PROCEEDINGS, Thirty-Seventh Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 30 - February 1, 2012
SGP-TR-194

DESIGN OF GEOTHERMAL ENERGY CONVERSION SYSTEMS WITH A LIFE CYCLE ASSESSMENT PERSPECTIVE

Léda Gerber, François Maréchal

Industrial Energy Systems Laboratory, Ecole Polytechnique Fédérale de Lausanne
LENI-IGM-STI, Station 9, EPFL
Lausanne, CH-1015, Switzerland
e-mail: leda.gerber@epfl.ch

ABSTRACT

The development of Enhanced Geothermal Systems (EGS) for the cogeneration of electricity and district heating has recently gained interest, and is expected to know an important development in the future. Major research questions on the design of the energy conversion system concern the increase of the efficiency in the usage of geothermal resources, as well as the increase of their economic profitability. The quantification and the minimization of the generated life-cycle environmental impacts is as well a key point for the public acceptance of geothermal energy and for the choice of both the conversion technologies and the depth of EGS by the engineers. This paper presents a systematic methodology for the optimal design and configuration of geothermal systems considering environomic criteria. Process design and process integration techniques are used in combination with life cycle assessment and multi-objective optimization techniques. It is illustrated by an application to the design of geothermal cogeneration systems in the context of Switzerland.

INTRODUCTION

In the perspective of increasing the share of renewable energy to mitigate global warming issues and to respond to fossil resources depletion, the use of geothermal energy has gained interest. Major usages of geothermal energy include electricity production (67246 GWh/y in 2010) and direct use for heating (117740 GWh/y in 2010) (Lund and Bertani, 2010). As stated by the International Energy Agency in its roadmap for geothermal energy (IEA, 2011), by 2050 the geothermal power production should be increased to 1400 TWh/y, and the direct use to 1600 TWh/y. These objectives are to be reached by developing both conventional resources like hydrothermal aquifers and emerging ones like Enhanced Geothermal Systems (EGS). Hence, geothermal combined heat and power (CHP) production from EGS is expected to know an important development in the future.

However, the economic competitiveness of geothermal energy is still a critical point (IEA, 2011), and several methodologies have been developed to increase its cost-effectiveness by an optimal geothermal system design. Important aspects to be accounted for in such methodologies are the geothermal resources characteristics, the design of the conversion cycle which has to be optimized in order to maximize its efficiency (Hettiarachchi et al, 2007, Franco and Villani, 2009), the choice of the working fluids for binary cycles (Saleh et al, 2007, Heberle et al, 2010, Guo et al, 2011a,b), and the district heating parameters for CHP systems (Guo et al, 2011a,b). In addition to the economic aspect, the thermodynamic aspect is as well critical to ensure an efficient use of the resource, and it can be assessed using the exergy efficiency as a performance indicator (DiPippo, 2004, Kanoglu and Dincer, 2009). Recently, Lazzaretto et al. (2011) have demonstrated the validity of the thermo-economic optimization approach to design geothermal power plants, and Gerber and Maréchal (2011) have developed a methodology integrating all the above aspects in a multi-objective optimization framework, using a multi-period approach and process integration techniques to identify the thermo-economic optimal configurations of geothermal systems in areas where the geothermal resource potential has been assessed. It can be used to identify the future optimal configurations of EGS considering it as a mature technology, in terms of depths, technology choice for conversion (flash systems, organic Rankine cycles, Kalina cycles) with their associated operating conditions, and ratio between electricity production and district heating.

A third aspect, relevant for public acceptance and that should be as well integrated in the design of emerging technologies for energy conversion is the environmental dimension. For evaluating renewable energy systems, Life Cycle Assessment (LCA) (ISO14040) is the most appropriate methodology, since it accounts for a wide range of environmental impacts and considers the overall life cycle in a quantitative way. Though many studies discuss the environmental impacts of geothermal systems (DiPippo, 1991, Mock et al, 1997, Rybach, 2003, Kristmannsdottir and Armannsson, 2003), very few use a quantitative life cycle perspective, especially for deep geothermal systems. In a recent study, Frick et al. (2010) perform a LCA for an EGS with a binary cycle. They demonstrate the relevance of using a life cycle approach for the environmental evaluation of geothermal systems and find that the efficiency of the conversion cycle is a critical parameter. However, they use a scenario approach based on average technologies, and do not consider systematically the thermo-economic optimal configurations of geothermal systems in the impact assessment. Gerber et al. (2011) have developed such a methodology for the integration of LCA in the conceptual design of renewable energy conversion systems and have demonstrated that accounting for the process design procedure in the environmental impact evaluation is critical for an accurate impact assessment of an emerging technology and for identifying the potential for mitigation at an early development stage. The method was however not yet applied to geothermal conversion systems.

Therefore, this paper aims at combining the thermo-economic multi-objective optimization approach for the identification of optimal configurations of geothermal systems presented in Gerber and Maréchal (2011) with the methodology for the integration of LCA in the conceptual design of renewable energy systems presented in Gerber et al. (2011). The resulting method is illustrated by an application case study, aiming at calculate and analyze the environmental impacts of the thermo-economic optimal configurations for EGS used for cogeneration in the economic and geological context of Switzerland.

METHODOLOGY

Geothermal system design aims at defining, for a given geographical location, the geothermal depth and flow, the configuration in terms of equipment sizes and operating conditions of the conversion system, as well as the operation strategy to supply the energy services of the area (i.e. electricity and district heating). It is a multi-period problem that accounts for seasonal variations of the demand in district heating. Due to the geological uncertainties, the present methodology is applicable only to orientate the decision-making and the future development of geothermal energy on a given area for which the geology is known and the demand in energy services characterized. Moreover, it applies to systems that can be operated in independent time intervals (i.e. without seasonal heat storage). It is used for preliminary design, leading to promising configurations for which detailed system engineering like in Lazzaretto et al. (2011) is still to be done.

Computational Framework

The general computational framework creates interfaces between different models and is described in Figure 1.

