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Environomic Optimal Design of Geothermal Energy Conversion Systems Using Life Cycle Assessment

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Environomic Optimal Design of Geothermal Energy Conversion Systems Using Life Cycle Assessment

Dominika Matuszewska

A 30 ECTS credit units Master´s thesis

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ABSTRACT

Recent years have seen an increased interest in reducing greenhouse gases emissions, reducing the consumption of non-renewable energy resources, and increasing energy supply security. This interest has created improved opportunities for renewable energy systems development, including the use of geothermal energy for electricity and/or heat production. Corresponding to this interest, the environmental impact of renewable energy systems, including geothermal energy, have become an important topic of study. To evaluate these impacts, a conventional life cycle assessment (LCA) is commonly used.

This paper proposed a strategy to integrate life cycle assessment (LCA) in thermo-economic model used to design geothermal conversion systems. Swiss and Polish case studies are considered for the validation of this methodology. The superstructure of system consist of the superstructure of exploitable resources with the superstructure of conversion technologies and multiple demand profiles for Swiss city Nyon and Polish city Konin.

The emphasis is put on the maximization of exergy efficiency of geothermal conversion systems and the minimization of their generated life-cycle assessment impacts.

The proposed strategy can be adjust to determine the optimal exploitations schemes and system configuration across the multiple periods. The evaluation of the methodology can give important tool to evaluate decision-making problems.

PREFACE

The use of geothermal resources for supplying simultaneously different energy services such as electricity, district heating and district cooling has recently gained interest.

The optimal design of such systems required knowledge of the geothermal resources that will be used, selection of appropriate energy conversion technologies, and specification of component operating conditions. This can be achieved using process integration techniques and multi-objective optimization in a multi-period time perspective, accounting for economic, thermodynamic and environmental criteria.

While economic and thermodynamic analysis methods have been widely applied, the dynamic evaluation of environmental impact in a process design context is still relatively new. Environmental evaluation of geothermal systems should be performed on a life cycle perspective since impacts from drilling and construction are likely to be important. Therefore, life cycle assessment is the appropriate method to quantitatively evaluate and compare the different systems configurations including resources, conversion technologies and services to be supplied. However, to be used as an effective design and evaluation tool for the optimal configuration of geothermal systems, life cycle inventory has to be fully integrated in the process design framework and to be operated in a multi-period time perspective to account for the variation of energy services to be supplied throughout the year.

This analysis attempts create a convenience tool for optimization the geothermal conversion system. It is believed that with time and development, this type of analysis can become one of the mostly used in geothermal project realization.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

CP	Chemical Products
CP_{drill}	Drilling Chemical Products
DA	Deep Aquifer
EGS	Enhanced Geothermal System
EPFL	Swiss Technology Institute, Lausanne
FD	Double Flash system
FS	Simple Flash System
FU	Functional Unit
GF	Geothermal Fluid
HP	Heat Pump
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LENI	Industrial Energy Laboratory
ORC	Organic Rankine Cycle
SA	Shallow Aquifer
WF	Working Fluid

1 INTRODUCTION

This study focuses on identifying the optimal configuration for geothermal system with a given resource and with a given multi-period demand profile. Consideration has been provided for economic, thermodynamic and environmental criteria. Emphasis is put on life cycle assessment integration, and how the inclusion of environmental criteria influences the resulting design decisions.

1.2 Geothermal Energy in Europe

In the recent years, most of the countries of the world have been interested in implementing the sustainable development. This new approach put emphasis on harmonization the economic development with the protection of natural environment. This interest has created improved opportunities for renewable energy systems development, including the use of geothermal energy for electricity and/or heat production.

Geothermal energy has a great potential to be applied on wide scale. Despite that, Europe is a world leader in direct use of geothermal resources; the contribution in renewable mix in Europe is still not significant.

The heat flow ranges from 30-40 mW/m^2 (the oldest part of the continent) to 60-80 mW/m^2 (Alpine system) cause that mainly medium and low temperature resources characterize the European continent. Highest values (80-100 mW/m^2) appear in area within seismically and tectonically activity (Hurter and Haenel, 2002; Kępińska, 2009).

Varies ranges of enthalpy cause that geothermal energy is reclaimed in different ways:

- power generation (Iceland, Italy, Greece, Turkey);
- direct use of hydrothermal resources in sedimentary basins (France, Germany, Poland, Italy, Hungary, Romania, and others);
- geothermal heat pump (Australia, Switzerland, Germany and Sweden).

Geothermal resources in European continent are shown in figure (Figure 1.1).

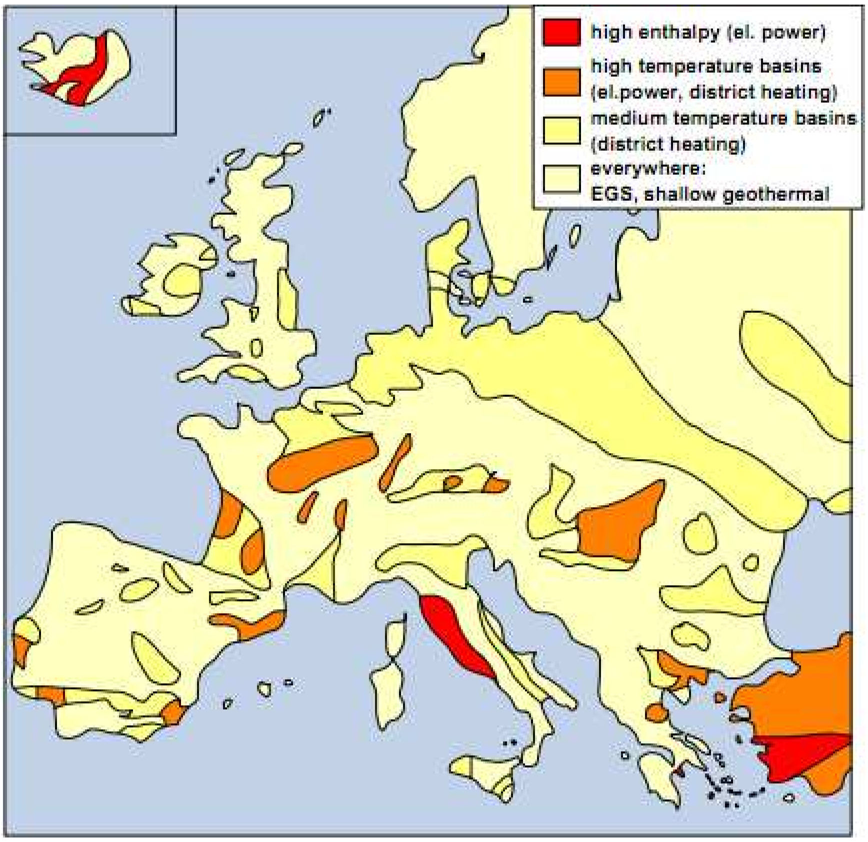

Figure 1.1 A sketch illustrating the general distribution of main basins and geothermal resources in Europe (from Antics and Sanner, 2007)

For European conditions Antics and Sanner (2007) report that installed capacity stands at:

- 1060 MW for geothermal power generation;
- 13600 MWt for direct use; in this 6600 MWt for geothermal heating from medium and low temperature sources (with 50 MWt increscent per year).

Geothermal Power Production Status

There is only a few places in Europe which generate power using geothermal steam. This is dedicated by the fact that there is only a few states in Europe with high enthalpy resources. To those places can be included: Iceland, Italy, Russia (Kamchatka), Turkey, Portugal (Azores), France (Guadeloupe). In 2004, 12% of electricity produced from geothermal energy was generated in Europe. Recently, the geothermal power plants start operating in Austria and Germany (Table 1-1).

Table 1-1 Geothermal power production in Europe (from Rybach, 2006, Antric and Sanner, 2007)

Country	**Installed Capacity [MWe]**	**Annual Energy Produced [GWh/y]**
Austria	1.2	3.2
Germany	0.2	1.5
Iceland	202	1483
Italy	810.5	5200
Portugal (San Miguel Island)	16	90
Turkey	30	108
Total in Europe proper	**1059.9**	**6885.7**
France (Guadeloupe island)	15	102
Russia (Kamtchatka)	79	85
GRAND TOTAL	**1153.9**	**7072.7**

Geothermal Direct Uses Status

In Europe, heat from geothermal energy is supplied as a hot water from deep aquifer, or in small or medium shallow geothermal plants. Besides the low and medium enthalpy, geothermal resources are directly applicable in greenhouse heating, fish farming (called aquaculture), space cooling or crop drying, etc. (Figure 1.2).

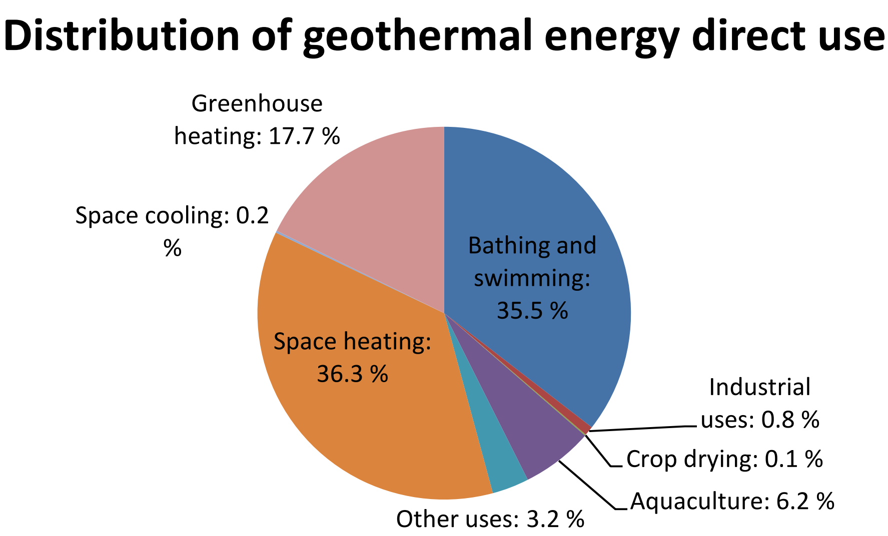

Figure 1.2 Distribution of geothermal energy for direct uses in Europe (% of TJ) (based on data from Antics and Sanner, 2007)

1.2.1 Geothermal Energy in Poland

Poland, like almost all European countries, does not lie in the area of seismic and tectonic activity, which cause that Polish geothermal resources characterize low and medium heat flows. It varies from 25 – 40 mW/m^2 in the Precambrian platform, through 50 low and medium temperature sedimentary basins. Their temperature change in the range 20 – 80°C, in some places reached above 100°C.

Distribution analysis of geothermal energy resources in terms of surface area indicates that the Polish geographical location has no significant effect on the size of this indicator. Comparison of 12 European countries (Table 1-2) shows that Polish resources are similar to Spain, Portugal and Great Britain. They fall in the range of average values and are approximately $2.9 \cdot 10^7$ J/km^2 (Górecki, 2006).

Table 1-2 Geothermal energy resources in selected European countries (from Górecki, 2006)

Accessible resources	10^{17}[J/km^2]	Accessible resources	10^{17}[J/km^2]	Accessible resources	10^{17}[J/km^2]
Belgium	2.2	Poland	2.9	Netherlands	3.8
Greece	2.3	Spain	2.5	Austria	4.4
Portugal	2.4	France	3.3	Hungary	32.2
Uk	2.4	Germany	3.3	Italy	211.5

Poland has a long tradition of using geothermal water in medicine, although in this field geothermal energy is used on a small scale. The eighties in Poland brought the use of geothermal energy for heating and the pilot-scale in agriculture and fish farming. It led to opening five geothermal heating plants: in Podhale, in Pyrzyce, Mszczonów, Uniejów and Stargard Szczeciński (Figure 1.3). Moreover, now on-line are several installations based upon groundwaters of temperature below 25°C, and several thousand installations using ground heat pump.

Figure 1.3 Localization of operating geothermal (without installations utilizing soil heat) and balneological plants versus geothermal units (from Atlas of Geothermal Resources of Mesozoic Formations in the Polish Lowlands)

1 – on-line geothermal plants, 2 – other planned to construct, 3 – spas using geothermal waters from springs and wells

Different sources give different data about installed capacity of geothermal energy in Poland. Bujakowski, Górecki, Kępińska and Ney estimate that total power exceeds from geothermal installation exceeds 210 MWt (Table 1-3). While the International Geothermal Associations (IGA) (Lund, Freeston, Boyd, 2005) provide value 170.9 MWt (838.3 TJ/y) (including heat pumps).

Table 1-3 Principal parameters of geothermal, balneological and heat-pump installation in Poland

Classification	**Installed capacity Total / from geothermal [MWt]**	**Annual heat generation [TJ/y]**
Group I – geothermal plants	125.6 / 44.8	578.6
Group II – balneotherapeutic installations	3.36	29.9
Group III – heat pumps	>81.8 / > 53.35	> 500.25
TOTAL	**>210.76 / > 101.51**	**>1 108.75**

The difference is cause by the way of computing. 210 MWt is represent for total power capacity of three groups of installations, where only half of this value is supplied from geothermal energy (over 101 MWt). The other half originates from gas, oil and electricity use in these installations.

In IGA estimations, the installed capacity is provided only from geothermal (even if it excludes total capacity of some utility). Moreover, in the IGA there are provided data not only for three type of installations like it was in keys of Bujakowski, Górecki, Kępińska, Ney but include others geothermal applications (Figure 1.4).

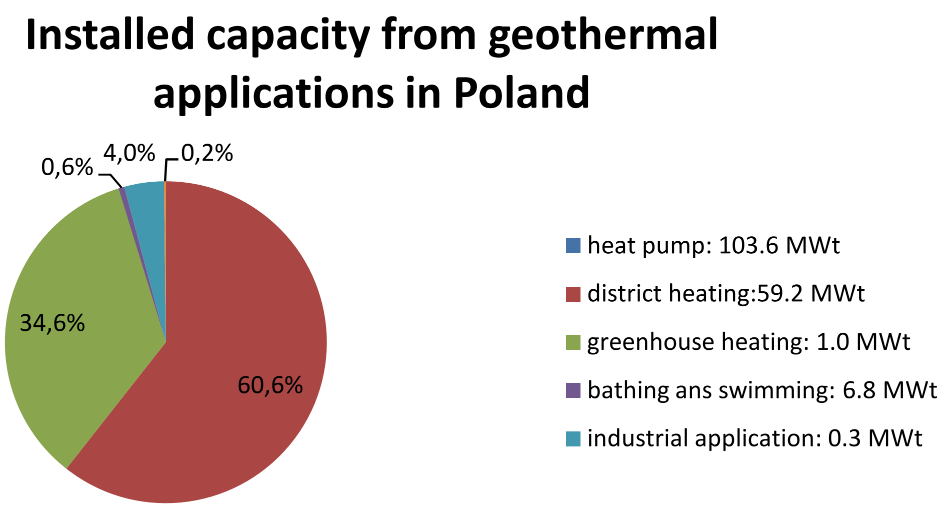

Figure 1.4 Installed capacity from geothermal applications in Poland (based on data from IGA)

The IGA divided installed capacity from heat pumps into two groups. First group for ground-source heat pumps with an installed capacity at least 80 MWt and heat production of 500 TJ/year (this values come from estimations that there is at least 8000 ground-heat heat pumps in Poland). The second group sets absorption heat pumps at geothermal plants, with installed capacity of 23.6 MWt (74.4 TJ/y). Besides it was add to the total installed capacity other various use of geothermal energy:

- district heating (59.2 MWt and 232.0 TJy);
- greenhouse heating with included fish farming and wood drying (1.0 MWt and 4.0 TJ/y);
- bathing and swimming (6.8 MWt and 26.9 TJ/y);
- industrial application in this salt or CO_2 extractions (0.3 MWt and 1.0 TJ/yr).

1.2.2 Geothermal Energy in Switzerland

Heat pumps mainly dominate the geothermal energy use in Switzerland. An available global data shows that Switzerland occupied prominent worldwide rank in installed capacity and energy use of heat pumps (Table 1-4). The estimation shows that one shallow heat pump statistically falls for each two km^2 of country area (Rybach, Gorchan 2000).

Table 1-4 Worldwide ranking (in order) of geothermal heat pump utilization in 2004 (from Rybach, 2005)

Capacity installed [MWt]	**Energy use [TJ/y]**
1. USA 2. Sweden 3. China 4. Switzerland 5. Norway	1. Sweden 2. USA 3. China 4. Denmark 5. Switzerland

The domination of low and medium temperature geothermal basins created good conditions to developing shallow geothermal applications through heat pumps.

The data provided by the IGA (Lund, Freeston and Boyd, 2005) shows that over 90 % of installed capacity of geothermal energy applications belong to heat pumps (Figure 1.5). The other uses of geothermal energy have marginal importance: district heating (6.1 MWt and 134 TJ/y); air conditioning (2.2 MWt and 11 TJ/y); snow melting (0.1 MWt and 0.3 TJ/y); and bathing and swimming (40.8 MWt and 1,230 TJ/y).

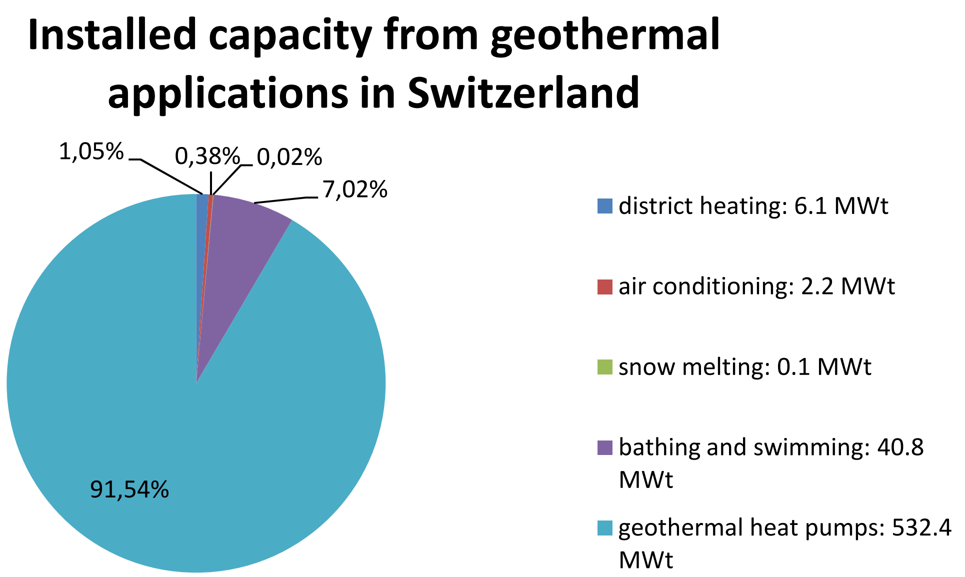

Figure 1.5 Installed capacity from geothermal applications in Switzerland (based on data from IGA)

Data provided for 1997 shows that heat pump had only 75% of total share of heat delivered in the Swiss geothermal mix (Rybach, Wilhelm, 1999). Comparing that to 90% in 2005 the significant growth is observed. It is believed that promotions, economical incentives, research, and technology create an excellent opportunity for rapid development of heat pumps in Switzerland. Rybach and Wilhelm (2003) find prospective field for heat pumps technology in usage the thermal energy contained in drainage water out of existing tunnels or new tunneling through an Alpine massifs.

The figure below shows that through the years Switzerland increase geothermal direct use capacity (Figure 1.6), and still occupies a leading position in Europe.

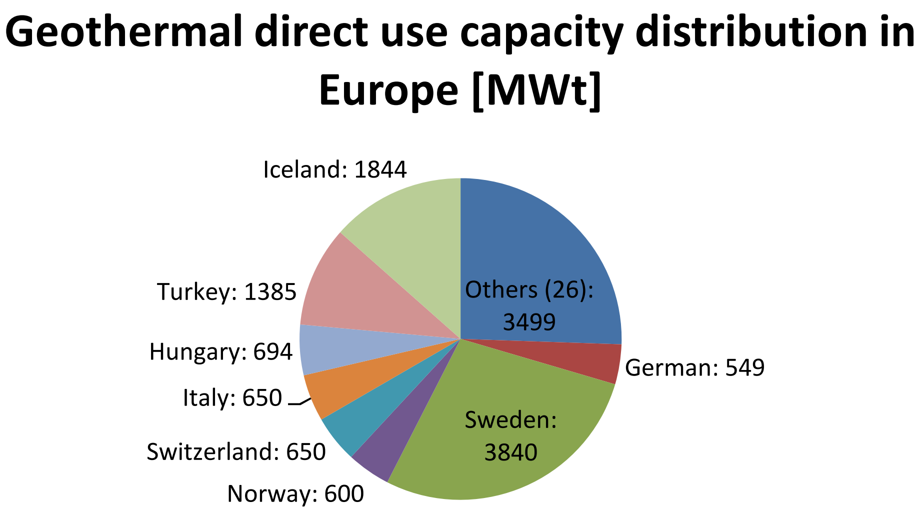

Figure 1.6 Geothermal direct use capacity distribution in Europe [MWt] (from Antics and Sanner, 2007)

In recent years an EGS (Hot Dry Rock) systems become topic of study. French, Germany and Switzerland countries involved in international project in Soulz-sous-Forests oriented in power generation. The result of project was electricity production launched in 2008.

1.3 Context

1.3.1 Interest of Study

The main objective of this project is to identify the optimal configurations for a geothermal system with a given resource and with a given multi-period demand profiles. Consideration is provided for economic, thermodynamic and environmental criteria. Emphasis is put on life cycle assessment integration, and on how the inclusion of environmental criteria influences the resulting design decisions.

The objective of this work provide to identify, in a given geological context, which type of geothermal resources should be used from both economic and environmental point of view (e.g. shallow aquifers, deep aquifers, or enhanced geothermal systems (EGS)). The work can help in identification which technologies (e.g. direct exchange, flash systems, binary cycles and heat pumps) are the best to provide multiple energy services (electricity, district heating, and district cooling) throughout the year.

Some people argue that environmental performance can be improved by simply increasing the system efficiency in the case of an energy system. Another subsequent goal for this study is the identification of possible trade-offs between the economic and environmental objectives, and as well between the thermodynamic and economic optimums.

Another objective is the development of methodology for the environomic (economic, thermodynamic and environmental) optima design of geothermal energy conversion systems. The life cycle impact assessment (LCIA) results obtained with the developed methodology can be compared with the result obtained by a conventional LCA of the same system. Another goal of this work is to show the importance of effects of process configuration, integration and efficiency on the environmental impacts of geothermal energy conversion systems.

1.3.2 Literature Review

Varieties of studies that use LCA in a process design have been done. The most general approach of using LCA in a product design context is presented by Keoleian (2003). However, the guidelines presented by Keoleian do not provide information on how to integrate the LCA in a process design environment with computer optimization techniques. Studies that did use LCA in multi-objective optimization which accounted for economic and environmental criteria were conducted by Kniel, Delmarco and Petrie (1996), Azapagic and Clift (1999) and Alexander, Barton, Petrie, and Romagnoli (2000). These studies focus on the product manufacturing, and they do not take under consideration the specificities of energy system design, the production of multiple energy services, nor the successive technology generation in the case of an emerging technology. Papandreou and Shang (2008) conducted studies about the use LCA in a multi-objective optimization approach for utility system design in the field of energy systems. However, in their work they put emphasis only on gaseous emissions, having only considered the use of fossil energy resources. When dealing with renewable energy conversion systems, the impact of off-site emissions is usually a large portion of the overall environmental impact. The studies of Li, Maréchal, Burer, and Favrat (2006), Bernier, Maréchal, and Samson (2010) focused on the use of LCA in a multi-objective framework. These studies accounted for the levelized cost for electricity and the life cycle global warming potential for the studied facility. The research results show that the increase in efficiency contributes to the minimization of the environmental impact in the fossil fuel resources case. Further, the LCA was used to calculate the impact of a CO_2 tax.

The studies of Hoban, Gerber and Maréchal (2009) developed a systematic methodology using thermo-economic modeling that can be used to identify the optimal exploitation schemes of geothermal resources. A multi-period approach was used to integrate exploitable resources with the conversion technologies and multiple demand profiles. However, LCA data was not included in that study. Anna Maria Ruiz Dern (2010) completed a study of the life cycle inventory for the models of resources and technologies that were used in this study. Moreover, these specific works on geothermal energy were conducted using LENI software.

