous research in these techniques applied to different fields, and proposes future research towards implementation at the Wairakei network.

# Introduction

Geothermal power is a hallmark of New Zealand renewable generation alongside hydro and wind. It makes up 13% of the nation’s electricity supply, with the first generator being commissioned in Wairakei in 1958. Although New Zealand is not the world’s largest geothermal producer, it is unique in that Wairakei is liquid-dominated, and most of the geothermal production is two-phase flow or ‘wet’ steam, which must be filtered to avoid damaging the turbines. This contrasts with the ‘dry’ steam in places such as Italy, which contains no water and is easier to handle [1].

This review will begin with the current and historical physical state of the Wairakei geothermal field, along with some of the processes used by the current operators, Contact Energy. A summary of literature surrounding operational management of geothermal power plants will follow, along with areas of potential research.

The scope of this review is the modelling of the surface network from the wellhead to the generator. This means we are less interested in effects such as subsidence, loss of pressure and the possible reoccurrence of injected fluid at production wells, which are typically simulated with subsurface modelling.

# Objectives of the Wairakei Geothermal Field

Currently, the Wairakei geothermal field has over 200 wells [2]. While many are retired, the wells in operation must primarily be managed to be sustainable and maintained to an operational standard, and secondly support a baseload New Zealand power generation.

Our understanding is that there is currently no automatic process in place to optimise the surface network flows. While Contact has tools to store, analyse and present data, these do not make recommendations and all operational decisions are made by experienced staff (e.g. whether to perform a workover) or by heuristic (e.g. the highest enthalpy wells in decreasing order are directed to Te Mihi, while lower enthalpy wells are directed to Wairakei).

## Long-Term Sustainability

The significance of sustainability is demonstrated by a period in 1960-1970 when temperature and pressure declined rapidly, affecting the production of some wells. The environmental impact of discharge was also not taken into account at commission, with 4500 t/h discharged into the Waikato River until 1997. Re-injection of fluids must be done carefully with regard to its effect on the pressure of the reservoir and potential suppression of hot fluids by cooler, re-injected fluid. Many of the limitations regarding environmental sustainability can be quantified by resource consents held by Contact, the geothermal field's current operator. These will impose environmental constraints in any potential research:

1. River discharge (e.g. temperature, mass, arsenic, hydrogen sulphide) [3],
2. Long-term pressure drawdown in the reservoir with:
   1. Daily mass uptake (280 kt/d),
   2. Average mass take over three months (245 kt/d [4]),
   3. Proposed to replace three-month limit with an annual limit,
3. Subsidence in the Taupo region as a result of pressure loss [4].

## Short-term Power Generation

The primary purpose of the Wairakei geothermal field is to produce renewable energy. Although the field is known to recharge over time, balancing continued production in the future with satisfying current New Zealand energy needs and operating profits is a difficult challenge because the recharge rate is slow. The resource consents held by Contact also include measures to maximise long-term power generation. Factors that have been taken into account previously include (but are not limited to):

1. Providing base-load power generation,
2. Scaling and work-overs of wells,
3. Operating conditions of wells and separators, e.g. enthalpy and pressure limits,
4. Start-up and shut-down times,
5. Safety valve pressures.

# Current Research

The operation of wells, whether they be geothermal or petroleum-based in nature, is discussed extensively in the scientific literature. We are mainly interested in three aspects of modelling and simulation: short-term prediction of production, methods to optimise a long-term strategy for a set of wells in a reservoir, and methods to cope with uncertainty in the network.

## Network Modelling Techniques

Modelling of the Wairakei field has taken place at the University of Auckland since the 1970s. However, the majority of this work is focused on flows within the reservoir; models of the pipe network are developed by Contact Energy.