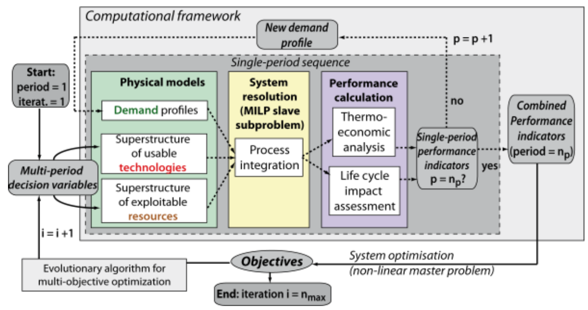

Figure 1: Computational framework for geothermal system simulation and design, adapted from Gerber and Maréchal (2011)

A superstructure including the optional technological solutions and the potential resources is built and the thermo-economic models of these components are developed. First the three different sub-systems composing a geothermal system are simulated separately. These include:

1) the potential geothermal resources from which heat can be harvested,
2) the potential conversion technologies,
3) the geo-localized demand profiles in energy services.

Each model of a resource or a technology included in the superstructure and of the seasonal demand in energy services is thus simulated for a given set of operating conditions (period=1...n_p). This allows one to operate the system in function of the seasonal variation of the energy service requirement.

These sub-systems are then integrated together using process integration techniques (Maréchal and Kalitventzeff, 1998) to build the overall system to supply energy services, solving the slave MILP sub-problem, which decision variables are the utilization rates of the different resources and technologies of the superstructure simulated at the previous step. At the end of the single-period sequence, thermo-economic performances of the integrated system are calculated, and a Life Cycle Impact Assessment (LCIA) of the system is as well performed, based on the process operating conditions and on the system design. This allows for having environmental indicators reflecting the variations in process configuration and efficiency. The whole sequence is repeated for each period (until period = n_p). Then, overall performance indicators are calculated for the yearly operation of the system by combining the seasonal performance indicators. It includes the objective functions of the MOO master problem, solved using an evolutionary algorithm (Molyneaux et al, 2010). The sequence with the n_p periods is repeated for n_{max} iterations to complete the MOO, with different values for decision variables at each iteration, which relate to:

1) the definition of the configuration extracted from the superstructure using integer variables (i.e. if a particular resource/technology is used or not)
2) the system operating conditions (temperatures, pressures)
3) the depth and size of the geothermal resource harvesting system (well size, flow and coverage)
4) the ratio between the electricity and district heating produced by the conversion system.

The thermo-economic models are briefly described at the next sub-section. A more detailed description can be found in Gerber and Maréchal (2011). The sub-section after describes how these models were extended to life cycle assessment models.

Thermo-Economic Model

The exploitable potential resources are defined by depth, temperature and expected mass flow rates. Thus, the applicability of the method involves that geological surveys have been performed in the area to assess the geothermal potential. Specifically regarding EGS, which is considered in this study, the model assumes a mature commercial technology. The depth is thus considered as variable, and goes from 3000m, which represents the upper limit of the bedrock in Switzerland, down to 10000m, which represents the limit for the accessible resource with the current drilling technology (Tester et al., 2006). The temperature is calculated in function of the depth, assuming a geothermal gradient of 0.035°C/m from 3000m. This value is taken from Sprecher (2011) and is considered as representative for the Swiss Plateau. For the expected mass flow rate, the pilot EGS project in Soultz-sous-Forêts has a planned extraction mass flow rate between 70-100 kg/s (Cuenot et al., 2008), while the project of Basel was targeting 100 kg/s (Haring, 2004) and that Tester et al. (2006) assume 80 kg/s for a mature technology. Thus, a value of 90 kg/s for extraction was assumed. The costs for the building of the EGS were taken from Tester et al. (2006) and updated with the inflation rate. A temperature difference between the bedrock temperature and the geofluid at the extraction well of 20°C is assumed, based on the data of Soultz-sous-Forêts.

The superstructure of potential conversion technologies from Gerber and Maréchal (2011) contained single and double-flash systems, organic Rankine cycles (ORC), with several potential working fluids, with or without an intermediate draw-off at the turbine for cogeneration of district heating within the cycle. ORCs can be used either as a single technology or as bottoming cycles in combination with the flash systems. To simulate the cycles, calculate the corresponding pressures, temperatures and energy and mass flow rates, a flowsheeting software is used. This basis superstructure was extended to include the Kalina cycle, supercritical ORCs and ORCs with two evaporation levels. In the present study, the working fluid selected for ORCs is either iso-butane or iso-pentane.

An example of the simulation results for an ORC with an intermediate draw-off at the turbine using iso-butane is given in Figure 2.

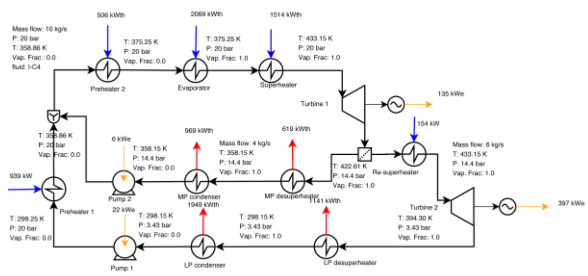

Figure 2: Example of simulation results for an ORC with an intermediate draw-off

The heat exchanger network design is not performed a priori at this stage, but at the next step of the simulation, the process integration, which aims at sizing the cycle and optimizing the heat exchanges within the cycle, and between the cycle, the heat available from the EGS and the district heating demand (Maréchal and Kalitventzeff, 1998). The nominal heat loads and power output and the temperature levels calculated are used for this. Finally, the results of the simulation and of the process integration are used for equipment sizing, such as turbines, pumps, heat exchangers or flash drums. Non-linear correlations from Turton et al. (1998) and Ulrich (1996) are used for calculating the grass root cost associated with each piece of equipment.

The geo-localized seasonal demand profiles in district heating have been identified for a residential area of Switzerland with the methodology of Girardin et al. (2010), and have been presented in Gerber and Maréchal (2011). Four periods are distinguished: summer, inter-season, winter and extreme winter. Here, since one of the objectives of the study is to determine the optimal ratio between electricity production and district heating, the temperatures of these profiles are kept constant, but the ratio between electricity production and district heating is left variable.