As it was presented above, there are several studies on the use of LCA in a process design context. There has been some methodology proposed for integrating LCA into termo-economic models used for the conceptual design of energy conversion systems. One example is the one developed for biofuels by Gerber, Gassner, Maréchal (2010). However, none of them has been applied specifically to the conceptual design of geothermal energy systems.

1.3.3 Scope

This report intends to outline the environomic (economic, thermodynamic and environmental) optimization of geothermal energy conversion technologies using Life Cycle Assessment (LCA). It is presented conceptual process design of such technologies in the frame of multiple energy services. Proposed strategy can be used as a tool for evaluating potential of different geothermal resources depending on conversion technologies and demand profiles.

2 METHODOLOGY

This chapter outlines approach to the problem of optimal design of geothermal energy conversion systems by using process integration techniques and multi-objective optimization (MOO) in a multi-period time perspective with putting emphasis on life cycle assessment (LCA) integration.

2.2 Research development

The development of environomic model including LCA part consists of a couple of resolution sequences presented in the figure below (Figure 2.1).

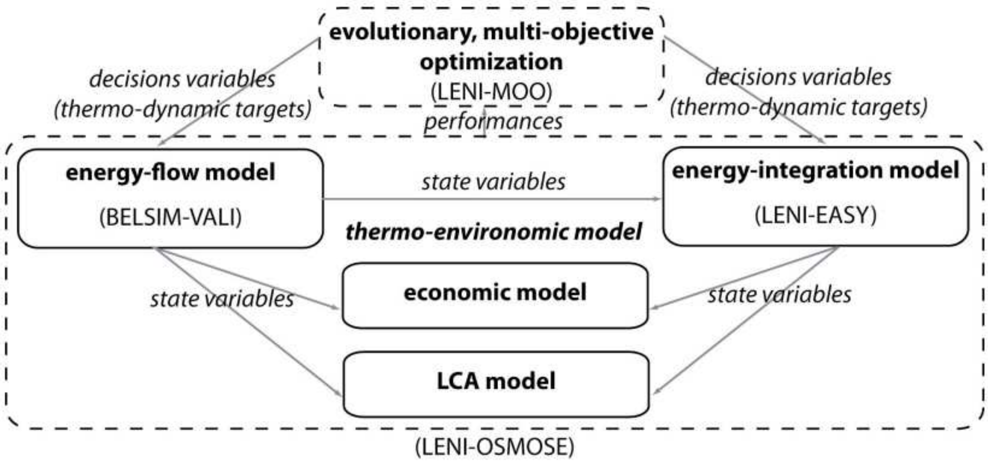

Figure 2.1 Architecture of the environomic process model (from Gerber, Gassner and Maréchal, 2009)

A usable technologies, exploitable resources and demand profiles made up the physical model, which is linked with computation methods by proper platform. Industrial Systems Laboratory (LENI) at the Swiss Federal Institute of Technology (EPFL) developed their own platform to this purpose, called OSMOSE. Thanks, to OSMOSE platform, working under MatLab, the physical model (based on exploitable resources, usable technologies, and demand profiles) can be compute using methods like Energy Integration (AMPL) or pinch analysis, costing or life-cycle analysis.

The usable geothermal energy conversion technologies are modeled in ValiModeller and what more important are available in EnergyTechnologies Database.

The thermo-economic design approach is used to create the interaction between different models required for the energy system design. In OSMOSE platform the energy flow models of the process unit operations and process integration techniques are combines.

In first step, given operating conditions are used to calculate the energy flow model. It is done to obtain not only mass and energy flows but also the corresponding thermodynamic states. These results are used in energy integration solver (AMPL), which is used to find the pinch point of the hot and cold fluxes. The results of energy-flow and energy integration models determine the size of the equipment, the number of units and the total area of the heat exchanger network.

Further, the thermodynamic and economic performance indicators are evaluated based on size. These include evaluation of the environmental impacts calculated by life cycle impact assessment (LCIA), which can be used as indicators of the environmental performances in multi-objective, environomic (i.e. energetic, environmental and economic) optimization (Gerber, Gassner, and Maréchal (2010)).

2.3 LCA model

The potential environmental impact of a product, a services or a system can be assessed based on LCA methodology (ISO norms 14’040 & 14’044). Thanks to looking at the process from cradle-to-grave stages, LCA technique eliminates the narrow outlook on the environment. The four main stages are emphasized from LCA method:

- goal and scope definitions;
- the life cycle inventory (LCI);
- the impact assessment (LCIA);
- the interpretation.

In figure below (Figure 2.2) conduction of LCA model in EnergyTechnologies in presented. Note the LCA connection with the process design has been distinguished in the figure. The crucial matter in listing LCI flows is to identify to which process units the flows are linked and what is their function. Because flows are mathematically expressed as a function of the decision variable of thermo-economic model, this identification is essential. The scaling of impacts due to changes in operating conditions and sizes of the process equipment may also be considered. The mathematical expressions for LCI flows and impacts due to process equipment are included in the LCA, which makes it possible to calculate the whole LCI for a given process configuration. For the process of the life cycle inventories and for the impact assessment methods, the Ecoinvent® life cycle inventories database has been used.

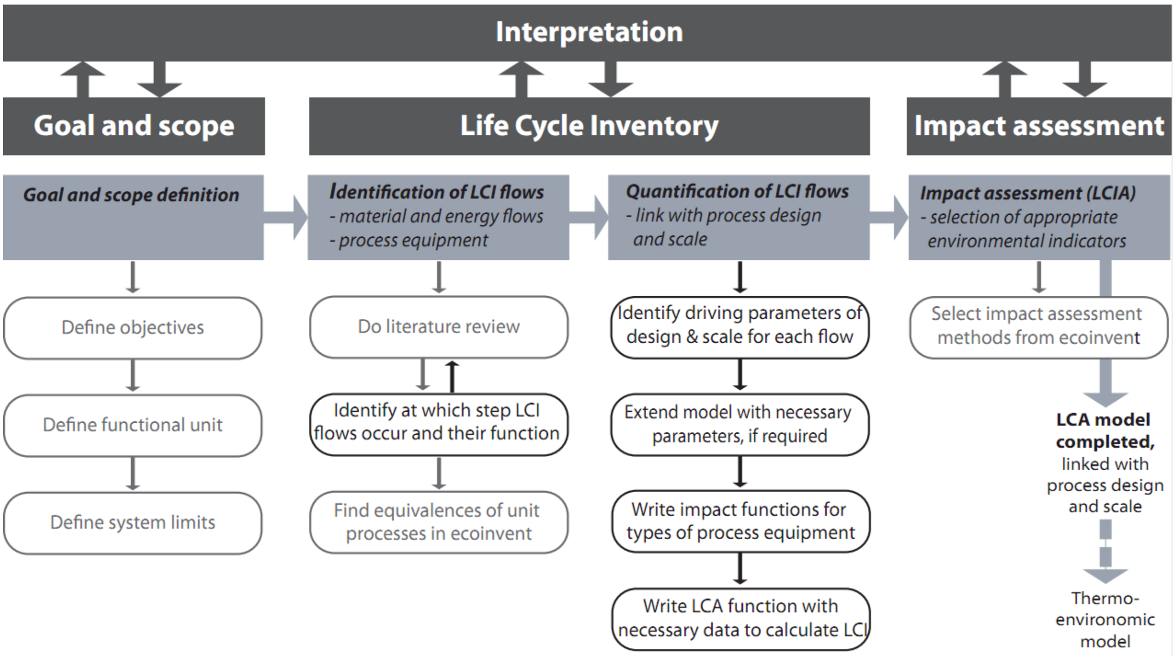

Figure 2.2 Developed general methodology for LCA model conception (from Gerber, Gassner and Maréchal, 2009)

2.3.1 Goal and scope definition

In the first phase, the goal and scope of the study are formulated. To ensure comparability of LCA results, a unique tool – called Functional Unit (FU) was introduced. FU is a value, which is used to quantify the functions of the system. Because of such approach, an every flow is brought back to FU. Then, the system boundaries determine which unit processes are included in the LCA.

From the LCA side, the goal and scope of this study is to identify the most suitable process configuration, which minimize the environmental impacts of geothermal energy conversion systems use to provide energy services. As FU the kWh of energy, available from the exploitable geothermal resources, is chosen. It seems to be important to check environmental impact for every 1kWh of usable energy provided by geothermal conversion systems. This approach cause that the main emissions from geothermal power station, as well as from usable energy production, will be investigated. The energy here is provided as net value. It is defined as energy generated during the lifetime geothermal power plant minus the energy consumption of the overall plant.

In this study the system boundaries are determined by the life of geothermal plant, it means that three main phases (construction, operation and dismantling) are taken under consideration.

2.3.2 Life Cycle Inventory

At the second phase, Life Cycle Inventory, the identification and quantification of every flow (extraction or emission) crossing system boundaries is done. Anna Maria Ruiz Bern

(2010) has done life cycle inventory for the models of resources and technologies used in this study. At the Figure 2.3 the emissions and extraction inventory or life cycle inventory (LCI) is presented as a vector of cumulated single substances, or elementary flows.

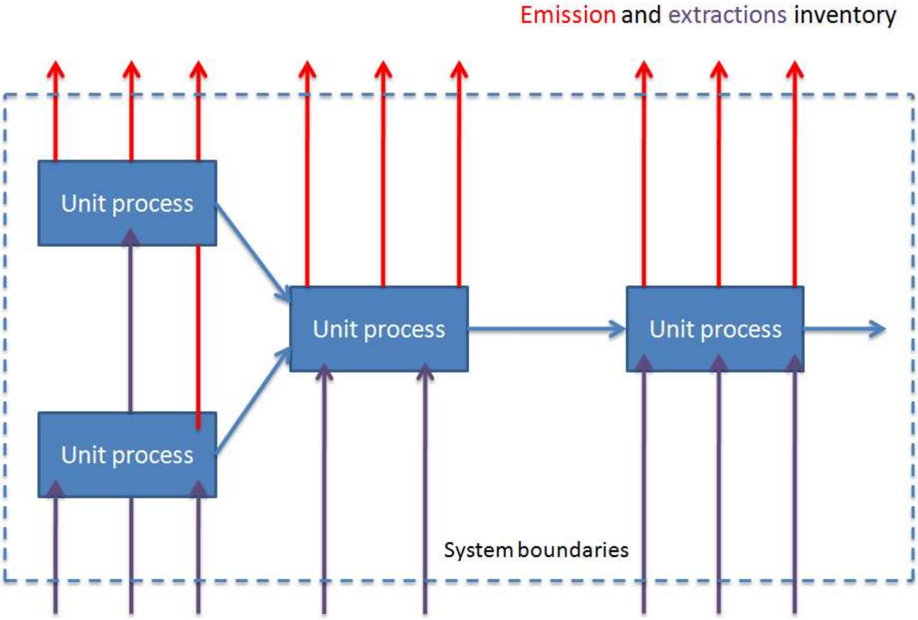

Figure 2.3 Schematic representation of the construction of a life cycle inventory (from EnergyTechnologies Documentation)

On the base of the defined systems, the different material and energy flows of the LCI are identified. Equivalence is determined for each flow by using Ecoinvent® life cycle inventories database. The identified LCA flows are quantified. Each LCA flow is expressed as function of design and scale parameters. That cause that scaled emissions and impact are returned as an output.

2.3.3 Life Cycle Impact Assessment

In this phase, the environmental impact is computed by cumulating the emissions and extractions from different substances emitted. In this way the global indicators are created, which are significant for environment. Gerber, Gassner and Maréchal (2010) present general equation useful in computing the general indicators by aggregating emissions and extractions of LCI (Equation 1).

$$\begin{bmatrix} F_{1,1} & \cdots & F_{1,n} \\ \vdots & \ddots & \vdots \\ F_{m,1} & \cdots & F_{m,n} \end{bmatrix} \cdot \begin{bmatrix} E_1 \\ \vdots \\ E_n \end{bmatrix} = \begin{bmatrix} I_1 \\ \vdots \\ I_m \end{bmatrix} \qquad (1)$$

Where:

$F_{i,j}$ – the weighting factor to convert LCI emission I into the impact category j;

E_i – the emission or extraction i calculated at the LCA;

I_j – the impact assessment method

Quiet important is fact that the weighting factors vary depending on used assessment methods. In this study, three different assessment methods have been used due to various environmental approaches (Table 2-1).

Table 2-1 Impact assessment methods used

Method	**Impact category**	**Unit**
Ecoindicator99-(h,a)	Human health	pts
	Ecosystem quality	pts
	Resources	pts
Ecoscarcity06	Air emissions	UBP
	Surface water emissions	UBP
	Groundwater emissions	UBP
	Top soil emissions	UBP
	Energy resources	UBP
	Natural resources	UBP
	Deposited waste	UBP
IPCC	Global warming pot., 100a	$kgCO_2$-eq

Ecoindicator99-(h,a)

Ecoindicator99 methodology is damage oriented one. It means that in Ecoindicator99 approach the weighting procedure has not concerned the impact categories but is interested in damages that are caused by these impact categories. These three damage categories refer to:

- Damage to Human Health, formulate as the number of year life lost and the number of years lived disabled;
- Damage to Ecosystem Quality, which can be explain as the loss of species during a certain time, over a certain area;
- Damage to Resources – the excess of energy needed for future extraction of minerals and fossil fuels.

Ecoscarcity06

The Ecoscarcity impact assessment method can be used only for Swiss context study. For various types of emissions, energy resources or waste, characterization factors are used to accumulate them to a present pollution level. They are compared with a critical pollution level, which was created on the basis of the scientifically supported goals of Swiss environmental policy.

Global Warming Potential at 100 years of the Intergovernmental Panel on Climate Change

Global Warming Potential (GWP) method is a problem-oriented method. It uses long-lived greenhouse gases to evaluate the warming effects. The emphasis is on a particular period during which the impact of the greenhouse gases is measured. GWP is expressed in terms of emissions of carbon dioxide.

The fourth phase of the LCA is interpretation, during which the results are summarized. This part is presented in section five with the results of optimization.

3 TECHNICAL ASPECTS

This section describes the technical aspects of developed models. It considers the resource, conversion technologies superstructures and the identification of the demand profiles for particular cities in Switzerland and Poland.

3.1 Geothermal resources

Geothermal resources can be modeled in various forms, which can be taken as independent systems or potentially be used as a combination of these forms. In this study, it is assumed that each form is taken separately. In this work, only types of resources are taken under consideration:

- hot dry rock or enhance geothermal system (EGS);
- deep aquifer;
- shallow aquifer.

Each resource can be examined from three different ways: extraction, injection and storage. It was modeled that each time when extraction is used, the injection appears. The geothermal resources has been modeled in Matlab and are provide in EnergyTechnologies database.

Below is presented figure (Figure 3.1) with possible solution for varying geothermal resources.

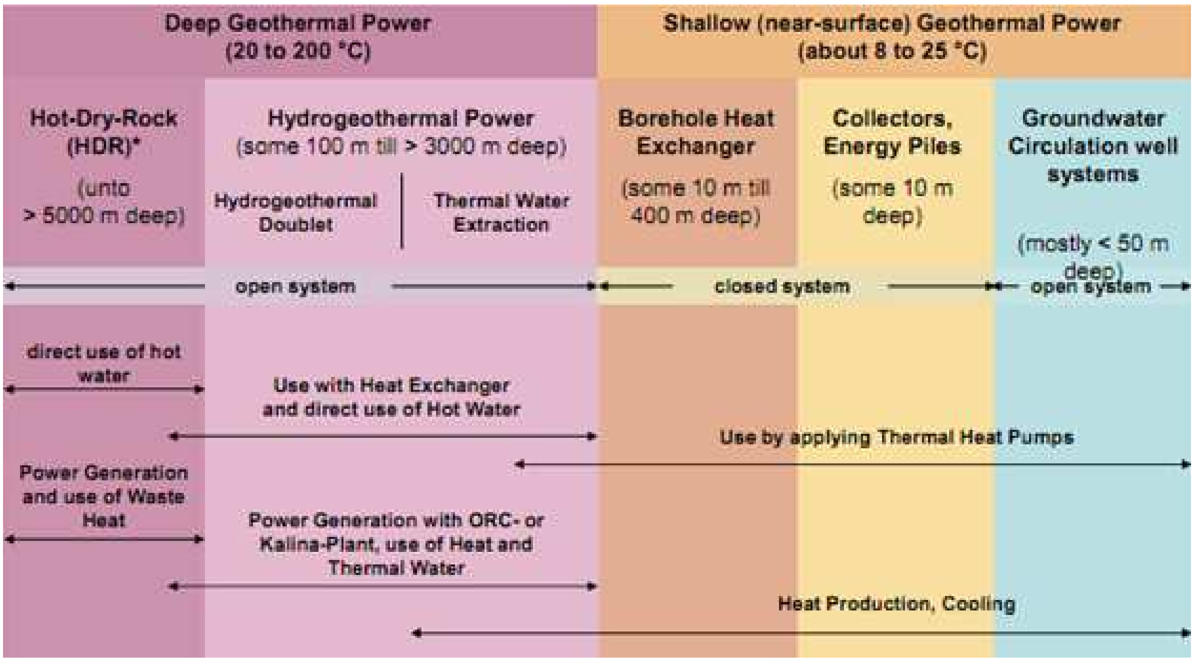

Figure 3.1 Possibility solutions for different types of geothermal resources (from Sass, 2010)

3.2.1 Hot Dry Rock

Hot Dry Rock (HDR) also enhanced geothermal system (EGS), or Hot Fractured Rock (HFR) is resource where both the fluid and the reservoir are artificial. The water under high pressure is pumped through drilled well into deep body of compact rock, which has sufficient temperature at depth but unfortunately not enough fluid to be extracted. The process causes hydraulic fracturing of rock, thank to what water can permeates these fractures and extracts heat from surrounding rock. In this phase, it starts behave as natural reservoir from which heated fluid is extracted through the second well (heat mining). (Dickson and Fanelli, 2004, Garnish, 1987) (Figure 3.2).

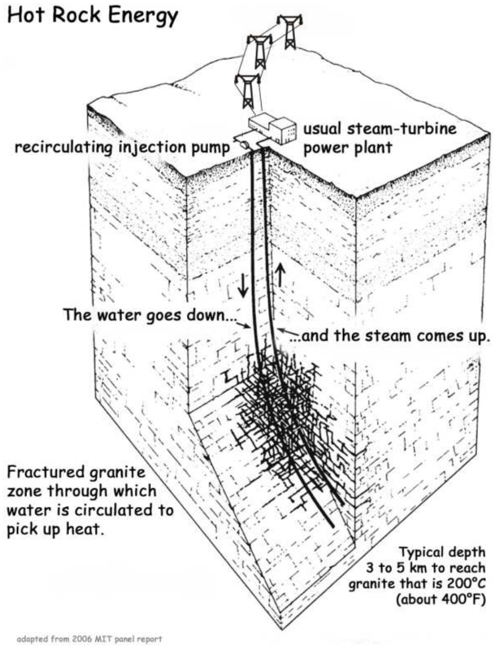

Figure 3.2 The schematic of hot dry rock (from MIT 2006 panel report)

The important matter in case of hot dry rock geothermal power plant is that this kind of power plant can be located anywhere that the access to hot rock is possible by drilling. This causes that hot dry rock projects can be implemented with large freedom of choice.

During work, it was assumed that there is linear thermal gradient, which was established by evaluating geothermal temperature profile demand for Switzerland conditions (Figure 3.3). For residential area of city in Switzerland, Nyon it was set 3.8°C for each 100m of drilling dept. Assuming that thermal gradient is linear it is possible to calculate the depth of the drilling.

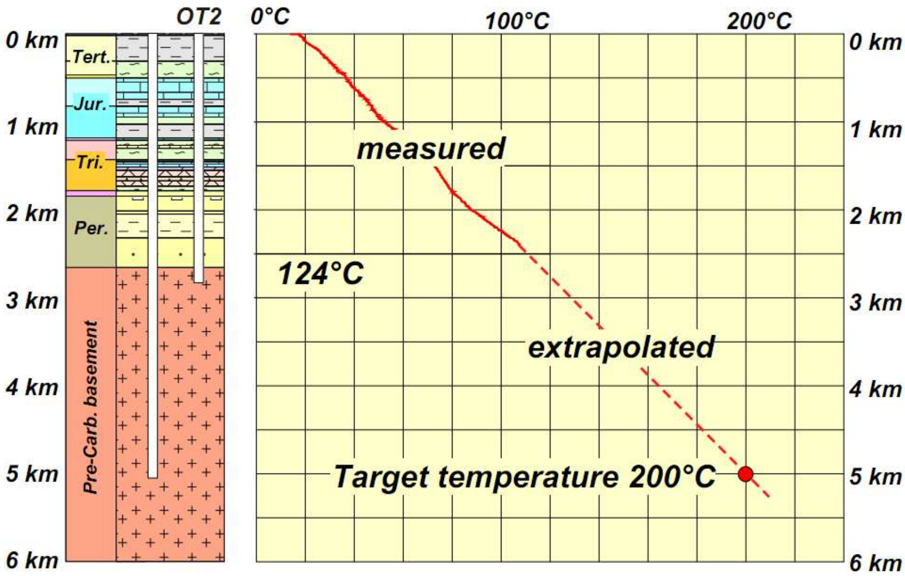

Figure 3.3Geotherml Temperature Profile for Switzerland conditions (from Haring)

For Polish conditions general, the temperature gradient change between 1 - 4°C per 100m. There relatively high water temperatures in the Lower Cretaceous basin are cause by increased geothermal gradient reaching 3.0-3.3 °C per 100m.

Because the thermal gradient is modeled as average value, consider as linear it will be used in all models in the geothermal superstructure.

The main decision variables of the hot dry rock resource are outline in Appendix A.

3.2.2 Deep Aquifer

In this study by deep aquifer (DA), it is understand a natural hydrothermal system in which fluid is spontaneously produced. This cause that there was no need to add make up water. The aquifer ability to replenish naturally simplifies modeling.

Modeled deep aquifer can be used to provide district heating and district heating. For providing electricity, the temperature of deep aquifer is not enough.

The model was based on the deep aquifer system that provides heat for district heating for city Riehen (in northwest Switzerland).

The main decision variables of the deep aquifer are outline in Appendix A.

3.2.3 Shallow Aquifer

The shallow aquifer (SA) essentially is similar to the deep aquifer, except depth and temperature. Sometimes it is called near-surface aquifer because it provides heat from lowest temperature (from couple of meters in case of open loop systems to even 400 m in case of close loop systems). The temperatures available at these depths are lower than in case of deep aquifer, which agrees with our model assumption about linear changing of thermal gradient.

Again, the main decision variables of the shallow aquifer are outline in Appendix A.

For both deep and shallow aquifers it is modeled that drilling depth depends from linear temperature gradient.

3.3 Conversion Technologies

A large number of physical processes are available for the conversion geothermal heat into useful services. In the large scale, only the thermodynamic processes are taken under consideration. The flash cycles, organic Rankine cycles (ORC), Kalina cycles, heat pumps and direct exchange are the most common used methods. The usage of this method depends mainly from geothermal conditions as well as demand for heat and/or cool of particular region. The superstructure of these conversion technologies is shown in the figure below (Figure 3.4). The process flow diagram (PFD) software ValiModeller was used to model conversion technologies.

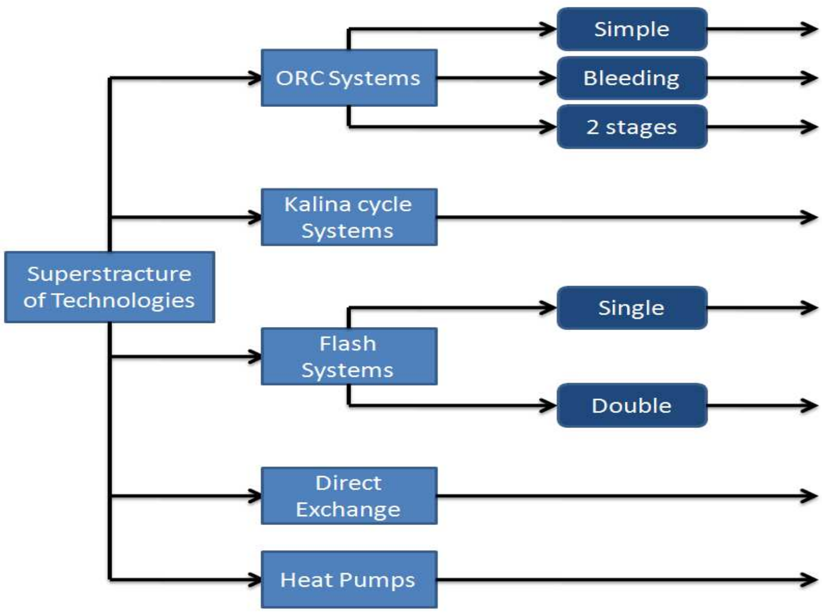

Figure 3.4 Geothermal Conversion Systems

At the figure above it are distinguished tree types of ORC system: simple, bleeding and 2-stages with high and low pressure turbines. In addition, the flash system can be classified as single and double one. In figure is also featured Kalina cycle system, unfortunately it is not be taken into account in further modeling due to the Osmosa problems with evaluating such systems.

