Integrated Thermo-economic Modeling of Geothermal Resources for Optimal Exploitation Scheme Identification

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Abstract: This paper details the development of a systematic methodology using thermo-economic modeling that can be used to identify the optimal exploitation schemes of geothermal resources. A multi-period approach is used, integrating the superstructure of exploitable resources with the superstructure of conversion technologies and multiple demand profiles. In the example case, exploitable resources include an enhanced geothermal system, a deep aquifer, and a shallow aquifer. Power generating systems considered are organic Rankine cycles and both single and double flash steam cycles, which can be used for combined heat and power production. Heat pumps are also considered, as well as back up systems in case geothermal resources alone cannot fully satisfy demand. Periods considered for the demand profiles of district heating and cooling are summer, winter, inter-seasonal, and extreme winter and summer conditions. These are based on the city of Nyon, Switzerland for the example case. In the next step, process integration techniques are then used to design the overall geothermal system. The economic and thermodynamic performance of the system is then calculated. Finally, an evolutionary algorithm is employed to determine the optimal exploitation schemes and system configuration across the multiple periods, with exergy efficiency and annual profit as objectives.

Keywords: Energy systems, Geothermal, Multi-objective optimization, Multi-period, Process design, Renewable energy conversion, and Simulation

1. Introduction

There has been recent interest in the use of geothermal resources to deliver utility scale electricity and district heating and cooling [1]. The first step developing a geothermal system is the identification of the resource. Geothermal resources can exist in a variety of forms, the majority of which fall into natural hydrothermal systems, geopressured systems, enhanced geothermal systems (or hot dry rock), magma, and ultra low-grade systems [1].

Next, there must be a determination of the service that the geothermal resource would provide. This must take into account nearby cities and their respective demand for electricity, heating, and cooling. As the demand for these services changes throughout the year, it is useful to consider the system for all the periods for which it is used.

Finally, it must be decided what is the best way to convert the geothermal source into the useful service to be delivered. Conversion technologies can include a number of power cycles including flash systems and organic Rankine cycles. Furthermore, a wide range of configurations for each of these conversion systems exists, including options for meeting a district heating demand. This includes the type of conversion and distribution system and in what ways the geothermal source is utilized (heat extraction, injection, or storage) and at what depth these actions are to take place [2].

For each of these configurations of the above-mentioned factors, there will be a set of associated thermodynamic and economic performance indicators. The need for a tool to evaluate the various resources, conversion technologies, and demand combinations using these performance indicators is readily apparent in order to identify the optimal configurations of the system. This can be achieved by the use and optimization of a model that can simulate the configurations and their associated performance within the multiple demand profiles throughout the year.

Girardin and Marechal (2007) [3] have applied pinch analysis methods for the optimal integration of the geothermal conversion system. This required modeling of the major geothermal conversion systems and their multi-objective optimization. However, this study does not take into account geothermal resource parameters, but solely the conversion technology parameters. Analysis of the multi-period problem has been explored by studies [4] and [5], but none pertain specifically to geothermal systems and the specific challenges they present.

This paper presents a systematic methodology for optimizing energy conversion system design and to identify the optimal exploitation scenarios of geothermal systems within the multi-period framework.

2. Methodology

The methodology is developed using a computational platform that creates interfaces between different models that represent the energy system design. The resolution of the system follows the diagram in Fig. 1. If the results of only a single set of decision variables are desired, the system optimization step is not performed.

