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ENERGY CONVERSION PROCESSES FOR THE USE OF GEOTHERMAL HEAT

Final Report

Prepared by:

Rudolf Minder
Minder Energy Consulting
CH-8917 Oberlunkhofen, Switzerland
E-Mail: rudolf.minder@bluewin.ch

Joachim Ködel, Karl-Heinz Schädle, Kathrin Ramsel
Gruneko AG
CH - 4002 Basel, Switzerland
E-Mail: Joachim.Koedel@gruneko.ch

Luc Girardin, François Maréchal
Ecole Polytechnique Fédérale de Lausanne EPFL
Laboratory for industrial energy systems LENI
CH-1015 Lausanne, Switzerland
E-Mail: francois.marechal@epfl.ch

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Mühlestrasse 4, CH-3063 Ittigen
Postadresse: CH-3003 Bern
Tel. +41 31 322 56 11, Fax +41 31 323 25 00
www.bfe.admin.ch
BFE-Projektleiter: Markus Geissmann, markus.geissmann@bfe.admin.ch
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Energy Conversion Processes for the Use of Geothermal Heat

Final Report - Synoptic Table of Contents

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Abstract

The study deals with theoretical as well as with practical aspects of the conversion of geothermal heat to electricity. The report is divided into three parts:

- Part I: General study
- Part II: Practical experience: planning & operation of geothermal power plants
- Part III: Methodology for the optimal integration of energy conversion system in geothermal power plants

In the first part the specific properties and characteristics of geothermal resources as heat sources are discussed. Both, EGS as well as deep aquifer resources are considered. Furthermore a general survey of conversion processes is presented with special emphasis on thermo-electric conversion. The various conversion processes are evaluated with respect to their possibilities and limits for future application in geothermal power plants.

The second part deals with practical aspects related to planning, construction and operation of geothermal power plants. The first chapter includes the technical basics, in particular relevant site specific conditions, drilling techniques, thermal water or brine quality, and requirement for materials to be used for the relevant system components. In the second chapter planning procedures of both sub-surface and surface installation including state-of-the-art power conversion systems is discussed. In the third chapter aspects of operation and maintenance are treated and the last part includes some basic information on costs and economics.

The third part of the report presents the methodology and results for the optimal valorization of the thermodynamic potential contained in deep geothermal fields. A pinch-analysis approach is applied to choose suitable conversion systems to be integrated into constrained geothermal processes. The optimal integration of the geothermal conversion system is achieved by the use of a multi-objective optimization technique including thermodynamic and economic objectives. Three case studies have been carried out: the EGS projects DHM Basel and GGP Geneva, and the aquifer project Lavey-les-bains. The results relate the trade-offs between installation costs and efficiency, and give the expected heat and electricity services delivered for the corresponding optimal systems. The selected methodology has been successfully validated with data from existing ORC plants, only minor differences between modeling results and measured values have been observed. The results presented for the three case studies are a valuable basis for further development of the actual projects as well as for new developments.

Zusammenfassung

Die Studie befasst sich mit den theoretischen und praktischen Aspekten der Umwandlung von geothermischer Wärme in Elektrizität. Der Bericht umfasst drei Teile:

- Allgemeine Studie
- Praktische Erfahrungen: Planung und Betrieb von geothermischen Kraftwerken
- Methodik der optimalen Integration von Energieumwandlungssystemen in geothermische Kraftwerke

Im **ersten Teil** werden die Eigenschaften von geothermischen Ressourcen als Wärmequellen diskutiert, wobei sowohl Aquifere höherer Temperatur als auch EGS-Systeme betrachtet werden. Im Weiteren wird ein Überblick über die wichtigsten physikalischen Umwandlungsprozesse gegeben. Die thermoelektrischen Verfahren werden in diesem Kapitel vertieft behandelt. Die verschiedenen Prozesse werden bezüglich ihrer Möglichkeiten und Grenzen für zukünftige Anwendung in geothermischen Systemen beurteilt.

Der **zweite Teilbericht** behandelt die praxisorientierten Probleme in Zusammenhang mit Planung, Bau und Betrieb von geothermischen Kraftwerken. Das erste Kapitel beinhaltet die technischen Grundlagen, insbesondere standortspezifische Bedingungen, Tiefbohrtechnik, Qualität des geothermischen Wassers sowie Fragen der Materialwahl für die Komponenten der Installation. Das zweite Kapitel befasst sich mit der Planung der unter- und oberirdischen Installationen mit besonderer Berücksichtigung der heute verfügbaren thermodynamischen Umwandlungssysteme. Im dritten Kapitel werden Aspekte von Betrieb und Unterhalt diskutiert und im letzten Kapitel einige Angaben zu Kosten und Wirtschaftlichkeit gemacht.

Der **dritte Teilbericht** befasst sich mit der Methodik der optimalen Nutzung des thermodynamischen Potentials geothermischer Quellen. Dabei wurden Daten von drei Schweizer Projekten für Fallstudien verwendet: die EGS-Projekte DHM Basel und GGP Genf sowie das Aquifer-Projekt Lavey-les-bains. Als Umwandlungssysteme wurden Flash-, Rankine- (ORC-) und Kalina-Prozesse bearbeitet wobei ein „pinch-analysis"-Ansatz gewählt wurde. Die Optimierung erfolgte mittels einer thermodynamisch-ökonomischen Zielfunktion, welche mehrere Kostenstellen (Bohrung, Pumpen, Anlage,...) berücksichtigt. Das Verfahren wurde mit Daten von zwei existierenden ORC-Systemen validiert, wobei zwischen Modellrechung und Messwerten nur geringe Abweichungen festgestellt wurden. Die Resultate der drei Fallstudien bilden eine wertvolle Grundlage für die Weiterverfolgung der genannten Projekte sowie auch für neue Vorhaben.

Part I: General Study

(Minder Energy Consulting)

Table of Contents

1. Introduction, Scope of Work

The present report deals with the conversion of heat from geothermal resources to electricity.
The past research and development in the area of the deep geothermal energy concentrated primarily on questions which concern the resources and their exploitation, i.e. above all problems of geology, drilling technology, reservoir engineering and modeling and the like.
Questions of conversion and use of the geothermal heat were treated only to a comparatively low extent. The reason was that the techniques for the generation of electricity from heat of low to medium temperature in principle are available and in use for years in “classical” geothermal power stations as well as other applications, e.g. for the use of waste heat or biomass. The more accurate view of the situation shows however that the use of heat from geothermal sources exhibits different characteristics which can have a large effect on the system choice and operation. The most relevant aspects are described in the following.

1. The characteristics of the heat source are not accurately known at the time a project is started. The optimization of the power conversion system therefore must take place in a relatively late project stage. Only after successful proof of a stable circulation in the primary cycle of an EGS – or after a stabilized mass flow and temperature from an aquifer resource – the detailed planning of the surface plant can take place.
2. There is a strong sensitivity of the development costs versus the use temperature. The borehole costs increase super-proportionally to the drilling depth (and thus to the reservoir temperature).
3. The use temperature may decreases over the life span of a geothermal system, whereby this process is not exactly foreseeable. Even with proven successful circulation the long-term development of the temperature and the mass flow remains unknown. For this reason the intended energy conversion system must be flexibly laid out concerning these parameters. This flexibility can either by the choice of a suitable process and/or by the combination with an external, controllable heat source such as e.g. a gas turbine or biomass fired boiler.
4. The pressure loss in the primary cycle and thus the power demand of the circulating pumps are substantial. This limits the mass throughput and thus the attainable thermal output.
5. The re-injection temperature has a lower limit, which likewise limits the thermal output. At the actual state of the art it is not clear to what level the re-injected water can be cooled.
6. The loss of water in the primary cycle can affect the total efficiency of the system strongly.

Although the detailed design of the aboveground systems can take place only in a late project stage, it is important that already during planning and development of the reservoir the most important relations and sensitivities are known in order to achieve a technically and economically optimized plant. Assuming for example that in a well at a depth of 5000 m a rock temperature of 190 °C is measured instead of the expected 210°C. The project management now has to decide whether a further increase of the drilling depth is economically justified. One needs to know whether the additional productivity at the higher temperature is improving the overall economics of the project. The decision in such a case has to be taken immediately since it will not be possible to keep the drilling rig idle for an extended period of time.

The present research project on **energy conversion processes for the use of geothermal heat** aims at supporting developers of EGS projects. Only a holistic approach right from the beginning will lead to an economically optimized solution. In addition to this main scope however the results shall be applied for the use of other sources in similar temperature range – as e.g. waste heat or heat from biomass.

The study report is subdivided into three parts.

Part I includes a general introduction, the characterisation of the geothermal resources, an overview over the various conversion processes and a review of non-conventional processes with special emphasis on thermoelectric devices.

Part II deals with practical aspects of planning, construction and operation of geothermal plants with a focus on surface equipment and plant infrastructure.

Part III describes a methodology for the optimal integration of energy conversion system in geothermal power plants including technical and economical aspects. Case studies for EGS as well as hydrothermal plants are presented making use of data from the Basel, Geneva and Lavey-les-bains projects.

2. Characterization of geothermal resources

The most important characteristics of a geothermal resource are the temperature and the useful thermal power. Beside these basic parameters a number of other values are of substantial influence on the selection of the power conversion unit (PCU).

In the present study, priority is given to the EGS type of geothermal power plants but also aquifer systems with lower temperature levels are considered.

2.1 EGS Systems

The principle of an EGS system for heat and power production is shown in figure 1.