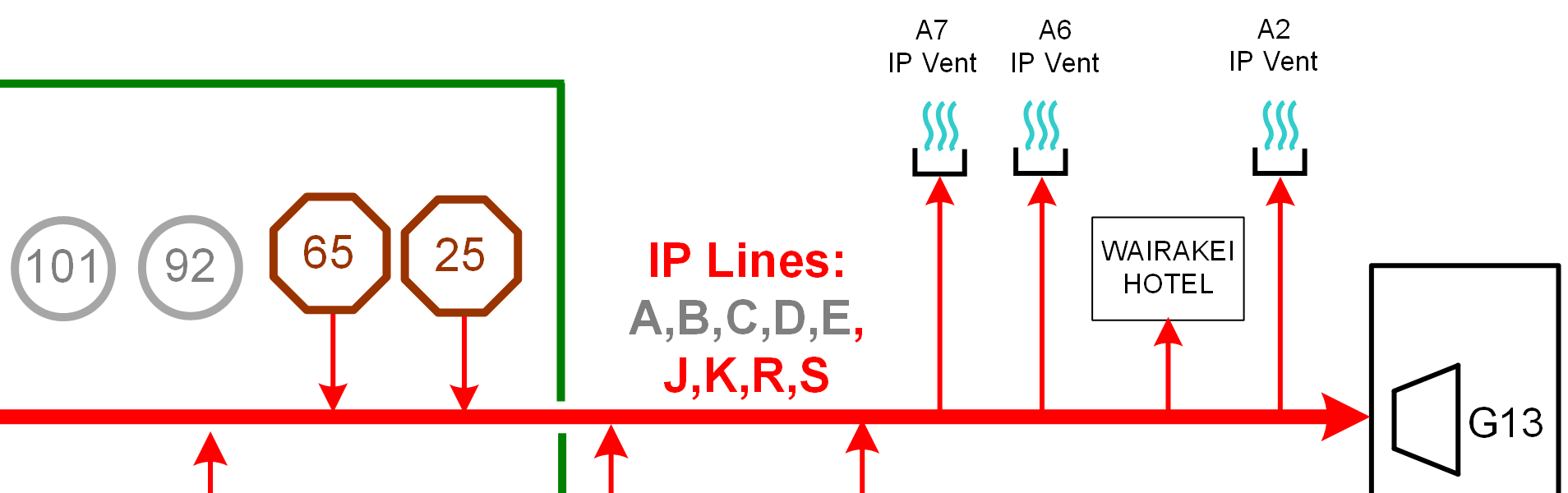


Figure : Snippet of the Wairakei schematic representation

### Graph Representation

The physical structure of the geothermal field can be represented as a directional graph, a small portion shown in Figure 1.

### Heat Loss

Loss of heat to the environment is a common cause of inefficiency for power systems. This will occur especially when there are events such as contact with machinery, creating friction and inducing conduction and convection. Zarrouk states that in pipes, heat loss is negligible at around 0.6% [5]. Heat loss for more complex components is much more difficult to estimate, and is likely contained within the overall efficiency for the component.

### Nonlinear Modelling

Linear equations are common when modelling a network, making the assumption that flows can be linearly super-imposed and exist in a tree-structure of pipes without loops. This makes finding the state of a system and optimisation of decision variables possible by techniques such as linear and mixed-integer programming.

However, there are limitations outlined by Y. Huang and D. H. Freeston [6]. For instance, head loss in a pipe is often of the form:

where is the head loss, is the friction factor, is the pipe length, is the volumetric flow rate and is the pipe diameter.

Inclusion of non-linear effects can more accurately capture the physical processes which might affect power generation at Wairakei. These sets of non-linear equations can be solved using derivative methods but rely on convergence, so Huang and Freeston had to be careful to ensure their method would converge.

### Outage Scheduling

Both the geothermal and petroleum extraction industries require well *workovers*, which are labourious interventions to restore the function of a corroded, damaged or otherwise impaired well. Workovers are limited by the number of rigs available. In a 1976 paper [7], workovers are scheduled to minimise the loss of having each well offline for a time plus lost production from before the workover, . The paper presents two heuristics for finding good solutions within 2% of optimality within half an hour for using a ‘desk calculator’. Nowadays, optimality should be possible using modern branch-and-bound techniques.