Life Cycle Assessment Model

According to the ISO norm (ISO14040, 2006), four stages are mandatory to conduct a LCA:

1) the goal and scope definition, where the system boundaries and the functional unit (FU) to which each quantity is then brought back are defined.
2) the life cycle inventory (LCI), where all the material and energy flows crossing the system boundaries are identified.
3) the life cycle impact assessment (LCIA), where the set of emissions and extractions of single substances obtained from the LCI are aggregated in a reduced number of indicators having environmental significance.
4) the interpretation, which aims at bringing the useful information for decision-making.

In the present context, the objective of the LCA, integrated in the framework for geothermal system design, is to obtain life cycle impact assessment indicators reflecting the variations in the system design and choices in terms of building depth of the EGS and of conversion technologies. Thus, particular attention has to be paid to the LCI, since each flow is not an average value representing a particular scenario, but has to be expressed mathematically in function of the system configuration. This is explained in Figure 3, which presents the adaptation of the LCA methodology in the context of conceptual energy system design (Gerber et al, 2011). The parts of particular importance are displayed in black.

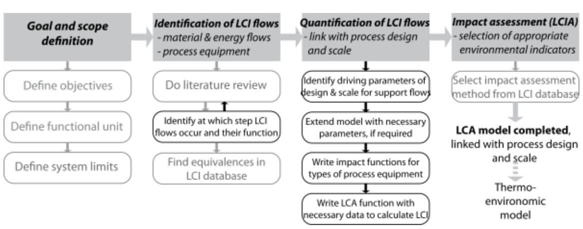

Figure 3: Methodology for LCA model linked with process design and configuration (Gerber et al, 2011)

Goal and scope definition

The objective of the LCA of the different geothermal system configurations aims at comparing their environmental performance for a wide range of environmental impacts, considering not only their mitigation potential of greenhouse gases emissions, but as well the effects on human health, ecosystem quality and non-renewable resources, considering its overall life cycle from cradle-to-grave. Thus, the functional unit, to which every quantity involved in the life cycle assessment is brought back, is defined as the construction, operation and dismantling of one EGS, to produce electricity and heat. The substitution of produced energy services (i.e. avoided impacts from conventional production of electricity and heating by fossil resources) has to be included, to account for the system conversion efficiency. A lifetime of 30 years is assumed for the EGS.

Life cycle inventory

The life cycle inventory to extend the thermo-economic model to a life cycle assessment model concerns three types of elements:

1) the flows and the emissions already included in the thermo-economic models having an environmental significance (e.g. the working fluid for the ORC during operation, the produced energy services)
2) the auxiliary materials and emissions of environmental significance not directly included in the thermo-economic models but necessary for the construction and operation of the system (e.g. the diesel burnt to run the drilling machines, the steel necessary for the well casing, the working fluid losses for ORC)
3) the process equipment, which is included in the thermo-economic models (e.g. the geothermal pumps, the turbines for electricity production)

In a first time, these different elements falling within the system boundaries defined for the life cycle have to be identified, either from existing thermo-economic models, for the equipment and for the flows of the thermo-economic models, or from the literature for the auxiliary materials and emissions. The resulting life cycle inventory for the life cycle of an EGS with the considered boundaries is displayed in Figure 4. Transportation of auxiliary materials is not displayed in the figure but is included in the LCI model. For avoided impacts from energy services, substitution from natural gas with the currently best available technologies is assumed: a natural gas combined cycle and a condensing natural gas boiler for electricity and district heating, respectively.

In order to account for the off-site emissions, the LCI database ecoinvent© (Frischknecht et al, 2005) is used, and for each LCI element, an equivalence is found in the database. Each one of the equivalences is a vector of single emissions and extractions cumulated for the overall production and supply chain, and for a nominal size or quantity.

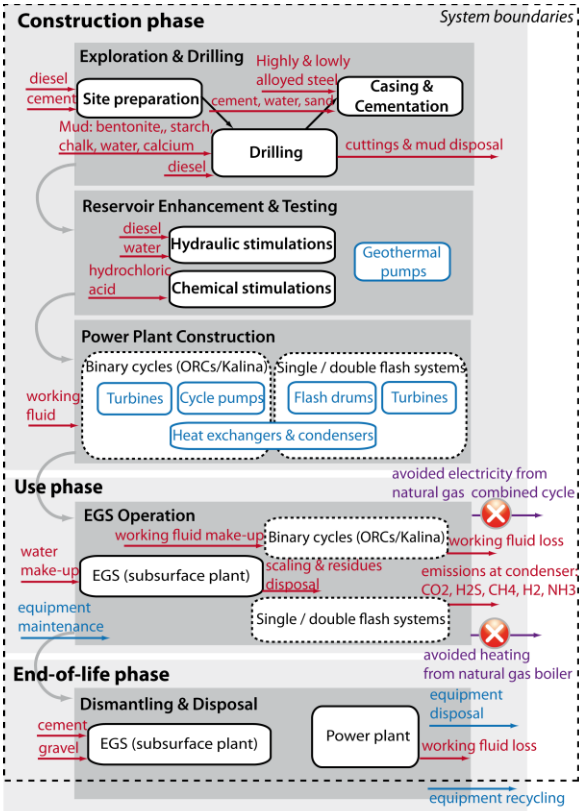

Figure 4: Major flows (red), equipment (blue) and substituted services (purple) of the life cycle inventory for an EGS

Each element has then in a second time to be scaled to its size corresponding to the thermo-economic model conditions and brought back to the functional unit. Therefore, mathematical expressions have to be developed to express the quantities of these elements in function of the state variables of the thermo-economic models, and if necessary these have to be extended.

For flows and emissions already included in the thermo-economic model, the value is directly taken from it. This is the case for the amount of electricity and district heating produced, and for the water make-up for injection, during the use phase.

For process equipment, the methodology presented in Gerber et al. (2011) is used for the impact scaling.

