METHODOLOGY OF PRE-FEASIBILITY STUDY FOR A BINARY GEOTHERMAL POWER PLANT UTILIZING LOW-MODERATE TEMPERATURE HEAT SOURCES

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ABSTRACT

The exploitation of low-medium temperature geothermal reservoirs in New Zealand is a potential resource that does not yet have mature commercial technology solutions. The development and exploration of the geothermal potential of New Zealand has been limited to high temperature resources due to the abundance of high temperature geothermal resources, the wide-spread availability of cheap hydro-generated electricity and the availability of natural gas (Hunt, 2006). This study describes the methodology used in a pre-feasibility study for a binary geothermal power plant utilizing a low-moderate temperature heat source. This pre-feasibility study can be a useful tool for decision making processes in the preliminary study.

The methodology is applied to an existing geothermal well located in the Taupo Volcanic Zone (TVZ) in New Zealand. Three common working fluids, namely: n-pentane, R245fa and R134a are analyzed. The cycle designs considered are standard (Std) and recuperative (Rec) cycles. The results of the analyses indicate that the Std designs using n-pentane and R245fa are feasible to be used for the geothermal well. The Std design using R245fa is more economical than the design using n-pentane, however the design using R245fa has a lower Energy Return on Investment (EROI) than the design using n-pentane. The present methodology can be utilized to estimate pre-feasibility of binary geothermal power plants using geothermal wells at the initial stage, reducing risk and indicating potential for further engineering investigations.

1. INTRODUCTION

There are about 260 low temperature geothermal (LTG) energy sites in New Zealand associated with faults and tectonic features. There are also about 170 other thermal sites such as disused coal mines, abandoned oil and gas wells and water wells (Gazo, Lind, & Science, 2010). These resources are widely spread across North and South islands, with some associated with areas of young volcanism and structural settings.

The heat resources with temperatures above 150^{0}C are categorized as high-temperature heat sources, while moderate-temperature heat sources have temperatures between 90^{0}C and 150^{0}C. The low-temperature heat sources have temperature less than 90^{0}C. The most common technology for utilizing low-to-medium enthalpy geothermal energy resources is Organic Rankine Cycle (ORC) technology. LTG heat sources have a large potential as a low-carbon energy resource (Tester et al., 2006) for base-load power generation and combined heat and power generation. The three major types of geothermal power plant are dry-steam, flash-steam and binary-cycle (Yari, 2010).

This feasibility study is an important first step in the development investigation. Some previous studies have discussed feasibility studies for several ORC system applications. Husband and Beyene (2008) discussed the feasibility of a low-grade heat-driven Rankine cycle for solar power generation. Janghorban, Esfahani and Yoo (2014) studied a systematic approach for combining a system injection gas turbine (SIGT) and a multi effect thermal vapor compression (METVC) in a desalination system. Some researchers (H. C. Jung, S. Krumdieck, & T. Vranjes, 2014; Khatita, Ahmed, Ashour, & Ismail, 2014; Macián, Serrano, Dolz, & Sánchez, 2013) investigated the feasibility of ORC plants utilizing industrial waste heat. Uris, Linares, and Arenas (2014) conducted a technical and economic analysis of an ORC system for a cogeneration biomass plant in Spain. These researchers reported that ORC is feasible for their specific areas.

Several researchers (Kopuničová, 2009; Kose, 2007; MFGI, 2012; Nazif, 2011; New-Zealand-Geothermal-Association, 2013; Preißinger, Heberle, & Brüggemann, 2013) presented feasibility studies for geothermal power plants. They focused on particular case studies and the particular geothermal resources. None of them focused on development of a binary geothermal plant considering optimal design of the plant and economical aspects in a feasibility analysis.

Some researchers have investigated optimal design of the ORC systems using different heat sources. Franco et al. (Franco & Villani, 2009) proposed an optimization procedure for the design of binary geothermal power plants. Other researchers (Khennich and Galanis (2012), Madhawa Hettiarachchi, Golubovic, Worek, and Ikegami (2007), Shengjun, Huaixin, and Tao (2011) and Wang, Wang, and Ge (2012)) investigated the optimization of ORC designs for low-temperature heat source with the optimization of some performance parameters as their objective function. They analyzed ORC systems by a multi-criteria approach. However, a thermodynamic approach combined with an economic approach (Dale, Krumdieck, & Bodger, 2012) has not been reported in the literature for geothermal project feasibility analysis. It is important to use this methodology at the beginning of the potential projects to support development and management decision making.