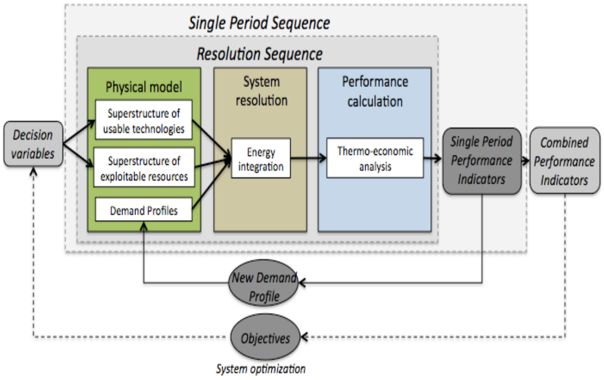

Fig. 1. Resolution Sequence

The multi-period aspect of the system specifically affects the demand profiles and as such, the system performs the resolution sequence for each demand period. The physical model stage includes the superstructures of usable technologies, exploitable resources, and demand profiles. System resolution uses process integration techniques to optimize heat exchange and to size various system components. A thermo-economic analysis is then performed to evaluate the performance of the system configuration. Iterations of the sequence can be performed in order to run an optimization while varying selected decision variables.

2.1. Physical model development

Physical models in this system are represented using process flow diagrams in the flowsheeting software Belsim-Vali. A separate model is created for each resource and conversion technology. This allows for calculating the operating conditions and thermodynamic states associated with a given set of input parameters. Demand profiles are implemented within the system resolution.

2.1.1 Resource Models

For the application of the methodology, three hypothetical geothermal resources are considered in the resource superstructure. They are an enhanced geothermal system (EGS), a deep aquifer (DA), and a shallow aquifer (SA). For each one, the geothermal fluid is assimilated to pure water. The table below contains the default parameters of these resources, where T1 and T2 refer to the production and injection temperatures, respectively.

Table 1. Resource Parameters

	EGS	DA	SA
T1 [K]	473.15	363.15	285.15
T2 [K]	373.15	318.15	283.15
Flow [kg/s]	50	20	20

The EGS model is based on the work done by Haring [6] in his paper on deep heat mining of an enhanced geothermal system in Basel, Switzerland. The DA and SA systems modeled in this study refer to a natural hydrothermal system that can produce fluid spontaneously. For the DA, the model is based on an existing system in Riehen, Switzerland, which is used to provide district heating [7]. All models use reinjection of the geothermal fluid. The amount of available heat is determined from the resource models. Additionally, the drilling depth is calculated using an assumed thermal gradient of 4°C for every 100 meters of drilling depth [6].

2.1.2 Conversion Technologies

Ten separate ways to convert energy from the geothermal resources are considered for the application of the methodology (see Fig. 2).

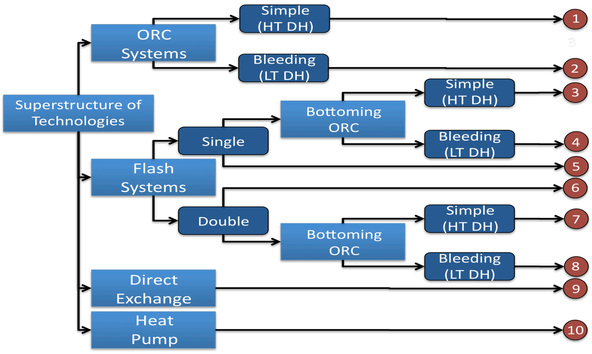

Fig. 2. Geothermal Conversion Technologies

In Fig. 2, ORC refers to an organic Rankine cycle. The ORC with bleeding is a cycle that includes intermediate bleeding in the turbine. HT DH and LT DH stand for high temperature district heating and low temperature district heating, respectively. LT DH uses intermediate bleeding in the turbine. The default working fluid in the ORC is iso-butane and the heat pump model uses ammonia as the working fluid. Direct exchange between the geothermal fluids and cooling stream with the district heating and district cooling streams is also considered. A boiler is included as a back up option in case the geothermal system is unable to meet the district heating demand alone.

2.1.3 Demand Profiles

Finally, it is necessary to consider the demand for the energy services and how this changes throughout the year. These periods and their associated demand profiles can be viewed in Table 2 below. DH and DC stand for district heating and district cooling, respectively.