For auxiliary materials, the formulation has to be developed case-by-case. For example, all the auxiliary materials linked with the exploration and drilling can be expressed as:

$$M_k = M0_k + c_k \cdot z \cdot n_{wells} \qquad (1)$$

Where M_k is the overall required amount of material k, $M0_k$ the initial amount required per site, c_k the amount of material required per unit length, z the average depth of the wells, and n_{wells} the number of wells to be drilled, which is assumed to be 3 in the present study. The c_k values have been taken from Frick et al. (2010). For the reservoir enhancement, since there is for the moment not a lot of experiences of EGS, fixed amounts of diesel, water and acid are assumed per site. For water and diesel used in hydraulic stimulations, values are available in Frick et al. (2010). For acid used in chemical stimulations, values are available in Portier et al. (2009). For the binary power plant construction, the amount of working fluid initially required was calculated from data in Frick et al. (2010) for iso-butane, and then adapted in function of the working fluid and of the size of the cycle in terms of power output. During the use phase, the value for scaling and residues disposal has been as well taken from Frick et al (2010). For binary cycles, the yearly losses from the working fluid, and thus the necessary make-up working fluid, can be expressed as:

$$L_{wf} = M0_{wf}\left(E_c^-, y_{wf}\right) \cdot l \qquad (2)$$

Where $M0_{wf}$ is the initial amount of working fluid, E_c^- is the electricity produced by the cycle, related to its size, y_{wf} are the thermodynamic properties of the working fluid, and l the yearly percentage of losses, estimated to 0-2% (Ormat, 2010). Thus, the maximal value of 2% was assumed in the present study. For flash systems, the condenser may emit single substances to the atmosphere, such as fossil carbon dioxide, methane or hydrogen sulphide. No data are currently available for potential emissions from flash systems using EGS. Thus, average data from hydrothermal systems have been used (Baldacci et al, 2002) for CO_2, H_2S, CH_4, H_2 and NH_3. Due to the different geochemistry of EGS and hydrothermal systems, these data should however be updated once emissions data are available for flash systems combined with EGS. For the end-of-life phase, data for cement and gravel used for well decommissioning have been taken from Frick et al. (2010), and are as well expressed in function of the depth of the well by Equation (1).

Life cycle impact assessment

The LCIA step computes the environmental impact by aggregating the vector of the different elementary flows of emissions and of extractions obtained for each flow of the LCI in indicators of environmental significance termed as impact categories. The aggregation is performed by using an impact assessment method, which is a matrix containing the weightings for the different elementary flows.

Here, two different impact assessment methods are used: the method of the Intergovernmental Panel on Climate Change (IPCC, 2007), which is used to quantify the global warming potential on a 100-year time-horizon in terms of CO2-equivalents, and the Ecoindicator99-(h,a) (Goedkoop and Spriensma, 2000), which is a damage-oriented approach and measures the impact on three impact categories: the human health, the ecosystem quality and the non-renewable resources, weighted and aggregated in a final single score measuring the environmental impact.

Accounting for the life cycle perspective and for the multi-period aspects of the system operation, the final impacts per functional unit for each impact category of the two impact assessment methods is given by:

$$I_{FU} = \frac{\sum_{p=1}^{n_p}\sum_{i=1}^{n_{eo}} I_{Oi,p}\cdot t_p \cdot t_y + \sum_{i=1}^{n_{ec}} \max(I_{Ci})_p + \sum_{i=1}^{n_{ee}} \max(I_{Ci})_p}{\sum_{p=1}^{n_p} t_p \cdot t_{yr}\cdot fu_p} \quad (3)$$

where $I_{Oi,p}$ 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 associated with operation phase, $I_{Ci,p}$ is the impact due to the construction phase of the LCI element i, n_{ec} being the total number of LCI elements associated with construction phase, $I_{Ei,p}$ is the impact due to the end-of-life phase of the LCI element i, n_{ee} being the total number of LCI elements associated with end-of-life phase, t_p is the time associated with period p and t_{yr} the lifetime of the system. For construction and end-of-life, a value is calculated independently for each period, and the maximal impact is then retained.

Multi-Objective Optimization

The goal of the multi-objective optimization is to identify the optimal configurations of geothermal conversion systems for EGS for the different potential combinations of technologies, at different resource depths, and with different ratios between electricity production and district heating. Three independent optimization objectives are selected.

1) The investment costs, to be minimized:

$$C_{inv} = C_{i,EGS}(z) + \sum_{w=1}^{n_w} \max(C_{i,w,p}(z, r_{DH}, x_d))_{n_p} + C_{i,DH}(r_{DH}) \quad (4)$$

where $C_{i,EGS}$ are the investment costs linked with the EGS, function of the targeted exploitation depth z, $C_{i,w,p}$ is the investment cost of the equipment w calculated for each period p and for which the maximal value is taken, function of z, of the ratio between electricity and district heating r_{DH}, and of the other decision variables of the optimization problem x_d, and $C_{i,DH}$ is the investment cost of the district heating network.

2) The annual profit, to be maximized:

$$P_{an} = \sum_{p=1}^{n_p} t_p \cdot (c_e^- \cdot \dot{E}_p^-(z, r_{DH}, x_d) + c_q^- \cdot \dot{Q}_p^-(r_{DH}) - c_{o,EGS}(z) - \sum_t^{n_t} c_{o,t}(z, r_{DH}, x_d)) \quad (5)$$

where t_p is the operating time associated with period p, c_e^- and c_q^- are the specific selling cost of electricity and district heating, respectively, E_p^- is the net electricity produced during period p (parasitic losses for geothermal pumps and cycle pumps are accounted for), Q_p^- is the district heating produced during period p, $c_{o,EGS}$ is the specific operating cost of the EGS and $c_{o,t}$ is the specific operating cost of the conversion technology t. c_e^- and c_q^- are assumed here to be 0.16 USD/kWh and 0.11 USD/kWh, respectively, which is representative of the average Swiss market conditions.