The main objective of the study is to develop a methodology for the pre-feasibility study of a new binary geothermal power plant utilizing a low-moderate temperature heat resource. The methodology incorporates technical, thermodynamic, EROI and economic analyses for the energy conversion plant. The methodology does not include the uncertainty in costs of geothermal resource development.

2. METHODOLOGY

The pre-feasibility study is a critical early step in the design of a system because decisions made then can affect up to 80% of the total capital cost of a project (Bejan & Moran, 1996). In this section, a methodology is proposed for simplifying the assessment of a geothermal project for generating electricity using binary energy conversion technology. Figure 1 gives a flow-chart of the methodology outlined in the following steps:

1. Problem specification:
   The main parameters that should be specified are geothermal fluid temperature (T_{geo}), rejection temperature (T_{rej}), geothermal fluid pressure (P_{geo}), mass flow of geothermal fluid ($\dot{m}_{geo}$), ambient temperature (T_o) and ambient pressure (P_o).
2. Synthesis:
   Synthesis is concerned with combining separate elements into a thermodynamic cycle. The step consists of four elements that should be conducted in parallel.
   a. *Selection of working fluid*: the selection of the most appropriate working fluid has great implications for the performance of a binary plant (DiPippo, 2008). The criteria used for the selection of the working fluid are good physical and thermodynamic characteristics providing high thermodynamic performance and a high level of exploitation of the available heat source. The selected working fluid should be environmentally friendly indicated by low toxicity, minimised global warming potential and characteristics of low to zero in-flammability. In order to have good availability and low cost, several common working fluids in commercial binary geothermal power plants are considered.
   b. *Selection of cycle design*: another key aspect affecting the ORC system performance is the thermodynamic cycle design (Branchini, De Pascale, & Peretto, 2013). A basic binary geothermal power plant is designed using a standard (Std) cycle (DiPippo, 2008). A recuperative (Rec) cycle is used when T_{rej} has any temperature limitation. The design is able to increase the T_{rej} and thermal efficiency, because the addition of a recuperator increases heat absorbed from geothermal fluid. However, the design is less economical than a Std design and the regenerator will not increase the produced power (Valdimarsson, 2011). The schematic diagrams of both cycle designs are shown in Figure 3.
   c. *Selection of component types*: the type of four basic main components of the binary plant (turbine, evaporator, condenser and pump) should be selected for further analysis in the following steps. The selection depends on operating conditions and the size of the plant. The two turbine types used for a binary power plant are axial turbines and radial inflow turbine (DiPippo, 2008). The shell-and-tube heat exchanger with brine on the tube side and working fluid on the shell side is the most commonly type used for the binary plants. DiPippo et al. (2008) mentioned that the preheater can also use a horizontal cylinder and corrugated plate type. Moreover, they stated that the evaporator/superheater can use a horizontal cylinder or kettle-type boiler. The dry cooling system uses air-cooled condenser. Centrifugal pumps are widely used for industrial applications (Bejan & Moran, 1996) and this type is also used in geothermal areas. The materials of the main components should be selected for calculating component costs in the further economic analysis.
   d. *Determination of cycle parameters*: the assumption of parameter values is required to create a thermodynamic cycle for the binary plant. Table 1 shows the parameter values that are usually used by various ORC research groups. A few degrees of superheat is required to avoid liquid droplets at the inlet of the turbine, although the superheated vapour condition gives penalties in terms of power and costs (Toffolo, Lazzaretto, Manente, & Paci, 2014). The superheat value in Table 1 may be changed for the optimization purpose.