## Production Prediction

An IPENZ report by K. Wigram [8], first presented at the New Zealand Geothermal Workshop 2012, outlines the need for prediction at Wairakei and gives an overview of current (pre-2012) methods. A brief summary follows:

### Predicting Generation Using the Past

Historical macro-trends can be extrapolated into the future. Trends such as pressure loss in each well tend to be linear and easy to predict. More complex trends such as the pressure restoration after a workover depend on the engineer’s knowledge of the well and can be inaccurate.

Simple linear models also fail to capture the interaction between wells. An given by Wigram demonstrates that if a 3 MW well were added to an existing field, the actual marginal power increase may only be 2 MW if pressure at existing wells is negatively affected.

### Building an Excel Model

Consistent with our own observation of the methods used at Contact, Wigram details the use of an Excel workbook to predict power output by tracking flows to and from each facility. This workbook contains basic physical and thermodynamic calculations, and also affords the operator some diagnostic capability if checked for behaviours such as conservation of mass. Wigram concludes that this model gives good predictions for events such as new wells and outages; however, it is not accurate for long-term predictions. The greatest benefit of this model is the ability to test hypothetical scenarios; e.g. restarting a high-pressure turbine, or estimating heating in the river.

A few of the conclusions drawn by Wigram are:

1. The ability to test scenarios to maximise economic gain or minimise loss,
2. Even if accuracy cannot be achieved, consistency is still useful as two outcomes can be compared,
3. There is no substitution for real experience; model validation and testing is necessary,
4. A good model can result in huge economic benefits.

## Uncertainty

Current models used at Contact do not take uncertainty into account. One source of uncertainty is due to measurement noise. For instance, measurements of mass flows from wells entering a flash plant do not always sum to the measured mass flow leaving the flash plant. Adjustments for this are often done using an ad-hoc correction factor. These are calculated manually and only made periodically.

A second source of uncertainty comes from a lack of exhaustive data. *Bore tests* involve taking a well offline, applying a testing apparatus to the well-head, and running the disconnected well at three different pressures to generate an elliptical estimate of the function , where is the mass extraction rate and is the well-head pressure. *Tracer flow tests* (TFTs) inject a tracer dye at the well-head under normal operating conditions. The well can continue production during the TFT and mass flow is measured under realistic conditions, but this only provides one data point which cannot describe a curve. **[There was also some data, can’t remember which, that had an unknown translation (error) but was consistent in the difference between measurements]**

Statistical methods are available to account for incomplete information.

### Bayesian Framework

Z. Poulakis et al. applied Bayesian methods to detect leaks in pipes based on pressure and flow measurements [9]. With *K* possible leak locations, analogous to *K* forms of decline in the network such as scaling or pressure decline, solving a multi-dimensional optimisation problem to find the maximum of the probability density function for leaks in the *K* pipes allows the most likely locations for the leak given the data to be estimated. Similarly, we could use Bayesian analysis to estimate the true condition of the wells given erroneous data. This method requires simulation over an exhaustive grid of parameters or expert knowledge to create realistic prior distributions.

### Monte Carlo Methods

Related to the Bayesian framework, the graph structure of the geothermal network lends itself to simulation under uncertainty with methods such as sampling using the open-source JAGS (Just Another Gibbs Sampler). This is either used to compute posterior distributions, or to generate synthetic prior estimates under the empirical Bayes method for further Bayesian inference.

Specifically, Monte Carlo estimates are applicable to scenario analysis under uncertainty. When making decisions involving significant capital, Contact is obligated to generate value for its shareholders. Sampling distributions offer management a better idea of the risk involved than point estimates. A method for estimating the probability of failure using net present value (NPV) is described by M. Goumas et al. [10] in their report on how to incorporate a range of technical, economic, social and environmental parameters into the decision making process. They conclude that MC methods require less prior information because guesses can be made, they make interpretation accessible for a layperson, and sensitivity analysis is easy to perform.