Table 2: Demand Profiles

	DH (MW)	DC (MW)	Hours	Ambient (°C)
Extreme Cold	30.0	0.0	40	-6.0
Winter	20.0	0.0	2900	1.0
Inter-Seasonal	10.0	7.0	2700	10.0
Summer	5.0	10.0	400	14.0
Extreme Hot	1.0	10.0	20	17.0

For the application, the demand profiles are based on data for the city of Nyon, Switzerland. The data are derived from a statistical demand calculation of the number and type of buildings. Factors affecting the individual building consumption include construction period and utilization. Geographical data including building position and area are also taken into account [8]. Demand for electricity is not included within the demand profiles. It is assumed that the geothermal system will be providing services for a grid connected region and as such, shortcomings in electricity generation will be met from other sources on the grid.

2.2. System Resolution

System resolution refers to the determination of the various heat loads and the relevant equipment sizing and integration. At this stage, the energy flows (the hot and cold streams of the system) calculated by the physical model are provided as inputs to perform the energy integration. This aims to determine the optimal integration of the energy conversion system to satisfy the demand of the current period using the available resources. The demand period heavily influences this as it affects the size of the district heating and district cooling streams. Process integration techniques are then used, whose methodology is defined in [9]. After this step, it is possible to determine the design of the heat exchanger network. This includes the minimum number of heat exchangers, the total heat exchanger area, and the sizing of any variable hot or cold streams and the units they belong.

2.3 Performance Indicators

After the completion of energy integration, the thermodynamic conditions of the system are defined and the necessary equipment identified and sized. Thermodynamic and economic performance indicators are now computed to evaluate the performance of the system configuration.

2.3.1 Thermodynamic Performance Indicators

Of interest to this study is how efficiently the conversion systems utilize the geothermal resources to deliver useful services. As such, energy efficiency, exergy efficiency, and electrical efficiency are calculated. Exergy efficiency is particularly relevant in the case of geothermal systems, as it allows for a better evaluation of the system in terms of electricity and district heating and cooling production [10]. Although other thermodynamic indicators are defined, this analysis will focus on exergy. Exergy efficiency will be defined as shown in (1).

$$ex_{eff} = \frac{\dot{E}_{Net\_Electric} + \dot{Ex}_{Heating} + \dot{Ex}_{Cooing}}{\dot{Ex}_{EGS} + \dot{Ex}_{DA} + \dot{Ex}_{SA} + \dot{Ex}_{Cool} + \dot{Ex}_{Boiler}}, \quad (1)$$

Note that if the net electricity is negative, the term will be made positive and divided by an assumed exergetic electrical generation of 0.35 and added to the denominator. This creates a significant penalty for a system that imports electricity. Since all exergy terms besides the net electricity are related to thermal streams, each one will be defined as seen in (2).

$$\dot{Ex} = \dot{Q} \cdot (1 - \frac{T_a}{T_{lm}}), \quad (2)$$

$\dot{Q}$ is the heat load of the stream and T_a is the ambient temperature. T_{lm} is the log mean temperature difference and is defined in (3).

$$T_{lm} = \frac{T_{in} - T_{out}}{\ln(T_{in} / T_{out})}, \quad (3)$$

Each thermodynamic indicator is computed for each demand period. Combined indicators are found taking a weighted average considering the operating hours of the period, as shown in (4).

$$ex_{total\_eff} = \frac{\sum_{i=1}^{6} ex_{eff,i} \cdot period_i}{8760}, \quad (4)$$

2.3.2 Economic Performance Indicators

Costs were estimated for the relevant capital, operations and maintenance, and fixed costs. The equipment cost is calculated using the data from [11] and [12]. The Marshall and Swift index is used to actualize these costs. Drilling costs were based on data from the WellCost Lite model as outlined in [13]. Equation (5) shows the general formulation, based on drilling depth, in million USD.

$$CI_{drilling}(D) = 3 \times 10^{-8} \cdot D^2 + 0.0019D - 1.3958, \quad (5)$$

Drilling at shallow depths is assumed to costs approximately 100USD per meter of drilling depth. The cost of the district heating network was based on data from the Riehen system in northwest Switzerland [7].

$$CI_{DH\_Network} = 38.7 \cdot DH_{load}, \quad (6)$$

Here, the maximum district heating load (usually extreme winter) will be used to size the system.

