Defining Optimal Configurations of Geothermal Systems Using Process Design and Process Integration Techniques

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1 Introduction

In the perspective of increasing the share of renewable energies to mitigate global warming and to respond to fossil resources depletion, the use of geothermal resources for the polygeneration of energy services has gained interest and is expected to know an important development in the future. Some of the major issues linked with the use of geothermal energy concern the increase of the efficiency in the conversion, the increase in their economical profitability and the minimization of their generated life-cycle environmental impacts. Several studies propose optimization strategies for increasing efficiency and cost-effectiveness of geothermal power generation (Desideri and Bidini (1997); Hettiarachchi et al. (2007); Franco and Villani (2009)). However, none uses process integration techniques, nor includes the potential exploitable geothermal resources or the systematic possibilities of heat cogeneration in the optimization procedure. A systematic methodology including process design and process integration techniques would allow for identifying the optimal configuration of geothermal systems, but has to consider simultaneously the exploitable geothermal resources, the potential conversion technologies and the seasonal demand in energy services. The bases of such a methodology are presented in Hoban et al. (2010), but without considering a systematic multi-objective optimization procedure.

2 Methodology

The geothermal system design is a multiperiod problem that accounts for seasonal variations of the demand. The general computational framework used creates interfaces between different models and is described in Figure 1. It has been presented in Hoban et al. (2010). First, a superstructure including the optional technological solutions is built and the thermo-economic models of the components are developed. The calculation sequence is applied separately for each period, which allows to have a different system design and operation considering the seasonal variation of the demand in energy services. First the three different sub-systems composing a geothermal system are modeled separately. These include not only the conversion technologies but as well the geothermal resources

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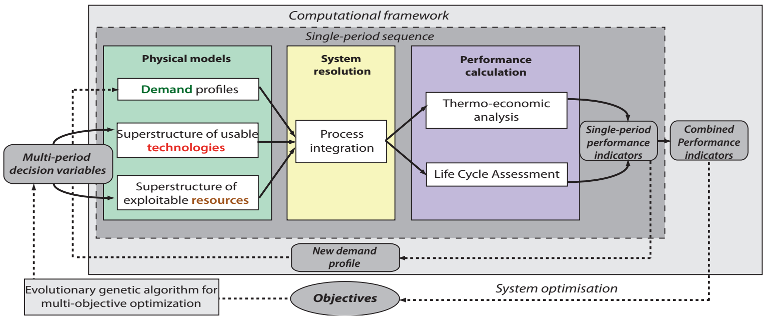

Figure 1: Computational framework

and the demand profiles in energy services. These sub-systems are then integrated together using process integration techniques to design the overall system. Performances of the integrated system are then calculated. The sequence is repeated for each one of the periods. Then, combined performance indicators are calculated for the overall system. Using these indicators, a multi-objective optimization problem is formulated and solved using a non-dominated evolutionary algorithm (Molyneaux et al. (2010)). Decision variables relate not only to the conversion technologies superstructure and their associated operating conditions, but also to the potential exploitable geothermal resources and their associated exploitation conditions.

2.1 System modeling

The developed methodology considers the overall geothermal system, including the three sub-systems of the superstructure of potential exploitable geothermal resources, the superstructure of usable energy conversion technologies, and the multi-period demand profiles in energy services to be supplied throughout the year.

Geothermal resources model. The superstructure of geothermal resources is a database of different geothermal resources: shallow aquifers, going from the surface down to a few hundred meters, deep aquifers, from a few hundreds meters down to the bedrock, and Enhanced Geothermal Systems (EGS), situated below the limit of the bedrock. The models of these different resources include geological information, such as the thermal gradient to calculate the temperature and the potential geothermal water mass flow rate available. Geotechnical information is as well included, such as the exploitation mode used to calculate the electricity consumption from the pumps, or the drilling technique and the number of wells, necessary to calculate the investment costs associated with the resource.

Conversion technologies. The superstructure of conversion technologies includes different cogeneration cycles and heat pumps, as well as boilers as back-up systems. Cogeneration cycles are flash systems and binary cycles with several designs and working fluids. Flowsheeting software is used to simulate the operating conditions and calculate the corresponding thermodynamic states of the technologies. These data are then further used to compute the energy and mass flows used for the system integration and sizing.

Energy services demand profiles. These are subdivided in periods, representing different seasonal conditions for the necessary supply of district heating or cooling, or hot water at a given location. Each period has therefore an associated temperature-enthalpy profile which is then used as a constraint for the system resolution. Electricity is not included in the profiles and can be bought from the grid if local production is not sufficient.