3.3.1 Organic Rankine Cycle

The Organic Rankine Cycle (ORC) is one of the better-known methods to convert heat to electricity. It is a Clausius-Rankine Cycle using an organic fluid, what create a good condition for use of relatively low temperature geothermal heat source. An organic working fluid is selected based on temperatures and pressures in the cycle (boiling- and condensing points) (Di Pippo, 2008). In Figure 3.5 the schematic Rankine cycle working with geothermal system is presented.

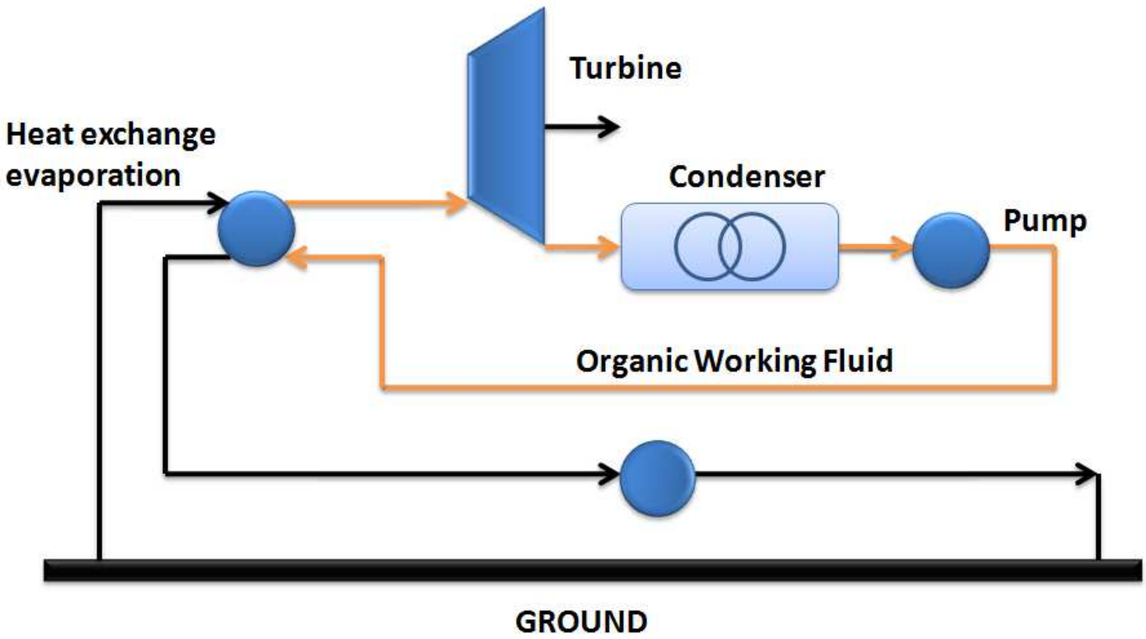

Figure 3.5 Schematic diagram of the Organic Rankine cycle

The water from geothermal resource passes through the evaporator and heat a secondary fluid (typically organic fluid with low boiling point). Saturated vapor is used to drive a turbine and generate electricity. The pressure and temperature drops during this process, when steam enters condenser, which leave as a saturated liquid (after condensation). After that, passes through pump, ending a cycle and creating close loop.

In the Figure 3.6 simulated saturation curves for several workings fluids are shown.

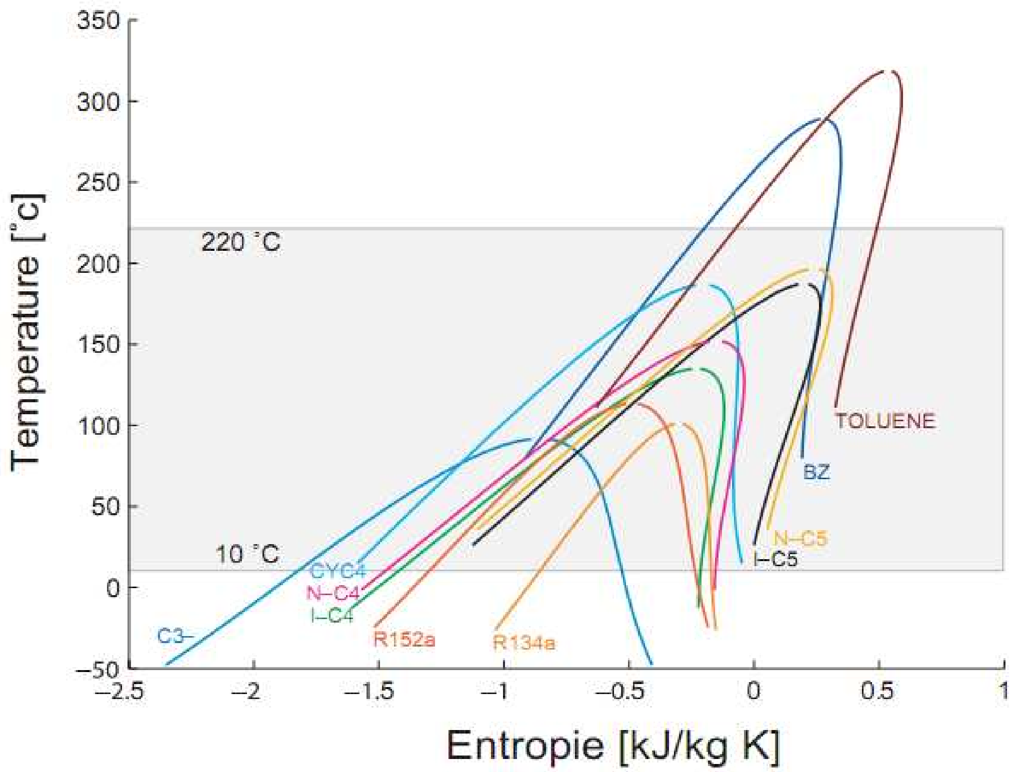

Figure 3.6 Organic Rankine Cycle for several Working Fluid (Girardin and Marechal, 2007)

The selection of working fluid can be very important for performance of the system as shown the work of Girardin and Marchel (2007). In this study the simulation with different working fluid for simple ORC has been done. The properties of working fluid are taken from the Belsim database and present at the table below (Table 3-1).

Table 3-1 Properties of working fluid

Fluids	**Formula**	**Critical temperature [K]**	**Critical pressure [bar]**	**Boiling temperature [K]**
n-Pentane (N-C5)	C_5H_{12}	469.78	33.7514	309.2
cyclo-Butane (CYC4)	C_4H_8	460	49.8519	285.66
Iso-butane (I-C4)	C_4H_{10}	408.13	36.477	261.32
Isopentane (IC5)	C_5H_{12}	460.4	33.3359	301
Benzene (BZ)	C_6H_6	562.1	49.244	353.3
Toluene (TOLUENE)	C_7H_8	592	42.1512	383.8
n-butane (N-C4)	C_2H_{10}	425.16	37.9665	272.67

The model of ORC conversion system with the flows which entering and leaving the system is shown below (Figure 3.7). The graphic presentation of environmental flows added to the thermo-economic model helps in identification systems limits and basic emissions that occur in different process phase.

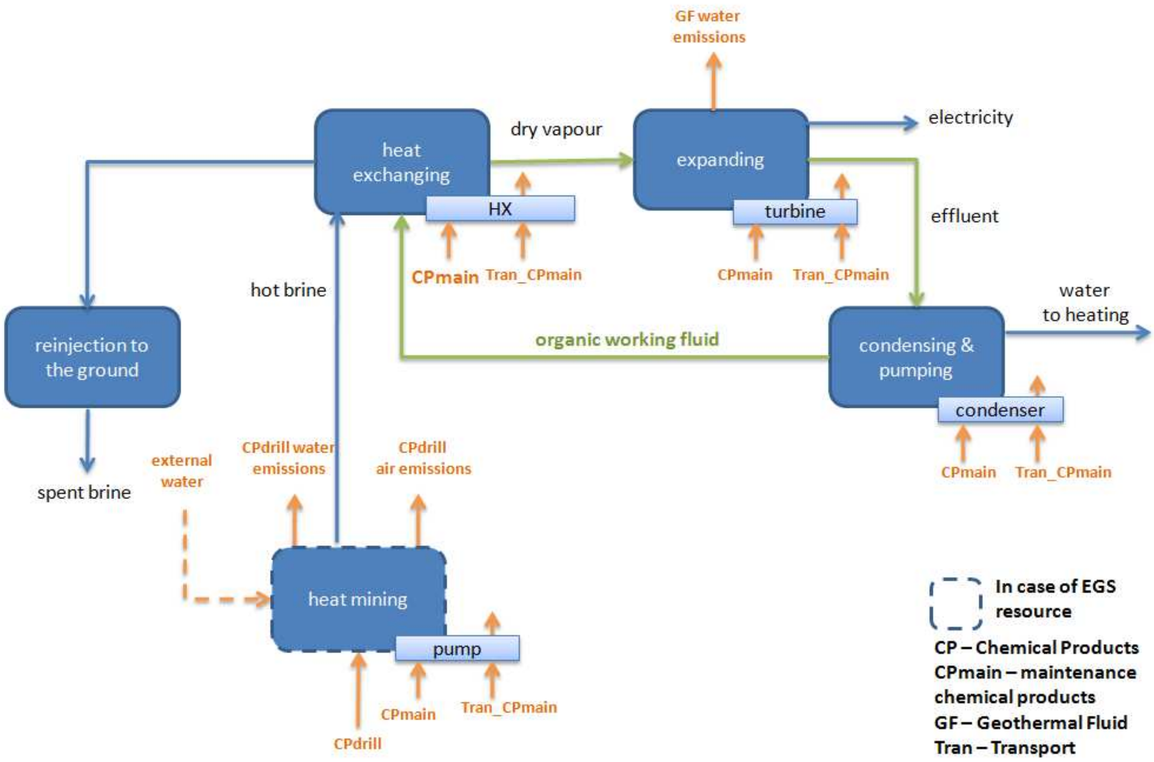

Figure 3.7 Flows of environmental concern in block diagram for Organic Rankine Cycle Power Plant

3.3.2 Flash Systems

The direct steam cycle is the simplest geothermal cycle that is used very often in geothermal power plant. The hot water form geothermal well is pumped under great pressure to the surface. In the moment, when it reaches the surface the pressure is reduced what cause that some of the water changes into steam. This causes a 'blast' of steam and is called 'flashing'. The brine, which left after flashing, is reinjected back to the ground. Steam, separated from the water, passes through turbine and produce electricity. The effluent is condensed by cooling water and next is reinjected. The schematic for single flash system is presented in the figure below (Figure 3.8).

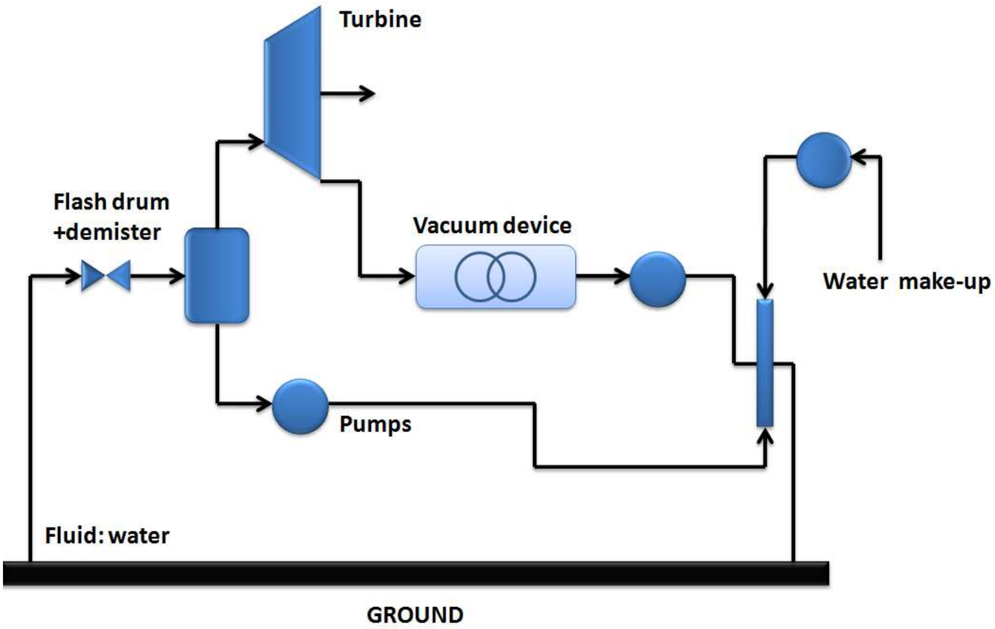

Figure 3.8 Schematic diagram of the Single Flash System

To increase the efficiency of the cycle a second stage in the fluid expansion can be added. Repeating of the flashing process can cause 15-25% increase of power from the same geothermal resources (DiPippo, 2008). In double flash system the water that is separated after the first flashing is again flashed. The exhausted steam form the first turbine is mixed with the steam that occurs after second flashing. This mixture passes through the second turbine to generate additional electricity. The schematic diagram of double flash system is shown in Figure 3.9.

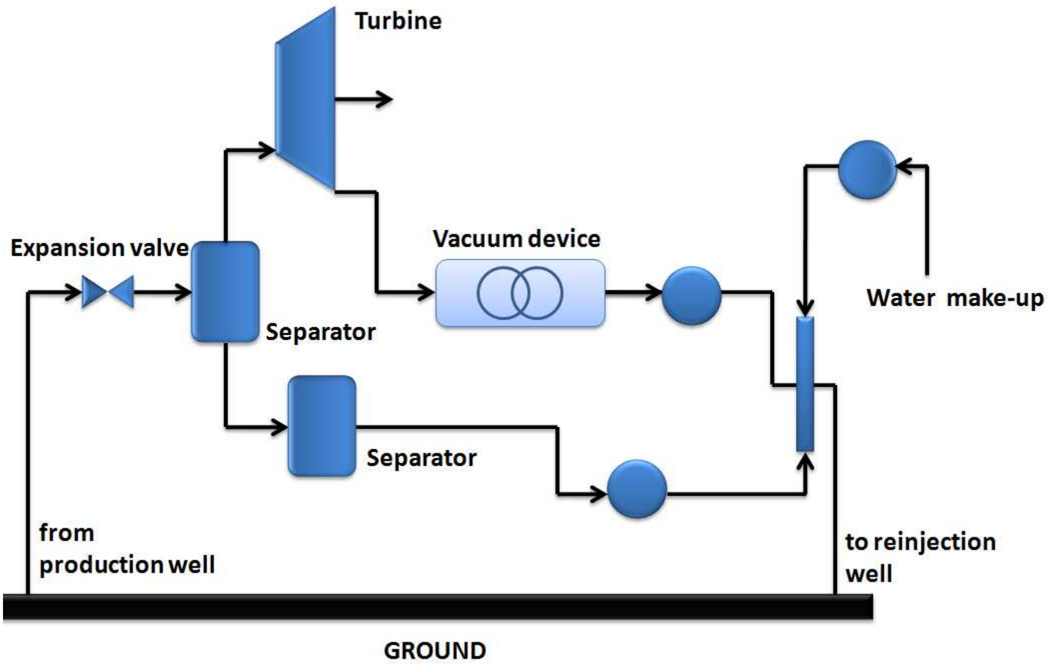

Figure 3.9 Double Flash Conversion System

The connection between LCA and thermo-economic model is presented below at the Figure 3.10. There are distinguished general emissions and the input necessary for process, which are treated as environmental flow and are base for system limits.

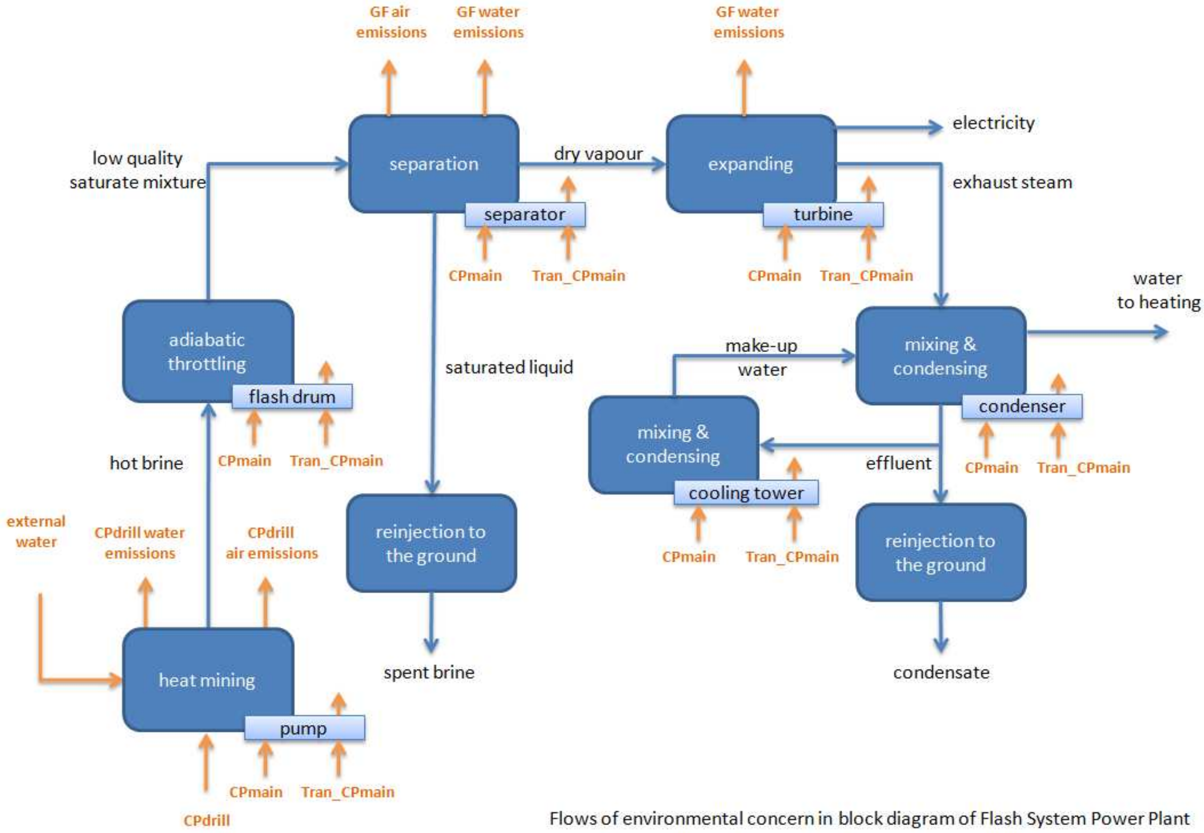

Figure 3.10 Flows of environmental concern in block diagram of Flash System Power Plant

Combine Cycle

It was not distinguished at the Figure 3.4 but bottoming ORC can be used in flash system to increase production of the power. This kind of system connects the advantages associated with both flash and binary systems. It exists plenty variations of the flash system. Below presented is flash-binary system where geothermal mixture serves portion of liquid to binary cycle, and portion of steam to drive a steam turbine (Kanoglu, Dincer, Rosen, 2007) (Figure 3.11).

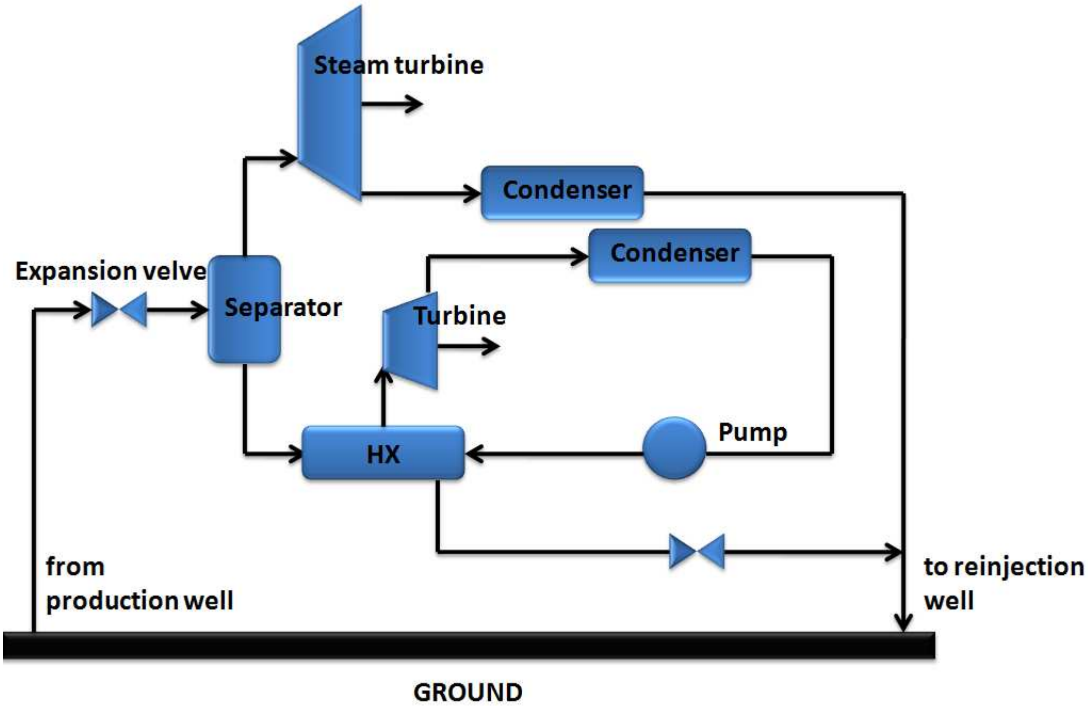

Figure 3.11 Combine flash-binary system

3.3.3 Direct Exchange

From technical point of view, direct exchange is not conversion technology. It concerns direct use of geothermal fluid for heating purpose. It can be obtained if geothermal fluid is relatively mild. In this case geothermal fluid can be directly pumped to pipe for heating. In case when fluid is chemically aggressive, it can be still use through exchanging heat with separate loop of district heating.

3.3.4 Heat Pumps

Geothermal heat pump (GHP) are one of the most significant growth applications among other renewable energy in the world (Lund et al., 2004).

It is cause by their ability to use normal ground or groundwater temperatures at range 5 – 30 °C what is appropriate in most countries in the world.

In geothermal heat pumps low-grade heat, form geothermal resource is used to produce high-grade heat that can be used in heating services (Figure 3.12). Reverse cycle, a compression refrigeration cycle, can be used to provide cooling.

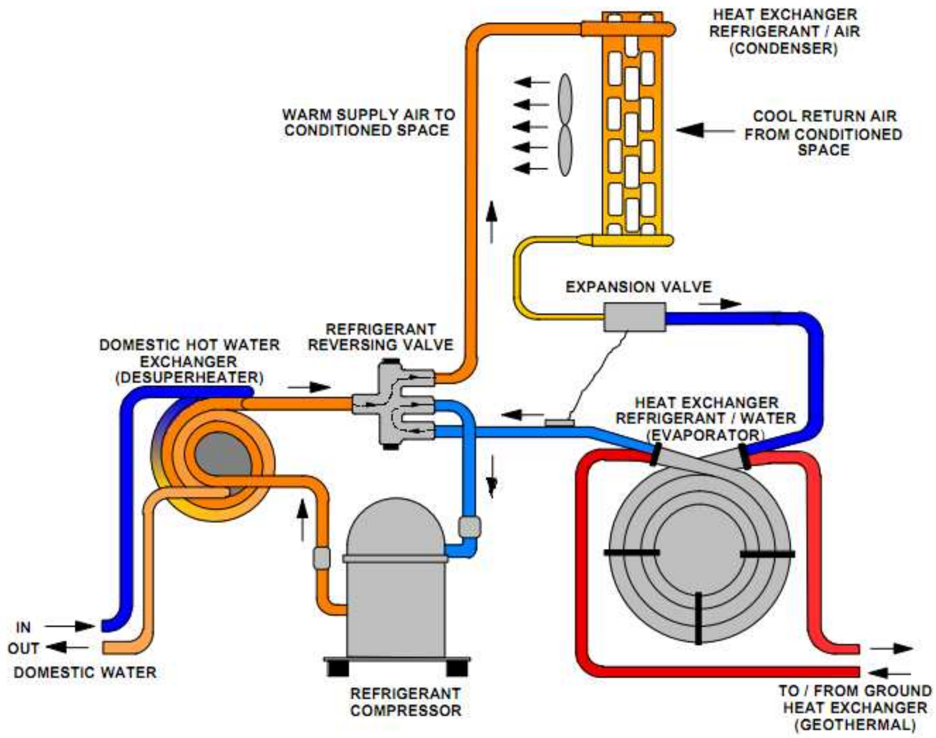

Figure 3.12 Geothermal heat pumps in heating cycle (from Oklahoma State University)

In both case a fluid with low boiling point is used. Low temperature geothermal resource provides heat to evaporate working fluid. Temperature of working fluid does not increase significant due to its low boiling point. In gaseous, low pressure and low temperature state passes into an electrically-driven compressor, what cause electricity consumption. This rises pressure of working fluid and, as a consequence, its temperature and is capable to fed heat exchanger (called condenser). The heat is transfer from hotter working fluid. The working fluid passes through expansion valve, where the pressure is reduced, in consequence, its temperature drops. Working fluid flows to the evaporator to start cycle again.