3) The exergy efficiency of the conversion system, which represents the ratio between the exergy services supplied and the exergy from the EGS entering the conversion system, to be maximized:

$$\eta = \frac{\sum_{p=1}^{n_p} t_p \cdot (\dot{E}_p^-(z, r_{DH}, x_d) + \dot{Q}_p^-(r_{DH}) \cdot (1 - \frac{T_a}{T_{DH,lm,p}(z)})}{\sum_{p=1}^{n_p} t_p \cdot \dot{Q}_{EGS,p}^+(z, x_d) \cdot (1 - \frac{T_a}{T_{EGS,lm,p}(z)})} \quad (6)$$

where $Q_{EGS,p}^+$ is the available heat from the EGS during period p, T_a is the ambient temperature, or temperature of the cold source, assumed to be 10°C, and T_{lm} is the logarithmic mean temperature of the hot source, calculated by:

$$T_{lm} = \frac{T_{in} - T_{out}}{\ln(\frac{T_{in}}{T_{out}})} \quad (7)$$

where T_{in} is the inlet temperature of the hot source and T_{out} is the temperature at which the hot source can be cooled. For the district heating, T_{in} is the return temperature and T_{out} is the supply temperature. For the EGS, T_{in} is the temperature at well, and T_{out} is the reinjection temperature.

Since both the investment costs and the annual profit are increasing with depth, this ensures that optimal solutions are selected at each potential construction depth for the EGS. For each potential combination of conversion technologies, the trade-off between these three objectives is calculated by a Pareto curve. The decision variables given for the optimization problem include the depth of EGS z (between 3000 and 10000m), the design size of the district heating network to operate in extreme winter conditions (between 0 and 60 MW), and the operating conditions of the technologies x_d: the reinjection temperature of the geofluid (between 120 and 70°C) the pressure drops in the flash drums of the single and double-flash systems, the evaporation temperatures of the ORCs in subcritical conditions, the higher pressure of the supercritical ORCs and of the Kalina cycles, the fraction of draw-off going for district heating for the ORCs with an intermediate draw-off.

The optimization is performed for the current market conditions and above-mentioned geological conditions for Switzerland. However, sensitivities and adaptations to other market or geological conditions can be done by recalculating the optimal points with other input data for parameters such as the drilling costs, the market prices for energy services, the geothermal gradient and the expected flow-rate from the EGS.

Selection of Final Optimal Configurations

Since the optimization results in a large number of optimal points, each one representing one configuration for the geothermal system, a selection of representative configurations has to be performed. This is done for each cluster of technologies by selecting one configuration each 500m between 3000 and 10000m, and each 5MW for district heating from 0 to 60MW for design size of district heating (0MW meaning single electricity production). To select the final configuration at a given depth and district heating size, the payback period of the overall system is used, and other associated thermodynamic and environmental indicators are as well calculated. The payback period is calculated by:

$$t_{pb} = \frac{c_{inv,an}}{P_{an}} \quad (8)$$

For the thermodynamic performance, the exergy efficiency of the conversion system (Equation 6) is used.

For the environmental performance, the indicators are:

1) the yearly avoided CO2-equivalent emissions, using the IPCC07 impact method. The life cycle CO2 emissions for construction, operation and end-of-life of EGS are compared with the production of the same services with a natural gas combined cycle for electricity and natural gas condensing boiler for heating.
2) the relative life cycle avoided impacts, using the single-score of the Ecoindicator99-(h,a). The impacts are again compared with the production of the same services. The best configuration of all is fixed as the reference (100% of avoided impacts), and the other ones are then compared with this value.

RESULTS

Figure 5 shows some of the Pareto curves obtained for the tri-objective thermo-economic optimization. For readability, only a fraction of the potential combinations of technologies are displayed as examples to illustrate the behavior of the system configurations in the optimization: one with a single flash system, one with a binary cycle (an ORC with an intermediate draw-off), and one with a combination of a single flash system and of an ORC with single-loop.

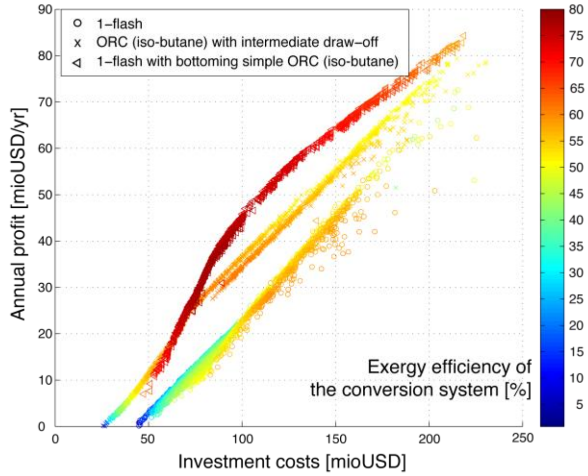

Figure 5: Examples of Pareto curves obtained from the tri-objective thermo-economic optimization

All the curves show a net trade-off between the investment cost and the annual profits, and, in most of the cases, another trade-off between the exergy efficiency of the conversion system and the economic objectives. Both investment costs and annual profit increase with depth, while exergy efficiency increases up to a certain depth and then starts decreasing again. District heating power increases the investment costs and decreases exergy efficiency, but increases the annual profit.

Final Optimal Configurations

The final optimal configurations are then selected from these Pareto curves, on the basis of the minimal payback period for a varying EGS construction depth and district heating design size. These are displayed in Figure 6. The associated exergy efficiencies, avoided CO2 emissions and relative avoided life cycle impacts with Ecoindicator99-(h,a) are displayed in Figure 8, Figure 9, and Figure 11, respectively. The following subsections discuss in details each one of these aspects.

Economic performance

For illustrating the explanations on the economic performance, a detailed cost-benefit analysis of five typical configurations is displayed in Figure 7, identified by a black circle on Figure 6. From Figure 6, it appears first that with the economic assumptions and the geological conditions taken for the case study, deeper EGS from around 7000m to 10000m are economically more attractive, due to an increased electricity production, except for some of the configurations using a Kalina cycle for cogeneration, having as well a high economic performance close to the one of the configurations with deep EGS.