2.2 Process integration

Then, resources, technologies and demand profiles are integrated using process integration techniques (Maréchal and Kalitventzeff (1998)). This is formulated as a mixed integer linear programming problem, which objective is to minimize the operating cost of the system for each single period:

$$min \sum_{r=1}^{n_r}(C_{O_r} f_r + c_e \dot{E}^{+}_{grid}) + \sum_{w=1}^{n_w}(C_{O_w} f_w - c_e \dot{E}^{-}_{grid}) \tag{1}$$

where C_{O_r} is the operating cost of the resource r, n_r being the number of resources included in the superstructure, f_r is the utilization factor of the resource r, c_e is the cost of electricity buying or selling to the grid, $\dot{E}^{+}_{grid}$ is the electricity consumed by the resource r, C_{O_w} is the operating cost of the technology w, n_w being the number of technologies included in the superstructure, f_w is the utilization factor of the technology w, and $\dot{E}^{-}_{grid}$ is the neat electricity produced by the technology w and sold to the grid. This is subject to the constraint of the heat cascade. The resolution of this problem extracts the configuration of the geothermal system from the superstructure. The state variables of this final configuration are then used to define the size of the equipment in the system.

2.3 Performance calculation

Based on the results of the process integration step, indicators of performance are calculated for each period and then combined together to obtain the yearly overall performance of the system. Indicators of performance cover the three aspects of economics, thermodynamics and environmental impacts. Major indicators for the overall yearly operation of the system are presented below.

For the economic performance of the system, the two major indicators of performance are the investment costs and the levelized cost of district heating. Investment costs will indeed be dominant in the case of geothermal systems, when compared with the operating costs. The investment costs include the total drilling costs of the geothermal wells, the geothermal pumps, the equipment of the conversion technologies to be used and the district heating network. The levelized cost of district heating is as well a relevant indicator in the case of geothermal cogeneration systems, since the constraint is put on supplying the district heating service for the different periods and that the electricity production represents therefore only an additional income. It is calculated by making the balance between the annualized investment costs, the yearly operating costs and the yearly income from electricity selling, and by dividing it by the yearly amount of district heating produced:

$$c_Q = \frac{\sum_{i=1}^{n_e} max(C_{I,an_i})_p + \sum_{i=1}^{n_e}\sum_{p=1}^{n_p} C_{O_{i,p}} t_p - \sum_{p=1}^{n_p} \dot{E}^{-}_p t_p c_e}{\sum_{p=1}^{n_p} \dot{Q}^{-}_p t_p} \tag{2}$$

where $C_{I,an}$ is the annualized investment cost of the equipment i associated with period p, n_e is the total number of equipments necessary to operate the overall geothermal system,

n_p is the total number of periods over one year, C_O is the associated operating cost with the equipment i, t_p is the duration of period p, E^- is the neat electricity produced by the overall system during period p, c_e is the specific cost to which the electricity is sold to the grid, assumed to be the average price of the Swiss market (0.117 EUR/kWh), and $\dot{Q}^-$ is the district heating produced during period p.

For the thermodynamic indicators, both yearly energy and exergy efficiency of the system are calculated. Yearly exergy efficiency of the conversion system is calculated by:

$$\eta = \frac{\sum_{p=1}^{n_p} \dot{E}_p^- t_p + \sum_{p=1}^{n_p} \dot{Q}_p^- (1 - \frac{T_a}{T_{lm}}) \cdot t_p}{\sum_{p=1}^{n_p} \dot{Q}_p^+ (1 - \frac{T_a}{T_{lm}}) \cdot t_p} \tag{3}$$

where $\dot{E}^-$ is the neat electricity produced by the conversion system during period p, t_p is the duration of period p, $\dot{Q}^-$ is the heat transfered to the district heating during period p, $\dot{Q}^+$ is the heat coming from the different geothermal resources and the back-up system, if necessary, during period p, T_a is the temperature of the cold source, and $T_{lm} = \frac{T_{in} - T_{out}}{ln(\frac{T_{in}}{T_{out}})}$ is the log-mean temperature of the geothermal resource, the back-up system or of the district heating, T_{in} being the higher temperature of the stream considered, and T_{out} its lower temperature. A similar approach is used to calculate energy efficiency.