3.4 Demand Profiles

The conversion of geothermal resources should meet real demand for heat and electricity. In this study, it was assumed that the conversion systems must meet demand for district heating. The electricity generates during process is additional advantages of used geothermal resources and conversion systems. It is necessary to create demand profiles for Switzerland and Polish conditions.

3.4.1 Swiss Demand Profiles

The demand profiles for Switzerland conditions were created for city Nyon. It has been awarded four separate periods: summer, interseason, winter and extreme winter (Figure 3.13). This distinction comes from the fact that in each period, there is different power demand and the heating system operates at different temperatures depending mostly on outdoor temperatures.

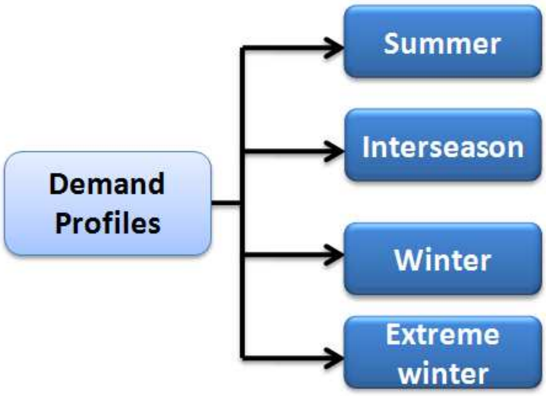

Figure 3.13 The structure of demand profiles for Switzerland

The demand profiles were created in based on data for city Nyon, Switzerland (*Methodology for Urban Energy Concepts – An Example of Nyon*, n.d.). To provide values of load, temperature of supply and return the software developed by LENI at EPFL was used. Entered data come from the statistical demand calculation for a specified number of buildings. There are provided factors that take under consideration construction, period and utilization for the individual building consumption. The time periods are grouped in ranges: pre-1920, 1920-1970, 1970-1980 and 1980-2005. The utilization is divided in several categories: residential, administration, commercial, industry, education, health, hotel, and other. Building position and area are also included. (Hoban, 2010).

In Table 3-2 is shows the structure of demand profiles for Nyon, that has been used in this study and combined with the other geothermal resources and conversion technologies provides models to developed.

Table 3-2 The demand profiles parameters for Nyon, Switzerland

Demand profile	Load [kW]	Supply temperature [°C]	Return temperature [°C]	Operating time [h]
Summer	200	60	25	525
	300	25	21	
Interseason	150	60	32	
	500	32	26	3942
	300	28	20	
Winter	100	60	50	
	1200	50	40	
	100	40	34	4205
	700	34	28	
	100	28	10	
Extreme winter	100	75	65	
	1750	65	50	
	150	50	40	88
	1000	40	32	
	100	32	10	

3.4.2 Polish Demand Profiles

Polish demand profiles are based on data for the city of Konin, Poland. Very important in developing methodology for creating demand profiles for Konin, was lack of the data, which could be useful. Due to difficulty into obtaining any information from Polish heating power plants these evaluations are based on general data. The data were obtained from municipal district heating company in Konin (http://www.mpec.konin.pl).

Characteristics of the heating system in Konin

The municipal district heating company in Konin supply district heating and hot water for city Konin. The heat is supply by single source – the Konin Heat Generating Plant with 474 MW of installed capacity.

The data from 31.12.2009 shows that the power demand in the system in 2009 was at the level of 133.60 MW and heat energy consumption was equal to 1385 TJ.

The structure of plant consumers is shown at the figure below (Figure 3.14).

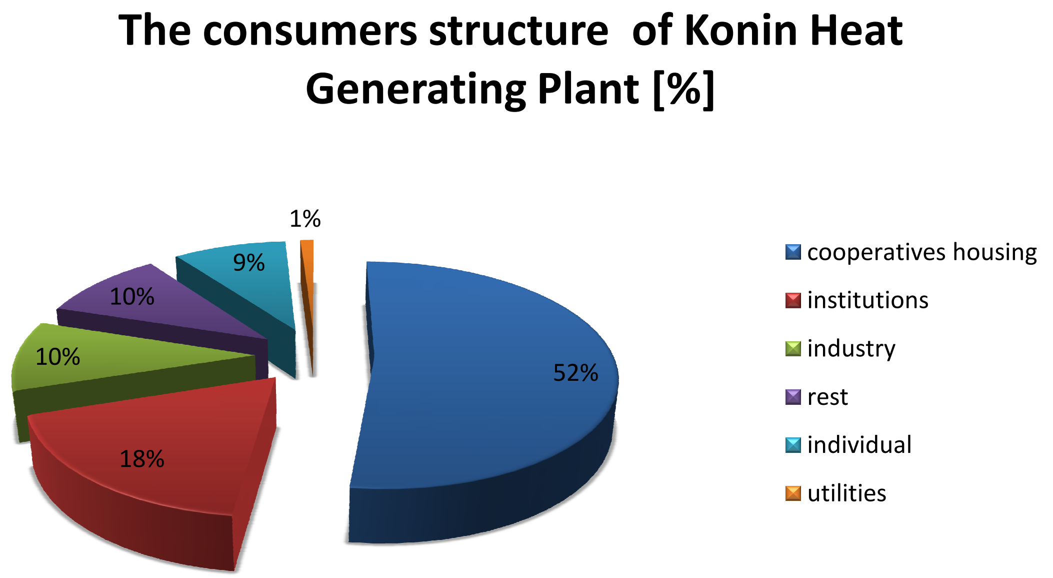

Figure 3.14 The consumers structure of Konin Heat Generating Plant [%]

Demand profiles preparation

First it has been assumed that demand profiles is prepared for load equal available power (474 MW) in Konin Heat Generating Plant, not the amount of heat consumed in 2009 (1385 TJ) or even power demand in the system in 2009 (133.60 MW). The reason for this assumption is to model the situation when geothermal conversion system can have the same available power as existing station and can easily replace it. Previous years shows that not all installed capacity was used, but it cannot be assume that this situation do not change in the future looking at the Poland development.

With this value and the structure of consumers of Konin Heat Power Plant the available power for each group was calculated (Table 3-3).

Table 3-3 Installed capacity per consumer group

Consumer Group	Share [%]	Installed capacity per group [MW]
Cooperatives housing	52	246.48
Individual	9	42.66
Industry	10	47.40
Utilities	1	4.74
Institutions	18	85.32
Rest	10	47.40
Sum	**100**	**474**

Based on Table 3-3 it has been assumed that 40% of available power (18.96 MW) is used for hot service water for industry and 30% (127.98 MW) for rest groups. The rest of available power (327.06 MW) is used for district heating (Table 3-4). It was assumed that hot water demand does not change during seasons and that the same amount of heat is supplied for industry processes during the year. The available power for district heating for industry is 28.44 MW. The demand for hot water is constant at the level of 16.774 kW per hour throughout the year.

Table 3-4 The use of installed capacity

Usage	Installed capacity [MW]
District heating water	
- Industry	18.96
- Rest of costumers	127.98
District heating	327.06
Sum	**474**

Hourly temperatures of typical meteorological year are provided by the Konin nearest meteorological station in city Koło and are accepted by Polish Ministry of Infrastructure for energy calculations (http://www.mi.gov.pl). They have been developed by International Organization for Standardization (ISO) and accepted as EN ISO 15927-4 '„Hygrothermal performance of buildings – Calculation and presentation of climatic data – Part 4 Data for assessing the annual energy for cooling and heating systems'. Annual series of weather data for the energy calculation are created from twelve months selected from the period of at least ten years of meteorological observations for a given location.

Yearly temperature distribution is presented at the figure in Appendix B .

The supply and return temperatures were calculated based on figure presented below (Figure 3.15). The supply and return temperature were evaluated depending on outside temperatures of typical meteorological year for city Konin.

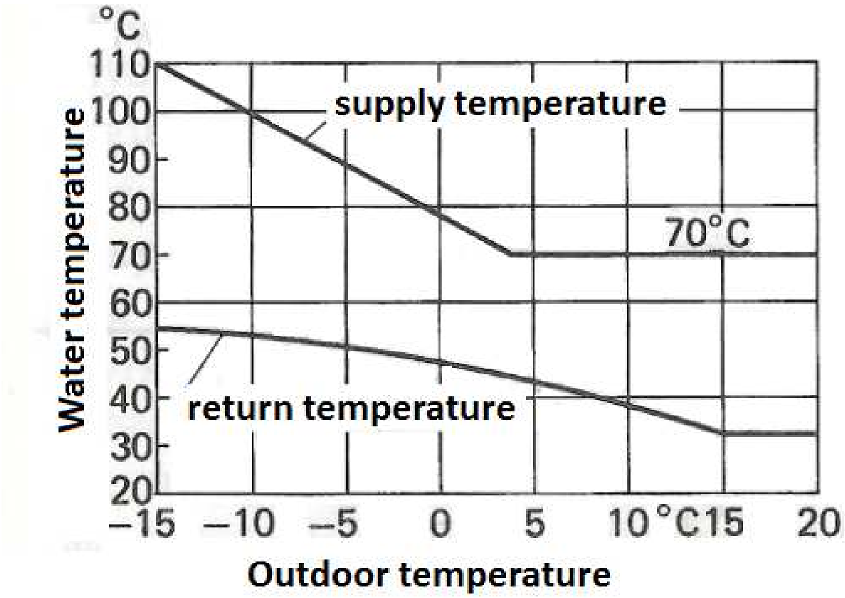

Figure 3.15 Practical temperature of heating water in two-pipe system with domestic hot water preparation and work 24 hours a day (from Recknagel at al., 2008)

The supply temperature varies depending on outside temperature. In the preparation of hot water for hot service water and for district heating, the supply temperature reduces only to 70°C when the outside temperature is equal around 3-4 °C and then remains constant. Also the return temperature depends on outside temperature. With the increase of outside temperatures the return temperatures decrease. For outdoor temperature above 15°C, the return temperatures remain at the same level of 35°C.

To find the correlation between supply/return temperature and outdoor temperature the points have been taken from the Figure 3.15 to calculate second-degree polynomial function coefficients. The polynomial function is expressed by equation (2). The method-used to that was least-squares fit while the MatLab software was used.

$$T_{s/r} = A_o \cdot T_e^2 + A_1 \cdot T_e + A_2 \qquad (2)$$

Where:

$T_{s/r}$ – supply or return temperature [°C]

T_e – outdoor temperature [°C]

A_0, A_1, A_2 – function coefficients

The function coefficients for the relationship between supply temperature and outdoor temperature and between return temperature and outdoor temperature are presented at the table below (Table 3-5):

Table 3-5 The function coefficients for evaluation of supply/return temperature

The function coefficients for:	**A_0**	**A_1**	**A_2**
Supply	-0.0122	-2.2741	78.6063
Return	-0.0103	-0.7192	47.6933
Load	-0.013	-3	54.9667

With help of the second-degree polynomial functions it is possible to evaluate annual distribution of the supply and return temperatures, which depends from annual distributions of outdoor temperature. In base on the Figure 3.15 it was assumed that for higher value of outdoor temperature than 15°C the return temperature is constant (35 °C). For supply temperatures, this limit was set at 3.75 °C for outdoor temperature.

The heating plant load, which supplies heat for district heating and hot service water, is presented below (Figure 3.16). The figure shows the load demand by consumers during the heating season. In general, the highest load occurs only in a few days or few hours during year. At other time, the ration of the power demand to the maximum thermal power is between 20-60%.

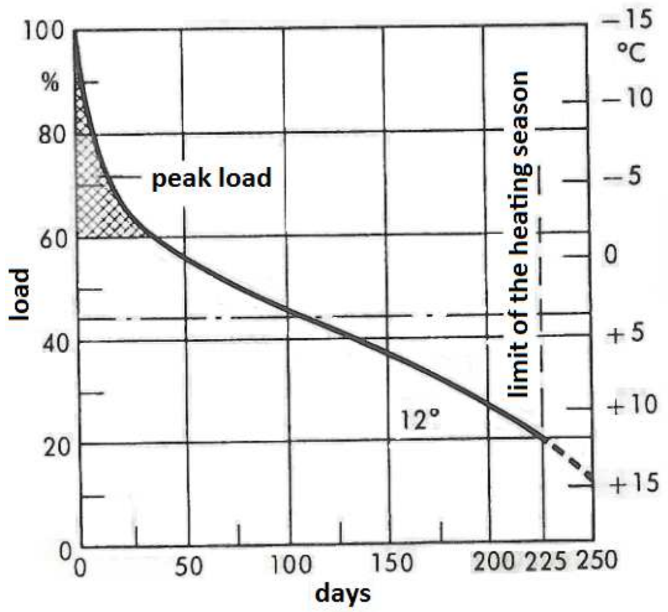

Figure 3.16 The heating plant load, which supplies heat during heating season (from Recknagel at al., 2008)

To find the correlation between the heating plant load and outdoor temperature the MatLab software has been used once again. The least-squares fit method has been used to find the second-degree polynomial function coefficients as previously (according to equation 2). The function coefficients are presented at the table below (Table 3-6):

Table 3-6 The function coefficients for load [%] evaluation

The function coefficients for:	A_0	A_1	A_2
Load	-0.013	-3	54.9667

The function coefficients for load evaluations are used to plot the function, which provide ratio between power demand and thermal power in percentages. The maximal thermal power for district heating for all consumers groups (without industry) has been calculates as 44.26 kW per hour. From this maximum thermal power and utilization percent, the load in kW per hour can be calculated. To all values obtained for heating seasons the constant value of heat for hot water heating and industrial heating processes must be added.

In the Figure 3.16 the boundary of the heating season is marked. It is for about 12.5 °C. From calculation with using second-degree polynomial function is for 12.4 °C. In Poland heat generating plants are obliged to supply district heat when temperature drops below 15°C. However, most customers begin heated at a temperature below 12.5, which coincides with obtained results. Above 15°C of outdoor temperature there is need to supply constant amount of heat for hot water heating and for district heating to industrial processes. This amount is equal 21.046 kW per hour and runs in 70/35 °C temperatures. From Figure 3.16 it was calculated that there is 2103 hours during year when the systems run in setting parameters (summer). For the range 12.4 – 15 °C of outside temperature (interseason), some of consumers start heating and the temperature of supply/return change gently. The other demand profiles were created by aggregating the data depending on the load expressed as a percentage. There has been created another four demand profiles for loads in range: 20-40, 40-60, 60-80 and 80-100 %. Within each group the maximal temperature of supply from data has been chosen. In the case of return temperature, the minimal one has been chosen. For load maximal value from each group has been selected. These general approach cause that the installed capacity was a little bit overestimated (12%) from the assumed one, but it is necessary to choose the boundary values to have a convenience that the heating system will be working for all calculated parameters. The demand profiles for Polish conditions are presented at the table below (Table 3-7).

Table 3-7 The demand profiles parameters for Konin, Poland

Demand profile	**Load [kW]**	**Supply temperature [°C]**	**Return temperature [°C]**	**Operating time [h]**
Summer	20	70	35	2103
Interseason	29	70	35	955
20 – 40 % of load	38	70	37	2314
40 – 60 % of load	46	82	44	2666
60 – 80 % of load	55	96	49	641
80-100% of load	67	112	53	81

3.4.3 Icelandic Demand Profiles

In table Table 3-2 and Table 3-7 the demand profiles for Swiss and Polish conditions are presented. It can be observed that the supply and return temperature in these systems change during the year. As it has been mentioned before it is connected with the variations of outdoor temperature and the load during the year.

Comparing obtained results with the largest geothermal district heating in the world in Reykjavik, Iceland the significant differences can be seen. The Figure 3.17 shows the simplified flow diagram of geothermal district heating for Reykjavik.

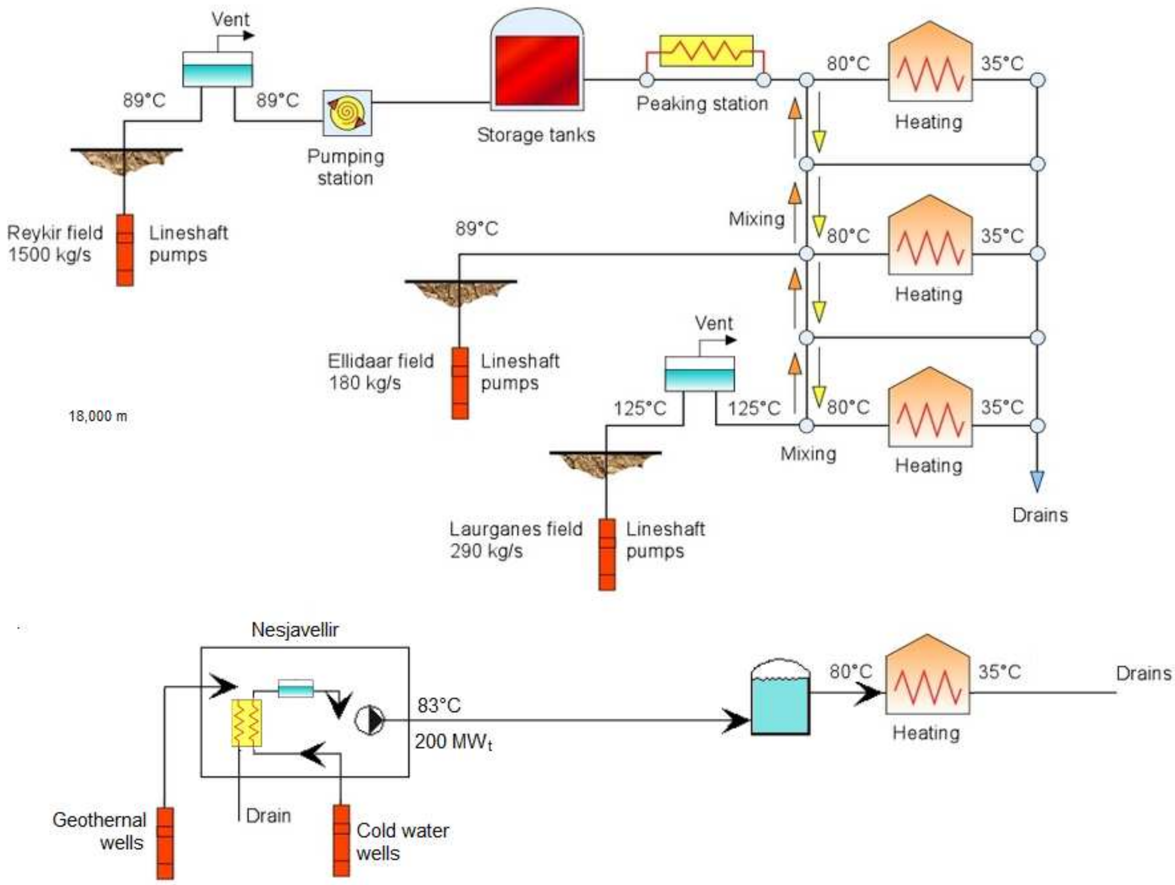

Figure 3.17 Simplified flow diagram of the geothermal district heating system of Reykjavik. (Gunnlaugsson, Frimannson, Sverrisson,2000)

The most significant difference between the systems is that in the Icelandic district heating system the supply temperature is constant. In Reykjavik district heating system, both single and double distribution systems are used. In double system the used geothermal water from consumers' radiators run back to the pumping station where is mixed with hotter geothermal water. Thanks to that, the water is cooled to the 80°C, before recirculation. In single system, the used geothermal water runs directly into the sewer system. The return temperature of hot water is 25-40°C and is commonly used to melt snow from pavements and driveways.

Very important seems that Iceland has the oceanic climate with mean temperature in Reykjavik about 5°C and average January temperature –0.4°C and July 11.2 °C. These conditions make the use of district heating all the time during the year, what is not necessary for Swiss and Polish conditions.

4 MODEL DEVELOPMENT

This section is devoted to compose and development of various types of the geothermal conversion systems. It shows some the results of one-run system resolution for default value which are showed in Appendix A. The main objective of this phase is to check if the models are working correctly, convert.

4.1 System modeling

The modeling of system considers possible combination of three sub-systems, which are modeled separately. The superstructure of potential exploitable geothermal resources, the superstructure of conversion technologies and the multi-period demand profiles that supply energy for services are taken under consideration as *the overall geothermal system*.

The presentation of possible combination of geothermal resources, conversion technologies, demand profiles and life cycle phases is shown in Figure 4.1.

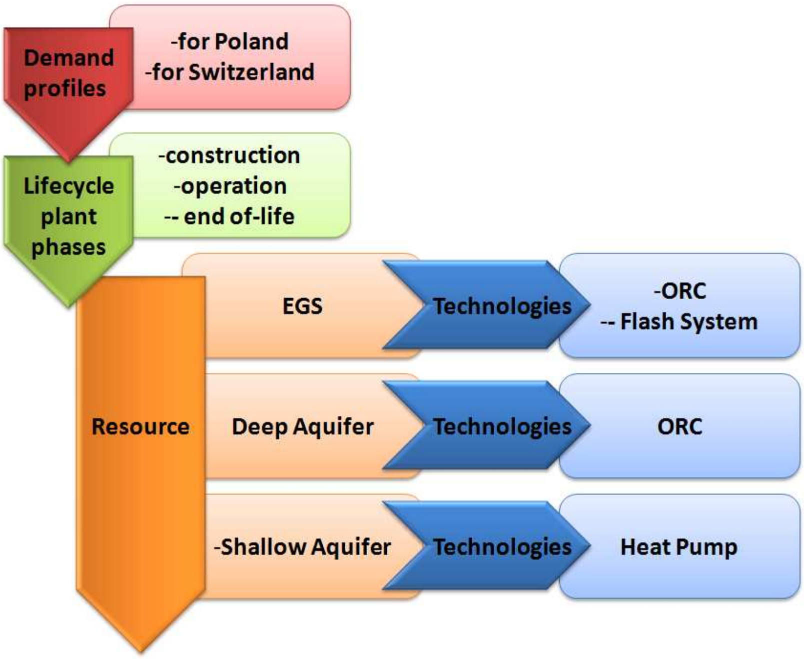

Figure 4.1 Scheme of geothermal system combination

Geothermal resources model

As it was shown in Figure 4.1 the superstructure of geothermal resources is divided into three types: EGS, deep aquifer and shallow aquifer. The descriptions of this resources has been provided in section 3.

In resource models, the emphasis is put on information need to model this kind of resources such as: geological information (thermal gradient, water mass flow rate, the depth, etc.), geotechnical information (exploitation mode, drilling techniques, number of wells). The main default values for geothermal resources are provided in Appendix A.

Conversion technologies

The superstructure of conversion technologies may consist from many different cogenerations cycles, boilers include as a back-up systems. In this study only ORC cycles, flash systems and heat pumps are taken under consideration.

The main are of interest in conversion technologies is the type of working fluid used in cycles.

Energy services demand profiles

This study focus on two energy services demands profiles: for Polish conditions (city Konin), and for Swiss conditions (city Nyon). For Polish case, six periods are provided, for Swiss – four. It is assumed that the district cooling is not taken to the evaluations. As well, electricity is not included into demands profiles – if electricity is generated, it will be sold to the grid.

4.2 Multiperiod strategy

The multiperiod strategy is used in this study, this mean that the geothermal system is designed in the way when a couple seasonal demand variations are taken under evaluations. The methodology for computation model has been described in section 3. However, in section 3 it has not been mentioned that in multiperiod strategy for each the calculation sequence is used separately. This approach results in possibility to model seasonal variations of demand.