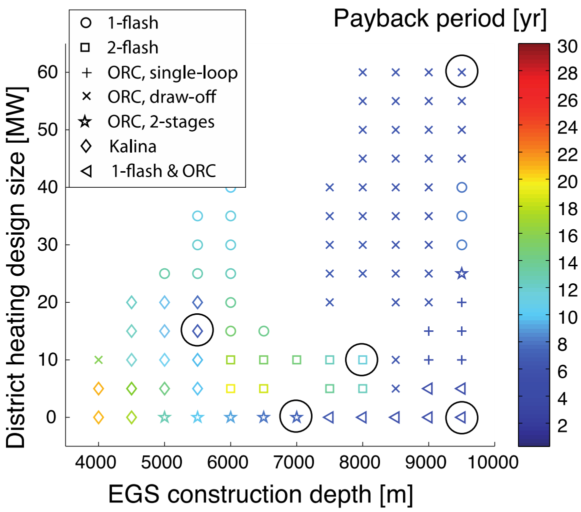

Figure 6: Best conversion technologies selected with payback period, in function of EGS depth and design size of district heating

Moreover, these deep EGS allow for an increased district heating design size. In the deepest range from 8000m to 10000m, though an increased district heating size decreases the electricity production, this introduces no penalty for the economic competitiveness of the system. This is as well true in the range from 5000m to 6000m. This is because the price assumed for electricity (0.16 USD/kWh) is quite low compared to the district heating (0.11 USD/kWh). Though the range from 3000m to 4000m was considered in the optimization, none of the configurations is profitable in terms of payback period.

Regarding the technologies selected, the lowest range of depths, from 4000m to 5500m, is dominated by the Kalina cycle (see configuration 1 on Figure 7), which is attractive for cogeneration of electricity and district heating. From 6000m to 8000m, the single-flash and then the double-flash system are a better option for cogeneration (see configuration 2 on Figure 7). For single electricity production and down to 7000m, an ORC with two evaporation levels is a better option (see configuration 3 on Figure 7). From 7500m to 10000m, cogeneration systems with a large district heating network use in majority an ORC with an intermediate draw-off (see configuration 4 on Figure 7). A few other cogeneration systems with a smaller district heating network use a single-flash or an ORC with a single-loop. In this range of depths, systems producing almost exclusively electricity use a single-flash system with a bottoming ORC (see configuration 5 on Figure 7).

No configuration using the supercritical ORC was selected as a final optimal configuration. This is due to the competition with the two evaporation levels ORC, which allows for achieving an almost equivalent electricity production with lower investment costs.

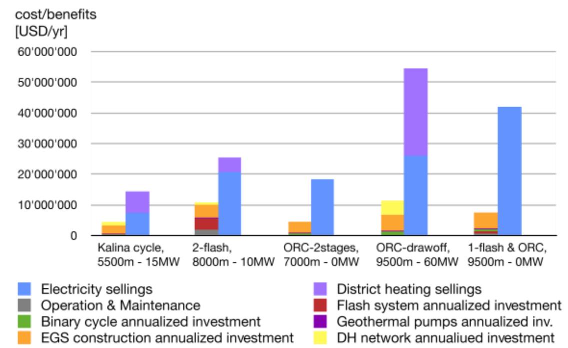

Figure 7: cost-benefit analysis on a yearly basis of 5 typical configurations from Figure 6

Thermodynamic performance

The exergy efficiency of the conversion system associated with the optimal economic configurations is displayed in Figure 8.

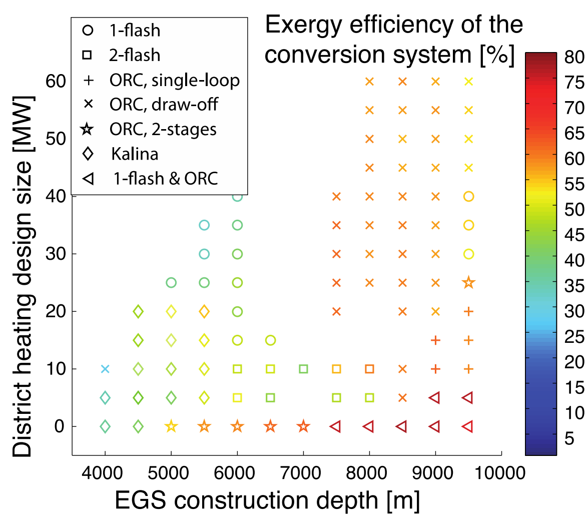

Figure 8: Exergy efficiencies of the conversion system associated with the best configurations of Figure 6

The exergy efficiency of the conversion system depends on the depth and on the district heating design size. The highest efficiencies of around 75% are achieved with a deep EGS from 7500m to 10000m using a single-flash system with a bottoming ORC, almost exclusively for electricity production. In the case of cogeneration systems, the highest efficiencies of around 60% are achieved by an ORC with an intermediate draw-off at 7500m. In the case of cogeneration systems, the exergy efficiency reaches a maximum at a certain depth and starts then decreasing again.

Environmental performance

The yearly-avoided emissions, in terms of CO2-equivalent, associated with the optimal economic configurations are displayed in Figure 9. For illustrating the explanations, a detailed CO2 balance of three of these typical configurations is displayed in Figure 10, identified by a black circle in Figure 9.

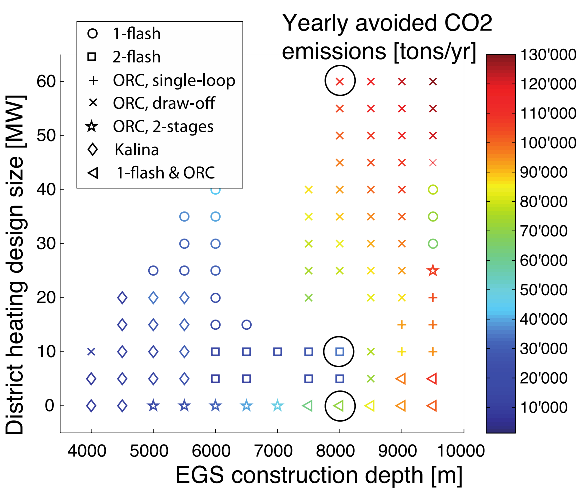

Figure 9: Yearly avoided CO2 emissions associated with the best configurations of Figure 6