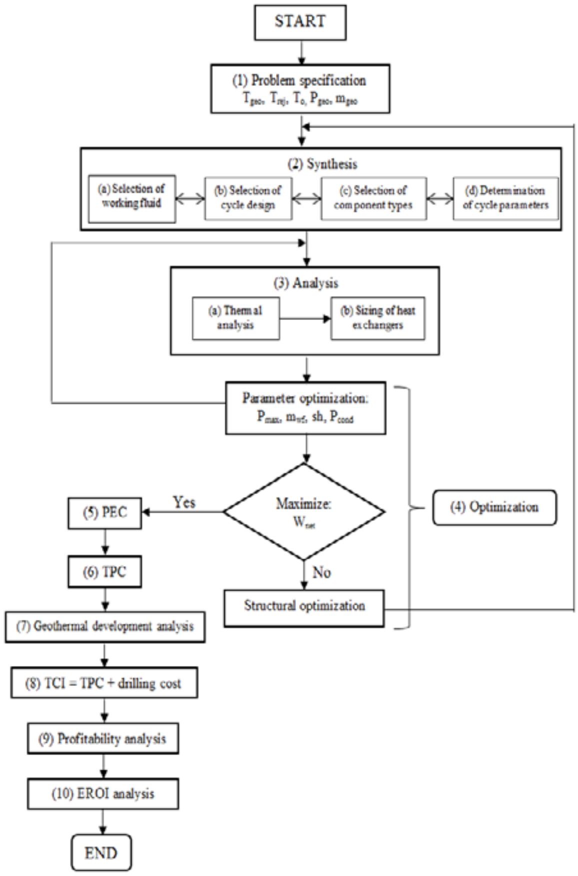

Figure 1: Flow chart of a pre-feasibility study for development of a binary geothermal power plant.

Table 1: Initial assumptions for thermodynamic cycle

Assumptions of cycle parameter	Value
Superheat (sh) (^{0}C)	5
Sub-cooling (^{0}C)	5
Pinch Point (^{0}C)	5
Turbine isentropic efficiency (%)	85
Turbine mechanical efficiency (%)	98
Pump isentropic efficiency (%)	80

3. Analysis:
   Analysis involves thermal analysis of the system and the components and sizing of heat exchangers.
   a. *Thermal analysis* generally entails solving mass and energy balances in the overall thermodynamic cycle

and in each component of the cycle. The thermal analysis here is implemented based on the strategy proposed by Franco and Villani et al. (2009). The strategies divide the binary cycle into three sub-systems (thermodynamics cycle, evaporator and condenser) and two hierarchical levels which sequentially define system level (thermodynamic cycle) and component level (evaporator and condenser). Figure 2 shows hierarchical organization proposed by Franco et al. At the system level, the thermal problems (mass and energy balances) are solved by thermodynamic variables matching between the binary cycle and the geothermal resource. At the component level, the convergent results from the system optimization level produce the input data for the detail design of components (evaporator and condenser). The results of the optimum component design (pressure losses (Δp), pumping power (W_T) and fan power (W_{fans}) are iterated at the system level. Thus, the results of the component level optimization can affect the results of the first level optimization particularly in the design of the dry cooling system.

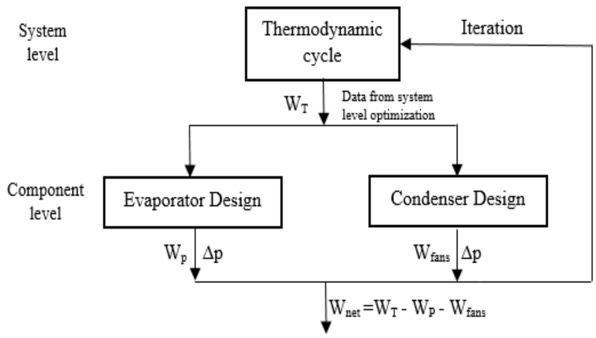

Figure 2: Hierarchical organization for the thermal analysis in the design of binary plants

b. *Sizing of heat exchangers*. The dimensions of the various sections of the heat exchangers (pre-heater, evaporator, superheater and condenser) are calculated by considering the required heat transfer, the allowed pressure drop and the minimum allowed temperature difference.

4. Optimization:
   Optimization involves two general optimization forms: parameter optimization and structural optimization. In parameter optimization, four decision variables are utilized to evaluate all the remaining dependent quantities of the system: (1) cycle maximum pressure (P_{max}); (2) mass flow of the working fluid (m_{WF}); (3) degree of superheating (sh), measured from the specific entropy of the point on saturated vapour curve for subcritical cycles; (4) condensation pressure (P_{cond}) (Toffolo et al., 2014). The objective is to maximize net electrical power output (W_{net}). This factor is crucial in the economic anlysis of geothermal power plants. The power output is even more crucial than exergy efficiency (Preißinger et al., 2013). In structural optimization, the optimization occurs when the re-selection of system elements is required to achieve an acceptable objective function. Structural optimization is indicated in Figure 2 by the returning arrow linked to the synthesis step. The structural optimization process generally consists of the re-selection of the working fluid and the cycle design.
5. Purchased equipment costs (PEC):
   The first step for any detailed cost estimation is to evaluate the PEC. The type of equipment, its size, and construction materials are determined from previous flow chart steps. The best source for estimating the cost can be obtained directly from vendors' quotations. At the preliminary stage, some background literature provides the cost estimations from various estimating charts and software packages.
6. Total plant costs (TPC):
   The TPC includes the plant capital costs and steam gathering system costs that are required for the geothermal plants. The plant capital costs accumulate four factors: direct costs, indirect costs, contingency and fee and auxiliary facilities. According to Turton, Bailie, Whiting, and Shaeiwitz et al. (2008), the plant capital cost can be evaluated by grassroots cost (C_{GR}):