In multiperiod strategy the evaluation of overall system is repeated for each periods, that provide the performances of the system for each period which in the next step are combined together. A multi-period strategy has significant influence on life cycle stages (construction, operation, end-of-life), which depend on different periods (Gerber, Maréchal, 2011).

Below the calculation of total impact is presented (Equation 3):

$$I_{tot} = \sum_{p=1}^{n_p} \sum_{i=1}^{n_{eo}} I_{O_{i,p}} + \sum_{i=1}^{n_{ec}} \max\left(I_{C_i}\right)_p + \sum_{i=1}^{n_{ee}} max\left(I_{E_i}\right)_p \qquad (3)$$

Where:

I_{tot} – the total impact of the system

n_p – number of the periods considered in the problem

n_{ec} – the number of LCI elements belonging to the construction phase

n_{eo} – the number of LCI elements belonging to the operation phase

n_{ee} – the number of LCI elements belonging to the end-of-life phase

I_c - the impact of the construction phase

I_o - the impact of the operation phase

I_e - the impact of the end-of-life phase

This approach can cause that total impact of system is higher than the impact calculated separately for some periods.

4.3 Process integration

As it has been mentioned above the overall geothermal system consists from three sub-systems: geothermal resource, conversion technology and demand profiles. These three sub-system are integrated together by using process integration techniques. The integration is treated as a problem in which the operating cost of the system is minimized for each period (Equation 4).

$$min \sum_{r=1}^{n_r} \left(C_{O_r} f_r + c_e \dot{E}^{+}_{grid} \right) + \sum_{w=1}^{n_w} \left(C_{O_w} f_w + c_e \dot{E}^{-}_{grid} \right) \qquad (4)$$

Where:

C_{O_r} - operating cost of the resource r

n_r – the number of resource include in superstructure

f_r – the utilization factor of the resource r

c_e – cost of the electricity (that is bought or sold to the grid)

$\dot{E}^{+}_{grid}$ – electricity consumed by the resource r

C_{O_w} – the operating cost of the technology w

n_w – being the number of technologies included in the superstructure,

f_w – the utilization factor of the technology w

$\dot{E}^{-}_{grid}$ – the neat electricity produced by the technology w and sold to the grid

Thanks to that the heat cascade is composed and the final configuration is determined This returns the size of the equipments (Gerber, Maréchal, 2011).

4.4 Performance indicators

The next is to define the thermodynamic, economic and environmental performance indicators that will be used in this study. Based on results obtained from energy integration they are calculated for each period, then to be combined in overall yearly performance.

Economical indicators

There are two most common use economic indicators: the investment cost and the levelized cost of district heating. In the case of geothermal conversion system the investment cost are mostly much higher than the operation costs. The total cost of drilling geothermal wells, the geothermal pumps, the equipment used to convert the heat form geothermal resource, the district heating network are taken under consideration as an investment costs. More useable for this approach is the levelized cost of district heating, since it has been assumed that district heating services is provided and the electricity production is additional benefit.

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

Where:

$C_{I,\ an}$ – the annualized investment cost of the equipment I associated with the period p

n_e – the total number of the equipments necessary to operate the overall geothermal system

n_p – the total number of periods over one year

C_O – the associated operating cost with the equipment i

t_p – the duration of the period p

E^- - the neat electricity produced by overall system during period p

c_e – the specific cost to which the electricity is sold to the grid

$\dot{Q}^-$ - the district heating produced during the period p

Thermodynamic indicators

One of the main thermodynamic indicators, next to energy efficiency, is exergy efficiency. Exergy efficiency is defined as the ratio of the output exergy of to the input exergy.

$$\eta = \frac{\sum_{p=1}^{n_p} \dot{E}_p^- t_p + \sum_{p=1}^{n_p} \dot{E}x_p^- t_p}{\sum_{p=1}^{n_p} \dot{E}x^+ t_p}$$

Where:

$\dot{E}^-$ - the electricity produced by overall system during period p

t_p – the duration of the period p

$\dot{E}x^{+}$ - the exergy transfer to the district heating during period p

In the case of exergy efficiency, all data are determined in the terms of environment that must be considered.

In the case of exergy efficiency, it is necessary to outline how terms were defined.

In case of electricity produced by overall system during period p it has been assumed that it is sum of all electricity produced by system minus all parasitic electrical loads as pump power from the resource and conversion systems or power to cooling system, etc. It is important that all electrical loads in calculation are used as 'pure' exergy.

The thermal streams are taken as it is shown in equation below:

$$\dot{E}x = \dot{Q} \cdot \left(1 - \frac{T_a}{T_{lm}}\right)$$

Where:

T_a - is the temperature of the cold source, either air or cooling water

T_{lm} - is the log-mean temperature difference of the stream

The log-mean temperature is calculated base on high temperature of stream (T_{in}) and the low temperature of stream (T_{out}). The equation is presented below:

$$T_{lm} = \frac{T_{in} - T_{out}}{ln\left(\frac{T_{in}}{T_{out}}\right)}$$

Before evaluation, two ways of calculating exergy efficiency were considered. The first approach focused on calculating the exergy efficiency of the conversion system and used for that the reinjection temperature of the hot source as the low temperature. The second approach for calculating the overall exergy efficiency of the system use the environmental temperature as the low temperature of the hot source. In further evaluation the first approach has been chosen in the multi-objective optimization because engineers can only influence on conversion itself and not on the temperature reinjection that is limited by the geochemistry of the geothermal water (L. Gerber 2011, pers. comm., 16 February).

The method of calculating the yearly energy efficiency is the same, except that the environment is not taken into account.

Environmental indicators

The environmental impact can become important performance indicators since significant emissions and extractions occurred during the construction phase including the impact of drilling, transportations, used material and so on. The methodology to link each equipment and material or energy flow with the thermo-economic model is presented in the section 2. As environmental indicators the specific impact of district heating per kWh generated is evaluated. It is calculated as the total life cycle impact for the overall system divided by the amount of district heating supplied during the lifetime of the system (Gerber, Marechal, 2011):

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

Where:

I_O - the impact due to the operation phase for period p of the LCI element i

n_{eo} – the total number of LCI elements from the operation phases

I_C – the impact due to construction phase of the element I for period p

n_{ec} – the total number of LCI elements from the construction phases

I_E – the impact due to end-of-life phase of the element I for period p

n_{ee} – the total number of LCI elements from the end-of-life phases

t_{life} – the overall lifetime of the geothermal system (in this study it was assumed 40 years).

4.5 One-run System Resolution in its Default State

The one-run of models in its default state were launched to verify if the geothermal conversion system is converted. Some problems occurred during the one-run system resolution. Most of them were connected to Matlab code, but one issue moved in to lead. During evaluation of models with ORC system as a sub-system the losses of working fluid were significant. The total process contributions in modeled system (EGS ORC bleeding system) came from only from working fluid losses and were at the level of 90 points.

Because the working fluid losses got significant contribution for all impact categories, the data provided for life cycle assessment has been verified. The data provided by Ormat company (2010) has shown that the working fluid losses during operation are much more lower and are in range 0-2 %. In further evaluations, 2% has been taken for working fluid loss during operation for all ORC systems. It can be observed how the total process contributions for the same model changed after providing a new data (Figure 4.2).

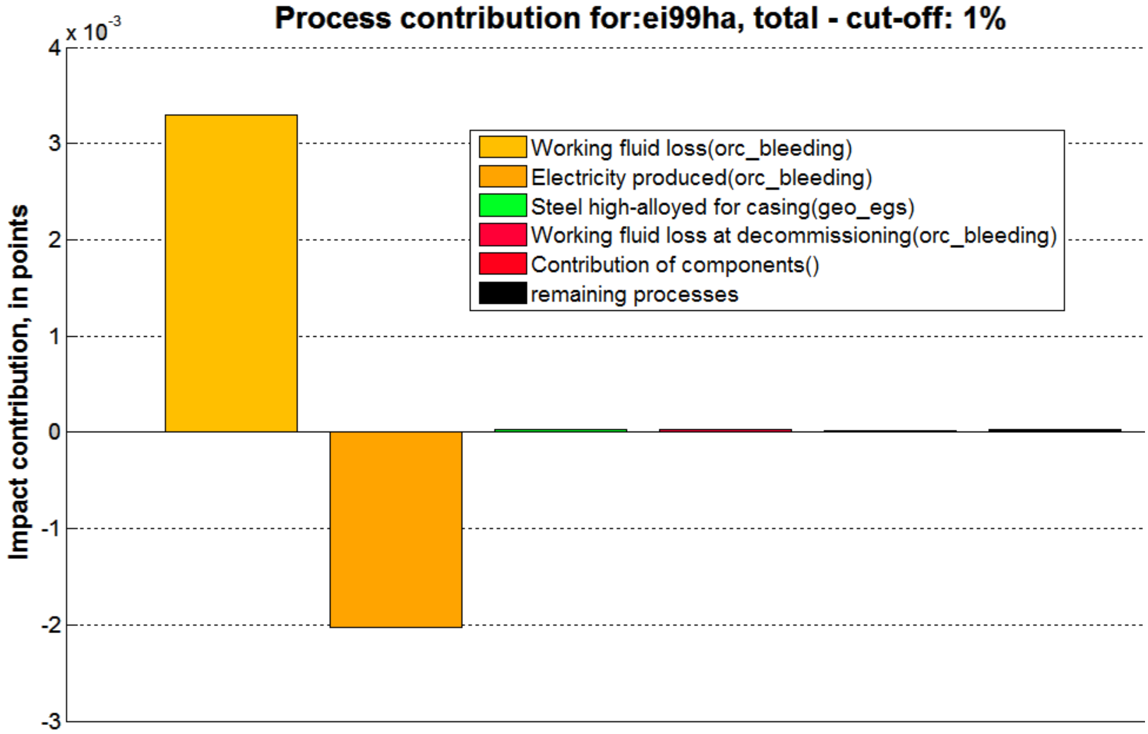

Figure 4.2 The total process contributions for EGS system with ORC bleeding for ei99ha impact method with using data provided by Ormat company

5 MULTI-OBJECTIVE OPTIMISATION

In this section, a multi-objective optimization of geothermal conversion systems is presented. A short description of the evolutionary algorithm used in the multi-objective problem is shown. In addition, the decision variables used in optimization are presented. The short explanation of used optimization strategy is presented. The effect of used decision variables on the performance indicators over the range of variables is analyzed.

5.1 The Multi-objective Approach

The multi-objective optimization is done by using “Moo” software developed at the Industrial Energy Systems Laboratory (LENI) at EPFL. Moo used for optimization process advanced evolutionist algorithm that has been implemented under MatLab.

The evolutionary algorithm that is used to multi-objective optimization is algorithm inspired by biology. The evolutionary algorithm imitates the process of natural evolution using biological evolution mechanism: reproduction, mutation, recombination and selection. What distinguished evolutionary algorithm from the others is that a set of solution (population) is used to converge to optimal design(s) (Büche, Stoll, Koumoutsakos, 2001).

The initial population is used to select the various combinations of decision variables with the best performance indicators, and then to generate a new population by using evolution mechanism: the recombination (Marechal, 2010) what is presented at the Figure 5.1:

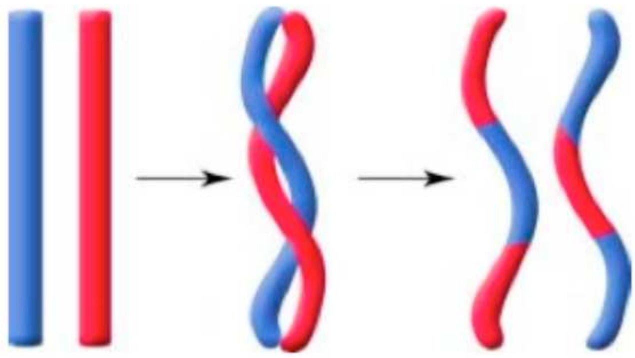

Figure 5.1 Recombination mechanism (from Marechal, 2010)

Recombination is not the only one evolution mechanism used in multi-objective optimization. Some mutations in the decision variables set occur what is comparable to the mutation mechanism in the genetic code of species. The use of mutation mechanism in evolutionary algorithm causes that the new set of additional combination can occur that could not be considered as results of only recombination (Marechal, 2010). The idea of mutation mechanism is shown at the figure below (Figure 5.2).

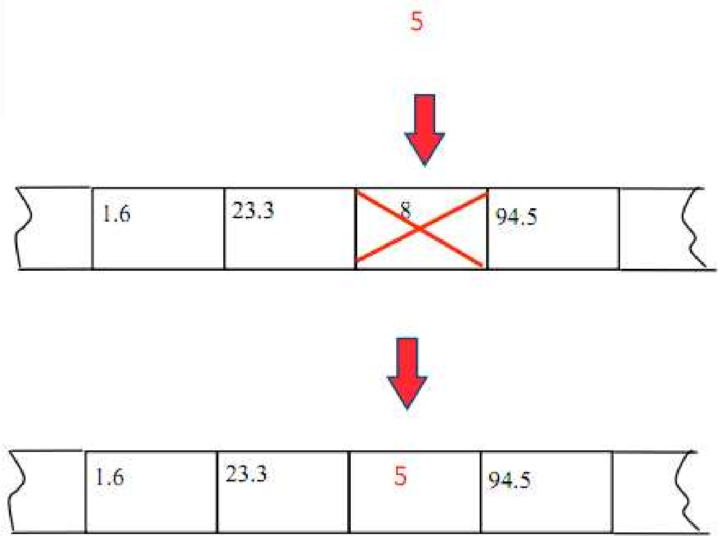

Figure 5.2 Mutation mechanism (from Marechal, 2010)

The new population is set on eliminating the worst individuals. The generated solutions go to outcomes with higher performances. However, it does not mean that the global optimum is necessarily guaranteed (but thankfully, it does not happen to often).

The evolutionary algorithm is robust optimization method that explores various options thanks to apply natural evolution mechanism within algorithm's structure. Additionally, they do not require the gradients of used objective function. What seems very important, the evolutionary algorithm does not premature convergence to local minima.

A major disadvantage of evolutionary approach to the optimization problem is the time of computation, which is significant.

In this study, the Pleiades2 parallel computing system at EPFL has been used to launch multi-objective optimizations. The launch models used 16 processors at one time, while the models have been calculates several hours.

5.2 Optimization strategy

Developed the model it is very important to define the performance indicators for which the models will be evaluated. These performance indicators are called objective functions and have been presented at section 4.

Although a couple of performance indicators can be used as objective functions, in this study only two were selected. The multi-objective optimization is performed to calculated the trade-offs between environmental performance indicators and the thermodynamic performance indicators of the system, such the exergy efficiency, to be maximized, and the total life cycle impact, to be minimized.

The overall exergy efficiency is chosen as objective function, because opposite to energy efficiency, it gives general view of how well systems convert a given resource. In case of geothermal resource that extraction rate and lifetime is limited, this is very important.

Exergy efficiency also known as the second-law efficient gives the real outlook of the system at a given state in a specific environment. This cause that the services provided (electricity, district heating and district cooling) is evaluated form the point of usefulness to the consumers, although that all are measured in watts. As it has been mentioned above, in this study exergy efficiency is maximized

The selection of second objective function is connected with the integration of LCA in a thermo-economic model. Although there has been chosen a three impact assessment methods to optimization, they are evaluated separately not to make the difficult in results interpretations. The environmental objectives have been chosen to show the impact of construction, operating and end-of-life phases on systems. The impact of emissions and extractions should be minimized to obtain optimal trade-off with respect to exergy efficiency.

Due to the lack of time, the economic performance indicator has not been taken under consideration. However, Gerber and Marechal (2011) have calculated the trade-off between thermo-economic models. The results of multi-objective optimization are presented at the figure below (Figure 5.3). Two objective functions have been used: the exergy efficiency, and the levelized cost of district heating, where the first is maximized, while the second one is minimized.

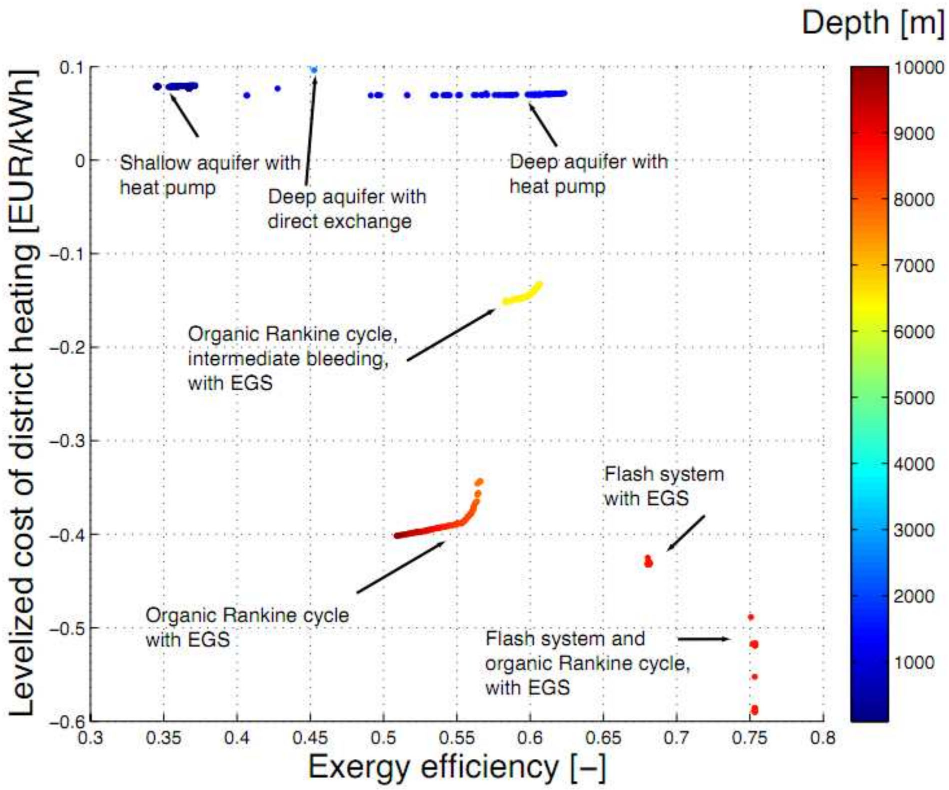

Figure 5.3 Pareto curves showing the exergy efficiency and the levelized cost of district heating for different geothermal resources and conversion technologies (from Gerber, Marechal, 2011)

In that study the most promising option seems the exploitation of EGS systems with the cogeneration of electricity for thermo-economic optimization. The income from electricity production is used to compensate the high investment costs from drilling, so that the levelized cost of district heating is negative (Gerber, Marechal, 2011).

5.3 Optimization one – the ORC Conversion System

In the first multi-objective optimization, the influence of used working fluid in ORC simple system using the EGS system is considered.

5.3.1 Decision variables

The model is evaluated taking under consideration four decision variables: the temperature of evaporation for ORC simple system, the superheating temperature of working fluid in ORC simple systems, the depth of EGS system and the temperature of reinjected water in EGS system. The ranges of these parameters are shown in table below (Table 5-1):

Table 5-1 Decision variables for optimization the ORC simple system with EGS

Decision variable	Variable	Min	Max	Unit
Evaporation temperature of working fluid	orc_wf3_t	80	120	°C
Superheating temperature of working fluid	orc_wf4_t	120	230	°C
Depth of hot dry rock (drilling)	geo_egs	3000	6000	m
Reinjection temperature	geo_egs	70	110	°C

The range of evaporation temperature for working fluid has been chosen between 80 - 120°C, while for superheating temperature between 120-230°C. The depth of EGS system, which is extracted to provide useful heat, vary between 3000 – 6000 m. The geothermal gradient changes linear with depth and is equal for city Nyon, 3.8°C per 100m. The temperature of reinjection water changes depending on how efficiently heat is extracted from geothermal brine. The temperature of reinjection water in EGS system can vary between 70-110°C.

5.3.2 Optimization and Results

The system is optimized for Swiss demand profiles. As it has been mentioned before the multi-objective optimization is performed to evaluated the trade-off between the environmental performance indicators and the exergy efficiency. Three impact assessment method have been used: Ecoscarity06, Ecoindicators99-(h,a) and IPCC.

With all decision variables and objective function defined, it is possible to launch the Moo. During the optimization, the initial population of 200 has been used and maximum 2000 iterations have been done.

EGS ORC Simple benzene

The results obtained by the use of three impact assessment methods shows that there is trade-off between chosen objective functions.

In the figure, it can be seen the influence of increasing exergy efficiency of the system on calculated impact. The exergy efficiency increase causes decrease of benefits from avoided impact. However, both exergy efficiency and impact change in small range, what cause that this variation can be negligence.

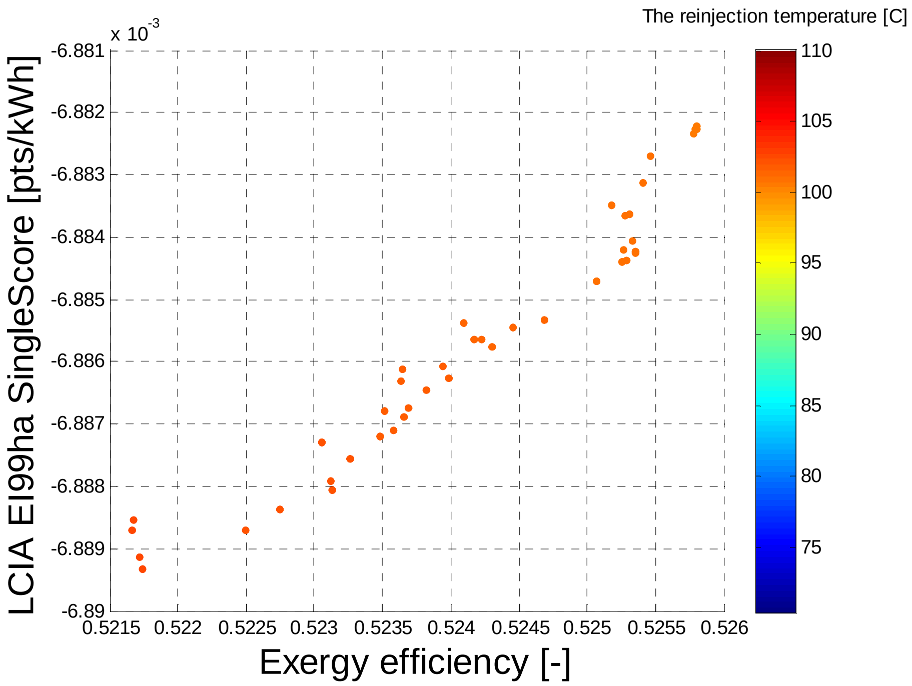

Figure 5.4 Pareto curve for Ecoindicator99-(h,a)and exergy efficiency with varying the reinjection temperature for EGS ORC Simple bz system

It is worth to mentioned that the impact varies for significant for Ecoindicators99-(h,a) and Ecoscarcity06 methods used. For Ecoindicators99-(h,a) method it changes in the range of thousandths of pts/kWh, while for Ecoscarcity06 method in range of hundreds (-178.15 ÷ -177.65).

The optimization show that all decision variables change in small range. Quiet important seems that the emission of about 0.09 kg CO_2 eq is omitted during 1 kWh generation (Figure 5.5).