Scenario evaluation with simulation also enables rudimentary multi-objective optimisation to be performed by comparing posteriors; the example presented is the balance of energy use, return on investment and jobs created.

### Model Fitting

Currently, Contact Energy estimates well-head pressure decline by using a parametric, fitted elliptical curve. While the exact manner they do this is in is not completely transparent, inspection reveals it to be an exact fitted curve to the three points obtained at a single bore test, . Using the curve to estimate the mass flow at a fixed well-head pressure , they create a plot of standardised mass flow over time, .

This method allows Contact to observe the changing conditions of the well, independent of operating pressure. It is used by the operator to indicate whether maintenance is required, and characteristics of the decline such as whether it is correlated with nearby wells can indicate the cause of decline, such as scaling, instrumentation error or reservoir pressure loss.

It is worth noting that this is not a typical regression, where observations are assumed to be independent and ordinary least-squares minimisation would be used.

# Potential Areas of Development

The aforementioned research, particularly around optimisation and stochastic modelling, has seen little application to the operational strategy of a geothermal network. Research has focused more on the prediction of pipe flows than operational decisions. This gives us several opportunities to research the applications of existing mathematical techniques to geothermal networks.

## Decision-Making in a Network of Pipes Over Time

Current research focuses on solving pipe flows where flows and pressures are the only variables. There is not much research on the discrete optimisation of pipe networks; i.e. which wells to activate and which pipe sections to route flows through.

Further optimisation can also include a scheduling component; for instance, we know that if a well is shut down, the pipes cool and this incurs a warm-up time before the well is restarted. Blowing of the trip valves also incurs a time delay, and by far the most disruptive activity that takes place at the geothermal field is wellbore workovers.

## Bayesian Analysis on a Transient Network of Pipes

Geothermal fluids contain more impurities than a city’s network of potable water pipes. This, combined with extreme changes in pressure and temperature, contributes to high levels of scaling and corrosion. Pressure decline is therefore expected to decline over time, compounded by the possibility of pressure and temperature loss in the reservoir itself.

Bayesian analysis (or, as an alternative, frequentist maximum likelihood estimation) can offer probabilistics distributions of the decline over time and the effects of taking certain actions. This has the potential to improve on the point-estimates currently made by the Contact operators, and the single snapshots in time, such as those used by some research such as Poulakis et al. [9].

# Research Intent

The work we intend to carry out centres around the implementation and adaptation of engineering science methods to the management of the Wairakei geothermal field. The goals of this project are:

1. Develop a mathematical/computational model of the Wairakei network that is flexible and can be reused in further research,
2. Create an optimisation program that generates policy recommendations in the near future regarding decisions such as bringing wells online/offline, redirecting flows and maintenance events,
3. Simulate network states and power plant performance under uncertainty to augment the existing prediction workbook.

## Resources

Historical flow meter data, schematics and details of some past events (such as which wells were routed to a flash plant) have been provided by Contact Energy in the form of several Excel workbooks.

An AMPL licence is desired for the optimisation component of this project because of its syntax and previous experience with the tool. However, there are also open-source alternatives, detailed in the methodology.

## Methodology

The three objectives listed above provide a framework for tracking the progress of this project in a relatively linear fashion. Although the research team consists of a pair of undergraduates, the separate tasks have dependencies which mean they will likely be done in series.

### Develop a Model

Previous models of pipe networks **[more research required]** have shown linear equations give good representations of the flows and thermodynamic physics in the network. The field can therefore be modelled by a system of linear equations with the intention of introducing an objective function to create a linear program.

Candidates for creating a linear programme include AMPL and Python via the PuLP package [11]. Pipes can be represented as flow arcs between components where conversions take place. Inspection of the enthalpy equations reveals linear conversions; any nonlinear equations found later on may need to be linearised or discretised.