Cooling tower costs are based on actual cooling tower costs and then scaled based on size as recommended by [14].

$$CI_{Cooling} = 154179 \cdot (Q_{Cooling} / 5193)^{0.93} \quad (7)$$

Other direct and indirect costs were estimated using relationships between the total purchased equipment costs and total direct costs [14]. The total capital investment was annualized using an interest rate of 0.06 and an assumed project lifetime of 15 years. The total operating costs are comprised of import costs, export costs, maintenance costs, and man power costs. It is assumed that there are no import costs associated with the extraction of the geothermal fluid. However, any purchased electricity or fuel for the back up boiler is considered here. Export costs are actually the profits produced by the system: electricity, district heating, and district cooling sold.

Maintenance costs will vary depending on the system used. For the flash systems, it is assumed to be \$100/kW/year [15]. ORC maintenance costs will be much lower, and are estimated to be \$10/kW/year. Employment or the specific manpower costs for all systems are estimated to be \$68/kW/year. This is assuming that 1.7 jobs per MW of capacity and each job is compensated \$40,000 [16]. The fixed cost, F, is assumed to be \$613/kW/year, independent of the type of system [13]. Operating costs are calculated for each period and then summed. Note that equipment costs are based on the maximum needed over the multi-period problem. The total annual cost of the system is therefore seen in (8).

$$C_{Annual} = CI_{Annual} + \sum_{p=1}^{6} OPEX(p) + F \quad (8)$$

A negative total annual cost signifies a net profit. This will also be referred to as total annual profit.

3. Validation and Optimization

With the completion of the model development and identification of the demand profiles, it is necessary to validate the methodology used. This is accomplished using a set of single runs of the model and a multi-objective optimization.

3.1. Single Run

Four separate scenarios were selected for the model validation. These can be seen in Table 3.

Table 3: Single Run Scenarios

Heat and Power		District Heating	
Flash	ORC	DA Cold	DA Hot
EGS on	EGS on	EGS off	EGS off
DA on	DA on	DA(LT)	DA(HT)
SA on	SA on	SA on	SA on
Flash on	ORC on	HP on	HP off

The first two scenarios focus specifically on combined heat and power production and the choice between the flash and ORC system. The deep and shallow aquifers are options that can be selected at energy integration if needed. In these situations, the temperature of the deep aquifer is sufficient to meet the district heating demand without a heat pump. The last two scenarios focus on the district heating capacity of the system and the choice of the temperature of the resource. The EGS is not considered here. DA(LT) is the first available deep aquifer, but with a temperature too low to provide direct district heating, therefore obligating the use of the heat pump. DA(HT) is a second available deeper aquifer (the same used in the combined heat and power scenarios), with a production temperature high enough to provide direct district heating but with an increased drilling depth.

3.1.1 Results for Combined Heat and Power

The combined indicators for the multi-period combined heat and power scenarios are seen in Table 4. Note that the revenue does not include operating costs, capital costs, and fixed costs.

Table 4: Combined Heat and Power Results

Indicator	Flash	ORC
Net Electricity [MWh]	7627	24716
Net DH [MWh]	115220	115220
Net DC [MWh]	42000	42000
Total energy efficiency	0.62	0.46
Total exergy efficiency	0.46	0.54
Revenue [M*USD/yr]	5.19	9.18
Investment [M*USD]	77.02	71.19

Of the two scenarios, the simple ORC scenario was shown to have the higher profitability and exergy efficiency. In this system, the performance is strong with relatively high exergy efficiency. Total investment is high, but the system is nonetheless profitable. In comparison, the flash system had higher total costs and lower energy and exergy efficiencies. As a result, the system is not profitable.