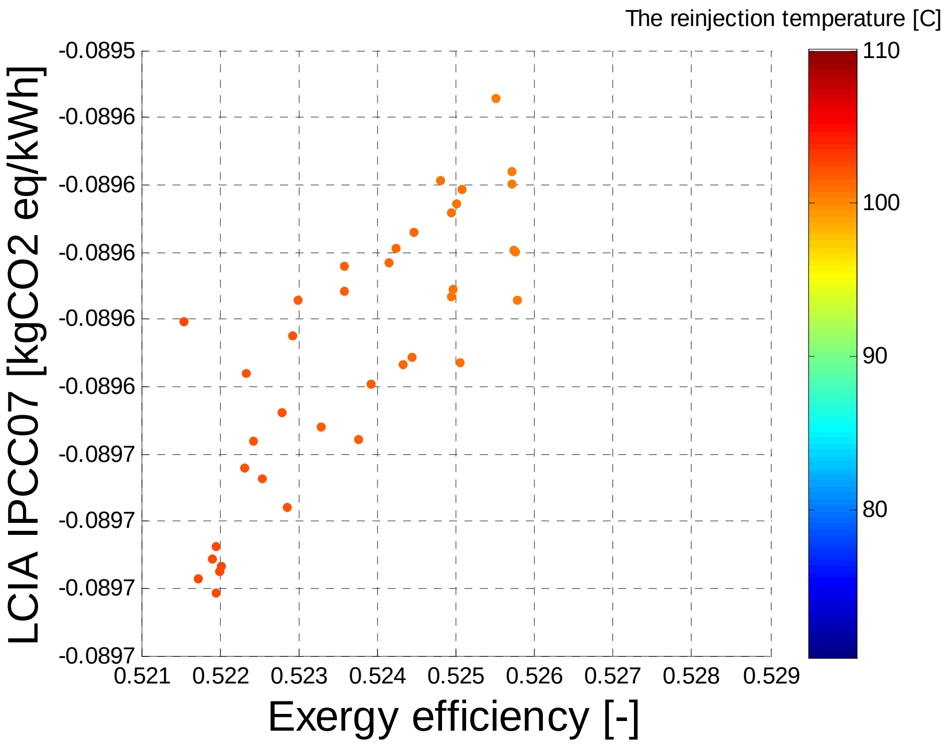

Figure 5.5 Pareto curve for IPCC07 and exergy efficiency with varying the reinjection temperature for EGS ORC Simple bz system

EGS ORC Simple cyclo-butane

In case of EGS ORC Simple system with cyclo-butane (CYC4) as a working fluid on first side there is no trade-off between impact calculated with Ecoindicators99-(h,a) method and exergy efficiency.

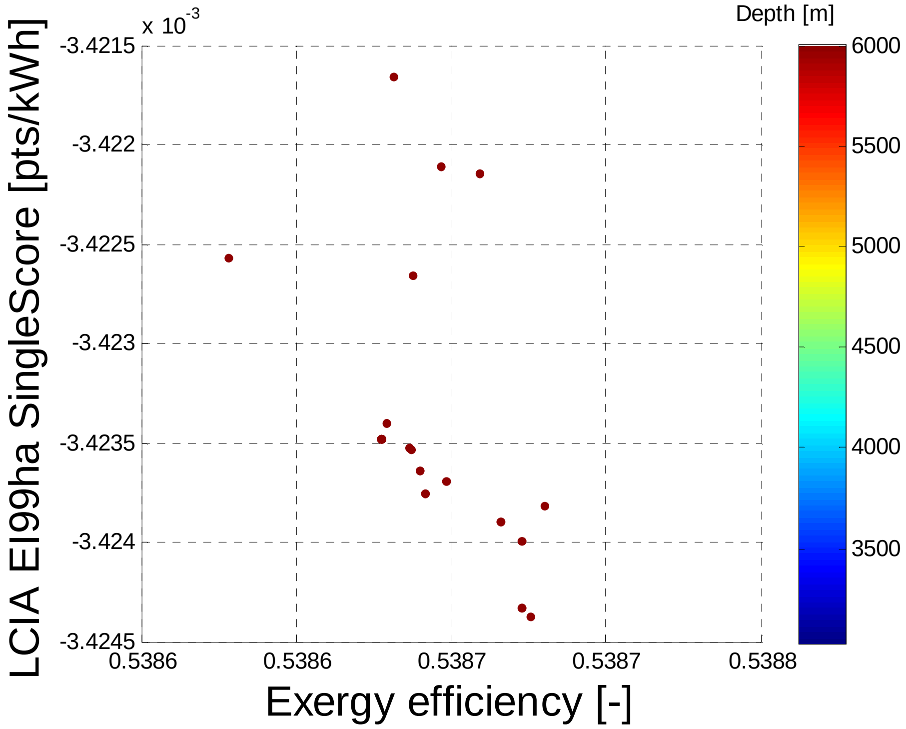

Figure 5.6 Pareto curve for Ecoindicator99-(h,a)and exergy efficiency with varying the depth for EGS ORC Simple cyc4 system

However, the objective function change in small ranges and it can be observed that the benefits from negative impact increase with exergy efficiency growth. Probably the highest number of the iterations would show the real relationship between impact and exergy efficiency. For Ecoindicator99-(h,a) methods all decision variable change in small ranges and it cannot be marked in the figure.

The multi-objective optimization brings interesting results for Ecoscarcity06 method.

During optimization two sets of results occurred. The first set is characterized by low exergy efficiency and less environmental impact than the second, but still harmful. The second set with significant growth of exergy efficiency is also characterized by increase of environmental impact. The evaporation temperature and the reinjection temperature change in small range for these two sets, while the superheating temperature (Figure 5.7) and depth (Figure 5.8) depend on set of solutions.

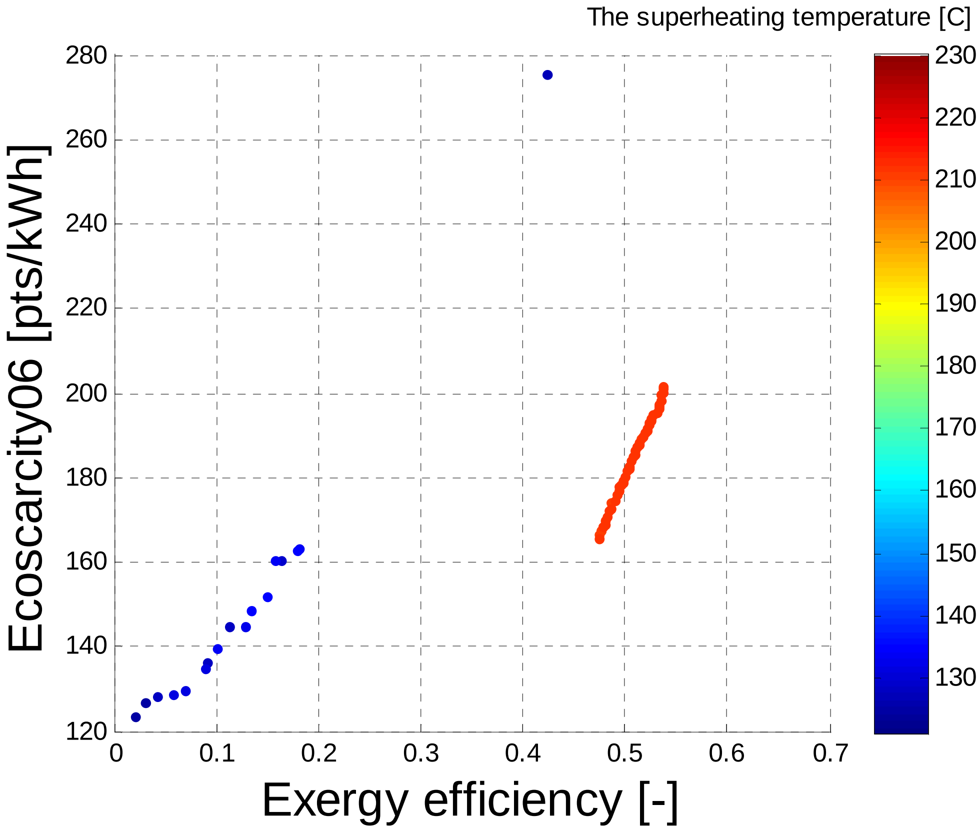

Figure 5.7 Pareto curve for Ecoscarcity06 and exergy efficiency with varying the superheating temperature for EGS ORC Simple cyc4 system

For solutions with low exergy efficiency, the system obtains the superheating temperatures from the minimum of range, while for high exergy efficiency from the maximum of range.

In ORC cycle, the higher temperature of superheating is favorable for higher efficiency. However, in this case the low heat exchange coefficients lead to very large and expensive heat exchanger. The future development of this study should consider those.

This is also connected with the depth of EGS system from which the brine is extracted. For low exergy efficiency solutions, there is no need to extract the brine with high temperature (no need to superheat working fluid to high level) so the systems with lower depth are preferred. For higher exergy efficiency the situation is opposite – the depth of extracted brine growth, which undoubtedly has influence on environmental impact increase. It is cause by growth of emission and extraction from drilling. In EGS system the costs of construction phase are the most significant, they heavily dependent on the drilling cost of geothermal wells, the geothermal pumps etc. so in further development this is another thinks to consider.

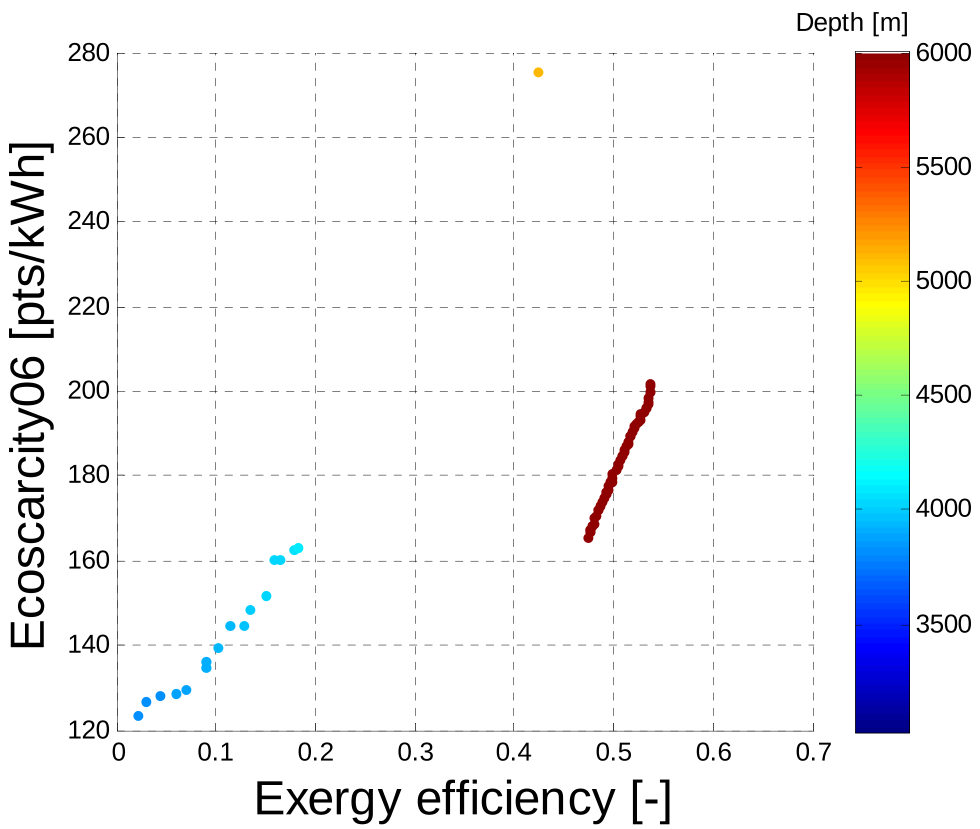

Figure 5.8 Pareto curve for Ecoscarcity06 and exergy efficiency with varying the depth for EGS ORC Simple cyc4 system

The results obtained with the IPCC07 are not displayed here. However, the use of this geothermal conversion technology can help to avoid about 0.09 kg CO_2 eq during 1 kWh generation at the exergy efficiency of the system 53-54%.

EGS ORC Simple iso-butane

The multi-objective optimization do not show the strong connection between exergy efficiency and environmental impact calculated with Ecoindicators99-(h,a) method. Both objective functions change in small range as well as decision variables.

The more suitable for Swiss case is Ecoscarity06 method, which has been created in based on Swiss environmental policy. The results obtained by this method are also much more interesting from optimization point of view. They are quite common to these presented for EGS ORC Simple cyc4 model. There are also two sets of solution – for low exergy efficiency and high exergy efficiency. The superheating temperature depends also from exergy efficiency and varies in its range (Figure 5.9).

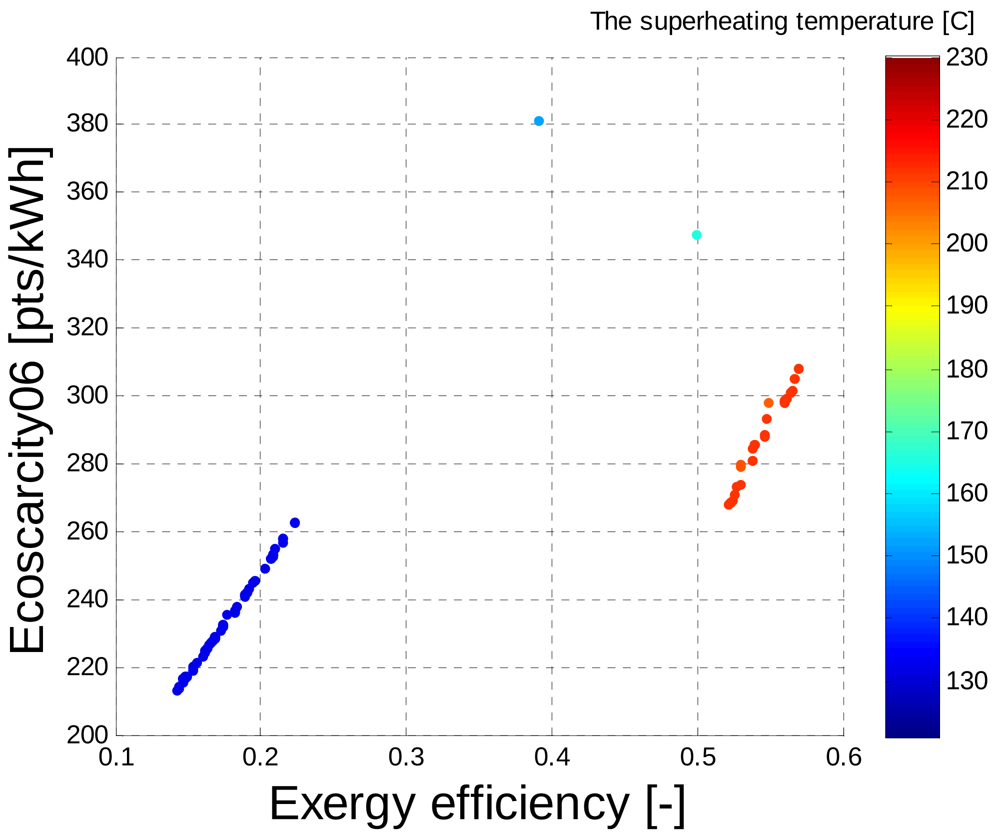

Figure 5.9 Pareto curve for Ecoscarcity06 and exergy efficiency with varying the superheating temperature for EGS ORC Simple ic4 system

Comparing to results obtained for EGS ORC Simple cyc4 system, the present system achieve the higher efficiency. Interesting is that this results are achieved in almost the same range of temperature as for EGS ORC Simple cyc4 system (Figure 5.10). Probably it is caused because system is better converted for iso-butane (ic4) as a working fluid. However, from the environmental point of view it has worse effect on environment.

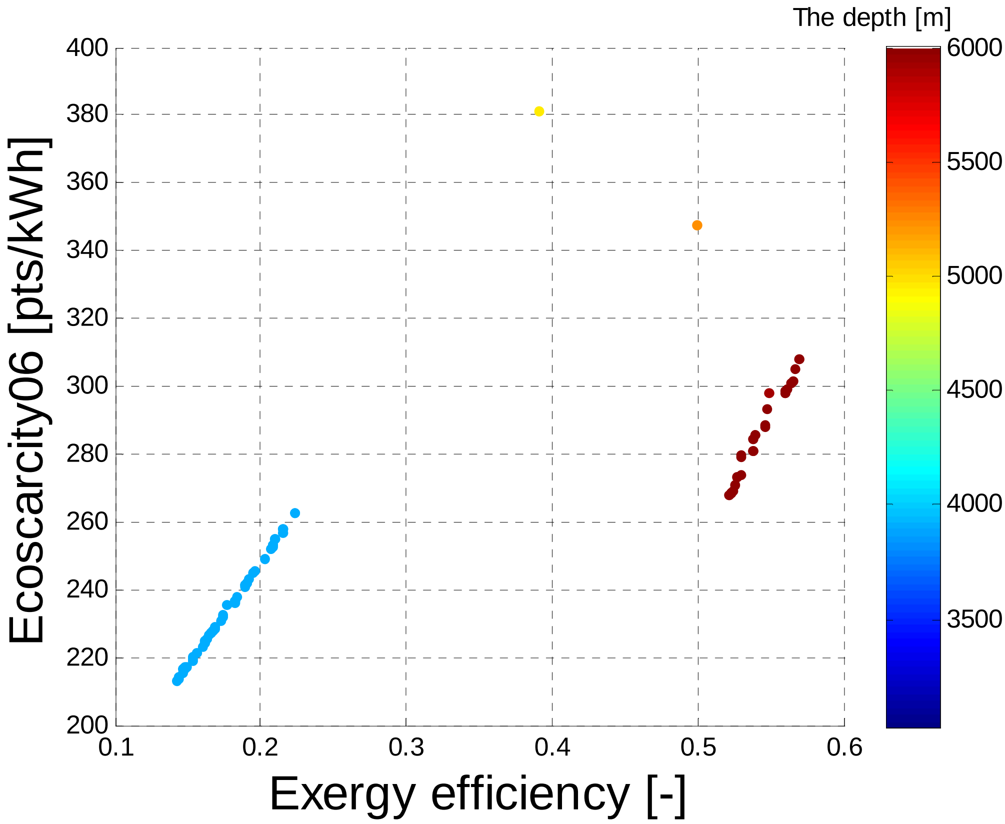

Figure 5.10 Pareto curve for Ecoscarcity06 and exergy efficiency with varying the depth for EGS ORC Simple ic4 system

There is also trade-off between the environmental performance indicator calculated with IPCC07 method and exergy efficiency (Figure 5.11). With the growth of exergy efficiency, the benefit form avoided impact decrease. It can be noticed that the temperature of geothermal water depends form exergy efficiency. Exergy efficiency is growing while the reinjection temperature is decreasing. Better use of geothermal brine by recovering greater amount of heat results in higher efficiency at a lower temperature of reinjection. However, the better recovery of heat from geothermal water, which affect on the reinjection temperature drop, cause decreases the benefits of avoided environmental impact.

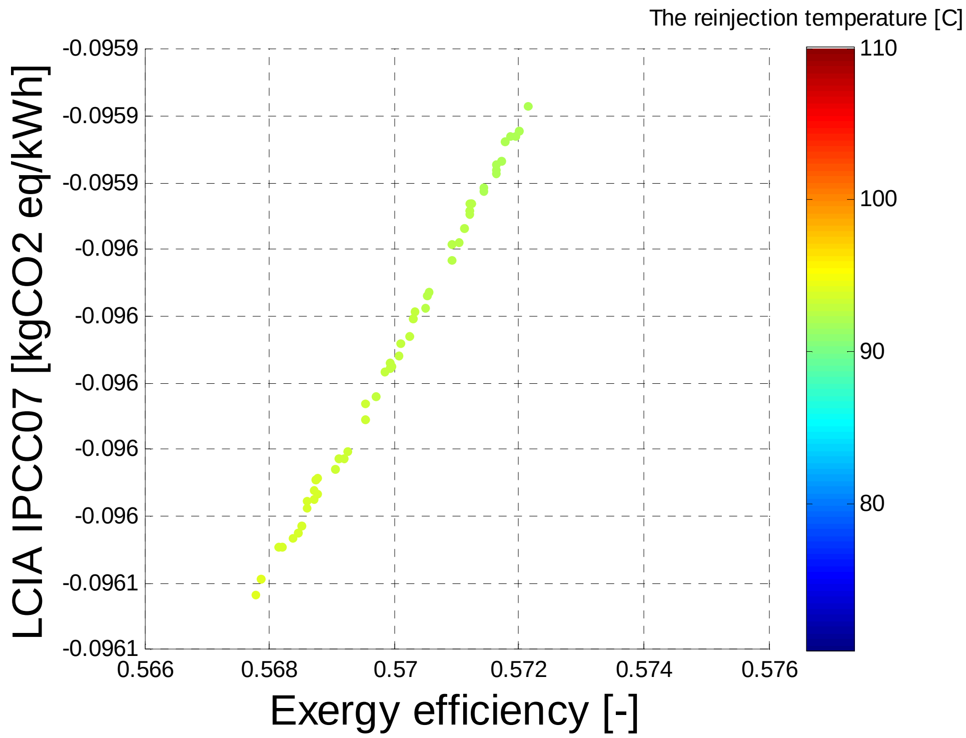

Figure 5.11 Pareto curve for IPCC07 and exergy efficiency with varying the reinjection temperature for EGS ORC Simple ic4 system

EGS ORC Simple isopnetane

The multi-objective optimization for EGS ORC Simple system, with isopentane (ic5) as a working fluid, results in trade-off between exergy efficiency and impact calculated in three different ways (Figure 5.12). The result obtained for Ecoindicators99-(h,a) and Ecoscarcity06 methods seem to be scattered but it is not significant since the objective functions change in small ranges. For all implemented methods the impact is beneficial, it means that they show the harmful impact which we avoid thanks to use geothermal conversion system. In all cases the environmental benefits decrease with increasing of exergy efficiency. The decision variables change in small range.

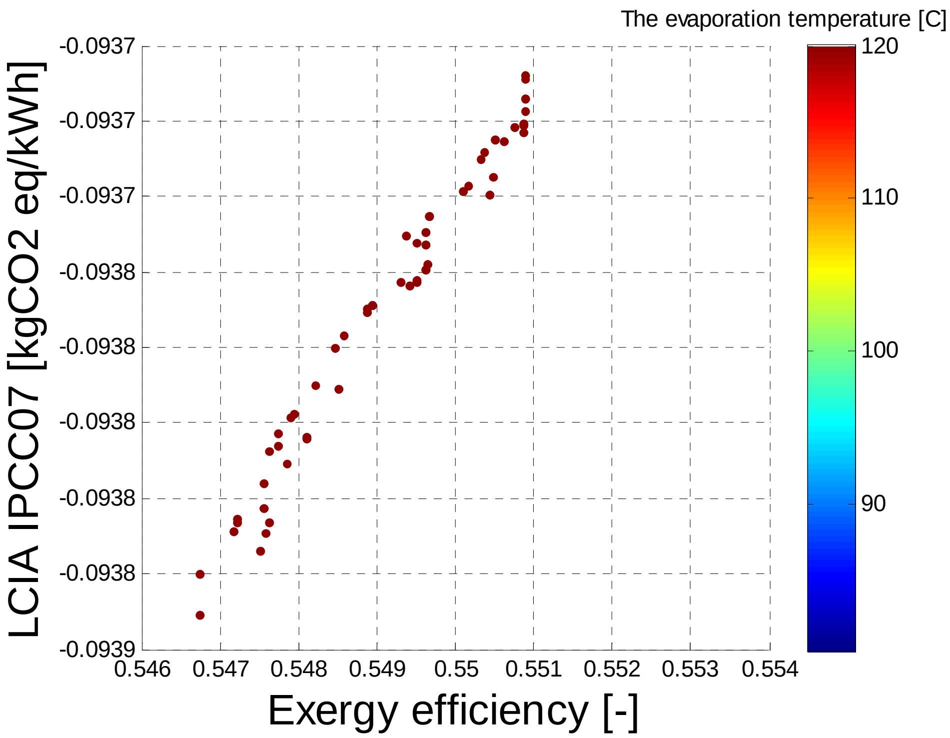

Figure 5.12 Pareto curve for IPCC07 and exergy efficiency with varying the evaporation temperature for EGS ORC Simple ic5 system

EGS ORC Simple n-butane

The results obtained during optimization for EGS ORC Simple n-butane (nc4) for Ecoindicator99-(h,a) are quite scattered in small range. These results are not display here, but it is worth to mention that the impact calculated with this method has got small beneficial influence on environment.

As it was in case of models with cyclo-butane and isobutene, the optimization with Ecoscarcity06 method results in two sets of solutions, for lower and higher exergy efficiencies. For lower values of exergy efficiency, the superheating temperature got values from lower range (Figure 5.13). The upper range of superheating temperature is connected with higher exergy efficiency. The system has harmful impact of environment that increase with exergy efficiency growth. In addition, the depth of geothermal water extraction changes with exergy efficiency. The connection between this objective function and decision variable was described above. The system with low exergy efficiency converts smaller amount of heat into useful services, what cause that there is no need to extract geothermal water from huge depth. The extraction of water significant depths cause that system performed with higher efficiency.