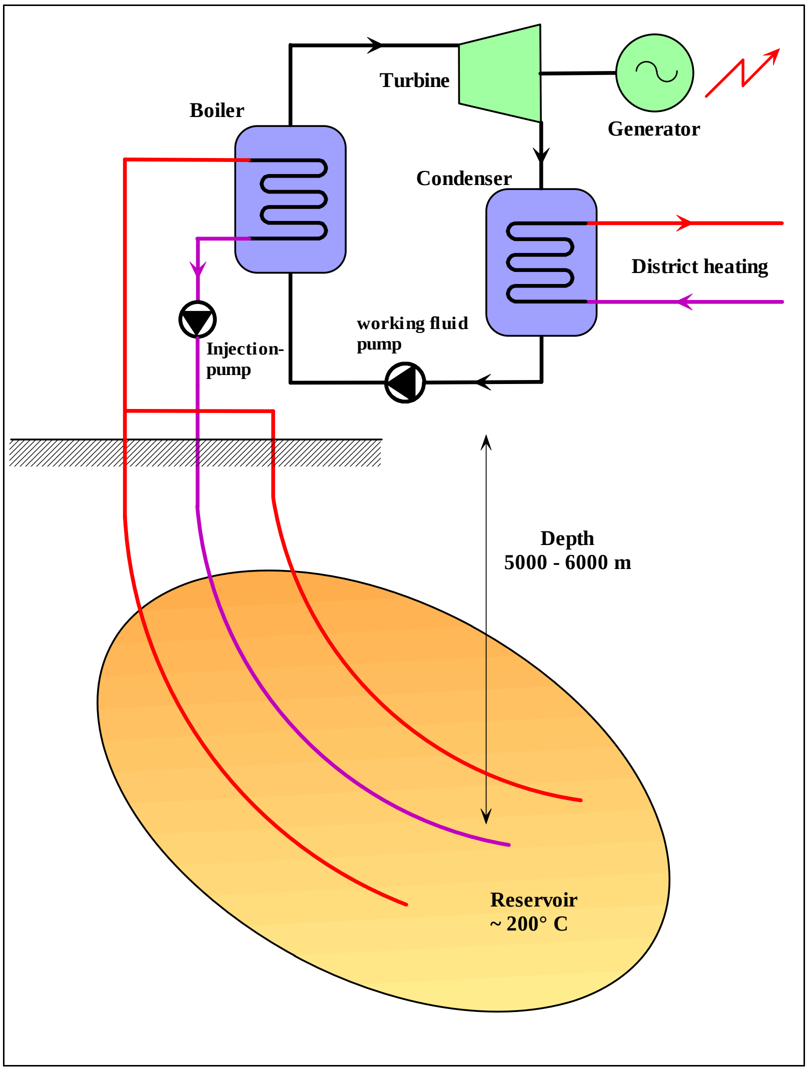

Figure 1: Principle of an EGS combined heat and power plant

In the course of the preliminary studies on the Deep Heat Mining project a number of key parameters have been defined and regularly updated as new research results became available. In table 1 these parameters are shown as design point values and as minimum/maximum values. At the actual state of the experience with EGS systems, the given values are to be considered as estimates. Only the realization and operation of pilot plants will reduce the uncertainty of these key values.

The values given in table 1 are initial values, i.e. values that are to be expected after the initial stabilization of the circulation. In the course of the depletion of the reservoir – after several years of power production – the initial values may change. Also the pressure loss in the reservoir might change due to mechanical effects such as change of number and size of the cracks and chemical effects (washing out or clogging).

It is expected that during the first years of operation the temperature at the extraction hole remains rather constant. During this period in none of the multiple parallel ways through the reservoir the front of the “cold” re-injected water reaches the extraction hole. After this phase of constant temperature a gradual decrease of the temperature will be observed because some regions of the reservoir might be thermally discharged more rapidly than others due to inhomogeneous distribution of the water flow in the rock. This behaviour is shown qualitatively in figure 2. The ideal EGS reservoir would be characterized by a temperature front moving regularly from the injection to the extraction boreholes. In practice, en EGS reservoir will more likely behave like a large number of stratified storages with different capacity and mass flow values connected in parallel to the injection and extraction boreholes making the prediction of long term output temperature very difficult.

Actually, only results from numerical modeling are available concerning the depletion of EGS reservoirs. In a few years hopefully there will be real results from the first pilot plants, in particular Soultz and Basel.

As mentioned in the introduction, the power conversion cycle must be able to cope with this situation. Since the changes are (most probably) happening slowly, it is possible to make modifications on the plant in order to keep it running under optimum conditions. As an example, in a cycle using a mixture of two fluids (e.g. ammonia and water) the concentration ratio of the mix could be adapted to the changing parameters of the heat source.

In the case of “hybrid” systems – e.g. an EGS combined with a gas turbine or a biomass fuelled boiler – the depletion of the geothermal source can be compensated for by increasing the output of the second heat source. Actually as there is very limited experience available such a combination is very attractive with respect to the availability of the plant.

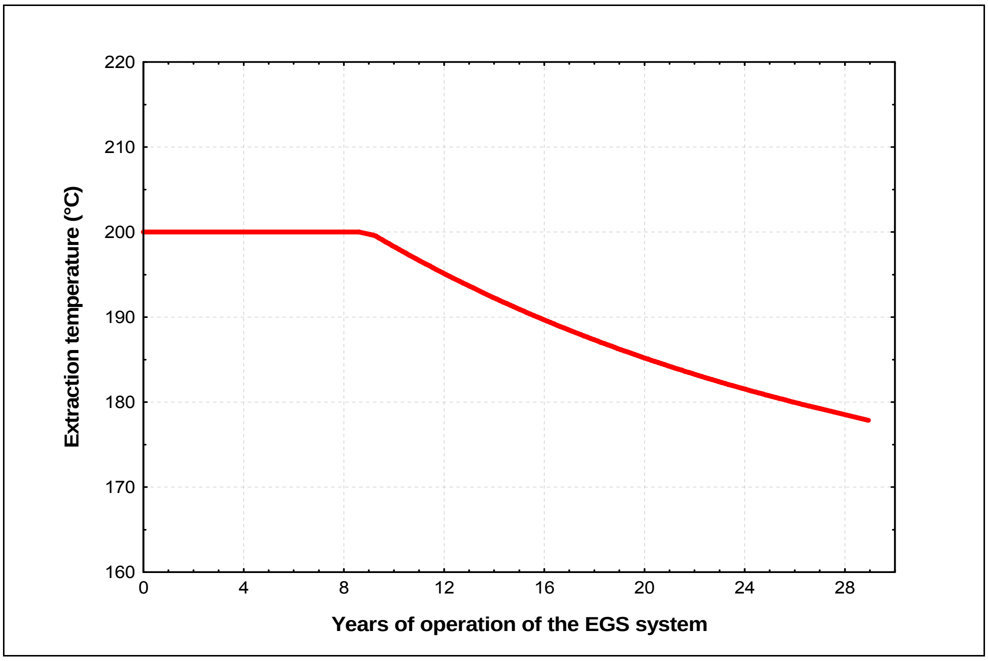

Figure 2: Assumed temperature depletion of an EGS

		Unit	Design point	Minimum	Maximum	Remarks
1	**Primary loop**					
	No. of boreholes injection / extraction		1 / 2			
	mass flow injection	kgs^{-1}	100	80	120	
	water loss	kgs^{-1}	10	0	25	
	overall pressure loss @ design point mass flow	Mpa	10	5	20	Including thermosyphon gain (Soultz: 20 MPa, decreasing)
	Temperature at top extraction hole	°C	200	170	230	
	Temperature at injection (electr. prod.)	°C	120	100	150	after mixing with fresh water
	Temperature at injection (heat prod.)	°C	100	90	120	after mixing with fresh water
	Injection pump efficiency	%	0.75	0.65	0.85	
	Injection pump input power	kW	1333			
	Extracted thermal power (electr. prod.)	kW	30146			
	Extracted thermal power (heat. prod.)	kW	37683			
2	**Power conversion unit (PCU)**					
	Turbine inlet temperature	°C	185	160	210	
	Condenser temperature	°C	25	20	35	
	Cooling water inlet temperature	°C	15	10	32	
	Cooling water outlet temperature	°C	20	15	35	legal restrictions, use of pre-mixing
	Cooling water mass flow	kgs^{-1}	1000	800	1500	
	PCU gross output	kW	4500	3000	6000	
	PCU net output	kW	3000	1800	4500	including PCU aux.power and injection pumps
	Waste heat thermal power	kW	20935			
	No. of full operation hours/year	h	3000	2500	4000	Summer production only
	Net electricity production/year	MWh	9000			Summer production only
	No. of full operation hours/year	h	7000	5000	8000	All year production
	Net electricity production/year	MWh	21000			All year production
3	**District heating system (DHS)**					
	Main heat exchanger outlet temp.	°C	170	160	180	
	Main heat exchanger return temp.	°C	100	80	120	
	secondary loop mass flow	kgs^{-1}	122.14			
	Thermal power injected into DHS	kW	35799			Heat use efficiency: 95 %
	No. of full operation hours/year	h	4000	3000	5000	
	Net heat production/year	MWh	143195			

calculated values (highlighted cells)

Table 1: Main parameters of a typical EGS-System (based on conditions assumed for DHM Basel)

2.2 Hydrothermal Systems

Hydrothermal resources suitable for electric power production are characterized by the availability of large quantities of hot water in the temperature range of up to 130°C. Depending on the local situation the geothermal water – after heat extraction – will be re-injected into the underground through a second borehole, or discharged into a nearby river. For the present study the hydrothermal site of Lavey-les-bains in the Canton of Valais has been chosen. Preliminary studies for this site have shown an interesting potential for power production [1]. The main characteristics of this geothermal source are shown in table 2.

Temperature of the deep fluid	100 to 130°C
Mass flow of the deep thermal fluid	50 to 100 kg/s
Maximum depth of drillings	3 - 4 km
Type of assumed power conversion system	ORC
Electric power output	0.7 to 2 MW_e
Annual electricity production	6 to 18 GWh_e
Thermal power output	4 to 8 MW_{th}
Annual heat production	40 to 80 GWh_{th}

Table 2: Main parameters of Lavey-les-bains hydrothermal system

In Switzerland as in many other countries, hydrothermal resources are available in very limited regions only. As an example the known resources in the Canton Valais are shown in figure 3. This type of geothermal resource therefore is much less “universal” as EGS for which large parts of Switzerland are well suited. On the other hand hydrothermal resources could produce heat at economically attractive conditions.