The variability of the economic and thermodynamic performance across the six demand profiles can be seen for the ORC scenarios in Fig. 3.

It is apparent that the profitability of the system corresponds to the combined district heating and cooling demand of the system. This is because electricity production is fixed across the demand periods and there are relatively small increases in operating costs associated with an increase in district heating or cooling delivery. Exergy efficiency approaches 60% during the inter-seasonal periods.

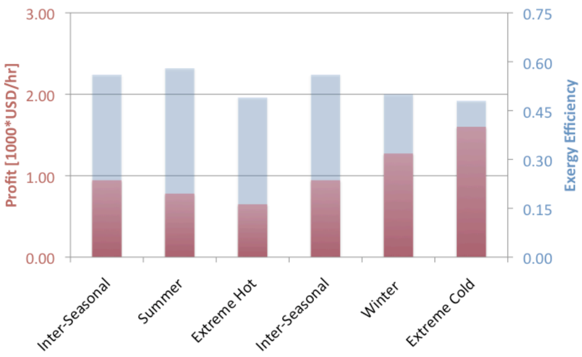

Fig. 3. Profit and Exergy Efficiency of the ORC

During this period, the system is fairly well optimized as seen in the results of the energy integration (Fig. 4). Compared with the worst performing period (the extreme cold period seen in Fig. 5), it is clear that the increase in the district heating usage creates some exergy losses. This is the result of increased usage of the DA for direct exchange with the district heating.

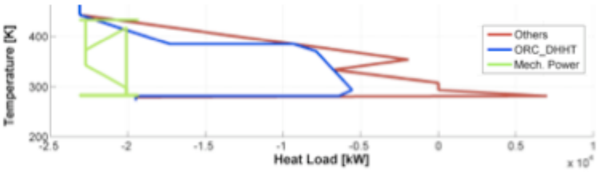

Fig. 4. Integrated Composite Curce of ORC for Inter-Seasonal period

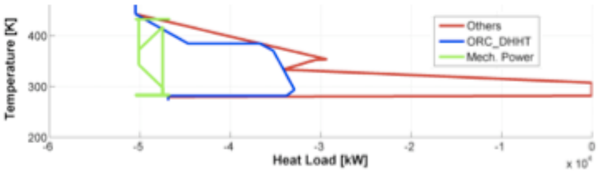

Fig. 5. Integrated Composite Curve of ORC for Extreme Cold Period

Overall, there is a net annual profit for this system. This makes the ORC system an attractive option economically, as long as reliable heat sources are available to meet the district heating demand. If the deep aquifer is not readily available or the extraction rate is limited, the results may differ significantly. Improvements for this scenario might include increasing the size of the ORC system within the feasible constraints of the EGS. The increase in power would be beneficial economically, and the increase in residual heat would be useful in helping to meet the district heating demand during colder operating periods.

3.1.2 Results for District Heating and Cooling

The last two simulations deal directly with variation in the production temperature of the deep aquifer. In the first, the production temperature of the deep aquifer is not of sufficient temperature to meet the district heating specifications. Therefore, drilling depth costs are reduced, but the heat pump must be used. The results of the two scenarios can be seen below.

Table 5: District Heating Combined Results

Indicator	DA(LT)	DA(HT)
Net Electricity [MWh]	-47843	0
Net DH [MWh]	115220	115220
Net DC [MWh]	42000	42000
Total energy efficiency	0.65	0.53
Total exergy efficiency	0.16	0.44
Revenue [M*USD/yr]	-6.72	3.66
Investment [M*USD]	221.25	21.46

Most striking about the results for the low temperature DA are the very high investment costs and negative yearly profit. Fig. 6 shows the profitability and exergy efficiency across the demand periods. Here, the profitability is shown to be negative for each period.