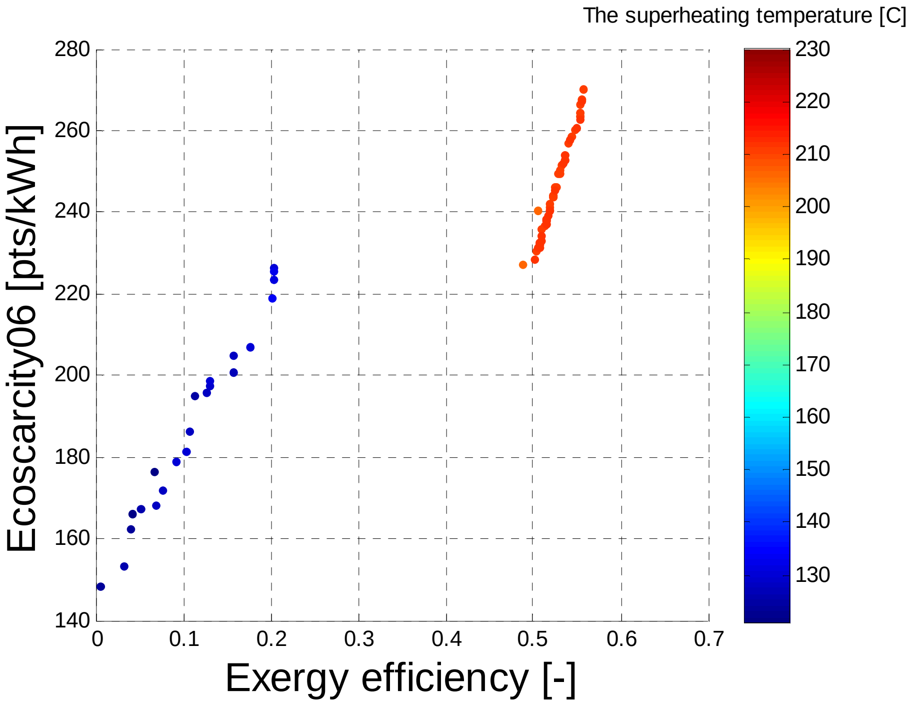

Figure 5.13 Pareto curve for Ecoscarcity06 and exergy efficiency with varying the superheating temperature for EGS ORC Simple cyc4 system

EGS ORC Simple n-pentane

The multi-objective for EGS ORC simple system with n-pentane optimization brings, as it has been in previous cases, the changes of objective functions in small ranges. The impacts calculated with Ecoinventory99-(h,a) and IPCC07 methods show small beneficial influence on environment which is decreasing with the increase of exergy efficiency.

The harmful environmental impact has been evaluated with Ecoscaricity06 method. All decision variables change is small range, except the reinjection temperature that changes significantly in given range (Figure 5.14). The environmental impact is smaller for lower value of reinjection temperature and grows with increase in reinjection temperature. Energy efficiency change in direct proportion to environmental impact of the system.

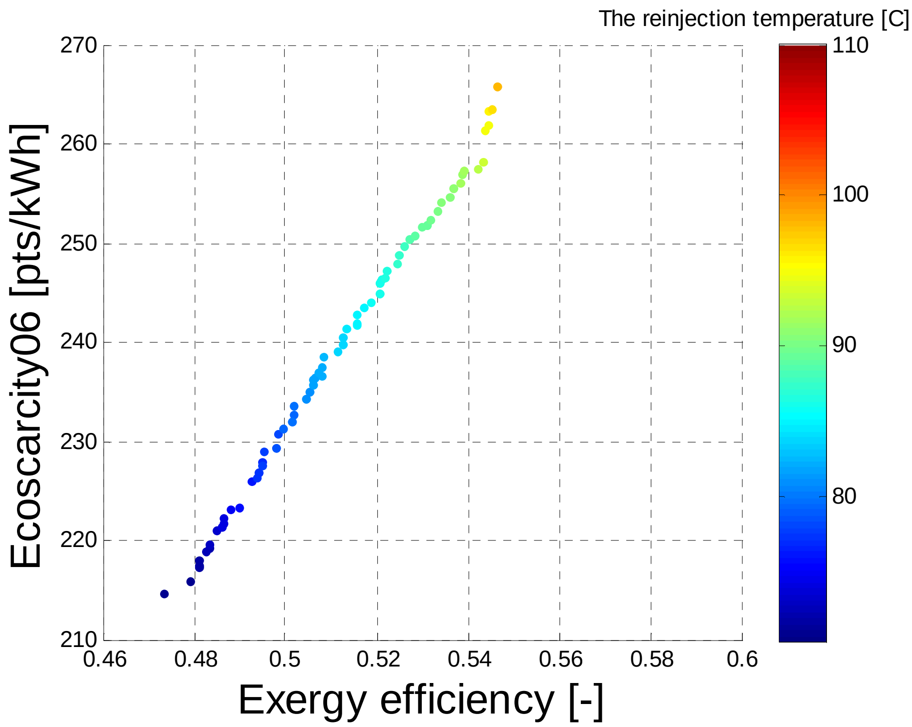

Figure 5.14 Pareto curve for Ecoscarcity06 and exergy efficiency with varying depth for EGS ORC Simple nc5 system

EGS ORC Simple toluene

Toluene as a working fluid in EGS ORC Simple system behaves different from working fluids discussed so far. In all impact methods, the scatter of the optimal solutions is observed. The smallest one is for Ecoscarcity06 method. Still this does not have significant influence on decision making since the obtained results do not differ greatly from each other.

For all implemented methods, the environmental impact is beneficial.

The most significant relationship can observed between impact calculated with Ecoscarcoty06 method and exergy efficiency (Figure 5.15).

All decision variables change is small range.

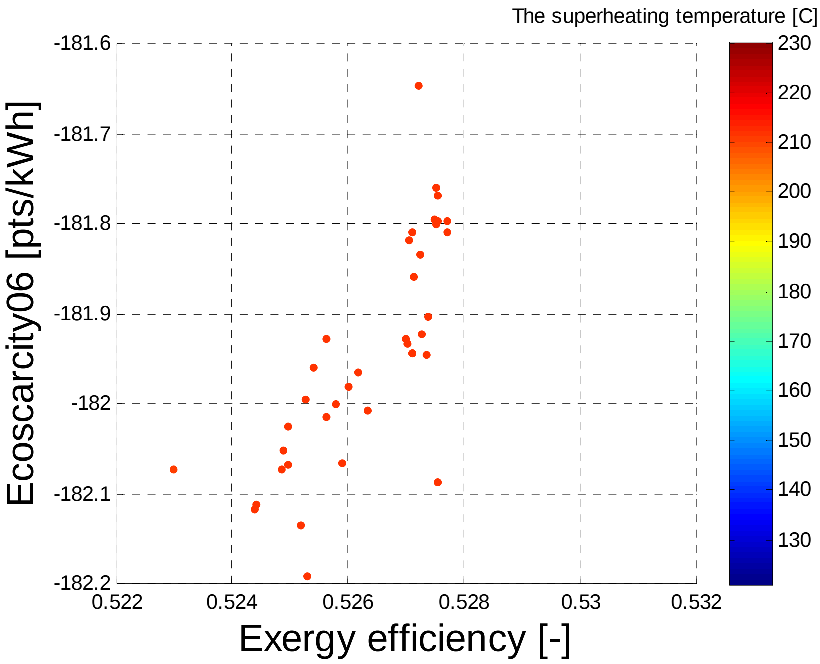

Figure 5.15 Pareto curve for Ecoscarcity06 and exergy efficiency with varying the superheating temperature for EGS ORC Simple toluene system

5.3.3 The Conclusion from the Optimization the ORC Simple systems with different working fluids

A number of different conclusions can be drawn from these optimizations. Although the optimized system was the same for each case, it can be observed how significant influence on optimization results has the selected working fluid. Not without significance is the choice of objective functions, including differences between methods used to calculate environmental impact.

Not without influence stay the choice of decision variables and their range.

In these optimizations, two objective functions have been chosen: exergy efficiency and the environmental impact. The efficiency as a objective function in each case remained constant, while three different methods have been used to calculate the environmental impact.

The decision variables have been determinate at the same ranges for each case. This cause that very often they do not change significantly in their range, but from the other hand, it gives possibility to compare all obtained results.

In Figure 5.16, the optimal solutions for different working fluids are presented. The presented figure shows the trade-off between the environmental performance indicators calculated with Ecoindicator99-(h,a) and exergy efficiency. There are sets representative for different working fluids. For this method the environmental impact for all working fluids have beneficial impact, in it for benzene, toluene and isopentane higher than for other used fluids. The best exergy efficiency has got isobutan. The good parameters obtain isopentane, which has good exergy efficiency and at the same time the best influence on environment from all optimized working fluids.

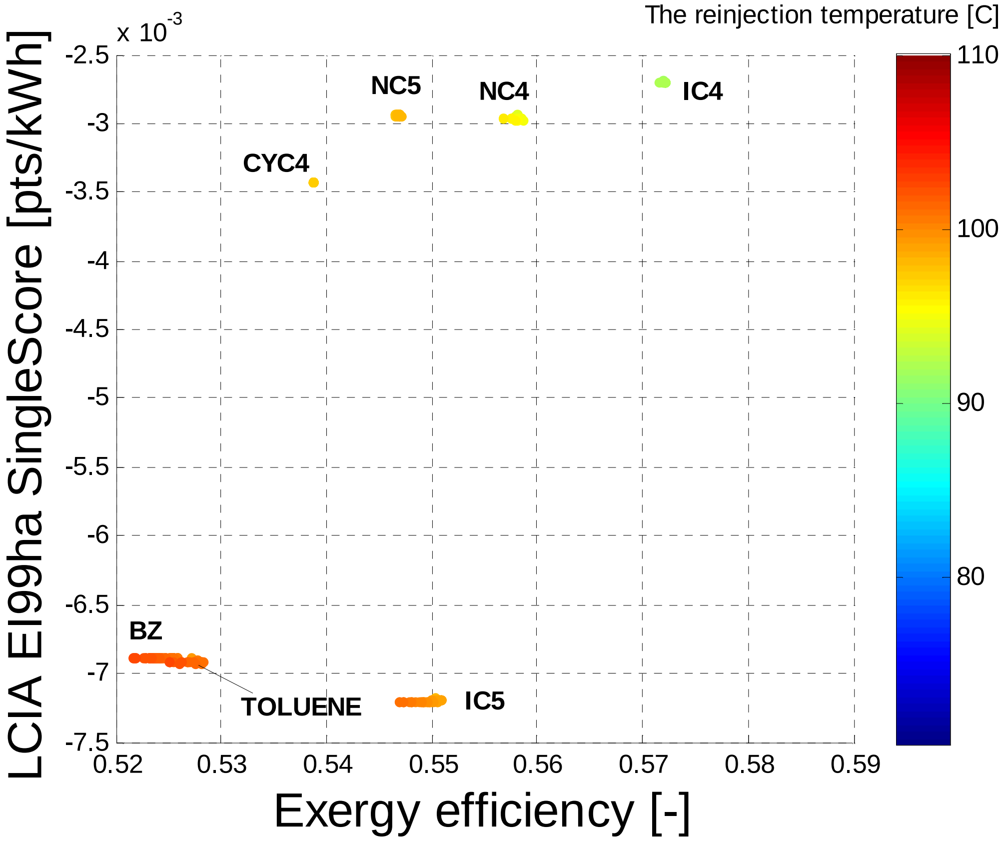

Figure 5.16 Pareto curve for Ecoindicator99-(h,a) and exergy efficiency with varying the reinjection temperature for EGS ORC Simple for different working fluids

In Figure 5.17 the results of Ecoscarcity06 method in optimization can be observed. The environmental impacts in this approach have not always beneficial impact on environment how it was in case of used Ecoindicator99-(h,a). The isobutane, nbutane, npentane and cyclo-butane have harmful effect on environment. For all working fluids, the superheating temperature obtains values from lower range for low exergy efficiency, while the high exergy efficiency is connected with values from upper range. The optimization results obtained for npentane are comparable to set of solutions with higher exergy efficiency obtained for nbutane.

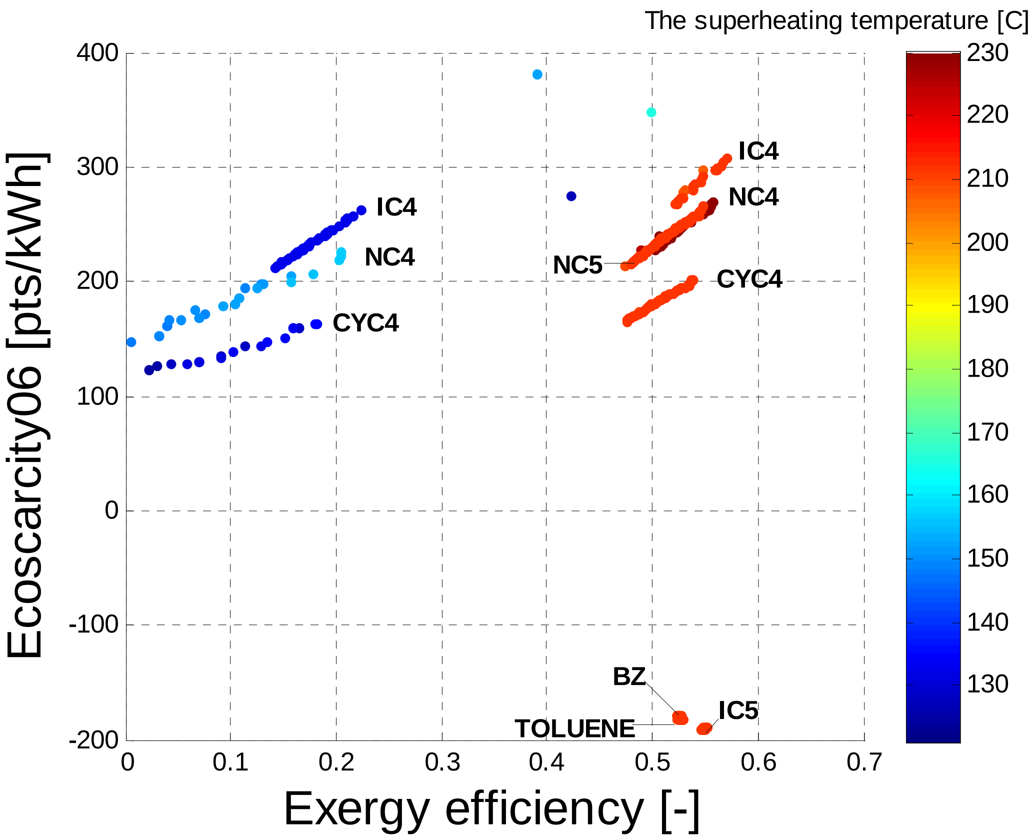

Figure 5.17 Pareto curve for Ecscarcity06 and exergy efficiency with varying the superheating temperature for EGS ORC Simple for different working fluids

To show more detailed the harmful environmental impact of all butane substances the Figure 5.18 is add. The optimization for these working fluids performed two sets of solutions. The Ecoscarcity06 method used in this case provide interesting results for lower and higher exergy efficiency. The environmental impact grows in direct proportion to exergy efficiency increase for both sets.

It can be observed that the decision variables change in almost the same range for each fluid. The exergy efficiency increases slightly in order: cyclo-butane, n-butane and isobutene. In the same, order the harmful environmental impact growth.

The different results received from the optimization with used the impact assessment methods are caused by different weighting connected with the impact assessment methods. These give more importance to one energy services produces or another. In case of Ecoscarcity06 the proposed solutions incline to the production of electricity, which can replace the Swiss mix.

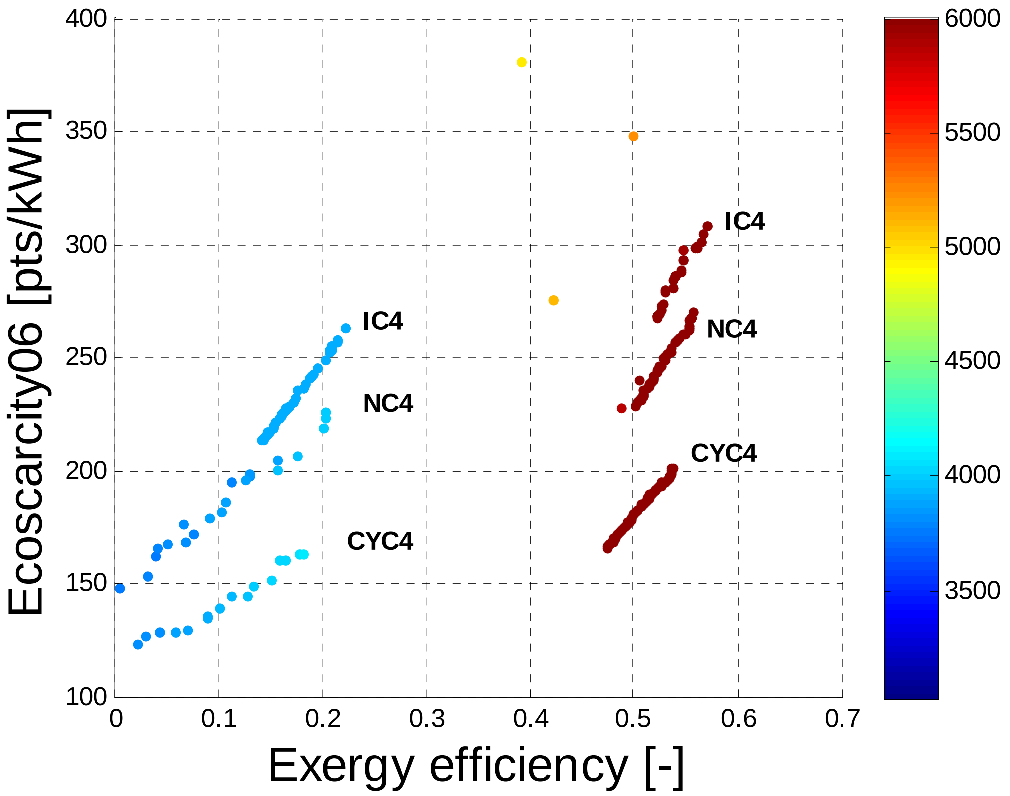

Figure 5.18 Pareto curve for Ecoscarcity06 and exergy efficiency with varying depth for EGS ORC Simple systems with butane substances

The third method used to calculate the environmental impact is IPCC07. The trade-off between optimized objective functions for each working fluid is presented at the Figure 5.19. The method gives an overview of the environmental impact on the global warming issue. In this study, foe each working fluid the impact from optimization is beneficial. It can be said how much kg CO_2 eq avoided by using proposed system with different working fluid. For this optimization, the worse set of solutions is provided for benzene as a working fluid. The best set of solutions has isobutan, which has significantly higher exergy efficiency than other fluids as well as positive impact on environment. In this statement, nbutane clearly distinguished among other working fluids due to the scattering of optimal solutions.

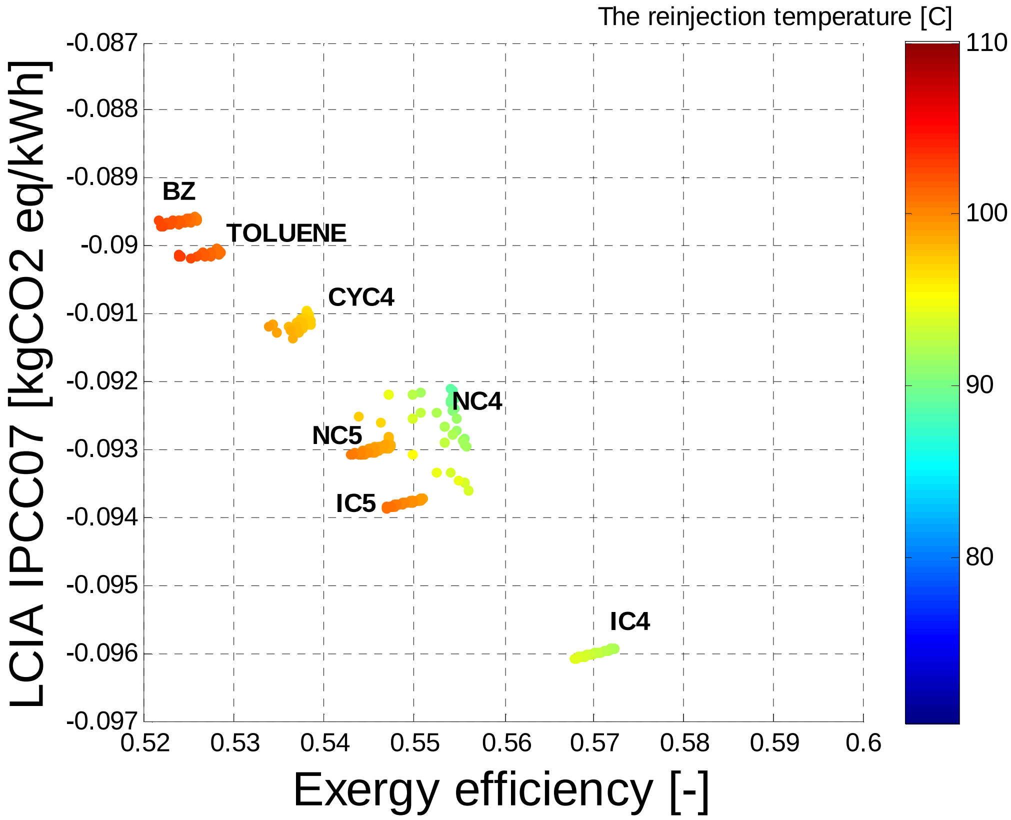

Figure 5.19 Pareto curve for IPCC07 and exergy efficiency with varying the reinjection temperature for EGS ORC Simple systems with different working fluids

5.4 Optimization Two – the Flash Systems

The second optimization has been launch for flash systems. The EGS has been used as geothermal sub-system with two conversion technologies: single flash system and double flash system. The optimization is run only for one environmental impact assessment method – the Ecoindicator99-(h,a). It is set for Nyon demand profiles.

5.4.1 Decision Variables

The optimization of flash single system is based on three decision variables: 1st flashing pressure, depth of hot dry rock and the reinjection temperature. For flash double system, one additional decision variable is provided: the 2nd flashing pressure. The ranges for all decision variables are shown in Table 5-2.

The pressure in high-pressure flash drum can be between 2 to 5 bars, while the low-pressure flash drum runs between 2 – 8 bars. The depth of drilling and the temperature of reinjection run in the same ranges as for ORC system.

Table 5-2 The decision variables for flash systems

Decision variable	**Variable**	**Min**	**Max**	**Unit**
1^{st} flashing pressure	fl_2_p	5	12	bar
2^{nd} flashing pressure	fl_7_p	2	8	bar
Depth of hot dry rock (drilling)	geo_z	3000	6000	m
Reinjection temperature	geo_inj_t	70	110	°C

5.4.2 Optimization and Results

As it was in previous case the Moo has used initial population of 200 results in optimization and 2000 iterations.

EGS Flash Single System

The result of multi-objective optimization for EGS flash single system is displayed in Figure 5.20. There is the trade-off between the environmental performance indicators and the thermodynamic indicators of the system. The growth of exergy efficiency causes increase of avoided impact on environment that is treated as a benefit. In addition, the relationship between the environmental impact and the depth of extract geothermal resource is shown. The depth of drilling has harmful effect on environment. The interested is that the optimization showed that the depth of drilling does not have significant influence on exergy efficiency. In figure we can seen set of solutions for different depth which provided the same value for exergy efficiency.

The results of optimization show that for the 1^{st} flash pressure optimal configuration is for lower range values, while for the reinjection temperature is for upper range values.

The optimization shows that the exergy efficiency of proposed system is not high. It varies between 36.4 – 37.6 %.