$$C_{GR} = 1.18 \sum_{i=1}^{n} C_{BM,i} + 0.50 \sum_{i=1}^{n} C_{BM,i}^{0} \quad (1)$$

   where n represents the total number of pieces of main equipment, C_{BM} is the sum of the direct and indirect costs, and C_{BM}^{o} is the bare module cost evaluated at base conditions. The value of 15% and 3% of the bare module cost are assumed for contingency costs and fees, respectively. The value of 50% is assumed for auxiliary facility costs because the binary power plant is assumed to be built on undeveloped land. The steam gathering system cost is the costs for the networking of pipes connecting the plant with all production and injection wells. For binary systems, only the hot brine line and the cooler brine injection lines are required. Entingh and McLarty et al. (1997) proposed the system cost of 95 USD per kW for binary power systems. NGGPP (1996) et al. suggested the lower cost of the steam gathering system cost at 30 USD per kW.
7. Geothermal development analysis:
   a. Costs
   The costs represent the drilling cost. The higher uncertainty is associated with the cost of drilling, because the cost is affected by resource characteristics which influences both the cost of individual wells and the total number of wells that must be drilled (Hance, 2005). Stefansson (2002) suggested drilling costs based on the analysis result of the drilling in 31 geothermal fields with capacities in the range 20-60 MW in the world. The drilling cost was calculated according to a correlation between the total investment cost and surface equipment cost (the plant itself and the steam-gathering system). In order to update this cost from 2002 to the end of 2014, the producer cost index for drilling of oil and gas wells was used (data from Bureau of Labour Statistics, U.S. Department of Labour). The producer cost index was 115.6 and 450.7 in 2002 and December 2014, respectively. Table 2 summarizes the drilling costs of geothermal power plants in 2014.

Table 2: The drilling cost of geothermal power plant in 2014 (Stefansson, 2002)

Drilling cost	Expectation value (USD/kW)	Range within a standard deviation (USD/kW)
In a known field	1170	1130-1949
In an unknown field	1805	1403-3119

b. *Project duration*
According to the geothermal energy association, a new geothermal power plant project takes a minimum of 3 to 5 years to start producing the electricity. Furthermore, Stefansson (2002) mentioned that a typical time schedule for a stepwise development of a geothermal field is about 6 years consisting of 3 years for reconnaissance, surface exploration and exploration drilling and 3 years for production drilling and power plant.

8. Total capital investment (TCI):
The TCI is the total investment amount that includes the TPC and drilling cost.
9. Profitability analysis:
The analysis is to evaluate the expected profit from the investment by implementing a method of profitability analysis such as discounted payback (DPB), net present value (NPV) and internal rate of return (IRR).
10. EROI analysis:
The analysis has a purpose to measure the future energy benefit from energy expenditure.

3. APPLICATION OF THE METHODOLOGY FOR A CASE STUDY

3.1 Problem specification

A case study was used to illustrate the implementation of the methodology. Table 3 shows the actual data of a geothermal well and cooling air from a location in the Taupo Volcanic Zone (TVZ) in New Zealand.

Table 3: Data of a geothermal well and cooling air

Data	Value
T_{geo} (^{0}C)	131
T_{rei} (^{0}C)	92
P_{geo} (bar)	9
$\dot{m}_{geo}$ (kg/s)	520
T_o (^{0}C)	20
P_o (bar)	1.53

3.2 Synthesis

3.2.1 Selection of working fluid

The working fluid selection criteria of this work focuses on the three common working fluids used in the commercial ORC power plants, which are n-pentane, R245fa and R134a.

3.2.2 Selection of cycle design

This work considers two types of the cycle design: Std and Rec cycles. The schematic diagram of both cycles is shown in Figure 3a and 3b. The Std design consists of a pump, an evaporator powered by geothermal fluid, a turbine and a condenser. The evaporator here represents preheater and evaporator. The generated high pressure vapour flows through the turbine and its heat energy is converted to work. The turbine drives the generator and electrical energy is produced. The exhaust vapour exits the turbine and flows to the condenser where it is condensed into working fluid. The working fluid with low boiling point is pumped to the evaporator, where it is heated and vaporized into high pressure vapour. The high pressure vapour flows back to turbine and a new cycle starts again. The Rec design of ORC has a recuperator that can be installed as a liquid preheater between the pump outlet and the turbine outlet as illustrated in Figure 3b. This reduces the amount of heat needed to vaporize the fluid in the evaporator.