For the environmental impacts, since an important part of the impacts from geothermal systems come from the construction phase due to the drilling, life cycle assessment methodology is applied. In order to link each equipment and material or energy flow generated by the life cycle of the overall system to its design and operating conditions, the methodology presented by Gerber et al. (2010) is applied to establish the life cycle inventory. The specific impact generated per kWh of district heating is calculated, by analogy with the economic calculations, with the total life cycle impact for the overall system divided by the amount of district heating supplied during the lifetime of the system:

$$I_Q = \frac{\sum_{p=1}^{n_p} \sum_{i=1}^{n_{eo}} I_{O_{i,p}} + \sum_{i=1}^{n_{ec}} max(I_{C_i})_p + \sum_{i=1}^{n_{ee}} max(I_{E_i})_p}{\sum_{p=1}^{n_p} \dot{Q}_p^- t_p t_{life}} \tag{4}$$

where I_O is the impact due to the operation phase for period p of the LCI element i, n_{eo} being the total number of LCI elements belonging to the operation phase, I_C is the impact due to the construction phase of the element i for period p, n_{ec} being the total number of LCI elements for the construction phase, I_E is the impact due to the end-of-life of the element i for period p, n_{ee} being the total number of LCI elements for end-of-life phase, and t_{life} is the overall lifetime of the geothermal system (40 years).

3 Application to the case study

To illustrate the methodology, we apply it to the example case of a city of 20'000 inhabitants, in Switzerland. For the resource models, a geological profile representative of the Swiss Plateau is used to calculate the temperature in function of depth, and the depth of bedrock, determining the depth from which an EGS can theoretically be built. The profile is as well used to determine the potential exploitable layers as aquifers, with their associated depth and temperature, between the surface and the bedrock. For the demand profiles in district heating, GIS-based data treated with the methodology presented by Girardin et al. (2010) were used to generate temperature-enthalpy profiles for four different periods of a year: winter, inter-seasonal, summer and extreme winter conditions. Multi-objective optimization is then performed for different combinations of resources and technologies, in order to determine the optimal configurations of the systems at different depths of exploitation, with or without electricity cogeneration. Two objective functions are selected to calculate the thermo-economic trade-offs: exergy efficiency, to be maximized, and levelized cost of district heating, to be minimized. Depth of the resource is a decision variable. Other decision variables, related to the operating or to the exploitation conditions, are treated using a multi-period approach, one decision variable taking different values throughout the periods.

4 Results

Results of the multi-objective optimization are displayed in Figure 2. The different clusters constituted by the possible combinations of geothermal resources and conversion technologies are as well displayed, with their corresponding depth in the color gradient. For the present case study, the exploitation of EGS systems with the cogeneration of electricity seems to be the most promising option in terms of economic and thermodynamic performance. Indeed, the high investment costs due to the drilling for deep resources is compensated by the income generated by electricity production, which leads to a negative levelized cost of district heating. Exergy efficiency is particularly high for flash systems. This is due to the use of the liquid part of the geothermal fluid for district heating, and to the seasonal adaptation of the operating parameters of the resource, such as the reinjection temperature and the geothermal mass flow rate, and of the operating parameters

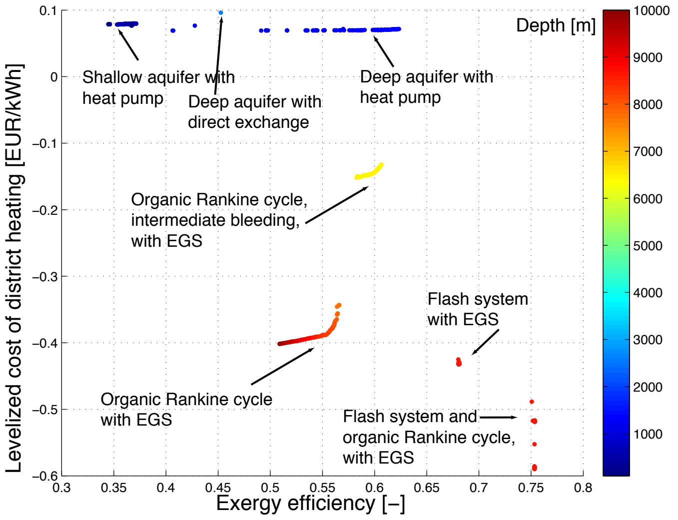

Figure 2: Optimal system configurations for different geothermal resources and technologies

of the conversion technologies, such as the flash pressure or the splitting fraction of the bottoming organic Rankine cycle. The use of shallow and deep aquifers for single district heating supply leads to a higher levelized cost of district heating, which is slightly higher for the deeper aquifer with a direct exchange than for the other aquifers using heat pumps.

5 Conclusions

A systematic methodology for the optimal design of geothermal systems including resources, conversion technologies and demand in energy services has been presented. It was applied to a case study of a Swiss city to extract the optimal configurations of geothermal resources exploitation and conversion technologies to satisfy a seasonal district heating demand. Results suggest that electricity cogeneration from EGS is the most promising option in terms of exergy efficiency and levelized cost of district heating. Including the parameters of geothermal exploitation in the decision variables and adopting a multi-period approach lead to a high exergy efficiency for some of the optimal configurations.

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