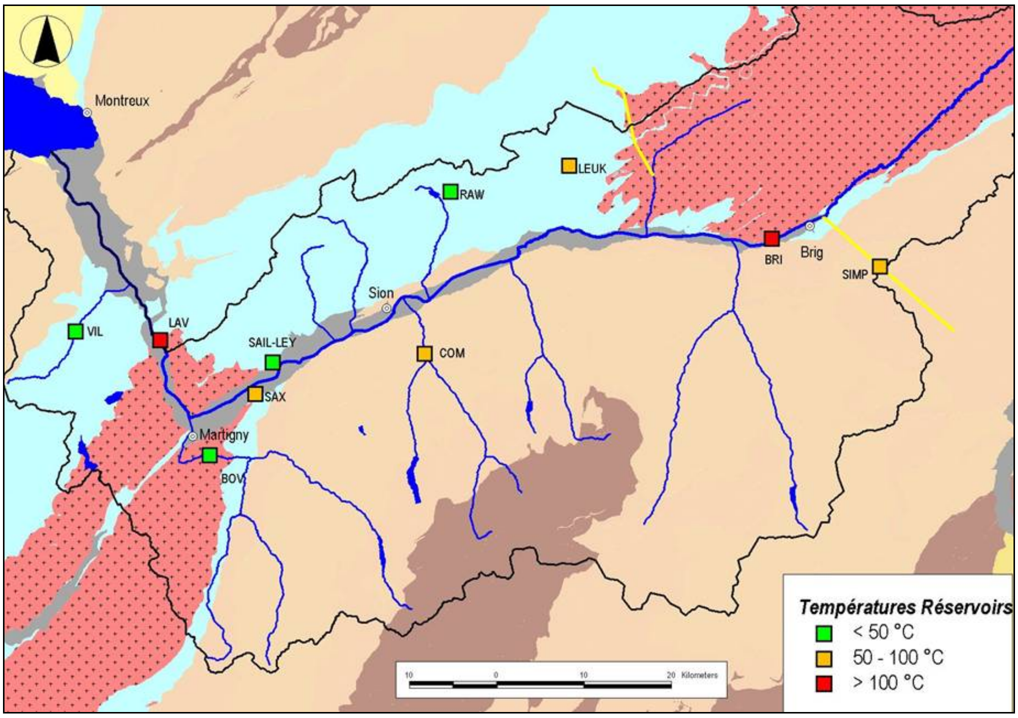

Figure 3: Map of the Canton Valais, showing some hydrothermal resources

The heat from hydrothermal resources can be utilized directly for space heating, cooling or industrial applications or – if the temperature is sufficiently high – for electric power generation. An example of such a combined system – the Neustadt-Glewe [2] project in Germany is shown in the following figure 4.

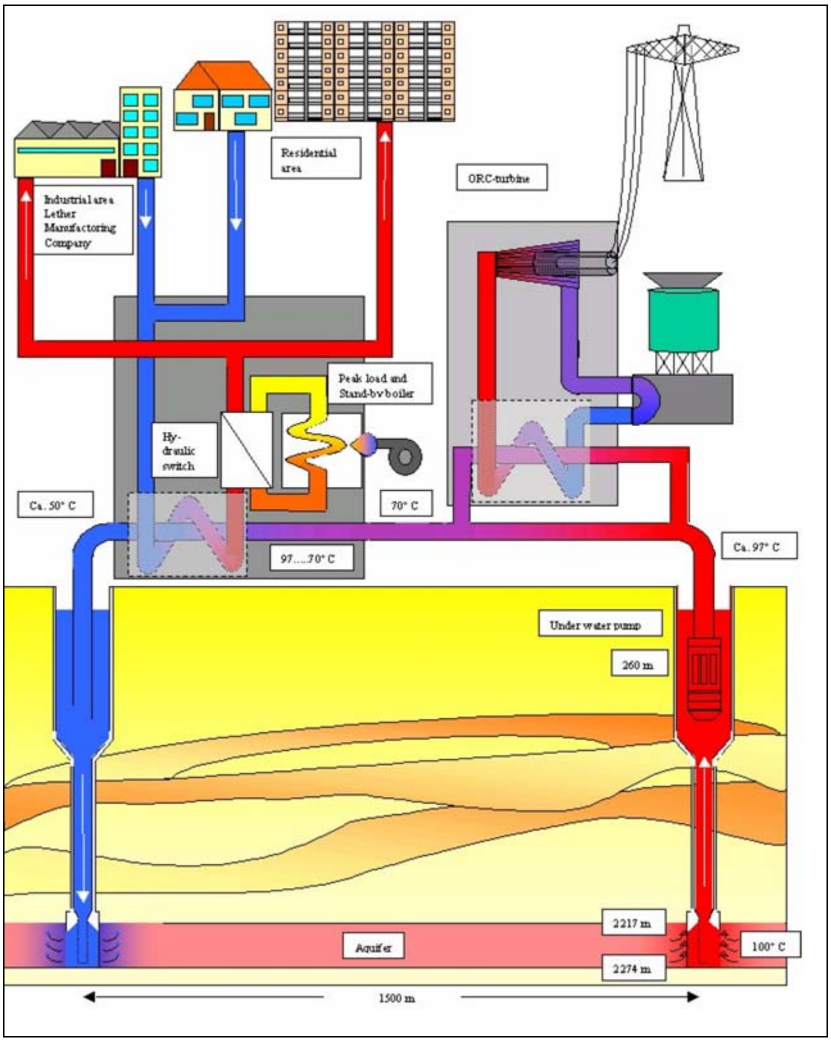

Figure 4: Typical hydrothermal plant with multiple heat and power utilization (Neustadt-Glewe, Germany)

The main characteristics of this project and of a second, larger German project (Unterhaching) are summarized in table 3.

The production of electricity from geothermal heat with a temperature of around 100°C is technically feasible but due to basic thermodynamic laws only with a very low efficiency. This is graphically shown in figure 5. In this figure the maximum theoretical efficiency that can be obtained by means of a thermodynamic conversion process is compared to the efficiency that can be reached in practice with two conversion cycles, the ORC and the Kalina cycle. Other literature sources however report similar efficiency values for optimized ORC systems as for Kalina cycles.

Project	**Neustadt-Glewe**	**Unterhaching**
Brine temperature extraction (°C)	96	120
Mass flow (kg/s)	11 - 33	150
Drilling depth (m)	2’450	3’400
Gradient (K/km)	45	35
Thermal power to district heating (MW_{th})	6.0	16
Electric generator (kW_e), cycle	210 (ORC)	4000 (Kalina)
Power plant cost (€)	800’000	8'000’000
Specific power plant cost (€/kW_e)	3’810	2’000

Table 3: Main characteristics of two German hydrothermal projects

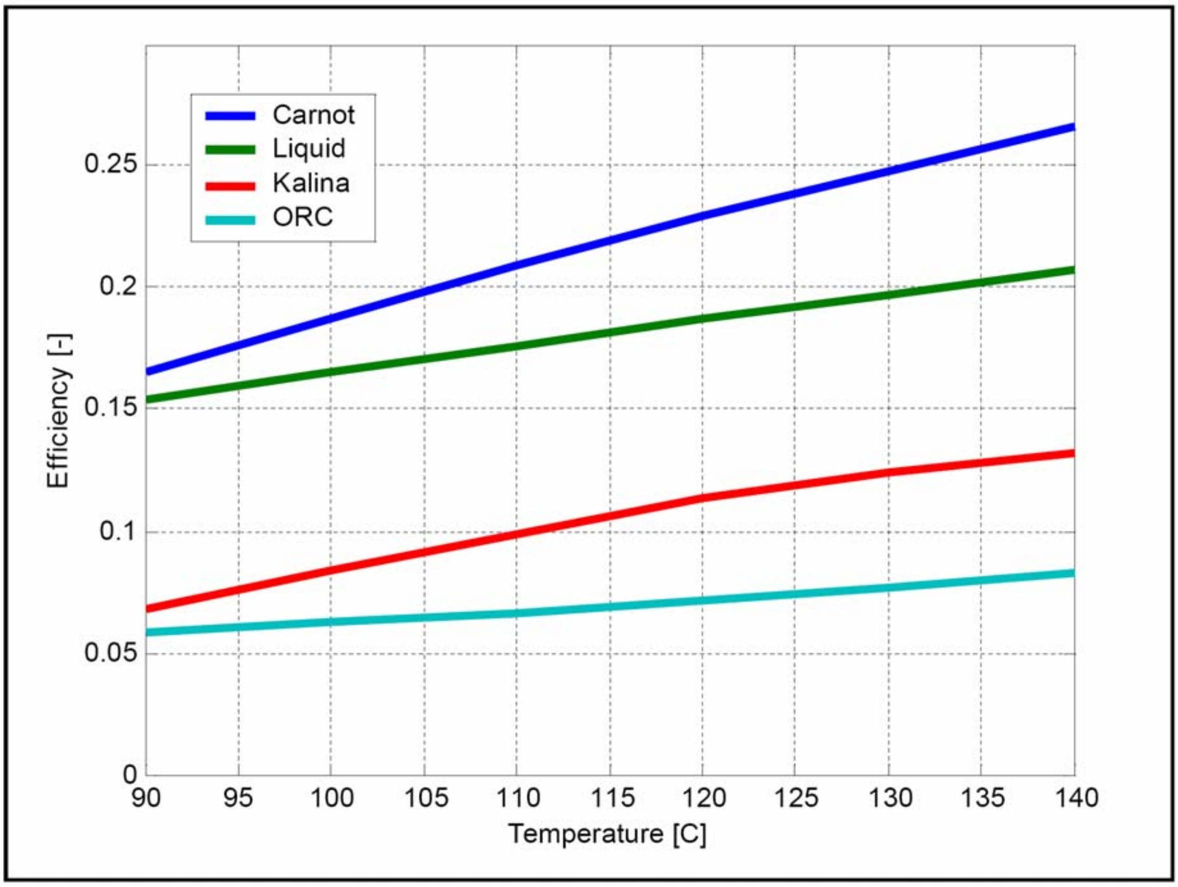

Figure 5: Efficiency vs. temperature: theoretical limit (Carnot), theoretical limit for hot water resources (Liquid), Kalina and ORC systems [3]

Due to the low conversion efficiency the question arises whether electricity production from low-temperature hydrothermal resources makes sense. In the case of a renewable resource the conversion efficiency is not as important as in the case of a fossil fired power plant where besides the economical aspects also the ecological impacts have to be considered. If large amounts of low-temperature geothermal water is available and if there is no competing direct use then the question of efficiency is essentially reduced to its influence on the project economy.