3.2.3 Selection of component types

A single radial turbine is considered in this work and the shell-and-tube heat exchangers are used for evaporator and recuperator. An air-cooled condenser must be selected because there is no water supply at the geothermal resource site. A centrifugal pump is selected for the feed pump. In addition, carbon steel (CS) is used as the material for cost calculation of the main plant components

Table 4: Properties of working fluids and list of ORC manufacturers (Quoilin, Van Den Broek, Declaye, Dewallef, & Lemort, 2013)

Working fluid	T_c (^{0}C)	P_c (bar)	Manufacturer
n-pentane	196.5	33.6	ORMAT (US)
R245fa	154.0	35.7	Bosch KWK (Germany), Turboden pureCycle (US), GE CleanCycle (US), Cryostar (France), Electratherm (US)
R134a	101.1	40.6	Cryostar (France)

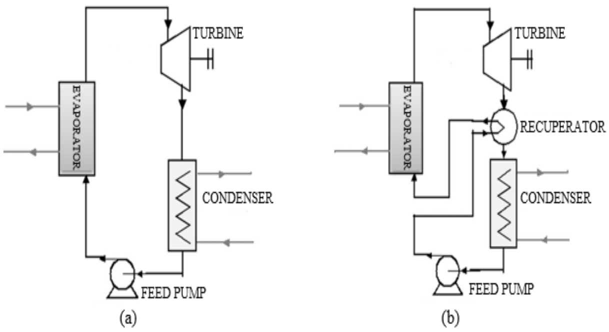

Figure 3: Schematic diagram of an ORC: (a) Std cycle and (b) Rec cycle

3.3 Analysis

The authors used the Aspen plus version 8.6 environment (AspenTech, 2014) to carry out the thermal analyses and calculations for the case study. The thermodynamic properties of the working fluids were calculated using the cubic Peng-Robinson equation of state (EOS) (Peng & Robinson, 1976). The heat exchanger models are constructed by integration of the Aspen plus and Aspen EDR (Exchanger Design & Rating) software from Aspen Technology, Inc (AspenTech, 2014).

3.4 Optimization

3.4.1 Objective function

The objective function to be maximised is W_{net}. The W_{net} is defined as turbine power pump and fan power deducted:

$$W_{net} = W_T - W_p - W_{fans} \quad (2)$$

The specific power consumed by the fans of the air cooled condenser is assumed to be 0.15 kW per kg/s of air flow (Toffolo et al., 2014).

3.4.2 Thermodynamic optimal design parameters

The optimal design parameters using three working fluid and two cycle designs are summarized in Table 5. The recuperative cycle uses only n-pentane, because the positive impact of a recuperator is higher for dry working fluids such as n-pentane than wet working fluids.

The W_{net} of optimal designs with n-pentane and R245fa are comparable at around 11 MW, but the W_{net} of design with R134a is significantly lower than others at 6,979.9 kW. This occurs because the maximum pressure of the system is significantly higher than others at 40.5 bar and the R134a design has the highest mass flow rate of working fluid. Therefore, the turbine power of the R134a design has deducted the highest pump power of 4,240.8 kW. The Std design with R134a has already been eliminated as not being feasible for this resource.

Table 5: Optimum design parameters of the alternative designs

Fluid Cycle design	n-pentane Std	n-pentane rec	R245fa Std	R134a Std
T_{rej} (^{0}C)	92	96.5	92	92
m_{wf} (kg/s)	184	184	366.2	420.6
P_{max} (bar)	7	7	16.1	40.5
$T_{T,in}$ (^{0}C)	113	113	116	121
P_{cond} (bar)	0.82	0.82	1.79	7.7
T_{cond} (^{0}C)	67.9	35.4	59.8	48.9
$m_{air,\ ACC}$ (kg/s)	7350	7700	7800	8400
W_T (kW)	12,600.4	12,600.4	12,858.9	12,480.7
W_P (kW)	253.9	253.9	543.3	4,240.8
W_{fans} (kW)	1,117.5	1,155	1,170	1,260
W_{net} (kW)	11,229	11,191.5	11,145.6	6,979.9

3.5 Economic evaluation

3.5.1 PEC

The PEC of pumps and turbines are estimated using a correlation from Turton et al. (Turton, 1998). The purchased equipment cost evaluated for base conditions (PEC^0) is expressed by:

$$\log_{10} PEC^0 = K_1 + K_2 * \log_{10} Y + K_3 * (\log_{10} Y)^2 \quad (3)$$

where K values are given in Table 6 and Y is the output power in kW. The number of pumps is calculated, so that the maximum Y is less than or equal to 300 kW. A single radial turbine is considered in this work and the cost equation is used beyond its maximum value at 1500 kW.