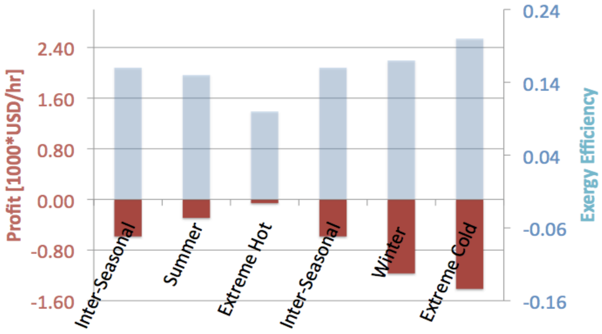

Fig. 6. Profit and Exergy Efficiency of the Heat Pump

The reason for this is that the ratio of the cost of imported electricity to the selling price of the district heating is higher than the coefficient of performance of the heat pump used to provide the heat for the district heating. Furthermore, the investment costs of the system with the low temperature district aquifer are an order of magnitude higher than that of the system with the high temperature deep aquifer. This can be explained by looking at the integrated composite curve for the extreme winter conditions (Fig. 7). During this demand period, the district heating demand exceeds that which can be provided by the shallow aquifer and heat pump. This is due to limitations placed on heat pump of 3.5 times the nominal size. This also represents a potential production limitation of the shallow aquifer.

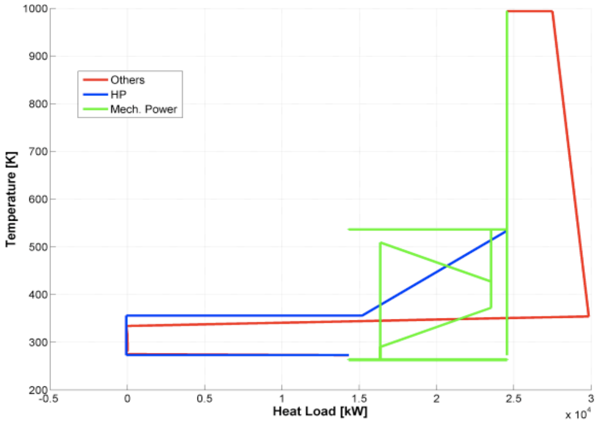

Fig. 7. Integrated Composite Curve of the Heat Pump for Extreme Cold Period

As a result, this system must purchase a large heat pump and a boiler, even though these components are used to their full potential for only 40 hours of the year. The low exergy efficiency of the system is the result of the penalty that occurs from the import of electricity from the grid. In contrast, the results from the scenario with high temperature DA show that a system, which increases the drilling depth, thereby avoiding the need for the heat pump, has lower investment costs and is profitable across all six demand periods. Therefore, the optimal exploitation scheme under these conditions is the use of the higher temperature aquifer. Although the drilling costs are higher, avoidance of the heat pump and boiler purchase is beneficial exergetically and economically.

3.2. Multi-Objective Optimization

Analyses of single run scenarios alone are limiting, as they do not allow for the methodical variation of decision variables and the identification of their optimal ranges. Moreover, it is necessary to account for the interactions between the different decision variables, and to calculate the trade-offs between conflicting objectives represented by the performance indicators. For these reasons a multi-objective optimization (MOO) is needed. An evolutionary genetic algorithm is used for this, and the two objectives are the total exergy efficiency to be maximized and the annual profit to be minimized.

3.2.1 Moo Using the ORC

From the single run results seen previously, it is apparent that usage of the ORC may be a promising approach to the utilization of the default geothermal resource. As such, a multi-objective optimization of the geothermal system in the multi-period framework will be performed, varying the decision variables as shown in Table 6. Integer decision variables are those that can only be integer values.