For practical applications it is of interest to look at efficiency values obtained from power plants in operation. Figure 6 shows how a number of geothermal power plants with different source temperature perform in reality.

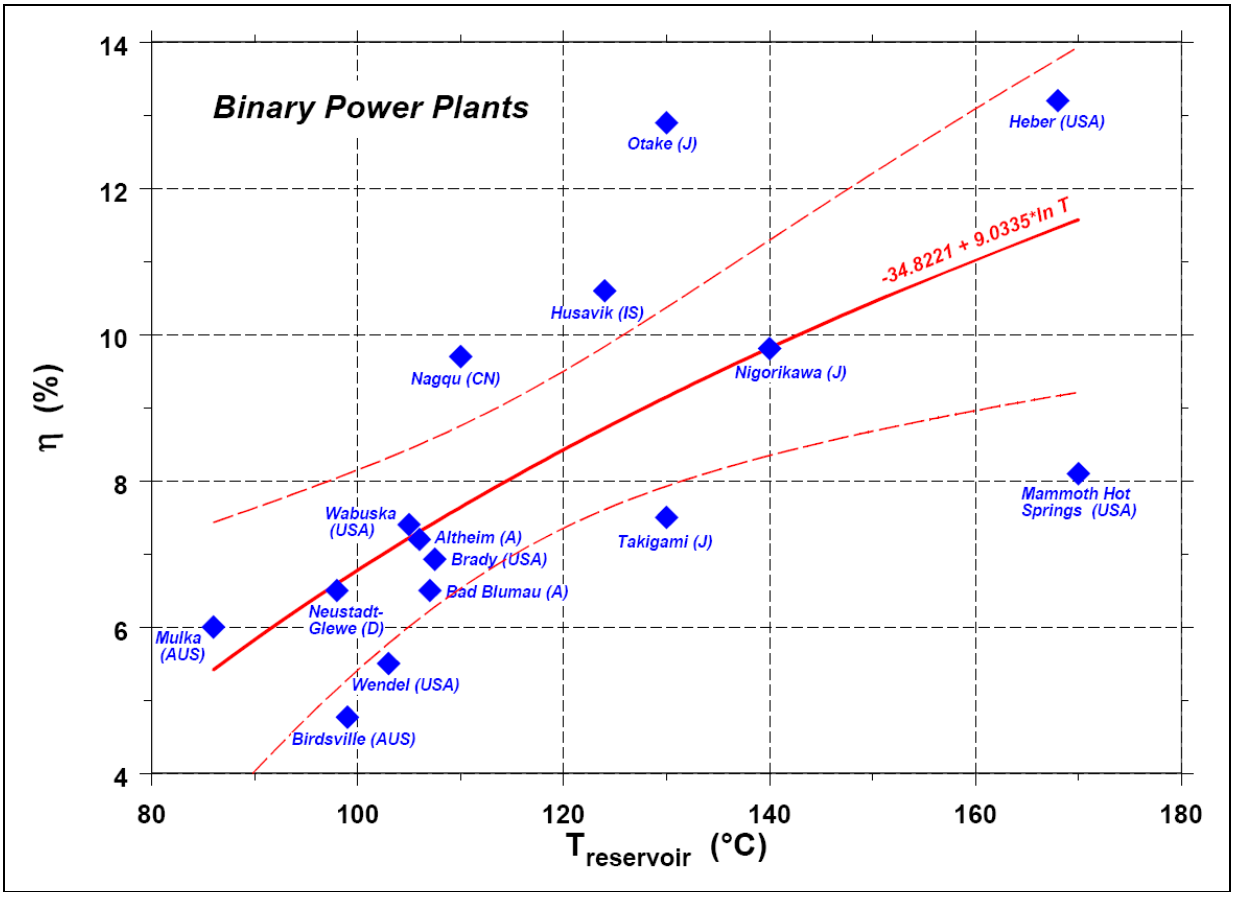

Figure 6: Net efficiency values of low-temperature geothermal power plants vs. source temperature for various binary cycle power plants (Husavik: Kalina cycle, all others: ORC, from [4])

The large scatter among the various plants shown in figure 6 may be due to different operation conditions, in particular the cooling principle of the systems. It also indicates that today there is ample room for improvements and optimization of the thermodynamic cycles. This issue in particular will be treated in part III of the present report.

3. Overview of the conversion processes

A large number of physical processes are available for the conversion of heat to electricity but only few of them are used in practice for power generation. In the large scale – from some 10 Kilowatts to Gigawatts only the thermodynamic processes are used. These processes are mostly characterized by a phase change of a working fluid leading to changes in volume and pressure. By means of a volumetric ore impulse-driven machine (piston engine or turbine) the thermal energy is converted to mechanical and then to electrical energy.

A number of non-thermodynamic physical effects can be used – at least in principle – to convert heat into electricity. These effects up to now have not been used for power production except for special applications in the very low power range. Most of these effects have been discovered a long time ago but due to their low conversion efficiency and/or high costs they have only been used for measurement purposes and not for power production.

Progress in the synthesis of new complex materials and in manufacturing of strongly anisotropic structures has created a strong new interest in some well known physical effects such as the thermoelectric or Seebeck effect. Some efficiency barriers which for many years seemed to be insurmountable could be overcome in the past years. Since there is a nearly unlimited number of possible compounds and/or structures, it cannot be excluded that developments will be made that could revolutionize the power conversion scene, at least in the lower power range. Some promising technologies will be discussed in the following chapter 4.

Figure 7 presents an overview of the best known conversion technologies without claim to be exhaustive. In the near term, only the thermodynamic cycles will be used for geothermal power generation. Some of these cycles are also treated in detail in part III of the present report.

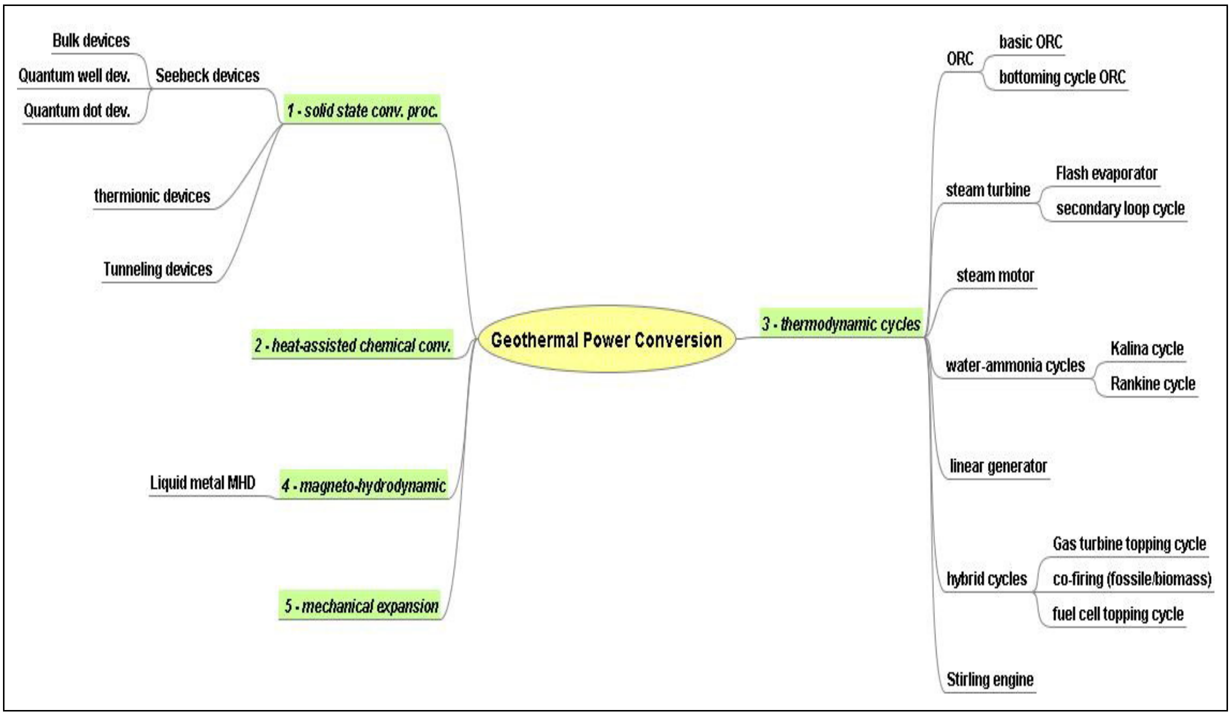

Figure 7: Overview of the best known conversion technologies

4. Non-conventional Conversion Technologies

The direct conversion of heat into electrical energy, or the reverse, in solid or liquid conductors is characterized by three interrelated phenomena the *Seebeck effect*, the *Peltier effect*, and the *Thomson effect* including the influence of magnetic fields upon each. The Seebeck effect concerns the voltage generated in a circuit composed of two different conductors whose junctions are maintained at different temperatures. The Peltier effect refers to the reversible heat generated at the junction between two different conductors when a current passes through the junction. The Thomson effect involves the reversible generation of heat in a single current-carrying conductor along which a temperature gradient is maintained. Specifically excluded from the definition of thermoelectricity are the phenomena of Joule heating and thermionic emission.

4.1 Thermoelectric devices

The effect most relevant for power conversion in this category is the thermoelectric or Seebeck effect that found practical use mainly for temperature measurements (thermo elements). The principle is represented in picture 8. Seebeck elements that are suitable for energy conversion are available only in small quantities and in the power range of some ten Watts. These elements also have rather low efficiency values compared to the respective theoretical Carnot efficiency. The US-firm Hi-Z Technology, inc. [5] offers such elements on the basis of bulk Bi_xTe_y with an area of 50 cm^2 and an electric power output of about 30 watts. These elements operate at a temperature difference of up to 250 K and the efficiency is approximately 4.5%. The costs per watt are comparable with the costs of photovoltaic cells, i.e. 3 – 5 US$/Watt. Similar products are available from a few other manufacturers worldwide.