Table 6: Parameters for the calculation of purchased equipment costs in equation (3)

Component	Y	K_1	K_2	K_3
Pumps	Power [kW]	3.3892	0.0536	0.1538
Radial turbines	Power [kW]	2.2476	1.4965	-0.1618

Deviations from the base conditions (base case of material: carbon steel and operating at near ambient pressure) are handled by using a pressure factor (F_p) and a material factor (F_m) that depend on the equipment type, the system pressure and material construction. The F_p is calculated by the following general form:

$$\log_{10} F_p = C_1 + C_2 \log_{10}(p) + C_3(\log_{10}(p))^2 \quad (4)$$

where p is the system pressure and C_1, C_2 and C_3 are coefficients given in Table 7. Equation (4) is valid for a pressure range of the pumps between 10 and 100 barg. But the maximum pressure of designs with pentane is 7 bar, which is out of the equation range, and therefore the F_p is assumed to be 1.

Table 7: Parameters for the calculations of the pressure factor and bare module factor in Equations (4) and (8)

Component	C_1	C_2	C_3	F_m	B_1	B_2
Feed pump	-0.3935	0.357	-0.00226	1.5	1.89	1.35

Thus, the actual purchased equipment cost *(PEC)* is expressed by:

$$PEC = PEC^0 . F_p . F_m \quad (5)$$

where PEC^0 and F_p are calculated by equations 3 and 4, respectively and F_m is given in Table 7.

The equation for updating PEC due to changing economic conditions and inflation (Turton et al., 2008) is:

$$C_{new} = C_{old} \left(\frac{I_{new}}{I_{old}}\right) \quad (6)$$

where C and I are cost (referring to PEC) and cost index, respectively. Subscripts old and new refer to base time when cost is known and to time when cost is desired, respectively. The data for cost indices are taken from info share of New Zealand statistics (StatisticsNewZealand, 2014) in Table 8.

Table 8: Capital goods price index for the calculation of updated PEC prices in equation (6)

Components	Year	
	2001	2014
Pump	1048	1381
Radial turbine	1064	1088

The cost calculation of heat exchangers is performed by Aspen EDR version 8.4 (Exchanger Design & Rating) software. The cost of the heat exchanger is estimated by the software once the geometry of each component part of the heat exchanger has been calculated. The calculations of the costs have considered the values of F_p and F_m.

Figure 4 shows the results of PEC calculations for three alternative designs. The PEC of the Std designs with n-pentane and R245fa is comparable at 25,606 and 22,994 thousand USD. However, the PEC of Rec design with n-pentane has a significantly higher PEC. This occurs because of the additional recuperator cost and because the smaller temperature difference in evaporator and condenser causes a higher heat transfer requirement, particularly in the condenser. The PEC of the Rec design is 1.76 times the PEC of Std design with the same working fluid (n-pentane). Therefore, the Rec design with n-pentane has to be eliminated for the consideration as not being feasible for further investigation.

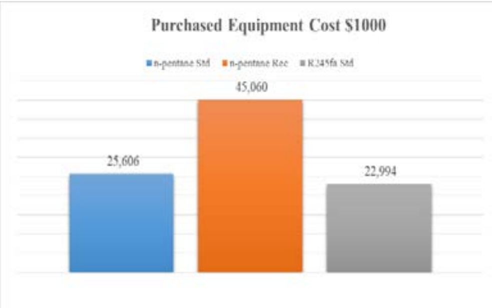

Figure 4: Total purchased equipment cost estimated in 2014 USD

3.5.2 TPC

The TPC consists of two main cost categories: the plant capital costs and steam gathering system costs. The estimation of the plant capital costs is performed based on the module costing technique (MCT) (Turton et al., 2008) and the steam gathering system costs are assumed at 30 USD per kW according to NGGPP in 1996. The update of the cost used capital good price index with asset type: other fabricated metal products from info share of New Zealand Statistics (StatisticsNewZealand, 2014). The price index increased by 36.3% from 1996 to 2014, therefore the cost in 2014 is 41 USD per kW.