### Optimisation

A linear representation of the network makes solving to optimality more straightforward. We want to make recommendations for the daily or weekly operations of the network in order to maximise revenue while remaining within environmental and operational constraints.

Decision variables include whether a well is enabled or disabled and for some wells, which flash plant their flows are directed to if there is a choice e.g. Te Mihi [12]. This will be done on a discretised time scale, starting large and decreasing to the daily level if the optimisation is performant.

A secondary goal for the optimisation is to take into account the scheduling of maintenance activities. Two considerations raised by Contact and a third that may be important are:

1. The necessity of activities on a well; will they make a difference?
2. Impact of maintenance on power output of the field,
3. Scheduling and availability of resources; this will require additional techniques than linear programming if the problem is hard, such as branch and bound or heuristics.

Ideally, stochastic optimisation will be performed. Approximations using expectations will also be considered. Successful optimisation can be verified by the Contact operators, assuming they have expert knowledge about running the field at optimal or near-optimal performance.

### Simulation

Simulation of the field will not involve novel methods, but instead an application of proven statistical methods on the mathematical/computational model and its optimal solutions to provide analysis to the operators.

As with previous studies on simulation to evaluate geothermal strategies [10], this will consist of a Bayesian approach to generate posterior densities of outcomes. These outcomes involve key parameters such as power generation, revenue, risk of adverse events and uncertainty of the outcomes.

Tools to perform analysis include the RJAGS package for R, a few MCMC (Markov Chain Monte Carlo) packages in Python, or implementing a custom Metropolis-Hastings algorithm in Python. While it may sound like more work, the advantage of the latter option is it may be possible to integrate an object-oriented approach into both the sampling and the optimisation simultaneously.

If using a package to perform analysis, several alternatives need to be explored. While both JAGS [13]/RJAGS [14] and PyMC [15] are new, WinBUGS is better established but is not cross-platform. The common language across the research team is Python.

We will know our simulation has worked if we can match observed outcomes, quantifiable by some metric such as DIC (Deviance Information Criteria), or by training on historical data up to a certain time, and then making predictions after that time where we have a ground truth and comparing the residuals. A working simulation model can then be turned into a tool to aid operators.

## Limitations of Scope

There are aspects we would like to explore given more time but are not necessary for this research.

### Integration with Excel

Excel is a standard within most businesses, and certainly Contact [8]. Their current prediction methods are implemented in Excel. We have observed that this is also the cause of much dissatisfaction, with the workbook taking several minutes to launch and requiring its own desktop to not delay other tasks. To develop a working demonstration sooner, we will use software more suited to mathematical analysis such as Python.

### Optimisation of the Entire Network

It has been made clear by Contact that optimisation in the field involves all facilities. However, they are numerous, and there are many different variations of each facility that would have to be manually implemented. This research will first focus on a section of the field with a smaller amount of distinct facilities for simplicity, and if time allows, may be expanded to the entire network.

### Global Optimisation

Our stochastic optimisation will first focus on optimisation of the expected value using linear programming. If the distributions of uncertain parameters can be estimated and computation time is not too long, global optimisation methods such as direct enumeration will also be experimented with but are not guaranteed.

## Significance of Research

With this research, we will deliver two outcomes: A proof-of-concept, and development of modelling in geothermal surface networks.

### Proof-of-Concept

A proof-of-concept will illustrate three main benefits to Contact:

1. Reduce the time spent updating data and performing tasks that can be automated such as regression, freeing staff to perform more advanced tasks,
2. Access to a transparent, user-friendly model that is not tied to a single operator,
3. A better understanding of uncertainty around sensor data, the inferred state of the system and outcomes of potential actions.

### Development of the Field on Geothermal Fields

This work will establish a precedent for the applications of optimisation and uncertainty techniques in any system where there are flows in a network with mechanical components, thermodynamic reactions and the need for corrective maintenance over time.

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