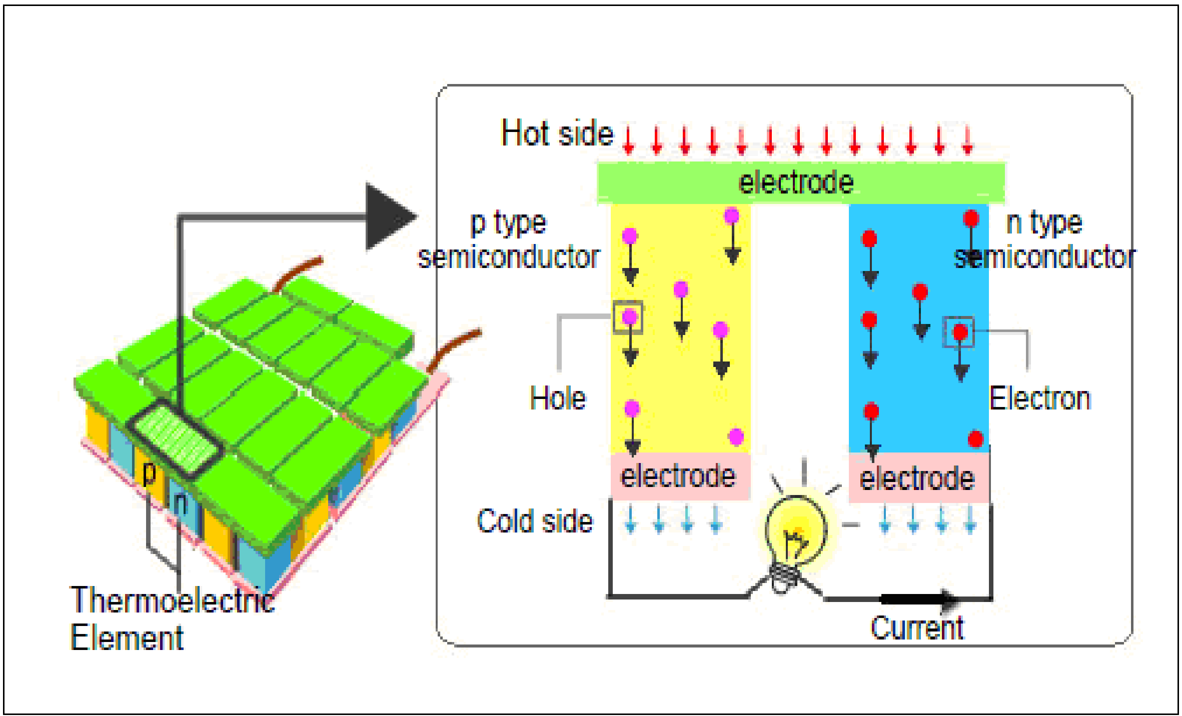

Figure 8: Principle of thermoelectric power generation

Regarding efficiency, commercial thermoelectric devices actually only reach approximately 25% of typical values for thermodynamic (e.g. ORC) systems. An improvement of efficiency by a factor of four at the same costs per unit area could lead to conversion systems with specific costs similar to ORC or Kalina cycle systems. Using classical thermoelectric bulk materials such as Bi-Te-alloys will most probably not allow reaching substantial improvements. The intrinsic properties of these compounds are limiting factors for a high figure of merit ZT. This value combines a material's electric and thermal conductivities with a measure of its capacity to generate electricity from heat. It is defined as follows:

$ZT=\alpha^2/(\rho.\kappa)$	Where: α=Seebeck Coefficient
	ρ=Resistivity
	κ=Thermal Conductivity
	T=Temperature

Bismuth telluride, still state-of-the-art after 40 years, has a ZT of, at best, 1 to 1.4 at ≈300K. In order to become competitive with thermodynamic cycles, it would need a figure of merit of 4 to 10. The following figure 9 illustrates the importance of ZT with respect to conversion efficiency. In order to reach 60% of Carnot efficiency, ZT value needs to be of the order of 10 at temperature conditions typical for geothermal power plants.

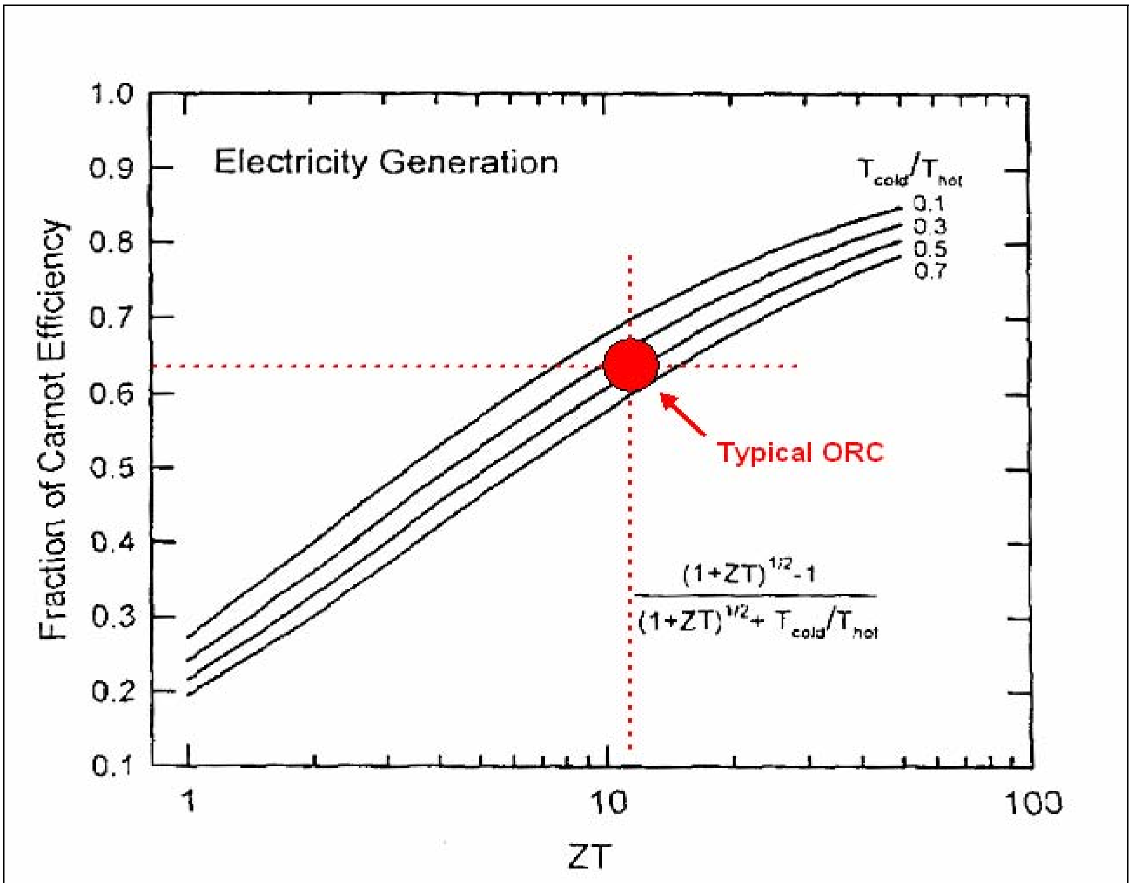

Figure 9: Fraction of Carnot efficiency vs ZT for different temperature conditions [19, ORC included by R.M.]

There are various options to reach substantially higher ZT values:

- New complex or “exotic” materials
- New structures, i.e. thin layers, nano wires

The ideal material should have a large Seebeck coefficient, conduct electrons as well as a metal does and resist the passage of heat as well as a glass does.

4.2 New thermoelectric materials

Besides the classical thermoelectric materials of the Bi-Te-type intensive research has been done in new materials.

One set of materials newly discovered to have significant thermoelectric properties are the skutterudites, named after a mineral found in Skutterud, Norway. Skutterudites consist of metals such as iridium, cobalt, or rhodium combined with phosphorus, arsenic, or antimony. Their structure contains large, open voids. The ability to populate these voids with other atoms makes them useful for thermoelectric devices. Putting atoms of another element in the skutterudite voids makes the materials more glasslike. These atoms disrupt vibrations of the crystal that carry heat energy and therefore reduces the thermal conductivity. So far atoms of rare earths such as lanthanum, neodymium, and gadolinium seem to work best; they are small enough to fit in the voids, yet heavy enough to absorb big vibrations. Skutterudites seem to be interesting materials, but there are hundreds of possibilities to test which makes the research difficult.

Another class of materials that seems to fulfill all the necessary requirements for good thermoelectric materials are the quasicrystals. Unlike true crystals, whose structures consist of small, repeating units, quasicrystals form orderly, complicated structures without a long-range pattern. Their electric conductivity can be tuned by changing their chemical composition, while their thermal conductivity remains inherently low. Of special interest are compounds of aluminum-palladium-rhenium and aluminum-copper-iron.

In Switzerland, a research group at EMPA Dübendorf is working on the synthesis and characterization of potential new thermoelectric materials [6]. This work is also supported by the BFE. Novel thermoelectric materials with p-type conductivity as well as compounds with n-type conductivity for cascades of thermoelectric devices will be developed to convert heat to electric power. In these devices several couples of p- and n-type-legs are connected electrically in series and thermally in parallel to produce an open circuit voltage of several volts at even low temperature gradients.

Low values of the thermal conductivity allow to reduce heat loss and to maintain a large temperature gradient. The optimization of thermoelectric properties via a low thermal conduction requires a decrease of the phonon contribution. Complex crystal structures, heavy element substitutions, solid solutions and reduction of the grain size can lower the thermal conduction by the reduction of the phonon contribution. Many perovskite-type oxides exhibit promising properties for thermoelectric applications. With this flexible crystallographic structure p- and n-type semiconductors can be obtained with suitable substitutions.