In the module costing technique, the bare module cost factor (F_{BM}) is used to account all the direct and indirect costs:

$$C_{BM} = PECxF_{BM} \qquad (7)$$

where C_{BM}, named "bare module equipment cost", is the accumulation of cost between the direct and indirect costs. The F_{BM} for turbine with material of carbon steel is 3.5 and the F_{BM} for pump is calculated by:

$$F_{BM} = B_1 + B_2 F_p F_m \qquad (8)$$

where B_1, B_2 and F_m values are given in Table 7 and the pressure factor (F_p) is calculated by equation 4.

The heat exchangers costs from Aspen EDR assumed that the calculation results have considered the direct and indirect costs, and so that the results are equal to C_{BM}. According to AspenTech (2014) support center, the exchanger cost includes three elements, which are the material cost, the labor cost, and the mark-ups on material and labor.

Equation (1) is used to evaluate the grassroots cost that represents the TPC. Table 9 displays the results of TPC and specific investment cost (SIC). The SIC is calculated by dividing TPC with the optimal W_{net}. The SIC of Std designs with n-pentane and R245fa is 4,069 USD/kW and 3,743 USD/kW, respectively. These values are fairly close to those shown by Quoilin et al. (2013). They stated that the ORC module costs for geothermal application with the size of few MWs is 3,000 EUR/kW (about 3,750 USD/kW). Roos, Northwest, and Center (2009) reported that the ORC systems have installed costs ranging from 2000 USD/kW to 4000 USD/kW. H. Jung, S. Krumdieck, and T. Vranjes (2014) reported that most of the systems (about 90%) assembled with the refrigerant system components have the specific capital cost ranging from 2,000 USD to 3500 USD/kW. The SIC of ORC system coupled with geothermal resources is a bit higher due to the additional costs for the steam gathering system.

Table 9: Total plant costs (TPC) and specific investment costs (SIC) of the three optimal ORC designs.

Cycle Design	TPC (USD)	SIC (USD/kW)
n-pentane Std	45,687,039	4,069
R245fa Std	41,719,472	3,743

3.5.3 Geothermal development analysis

The geothermal field in this work is located in the Taupo Volcanic Zone (TVZ) in New Zealand where several geothermal power plants have been constructed. Therefore, the drilling cost is assumed to be similar to that in a known field and the expected value is taken from Table 2 at 1170 USD per kW.

The construction time for the geothermal power plant in this work is assumed to be 3 years. The plant can produce the electricity in the fourth year at the Wnet rate, multiplied by the plant availability factor, which for commercial geothermal plants is around 90% (Coskun, Bolatturk, & Kanoglu, 2014).

3.5.4 Profitability analysis

3.5.4.1 Calculation methodology

Net present value (NPV) and discounted payback (DPB) are used to evaluate profitability of the projects in this work. Bejan and Moran et al. (1996) defined the NPV as the sum of the present values of incoming and outgoing cash flows over a period of time:

$$NPV = \sum_{i=1}^{N} \frac{R_i}{(1+q)^i} - TCI \qquad (9)$$

where N is the equipment lifespan, q is the interest factor, TCI is the total capital investment, and R is the annual income.

The estimation of plant lifetime is about 30 years (Sullivan, Clark, Han, & Wang, 2010). The electricity revenue price is about 0.083 USD/kW with 3% of electrical price increment per year over the plant lifetime (H. Jung et al., 2014). According to the Geothermal Energy Association (Hance, 2005), the total operation and maintenance (O&M) costs is expected to average 0.024 USD/kWh where the cost includes operation cost of 7 USD/MWh, power plant maintenance of 9 USD/MWh and steam field maintenance & make-up drilling costs of 8 USD/MWh. The value of inflation rate was taken from New Zealand Consumer Price

Index (CPI) where the inflation rate has averaged around 2.7% since 2000 (Zealand). The financial model used the assumptions that 20% of TIC is spent in the first two years for exploration and confirmation of resources and the remaining 80% is invested in the third year. Table 10 summarizes the assumed parameters used for calculating NPV and DPB in this study.

Table 10: Assumptions for calculating NPV and DPB

Plant lifetime	30 years
Plant availability	90%
Electricity revenue unit price	USD $0.083/kWh
O&M cost	USD $0.024/kWh
Annual electricity price escalation	3.0%
Inflation rate	2.7%
Discount rate	10%

3.5.4.2 Calculation results

Table 11 shows the profitability factors for the two candidate designs. Both designs have almost the same values of TCI, NPV and DPB, where the design using R245fa has better economic performance than design with n-pentane. The NPV of the designs with n-pentane and R245fa is USD 34,296,419 and USD 37,059,060, respectively. The DPB of both designs is consistently between 15 years and 16 years. The total cost of investment ranges from USD 58,824,956 to USD 54,759,837.