Table 6: Moo Decision Variables

Decision Variable	Type	Range	Unit
DA	Integer	[0,1]	-
SA	Integer	[0,1]	-
ORC	Integer	[1,2]	-
Simple ORC, Max Pressure	Variable	[10,30]	bar
ORC w/ bleeding, Max Pressure	Variable	[10,30]	bar
Simple ORC, Min Temp Diff	Variable	[1,5]	K
Split fraction of flow to second turbine	Variable	[0,1]	-
ORC w/ bleeding, min temp diff: condenser 1	Variable	[1,5]	K
ORC w/ bleeding, min temp diff: condenser 2	Variable	[1,5]	K

Here, the use of the EGS system is obligatory. Usage of the deep and shallow aquifer is either on (1) or off (0), and usage of the ORC is either a simple ORC (1), or an ORC with bleeding (2). Other variables concern the conversion system design. The results of this optimization are shown in Fig. 8. All of the final configurations make use of the deep aquifer to provide district heating and none use the shallow aquifer. A trend exists between decreased annual profit and increased exergy efficiency. Configurations with the lowest efficiency but highest profitability are those with the simple ORC selected and the high-pressure region of the cycle from 11.5 to 13.5 bars. The minimum temperature difference is in the range of 1.1 to 2.1 °C. Upon close inspection of Fig. 8., it is apparent that two distinct trend lines exist in the more profitable regions corresponding to the clusters of the MOO. For two configurations of the same exergetic performance, the more profitable configuration has a lower maximum pressure and a lower minimum temperature difference.

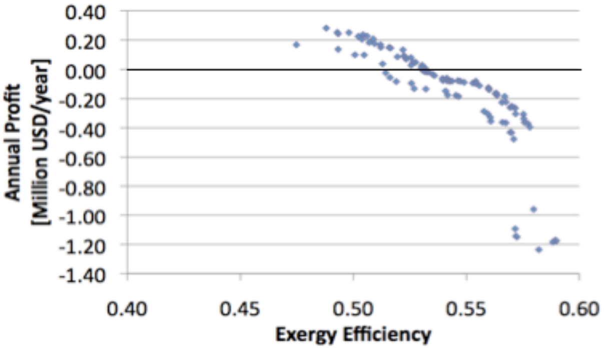

Fig. 8. Annual Profit vs. Exergy Efficiency

The most exergetically efficient configurations have high maximum pressures, approaching 30 bars. Four of the top fifteen best performing systems in terms of exergy efficiency utilize the ORC system with bleeding. However these configurations are not economical due to the high investment cost of the system.

As both objective functions within a demand profile depend strongly on the period duration, the MOO results will favor performance in those periods. However, configurations that avoid capital-intensive consequences in the extreme periods are also maintained, highlighting the importance of consideration of extreme conditions.

4. Conclusions

The development of a methodology for the thermo-economic evaluations of geothermal systems within the multi-period framework has been completed. Validation of this methodology was accomplished with the use of single run results and multi-objective optimizations using an evolutionary genetic algorithm.

Single run results clarified the importance of the multi-period approach. For the assumed conditions, the ORC system performed better than the single flash. The amount of DH, DC, and electrical production is important for the annual profit and exergy efficiency. In the case where no electricity is produced, results suggest that the use of deeper resources with higher production temperatures is the best approach, as it does not require the investment of a large heat pump for extreme conditions. The multi-period approach is specifically relevant as there are large variations in system performance over the different periods. Some periods have significant potential of improvement if the seasonal storage of heat is considered, especially in summer.

Multi-objective optimizations were successful in demonstrating the ability of the system to select between integer decision variables, such as the selection of a conversion technology or resource, as well as specific parameters for a given configuration across the different periods. The optimization within the multi-period approach favors the inter-seasonal demand profiles as the demand periods are the longest and therefore have the greatest effect on the combined performance indicators. However, extreme conditions have an important influence on investment costs, as they change the maximum size of some capital-intensive components.

Future work includes more intensive multi-objective optimizations considering additional scenarios and conversion technologies. Furthermore, additional development of the model is required, especially for the inclusion of an option for heat storage in the aquifer, which will allow for an assessment of the potential of seasonal heat storage to increase the overall system performance.

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