A French group presented on the web a new development under the label "Calopile" [7]. The physical principle is explained as "dual-temperature PN-junctions, as opposed to the single-temperature welds used in conventional thermoelectric generators”. From the information given it is difficult to understand the physics behind this type of device but the performance claimed by Calopile are revolutionary. With a temperature on the hot side of 372 K and on the cold side of 293 K, the conversion efficiency should amount to over 15%. This would be equal to about 75% of the Carnot efficiency surpassing clearly any ORC or other thermodynamic cycle in this temperature range. Figure 10 shows a picture of a calopile module, table 4 the corresponding technical data. The company now based in Geneva claims to start production of their modules at end of 2006.

Figure 10: Calopile thermoelectric module

External diameter	170 mm
Thickness	21 mm
Weight	640 g
Possible temperature range	- 50°C to + 215°C
Hot source	hot water 99 °C
Cold source	cold water 20 °C
Electric voltage	1.5 Volts DC
Power	25 Watts
Heat/electricity conversion yield	15.2 %

Table 4: Technical data of the Calopile thermoelectric module

It will be interesting to follow up this development and to look at the results from the first prototypes and applications.

As the development of the high-temperature super conductors has shown, surprises are not to be excluded in the physics of complex materials, although at present no theoretical models predict such thermoelectric "super materials".

4.3 Quantum Well Thermoelectrics

As mentioned earlier in chapter 4.1 the strong coupling between thermal and electrical conductivity in most thermoelectric bulk materials can be overcome by creating strongly anisotropic or low-dimensional structures [8]. Examples for such structures are thin layers (2-dimensional structures) or “nano-wires” (1-dimensional structures).

Researchers at the Massachusetts Institute of Technology showed in 1993 theoretically and experimentally that ZT increases above 1 for thin semiconductor films constituting so-called quantum wells, in which electrons can move only within a confined layer. Their results suggested that quantum wells could lead to thermoelectric devices competitive with conventional technology. Scientists and engineers on the industrial side of thermoelectric research are also working towards higher ZT values.

The results recently reported by academic [9] as well as industrial [10] research groups are very encouraging. As an example figure 11 shows the efficiency vs. temperature obtained from measurements at layered quantum well structures [11]. These efficiency values are comparable to small scale ORC systems. If such systems could be brought to industrial fabrication a wide field of applications could open.

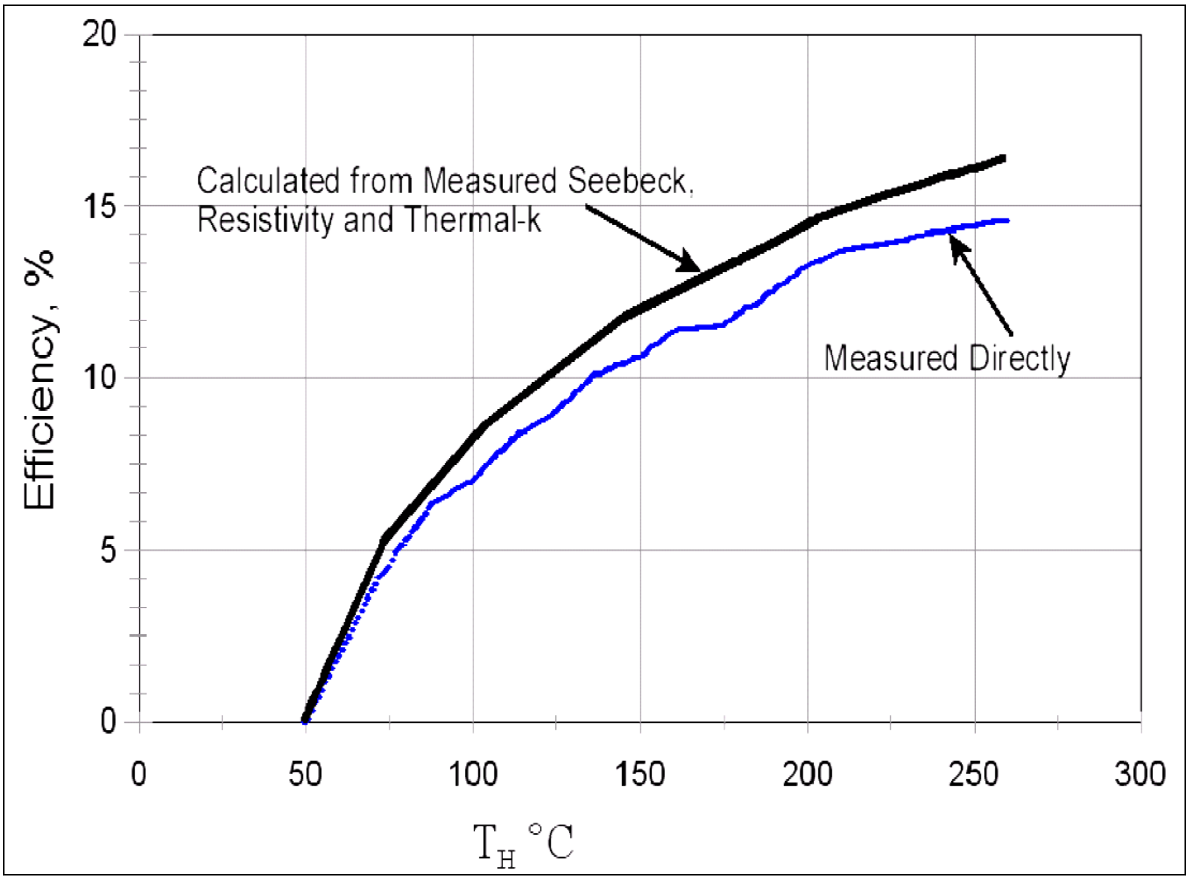

Figure 11: Measured quantum well couple efficiency vs. temperature at a T_C = 50°C (n-leg Si/SiGe, p-leg B_4C/B_9C; both films 11 µm, deposited on Si substrate)

The results shown in figure 11 have been published by the US company Hi-Z technology [5] who is currently manufacturing and selling classical bulk type thermoelectric modules. Generally, the researchers at Hi-Z expect quantum well devices to reach efficiency values similar or better than small scale thermodynamic cycles such as ORC or Kalina. Especially at temperature and power conditions typical for geothermal heat resources, these converters could become an interesting alternative. Figure 12 shows the comparison of efficiency for the ideal Carnot cycle, classical bulk Bi_2Te_3 thermoelectric converters and the anticipated quantum well thermoelectric converters for the temperature range of 200 to 800°C.

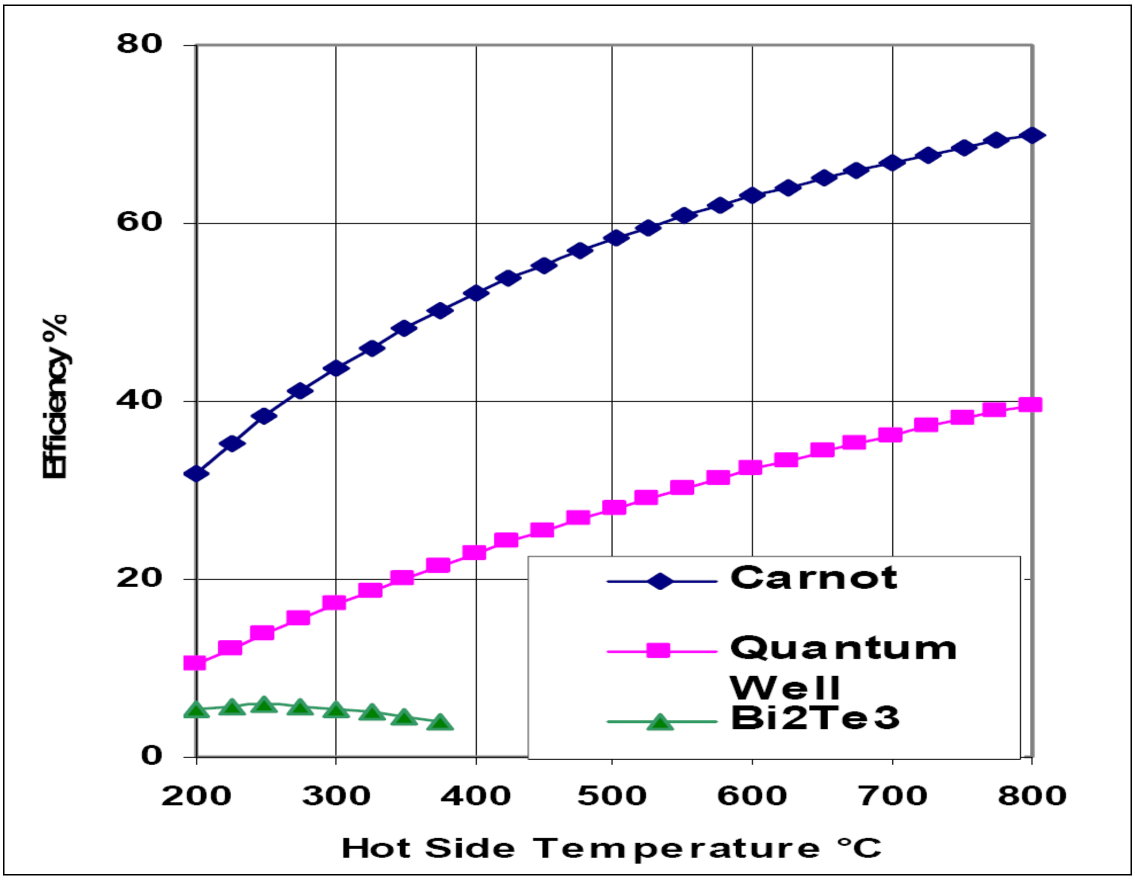

Figure 12: Efficiency values for the Carnot cycle, bulk Bi_2Te_3 thermoelectric converter and quantum well thermoelectric converter. [5]

The EU supported research in the area of the thermoelectrics in the 5th frame program. Under the name NanoThermel, an international project was carried out in the years 2001 – 2004 [12].