Table 11: The results of NPV and DPB for two design alternatives

Cycle Design	TCI (USD)	NPV (USD)	DPB (Years)
n-pentane Std	58,824,956	34,296,419	15.96
R245fa Std	54,759,837	37,059,060	15,00

3.5.5 EROI analysis

3.5.5.1 Calculation methodology

The energy return on investment is given by general form (King & Hall, 2011):

$$EROI = \frac{E_{out}}{E_{in}} \quad (10)$$

where E_{out} is the summation of all energy produced for a given timeframe and E_{in} is the sum of direct and indirect energy costs. The *EROI* of an energy production project is defined as (Murphy, Hall, Dale, & Cleveland, 2011):

$$EROI = \frac{E_g}{E_c + E_{op} + E_d} \quad (11)$$

where E_g is the energy produced over the lifetime of the project, E_c is total construction energy, E_{op} is energy required to operate and maintain the project and E_d is energy required for decommissioning of the plant. The E_d in this work is neglected.

The energy intensity value is often used to convert dollars to energy units, because the availability of energy data is limited for high level energy analysis. The average energy intensity for the U.S. economy in 2005 was 8.3 MJ/USD (Murphy et al., 2011). They recommended the use of the consumer price index to modify that value for another nearby year. The consumer price index from Bureau of Labor Statistics, U.S. Department of Labor was used. The conversion result of the average energy intensity in 2014 was 6.85 MJ/USD.

3.5.5.2 Calculation results

The EROI for Std n-pentane and Std R245fa is 5.35 and 4.83, respectively. Table 12 details the calculated results of E_g. E_c, and E_{op} for each design alternative. The EROI of Std n-pentane is higher than EROI of R245fa, because the design has a higher system pressure and mass flow rate impacting to a higher pump power, resulting in a higher value of E_{op}.

The study of EROI calculation results with EROI literature reveals that the results of some researchers are fairly close to the EROI calculated in this paper. Frick, Kaltschmitt, and Schröder (2010) used current data from European geothermal plants to calculate an average EROI of about 4.5 for low temperature binary geothermal plants. Southon and Krumdieck (2013) calculated that EROI of small geothermal power plants had an EROI of 3.2 and 2.4 for the Waikite system and the Chena power plant, respectively. Icerman (1976) calculated that the EROI of a flash-steam geothermal plant between 7.0 and 11.3. The flash-steam geothermal plants have a higher EROI than binary geothermal power plants.

Table 12: The results of EROI calculation for two design alternatives

Item	Values		Units
	Std n-pentane	Std R245fa	
E_q	10,729	10,949	TJ
E_C	403	375	TJ
E_{op}	1,604	1,892	TJ
EROI	5.35	4.83	-

4. CONCLUSION

The main objective of this work was to propose a methodology of pre-feasibility study for a new binary geothermal power plant utilizing moderate temperature heat sources by considering technical, thermodynamic, EROI and economic analyses. This work still deals with uncertainty in cost analyses, as the scope of cost breakdown included in the capital cost is quite variable and unclear in the preliminary study. Furthermore, the drilling cost has higher uncertainty due to resource-specific characteristics. Analyzing geothermal investment costs is a long and difficult process. The change of assumptions in further analyses will impact the change of profitability and EROI results. However, this methodology has included a typical cost breakdown of geothermal power plant projects.

The methodology is applied to an existing geothermal well located in the Taupo Volcanic Zone (TVZ) in New Zealand. Three common working fluids n-pentane, R245fa and R134a and two cycle designs Std and Rec cycles are analyzed. The results of the analyses indicate that the design using R134a has the lowest net electrical power output (W_{net}) at 6,980 kW. The PEC of the Rec design is very expensive. The total PEC of Rec design is about 1.76 times PEC of Std design with the same working fluid. Therefore, both designs were not considered for further analyses. Furthermore, the Std designs with n-pentane and R245fa are feasible to be implemented in the geothermal resource. The profitability analysis reveals that the Std design with R245fa is more economical than the Std design with n-pentane, and the different NPV and DPB of both designs are very small at 8 % and 6.4 %, respectively. The EROI comparison of both designs shows that the EROI of a Std design with n-pentane is higher than the EROI of a Std design with R245fa at 5.35 and 4.83, respectively. Considering the superior availability of n-pentane over R245fa in the market, the Std design with n-pentane is preferable.

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