The yearly-avoided CO2 emissions, calculated on a life cycle basis, increase with the EGS depth. Though there is a high variation between the shallowest and the deepest configuration, none of the selected optimal configurations has a negative CO2 balance. Like the economic calculations, this is however only valid for the geological conditions assumed in the present case. From 4000m to 6500m, there are no significant differences in function of the depth and of the district heating design size. From 7500m to 10000m, the configurations with cogeneration using the ORC with an intermediate draw-off (see configuration 1 on Figure 10) have higher avoided CO2 emissions than the configurations producing almost exclusively electricity and using flash systems (see configuration 2 and 3 on Figure 10), either alone or with a bottoming cycle. One of the reasons is because the flash systems directly use the geothermal steam, containing CO2 and other gases. This geothermal steam is then emitted in the atmosphere through the condensers. However, since the data used here to calculate these emissions are not for EGS, this particular point has to be verified once reliable data are available for the emissions from geothermal steam from EGS. In the present case, the use of a bottoming binary cycle with a single flash system (see configuration 3 on Figure 10) allows to increase significantly the electricity output, and to decrease the emissions from the flash, which has a smaller size and uses thus less steam. Though electricity production avoids more CO2 than district heating on the basis of the kWh (0.425 against 0.241 kgCO2-eq), cogeneration systems with large district heating networks (see configuration 1 on Figure 10) have higher energy efficiencies due to an increased district heating production, and avoid more CO2 than the single electricity production.

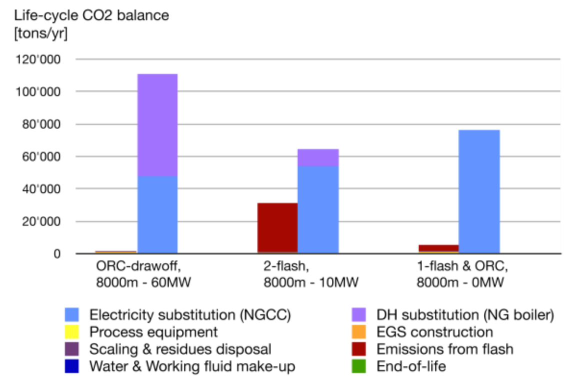

Figure 10: CO2-equivalent balance on a yearly basis for 3 typical configurations of Figure 9

The yearly-avoided impacts, calculated with Ecoindicator99-(h,a), associated with the optimal economic configurations are displayed in Figure 11.

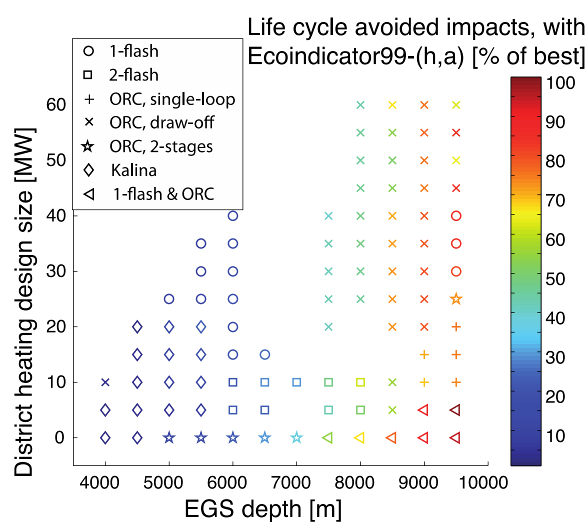

Figure 11: Relative life cycle avoided impacts with Ecoindicator99-(h,a) associated with the best configurations of Figure 6

Like the payback period and the avoided CO2 emissions, the avoided impacts increase with the EGS construction depth, due to the increased output of electricity and district heating, and no configuration has a negative environmental balance. The best configuration is the flash system with a bottoming ORC using a deep EGS. However, unlike for the avoided CO2 emissions, there is no clear difference between flash systems and binary cycles in favor of the binary cycles. This is because the impact assessment method used, the Ecoindicator99-(h,a), offers a broader environmental perspective on different types of environmental perspective, taking into account the impacts on human health, ecosystem quality and non-renewable resources. Thus, the impact of potential CO2 emissions from the flash systems are diluted by the other harmful impacts due to the EGS and power plant construction, and by the benefits of substitution of electricity and district heating from natural gas.

CONCLUSIONS

A systematic methodology has been presented for the conceptual design of geothermal energy conversion systems, considering combined heat and power production and a varying construction depth for EGS. The method includes economic, thermodynamic and life-cycle environmental indicators, all of them being expressed as a function of the conversion technology and of the system configuration. It has been applied to determine the optimal configurations of a mature EGS technology in the geological conditions and market context of Switzerland.

The results of the case study in terms of economic, thermodynamic and environmental performance reflect the variations in the system design: EGS construction depth, design size of the district heating network, choice of the conversion cycle and operating conditions. The following major conclusions can be drawn from this case study:

1) The economic and environmental performances of the geothermal conversion system tend to increase with EGS construction depth. Indeed, economic and environmental investments are compensated by higher electricity and district heating outputs.
2) With an efficient selection and design of the conversion system, the cogeneration of district heating in addition to the electricity production does not decrease the performances and even improves it in terms of avoided CO2-equivalent emissions.
3) All the optimal economic configurations have a beneficial environmental balance, both in terms of avoided CO2-equivalent emissions and avoided aggregated impacts on human health, ecosystem quality and non-renewable resources, calculated with the Ecoindicator99-(h,a).

Though the approach is promising, the methodology needs to be extended to include geological and economic uncertainties in future work. Another aspect to be improved are the data used for the environmental performance, since it is presently not possible to model with certainty the required material and energy flows for the drilling and reservoir enhancement in function of the geology, which could potentially vary in an important way.

REFERENCES

Baldacci, A., Brunazzi, E., Galletti, C. and Paglianti A. (2002), "Modelling and experimental validation of H_2S emissions in geothermal power plants", *Geothermics*, **31**, 501-517.

Cuenot, N., Faucher, J.-P., Fritsch, D., Genter, A. and Szablinski, D. (2008), "The European EGS project at Soultz-sous-Forêts: from extensive exploration to power production", *IEEE Power and Energy Society 2008 General Meeting: Conversion and Delivery of Electrical Energy in the 21st Century, PES, art. no 4596680.*

DiPippo, R. (1991), "Geothermal energy: electricity generation and environmental impact", *Energy Policy*, **19**, 798-807.