4.4 Thermoelectric devices using electron tunneling

Another approach aiming at high conversion efficiency has been taken by the company PowerChips [13] based in Gibraltar. They are investigating devices where a microscopic vacuum layer of some 10 Å improves the separation of thermal and electrical conductivity. PowerChips expects the conversion of geothermal energy to become a major application of their technology, as the following citation from their company presentation illustrates:

> *"The Power Chip geothermal plant of the future will enhance and modify the flash steam cycle, and binary Rankine cycle, turbine driven plants. We expect to run these plants at 60% - 70% of the Carnot-defined maximum possible efficiency. Operating at these efficiencies changes the economics of geothermal development giving developers more electricity to sell per unit of geothermal heat. The increase in monetary return will have a ripple effect creating a greater demand for exploration and field service work. Power Chips will allow for the exploitation of geothermal resources with temperatures below 95°C. This changes many of the rules we as an industry have previously lived by. With the ability to produce power at these relatively low temperatures, "Hot Dry Rock" power production becomes a much more realistic endeavor."*

Observing the development of the PowerChips technology for several years now it must be concluded that the transfer of this technology from the laboratory to a commercial device is difficult, if possible at all. It cannot be expected that in the near term such devices will be commercially available in quantities and at costs that make them interesting for the conversion of geothermal energy.

4.5 Thermal diodes

Thermal diodes have the same functional components as thermionic converters but with a semiconductor wafer substituted for the vacuum gap. Whereas thermionic conversion shows a practically useful efficiency only at very high temperature (> 1000 °C) thermal diodes can be used at much lower temperatures (100 - 400°C). A layout of an n-type thermal diode is shown in Figure 13.

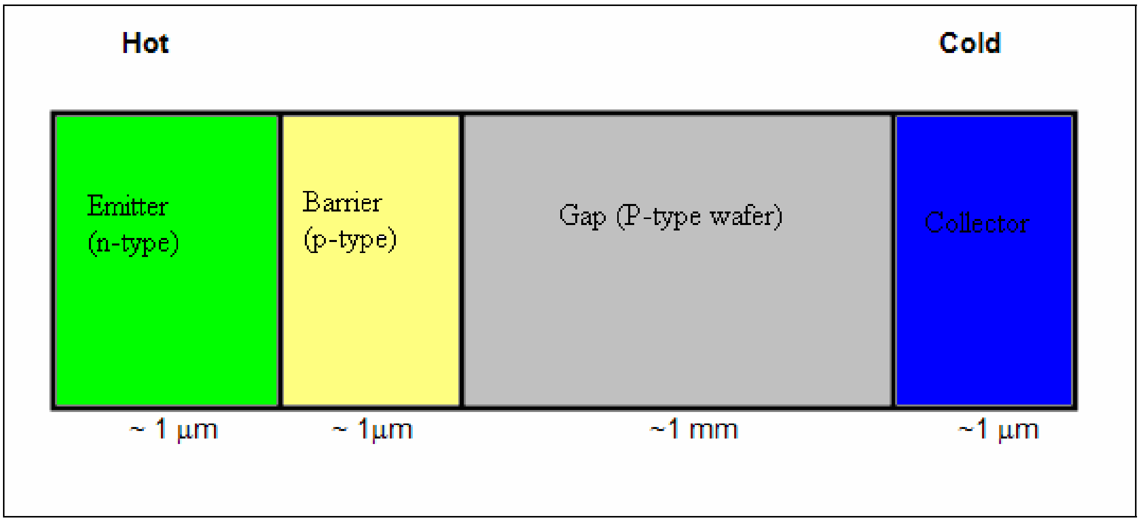

Figure 13: Layout of n-type thermal diode

A thermal diode is built onto a thermoelectric semiconductor wafer (gap) on which a thin barrier layer is deposited. The barrier layer is made of the same semiconductor, but doped differently. The deposited emitter layer is a heavily doped layer of the same semiconductor or a metal. The collector structure is basically the same two layers as on the hot side. Potential barriers at the interfaces between emitter and barrier layers and barrier layer and gap serve the same purpose as the work function in a thermionic converter. By changing dopant concentration these potential barriers can be adjusted and optimized for any temperature. The first barrier on the emitter layer side sorts electrons by energy and the second barrier on the gap side prevents back flow of electrons from the gap into the emitter layer. Without potential barriers, the output of this device will be defined by the thermoelectric properties of the gap material. Barrier action leads to accumulation of electric charge behind the barrier, leading to increased operating voltage. The electric resistance of the device is dominated by the macroscopic gap with very little change from its thermoelectric value, leading to current increase due to increased voltage compared with the thermoelectric performance of the semiconductor gap. Voltage multiplied by current gives electric power output and if the heat flow through the device stays the same, the result is increased efficiency, defined as the ratio of electric power delivered to the load to the heat flow through the device. Up to nine times improvement relative to the initial thermoelectric performance has been observed with a single barrier [14].

An important attribute of barriers is that the contribution of barriers placed thermally in series is additive. This is unlike thermoelectric behavior, when stacking separate plates made from the same material does not change resulting efficiency unless the hot side and cold temperatures are changed. This leads to the conclusion that efficiency approaching the theoretical limit can be achieved with a multi-barrier thermal diode with stacked barriers separated by relaxation gaps at least five scattering lengths thick. In many cases this is not practical, for example a thermal diode made of silicon must have approximately 200 barriers to achieve 80% of theoretical efficiency. For other substrates, such as HgCdTe, a single barrier is sufficient. The absolute efficiency limit in all cases is 50% of ideal Carnot efficiency, since 50% reduction of the internal conversion efficiency results from the requirement to match the external electric load to the diode's internal resistance for maximum power transfer to the load. Internal conversion efficiency can be extremely high. The highest experimentally observed internal efficiency of a thermal diode is 88% of Carnot efficiency.

Thermoelectric generator devices based on the principle of thermal diodes are being developed by the US company Eneco, Inc. under the label "Thermal Chips" [15]. The company expects their devices to deliver about 40% - 50% of the Carnot value for a given set of operating temperatures. The power density that can be obtained strongly varies with the operating temperature. Estimated output power density for PbSnTe diodes, 0.5mm thick, with the cold side at 20°C and the hot side at 320°C is about 9 W/cm^2, at a hot side temperature of 130°C about 1 W/cm^2.

4.6 The Magnetocaloric effect (MCE)

Some magnetic materials heat up when they are placed in a magnetic field and cool down when they are removed from a magnetic field. This is known as the magnetocaloric effect. This effect was discovered by E. Warburg in 1881 in pure iron. The size of the effect has been around 0.5 to 2°C per Tesla change in magnetic field. Recently, alloys of gadolinium, germanium and silicon have produces a much larger effect size of 3 to 4°C per Tesla change. The general formula for this material is $Gd_5(Si_xGe_{1-x})_4$.

The MCE can be understood using an analogy to thermodynamic cycles, as shown in the following figure 14.

The external magnetic field (+H) causes the magnetic spins of the atoms to align, thereby decreasing the material's magnetic entropy and heat capacity. Since energy cannot be lost and the entropy cannot be reduced according to thermodynamic laws, the net result is that the item heats up ($T + \Delta T_{ad}$). What happens is that this decrease in the magnetic entropy results an increase in the entropy of the material's lattice, consequently increasing the material's temperature. This added heat can then removed by a fluid like water or helium, for example (-Q). Once the magnetocaloric material and the field are parted (H=0), the material will be cooler than before entering the field, and thus is inclined to absorb heat from its surroundings (+Q). The magnitudes of the magnetic entropy and the adiabatic temperature changes are strongly dependent upon the magnetic order process: the magnitude is generally small in antiferromagnets, ferrimagnets and spin glass systems; it can be substantial for normal ferromagnets which undergo a second order magnetic transition; and it is generally the largest for a ferromagnet which undergoes a first order magnetic transition. Also, crystalline electric fields and pressure can have a substantial influence on magnetic entropy and adiabatic temperature changes.

Experimental refrigerators based on the magnetocaloric effect have been tested in laboratories using magnetic fields of around 5T produced by superconducting magnets. In Switzerland, the University of Applied Sciences of Western Switzerland in Yverdon has carried out research on the magneto-caloric effect [16]. This work was partially funded by the Swiss Energy Office.

The reversed process – power generation by thermal cycling of appropriate devices – is also feasible. Electric power can be produced by cycling a ferromagnetic material thermally through a range of temperatures such that its magnetization changes appreciably and of utilizing the change of magnetization and its interaction with a magnetic field. Thermodynamically, appropriate cycles to make this form of power practical have been evaluated and it was found that potentially competitive heat engines based on magnetocaloric devices are possible.

In the frame of this study however, no detailed information on theoretically or practically possible efficiency values could be collected.