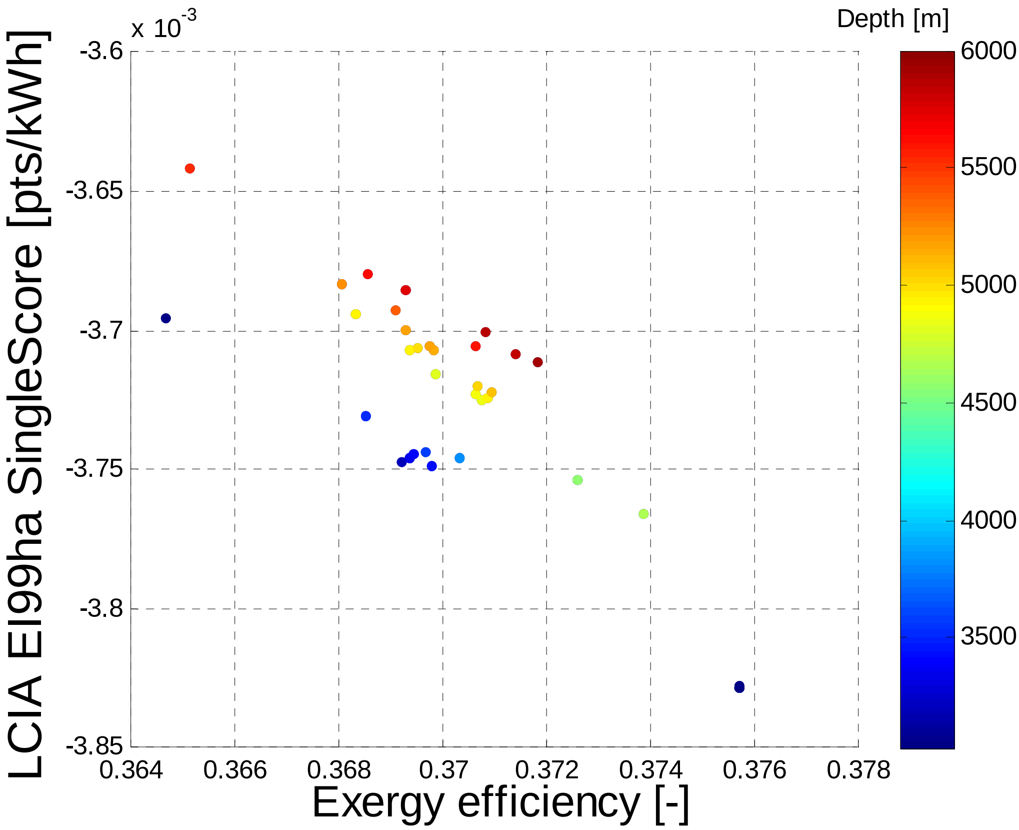

Figure 5.20 Pareto curve for Ecoindicator99-(h,a)and exergy efficiency with varying the depth for EGS Flash Simple system

EGS Flash Double System

The optimization of EGS flash double system gives an interesting result. The trade-off between objective functions can be observed. However, for exergy efficiency in the range between 85.6 – 85.9% there is no significant change of environmental impact. This significant change shows for range 85.6 - 86% and cause marked reduction in environmental benefits.

The system seems to be converted for depth around 3000 – 4500 m, which certainly has a positive impact on the cost and the environment.

In further development of the project, this influence should be considered.

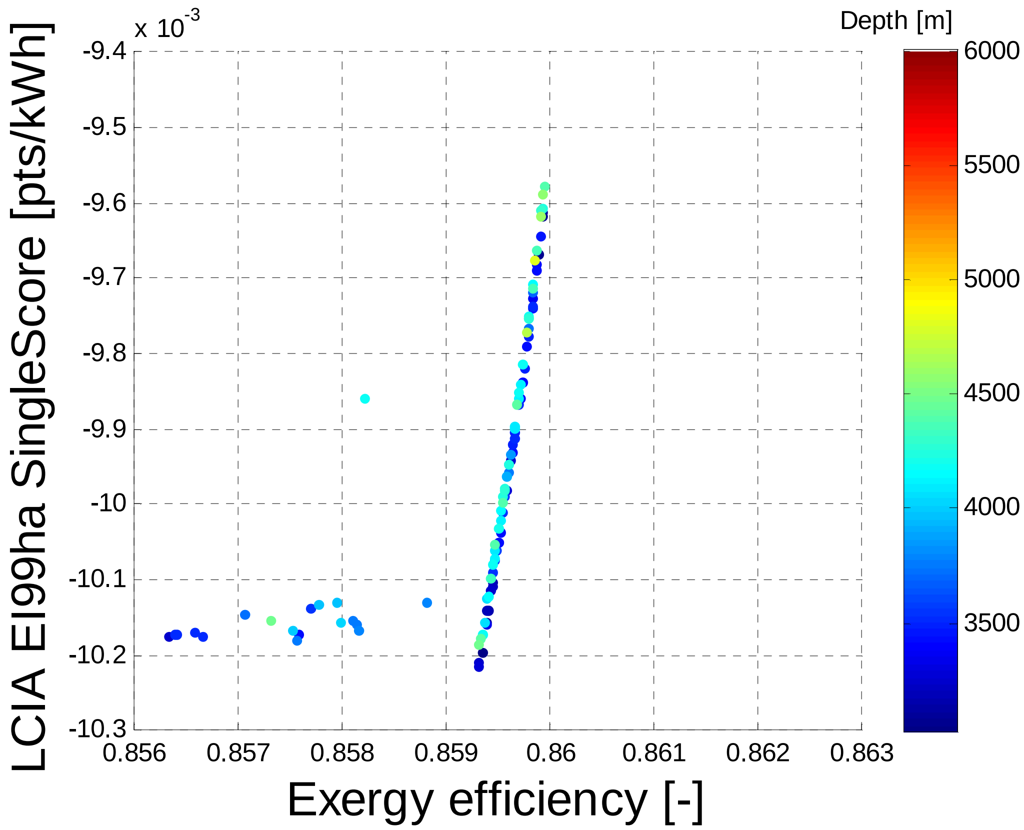

Figure 5.21 Pareto curve for Ecoindicator99-(h,a)and exergy efficiency with varying the depth for EGS Flash Double system

5.4.3 Conclusion from the Optimization of Flash Systems

The optimization of flash systems shows that the flash double system has much higher exergy efficiency. At the same time the environmental benefits of avoided impact seems more significant.

The optimization shows that flash single system obtained the optimal configuration in all set range, while the double flash system needs shallower depth to extract geothermal water. This can have significant influence on construction cost, what can be optimized in further study.

6 ONE-RUN SYSTEM RESOLUTION

In this section the one-run system resolution for chosen optimal solution for each optimized configuration is presented. The one-system resolution is shown from environmental impact side.

6.2 Environmental impact of optimized configurations

The optimizations provide the set of optimal solution. From these sets, the single points have been chosen. The systems have been evaluated from environmental point of view. As it can be noticed below, the most significant impact on environment has operating phase of geothermal conversion systems.

The impact on ecosystem quality is presented in Figure 6.1 below. From all optimized systems, the most significant beneficial influence on environment has Flash system. From Organic Rankine system the use of isopentane, benzene and toluene have beneficial impact. The other working fluids used in this system have harmful impact on ecosystem quality.

In general overview, the harmful influences on ecosystem quality have construction and end-of-life phases of geothermal utility. The influence of Flash system is significantly higher than ORC systems.

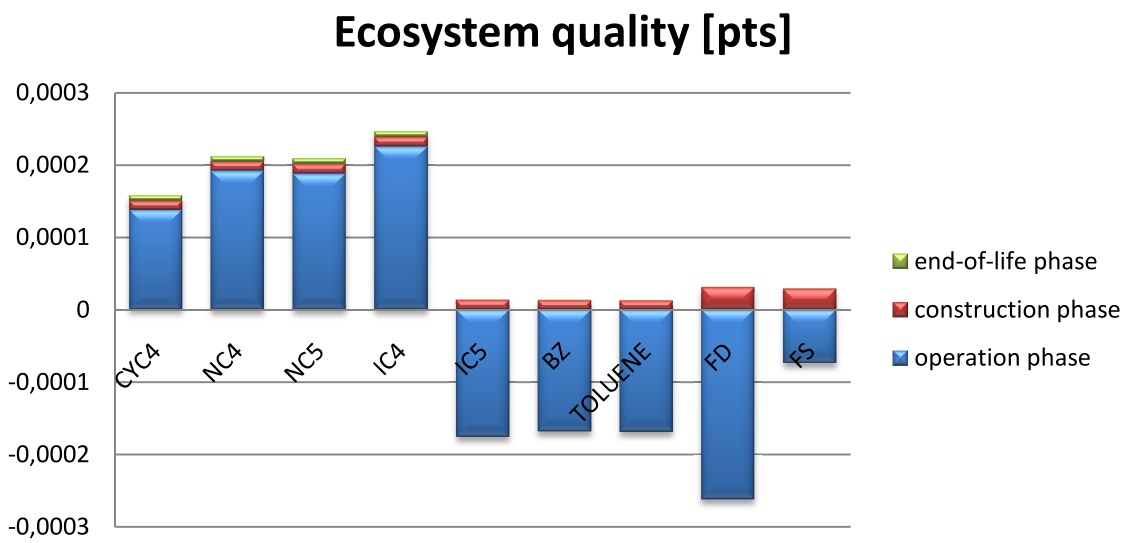

Figure 6.1 The impact on ecosystem quality [pts] for optimized geothermal conversion systems

In Figure 6.2 the impact on human health is presented. All analyzed systems seem not have influence on human health in total. The negligible harmful impact is observed for construction and end-of-live phases for all systems. The biggest beneficial impact has Flash double system, while the smallest (but still beneficial) the ORC simple system with isobutene as a working fluid. Also the beneficial impact of isopentane, benzene and toluene are essential.

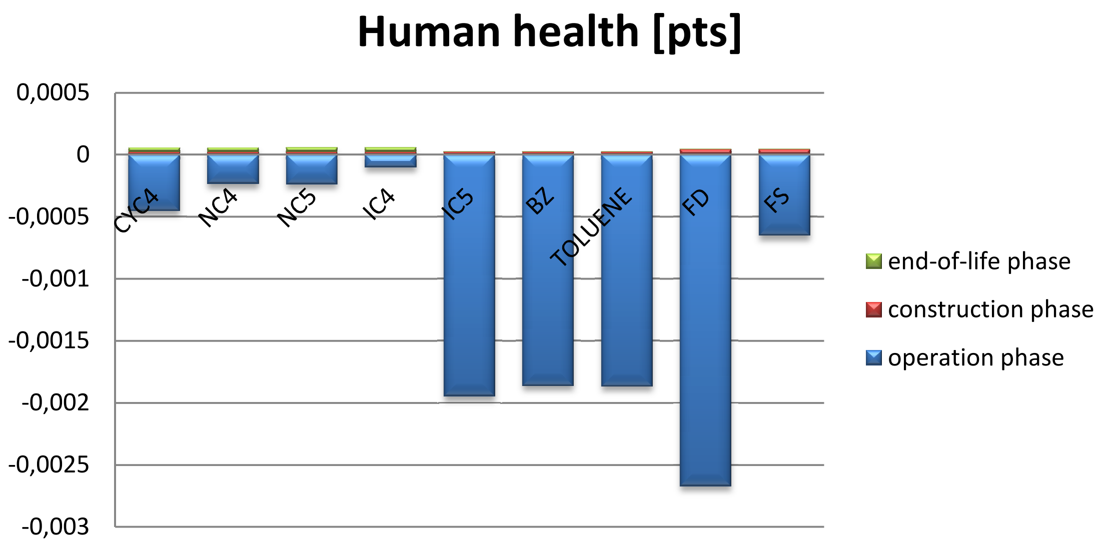

Figure 6.2 The impact on human health [pts] for optimized geothermal conversion systems

The resource impact for all working fluids use in ORC simple system is beneficial and at the same level (Figure 6.3). In figure it can be noticed that the Flash double system has the biggest beneficial impact, while the Flash single the lowest, but still beneficial.

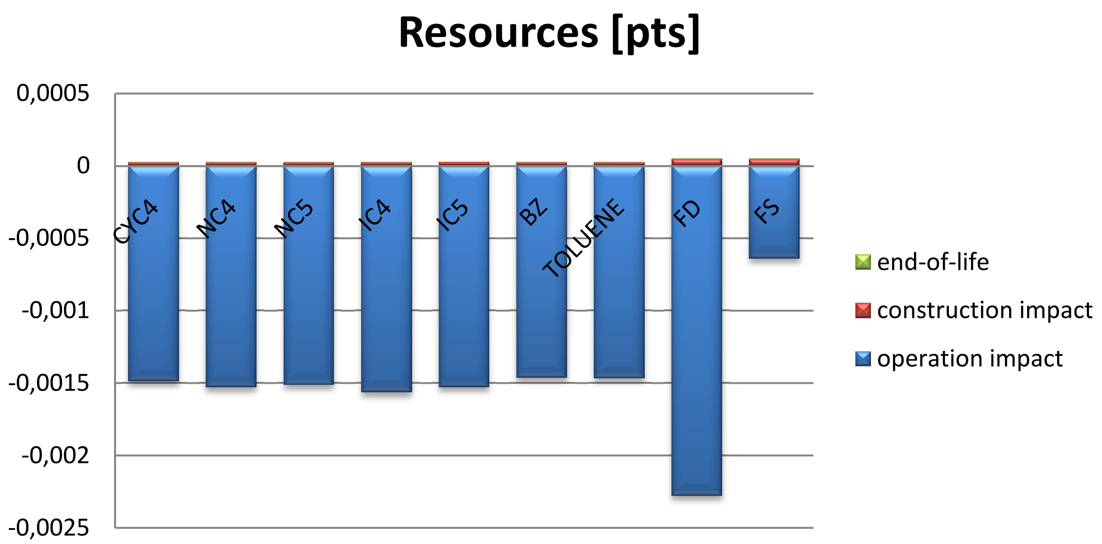

Figure 6.3 The resource impact [pts] for optimized geothermal conversion systems

The total impact of all optimized systems is presented in Figure 6.4. Overall environmental impact of all analyzed system is beneficial with the individual variations among the group. The least harmful to the environment is Flash Double system. In ORC simple system the use of isopentane, benzene and toluene as a working fluid is the best solution from environmental point of view.

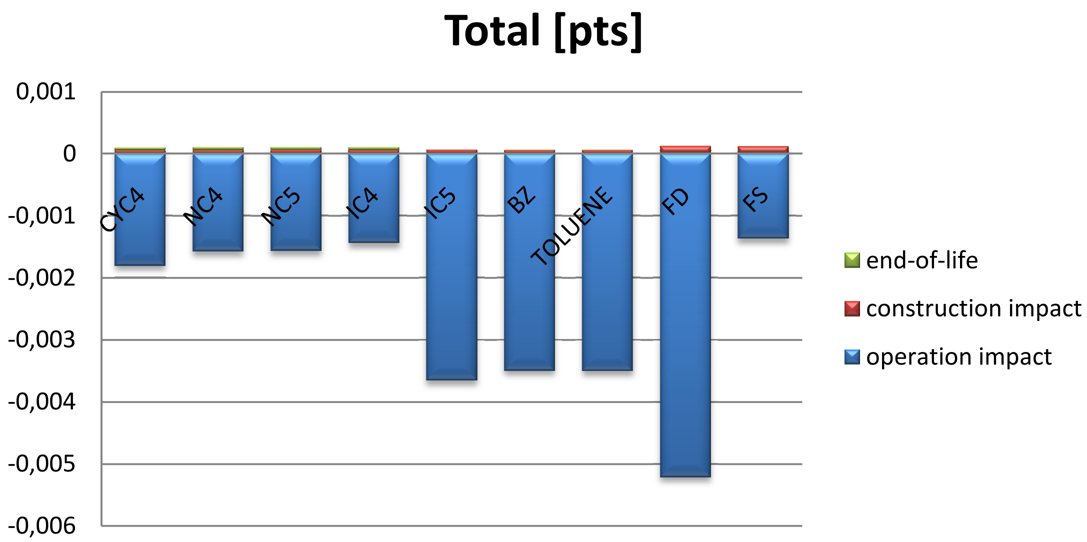

Figure 6.4 The resource impact [pts] for optimized geothermal conversion systems

Below, it is presentation of impact category for all optimized systems. In this statement, the least impact in context of category is on ecosystem quality, but only for this category, the impact is harmful. For all working fluids used in ORC simple system the resource impact seems at the same level but still beneficial.

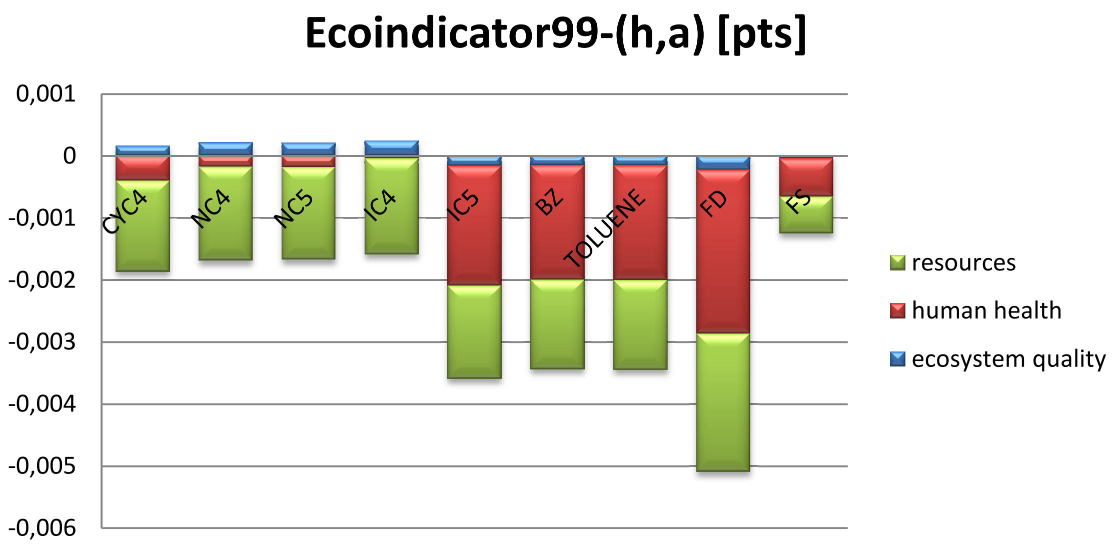

Figure 6.5 The impact category influence on environment

7 CONCLUSION

This report detailed the methodology to integrate life cycle assessment (LCA) in thermo-economic model used for energy conversion system design. The methodology is use to identified the optimal exploitation of geothermal resources in emphasis on environmental criteria. The model has been divided into substructures of exploitable resources, geothermal conversion technologies and multiple demand profiles. The models were validated using case studies for Polish and Swiss conditions.

The resource model consists of enhanced geothermal system, deep aquifer and shallow aquifer. The superstructure of conversion technologies includes Organic Rankine cycles (simple, double and bleeding), Flash systems (simple and double) and heat pumps. Yearly demand profile for Swiss conditions is based on data for city Nyon, and divided into four periods (summer, interseason, winter, extreme winter). The demand profiles for Poland was created for city Konin, and divided into six periods.

Leni-Osmose platform was used in resolution. The Ampl software was used in energy integration to provide the data about optimal sizing of the evaluated systems, the heat exchanger network, and about hot utility demand.

During evaluation, the thermodynamic and environmental performance indicators were used. As thermodynamically indicator, the exergy efficiency was chosen, while for the environmental indicators the three different methods were provided in evaluations. These methods are: Ecoindicator99-(h,a), Ecoscarcity06 and IPCC07.

Validation of methodology was based on use number of one-run scenarios and multi-objective optimizations for developed the proper models.

The multi-objective optimizations gave a set of optimal solutions, based on integer decision variables. The problems that occurred during optimization depend on the range of decision variables, with the long time of computing and poor initial population. The optimization was launched for Organic Rankine cycle with the enhanced geothermal system and for flash systems with hot dry rock resource. The optimization were done for Swiss conditions. The significant amount of time needed for optimization cause that the revised models for deep and shallow aquifers and for Polish conditions were not optimized.

The one-run system resolutions were launched for optimized decision variables. The environmental impact of these systems was shown in context of construction, operation and end-of-life phases. In one-run system resolution one optimal point was chosen from set of solutions for geothermal conversion systems. The influence of applied working fluids for organic Rankine systems was presented. The method used to calculation was Ecoindicator99-(h,a), which present the impact contribution in such area as: ecosystem quality, human health, resources and total.

Conclusion

The multi-objective optimizations have been launched for enhanced geothermal systems with ORC system (for seven different fluids) as well as for flash single and double systems.

The optimization for enhanced geothermal system with ORC systems show that the different working fluid used in ORC system has different influence on obtained results.

The EGS ORC systems have been evaluated in use of three methods: Ecoindicator99-(h,a), Ecoscarcity06 and IPCC. The results obtained for each method are different. The best suited method for Swiss conditions in Ecoscarcity06, which was developed in based on the Swiss environmental policy goals.

The results obtained by using Ecoindicatr99-(h,a) show that the benzene, toluene and isopentane have highest beneficial impact for environment. From thermodynamic point of view use of isobutene as the working fluid provide the highest exergy efficiency. Interesting is that the all used fluids have beneficial impact on environment clarified by Ecoindicator99-(h,a).

The results obtained by the Ecoscarcity06 shows that the same fluids (benzene, toluene and isopentane) have the highest beneficial impact. In addition, isobutene obtains the highest exergy efficiency in use of this method. The results for cyclobutane, isobutene and nbutane shows that these fluids have harmful environmental impact, as well as the two set of solution for low and high exergy efficiency are calculated.

The IPCC method shows that all working fluid have beneficial influence on the global warming effects. Both beneficial impact and exergy efficiency obtain the best set of solutions for isobutene.

The EGS Flash single and double systems are evaluated in use of only one method: Ecoindicators99-(h,a). The multi-objective optimization shows that the flash double system has got higher exergy efficiency as well as the greater environmental benefits. Quite interesting is that the single flash system obtains the optimal configuration in all set ranges. In additions, the flash systems need shallower depth to extract geothermal water what significantly influence not only on environment but also on costs.

The comparison of all optimized conversions systems for hot dry rock show, that the flash double system has the best results from all structure. The efficiency of double flash system is the highest one of all analysis systems as well as the beneficial impact on environment.

The optimization shows that the most harmful influence on environment have construction and decommission phases. The operation phases has the biggest beneficial impact. The flash double system has significantly higher beneficial impact of operating phases thank other analyses systems.

Recommendations for future work

In future work many additional improvement can be considered. First, the optimization for created models should be launched. The multi-objective optimizations for enhanced geothermal system with ORC bleeding and double systems for all considered fluids, deep aquifer with ORC system and shallow aquifer with heat pump should be launched. In addition, the district cooling demand should be taken under consideration.

Optimization should be also provided for Polish conditions, for city Konin.

The results of these optimization can give detailed view on the optimal solution for Swiss and Polish conditions. The comparison of the best technology and exploitable geothermal resources for these conditions should be done, as well as the analysis of the factors that have the biggest influence on results.

The multi-objective optimizations have been done for thermodynamic and environmental criteria. Because the costs are also significant, part of decision-making process the optimization with economic performance indicators should be launched. The trade-off between economic and environmental objective functions should be examined to show where is the line between beneficial and harmful for environment projects.

The multi-objective optimization for ORC systems have taken into account only four decision variables (superheating temperature, evaporation temperature, depth and reinjection temperature). For flash system the pressure of 1^{st} flash (for double one also the pressure of the 2^{nd} one), the depth and the reinjection temperature were evaluated. In recommendation for future work, the different decision variable can be considered. In addition, the different range of existing decision variables should be considered.

In the first part the model for Kalina cycles where created, unfortunately the platform Osmose was not adapted to launch such a model. It is recommend in future work to create models with Kalina cycles and launch theme. In addition, the triangular cycle as well as the isentropic plant models should be include in modeling and optimization.

The other recommend improvements should focused in models integration with seasonal heat storage systems or with cogeneration to improve the efficiency of the geothermal energy conversion systems.

The sensitivity analysis for modeled system should be provided.

Overall, this study has shown the importance of determination of the optimal exploitation scheme of geothermal resource. The emphasis has been put on determination of optimal superstructure available resources, conversion technologies and demand profiles in terms of environmental impact. This study gives not only tangible results but is also base for further development geothermal conversion systems, as well as the general approach for other energy conversion systems. This type of analysis has potential to become important aid in real decision-making process.

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APPENDIX A

Type of resource	Variable	Description	Default value	Unit
EGS	geo_t_hdr	Temperature of hot dry rock	200	C
	geo_grad	Geothermal gradient	0.0038	C/m
	geo_massf_ref_inj	Reference mass flow rate	50	kg/s
	w_t_mkup	Water make-up	15	C
	geo_inj_t	Temp. of reinjection of water	100	C
	pump_lp	Lower pressure of the pump	15	ba
	pump_eff	Pump efficiency	0.85	-
	pump_hp	Higher pressure of the pump (at reinjection)	115	bar
Deep Aquifer	geo_t	Temperature of geothermal water	70	C
	geo_grad	Geothermal gradient	0.0038	C/m
	geo_massf_ref	Reference mass flow rate	40	kg/s
	geo_inj_t	Temperature of reinjection of geothermal water	50	C
	pump_eff	Pump efficiency	0.85	-
Shallow Aquifer	geo_t	Temperature of geothermal water	12	C
	geo_massf_ref	Reference mass flow rate	10	kg/s
	geo_inj_t	Temperature of reinjection of geothermal water	8	C
	pump_eff	Pump efficiency	0.85	-

APPENDIX B