DiPippo, R. (2004), "Second Law assessment of binary plants generating power from low-temperature geothermal fluids", *Geothermics*, **33**, 565-586.

Franco, A. and Villani M. (2009), "Optimum design of binary cycles power plants for water-dominated, medium-temperature geothermal fields", *Geothermics*, **38**, 379-391.

Frick, S., Kaltschmitt, M. and Schröder, G. (2010), "Life cycle assessment of geothermal binary power plants using enhanced low-temperature reservoirs", *Energy*, **35**, 2281-2294.

Frischknecht, R., Jungbluth, N., Althaus, H.-J., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, T. and Spielmann, M. (2005), "The ecoinvent database: Overview and methodological framework", *International Journal of Life Cycle Assessment*, **10**, 3-9.

Gerber, L., Gassner M. and Maréchal, F. (2011), "Systematic integration of LCA in process systems design : Application to combined fuel and electricity production from lignocellulosic biomass", *Computers & Chemical Engineering*, **35**, 1265-1280.

Gerber, L. and Maréchal, F. (2011), "Defining optimal configurations of geothermal systems using process design and process integration techniques", *Applied Thermal Engineering*, doi : 10.1016/j.applthermaleng.2011.11.033.

Girardin, L., Maréchal F., Dubuis, M., Calame-Darbellay, N. and Favrat, D. (2010), "EnerGis: A geographical information based system for the evaluation of integrated energy conversion systems in urban areas", *Energy*, **35**, 830-840.

Goedkoop, M. and Spriensma, R. (2000), "The Eco-Indicator99: A damage oriented method for life cycle impact assessment”, *technical report*, PRé Consultants, Amersfoort, Netherlands.

Guo, T., Wang, H. and Zhang S. (2011), "Selection of working fluids for a novel low-temperature geothermally-powered ORC based cogeneration system”, *Energy Conversion and Management*, **52**, 2384-2391.

Guo, T., Wang, H. and Zhang S. (2011), "Fluids and parameters optimization for a novel cogeneration system driven by low-temperature sources”, *Energy*, **36**, 2639-2649.

Haring, M. (2004), "Deep heat mining: Development of a cogeneration power plant from an enhanced geothermal system in Basel, Switzerland”, *Geothermal Resources Council Transactions,* **28**, 219-222.

Heberle, F. and Brüggemann, D. (2010), "Exergy based fluid selection for a geothermal Organic Rankine Cycle for combined heat and power generation”, *Applied Thermal Engineering*, **30**, 1326-1332.

Hettiarachchi, H., Golubovic, M., Worek, W. and Ikegami Y. (2007), "Optimum design criteria for an Organic Rankine cycle using low-temperature geothermal heat sources”, *Energy*, **32**, 1698-1706.

IEA (2011), "Technology Roadmap – Geothermal Heat and Power”, *technical report*, International Energy Agency, Paris, France.

IPCC (2007), "IPCC(2007) Climate Change 2007: The Scientific Basis. In: Fourth Assessment Report of the Intergovernmental Panel on Climate Change (2007)”, *technical report*, Intergovernmental Panel on Climate Change.

ISO (2006), "Environmental Management – Life Cycle Assessment – Principles and framework”, *International Standard, ISO 14040*.

Kanoglu, M. and Dincer I. (2009), "Performance assessment of cogeneration plants”, *Energy Conversion and Management*, **50**, 76-81.

Kristmannsdottir, H. and Armannsson, h. (2003), "Environmental aspects of geothermal energy utilization”, *Geothermics*, **32**, 451-461.

Lazzaretto, A., Toffolo, A., Manente, G., Rossi, N. and Paci, M. (2011), "Cost Evaluation of organic Rankine cycles for Low temperature geothermal sources”, *Proceedings of the 24 International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*, 3854-3868.

Lund, J. and Bertani, R. (2010), "Worldwide Geothermal Utilization 2010”, *Geothermal Resources Council Transactions*, **34**, 182-185.

Maréchal, F. and Kalitventzeff, B. (1998), "Process integration: Selection of the optimal utility system”, *Computers & Chemical Engineering*, **22**, S149-S156.

Mock, J. E., Tester, J. W. and Wright, P. M. (1997), "Geothermal energy from the earth: Its potential impact as an environmentally sustainable resource”, *Annual Review of Energy and the Environment*, **22**, 305-356.

Molyneaux, A., Leyland, G. and Favrat, D. (2010), "Environomic multi-objective optimisation of a district heating network considering centralized and decentralized heat pumps”, *Energy*, **35**, 751-758.

Ormat Systems Ltd (2010), e-mail communication from the 12/06/2010.

Portier, S., Vuataz, F.-D., Nami, P., Sanjuan, B. and Gérard, A. (2009), "Chemical stimulation techniques for geothermal wells: experiments on the three-well EGS system at Soultz-sous-Forêts, France”, *Geothermics*, **38**, 349-359.

Rybach, L. (2003), "Geothermal energy: Sustainability and the environment”, *Geothermics*, **32**, 463-470.

Saleh, B., Koglbauer, G., Wendland, M. and Fischer, J. (2007), "Working fluids for low-temperature organic Rankine cycles”, *Energy*, **32**, 1210-1221.

Sprecher, J. (2011), "Tridimensional modeling of the deep geology of the Molassic Plateau of Western Switzerland”, *master thesis*, effectuated at the Ecole Polytechnique Fédérale de Lausanne, Switzerland

Tester, J., Anderson, B., Batchelor, A., Blackwell, D., DiPippo, R., Drake, E., Garnish, J., Livesay, B., Moore, M., Nichols, K., Petty, S., Toksoz, M. and Veatch, R. (2006), "The Future of Geothermal Energy – Impact of Enhanced Geothermal Systems in the 21st Century”, *technical report*, Massachusetts Institute of Technology, USA.

Turton, R., Bailie, R., Whiting, W. and Shaiewitz, J. (1998), *Analysis, synthesis and design of chemical processes*, Prentic Hall, New Jersey, USA.

Ulrich, G.-D. (1996), *A guide to chemical engineering process design and economics*, Wiley, New York, USA.