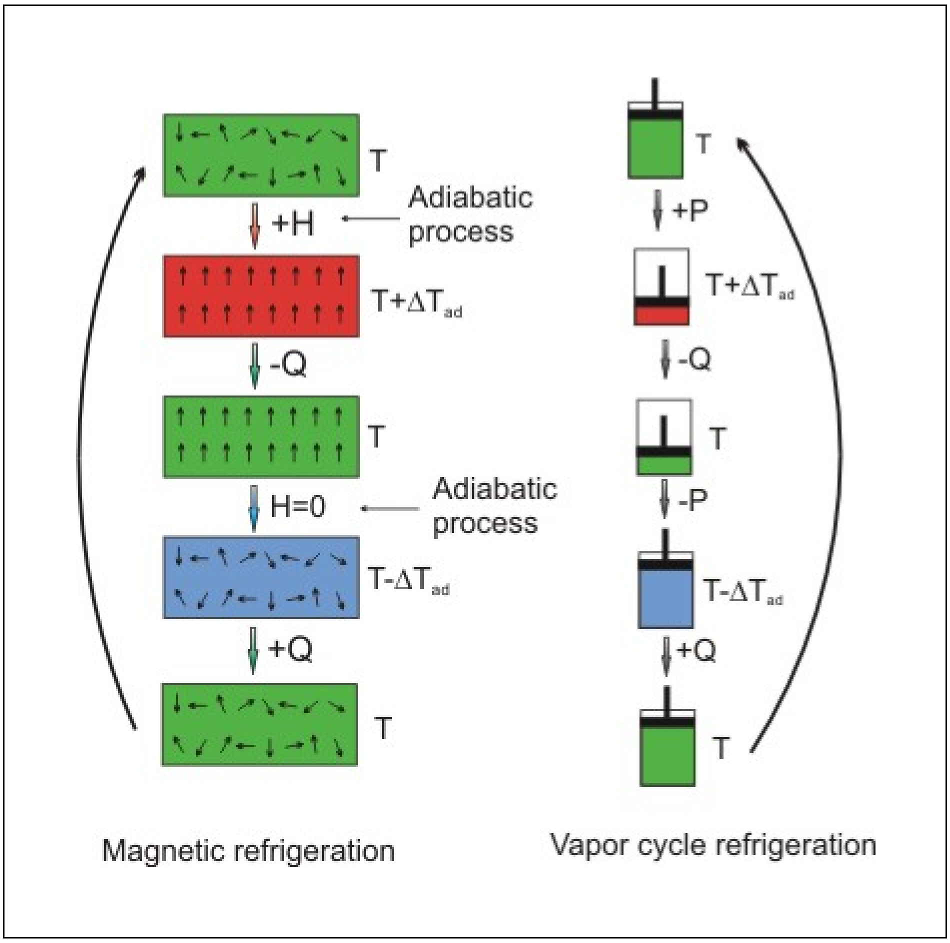

Figure 14: Analogy between magnetic refrigeration and vapor cycle or conventional refrigeration. (H = externally applied magnetic field; Q = heat quantity; P = pressure; ΔT_{ad} = adiabatic temperature variation), Source of figure: Wikipedia.org

5. Geothermal applications of non-conventional conversion technologies

In the field of geothermal energy systems the required power level usually is in the megawatt range. The non-conventional power conversion technologies as described in the previous chapter however are basically small devices typically in the Watt range. That means that for a full sized power plant as required for a typical EGS or hydrothermal system, a large number – e.g. 100'000 - of these elements would have to be installed in order to reach the necessary capacity. The surface of the heat exchangers also would be large, since the heat transfer would only be through conduction and not through a phase change as in an evaporator.

Assuming a power density of 2 W/cm^2 for the thermoelectric modules, a 5 MW_e power plant would require a total module surface of 250 m^2. With an appropriate heat exchanger design, this surface should not present a fundamental problem.

Thermoelectric devices have some intrinsic advantages with respect to geothermal hot water resources. The geothermal water can in principle be cooled down to the temperature level of the cold source. Of course the efficiency and the power output per unit module area will be reduced at low temperature setting limits from the system economics. Furthermore the technology is not sensitive towards changes in temperature both at the hot and cold side.

For these reasons, developers of thermoelectric devices are considering geothermal energy a major market segment for their products.

An interesting albeit somewhat exotic way to use shallow geothermal energy in combination with ambient heat has been proposed by J. Stevens [17]: the ground-source power converter. The principle of this system is shown in figure 15.

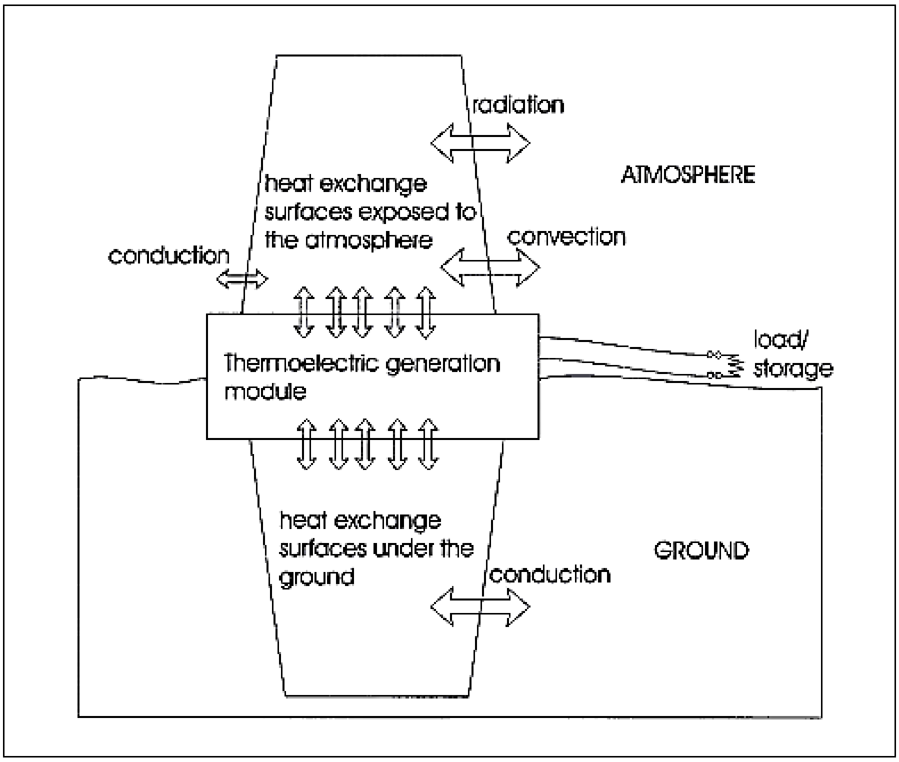

Figure 15: Ground-source power converter

The daily variation in air temperature is large compared with the temperature changes a short distance below the surface of the ground. In theory, a heat engine can be arranged to produce electricity from this temperature difference. In practice, the thermal efficiency of such a device will be low because of the small temperature differences involved. An energy harvesting device could produce electrical power by using a thermoelectric generator operating between the air and ground temperatures.

The idea is similar to the concept of the ocean thermal energy converter (OTEC) where the temperature difference between the warm surface waters and the cold deep waters are used to drive a low temperature heat engine.

In order to produce utility-scale power, the required land surface will be very large and the use will be limited to unused land, e.g. deserts. The question remains open if this concept will be competitive to other renewable power systems such as photovoltaics.

A more realistic application could be the use of hydrothermal resources for power production. Existing hydrothermal sources where currently only the heat at low temperature is used – e.g. as thermae - thermoelectric generators could provide some additional electric power without major influence on the system and at low operation and maintenance costs.

At the Swiss Federal Institute of Technology in Zurich a research project has been started in the year 2005 under the name of "The Thermoelectric Power Plant". The project will look at the possibilities to use deep borehole heat exchangers to produce electricity for buildings. For the study and system modeling it is assumed that advanced thermoelectric devices will be available with ZT values in the range of 3 to 10 [18].

6. Conclusions: relevance of the conversion processes

The generation of electric power from heat – be it from a geothermal source, fossil or nuclear fuel or any other heat source today is en exclusive domain of thermodynamic cycles. Despite the fact that there is a large number of physical effects that would, in principle, be suitable for energy conversion, no one of these effects has been developed up to commercial use. This is mainly due to the fact that the conversion efficiencies obtained are far below the values of thermodynamic cycles.

With respect to the reverse process – the heat pump or refrigerator – solid state devices are being used in the low-power sector where efficiency is less important than simplicity or reliability.

In the recent years, materials research including thin film and nano technology has made enormous progress. Theoretical studies have shown that there are no basic physical laws that limit the efficiency of solid-state devices at levels far below the respective Carnot efficiency. The encouraging results of theoretical modeling could be confirmed to some extent by experiments and measurements in laboratory scale. It has been demonstrated that the de-coupling of electrical from thermal conductivity is possible to a much larger extent than had been assumed for many years. The use of complex materials and/or of strongly anisotropic structures such as thin layers or nano-wires lets us hope that in the not too far future a competitive alternative to thermodynamic cycles will be available.

This will first be of interest for the use of geothermal resources of low to moderate temperature and relatively low thermal capacity up to a few Megawatts. In this power range thermodynamic cycles are less efficient and more costly than at high temperature and power levels.

The main advantages of solid state conversion devices are:

- Modularity: any plant size from Watts to Megawatts can be built
- Large temperature range: varying temperature on hot and cold side is no problem
- No moving parts: low operation and maintenance costs
- Probably long lifetime and high reliability
- No turbine noise
- No toxic or environmentally problematic working fluid

In Table 5 the short-, medium- and long-term relevance of selected conversion processes is presented together with some additional characteristics. This table has been compiled based on a large number of publications and information from manufacturers. It cannot claim to be exhaustive but it should include the processes with the best chances for the future.

Despite the interesting long-term prospects of this group of processes it must be assumed that their development up to first commercial applications will need both substantial R&D funds and time. For the next decade certainly new geothermal power plants will be based on thermodynamic cycles. As will be shown in Part III of this report, there is ample room fore R&D, improvements and optimization also in the field of thermodynamic cycles.

Class of conversion process	State of art	Range of temperature	Power range	Efficiency (% of Carnot)	short–term relevance	mid–term relevance	long–term relevance
1 - solid state conv. proc.							
Seebeck devices					**3**	**2**	**1**
Quantum well/tunneling devices	R+D	< 300°C	W	>75			
Quantum dot devices	R+D	< 300°C	W	>75			
Bulk material	Commercial	< 300°C	W	25			
magneto-caloric devices	R+D	< 300°C	W	?	**3**	**3**	**3**
thermionic devices	R+D	> 1000°C	kW	> 75	**3**	**3**	**2**
2 - heat-assisted chemical conv.		> 300°C	kW	?	**3**	**3**	**2**
3 - thermodynamic cycles							
ORC					**1**	**1**	**2**
basic ORC	Commercial	80 - 300°C	kW	> 50			
bottoming cycle ORC	Commercial	80 - 200°C	kW	> 50			
steam turbine					**1**	**1**	**2**
Flash evaporator	Commercial	< 500°C	MW	75			
secondary loop cycle	Commercial	< 500°C	MW	75			
steam motor	Commercial	150 - 300°C	kW	< 50	**3**	**3**	**3**
water-ammonia cycles					**1**	**1**	**2**
Kalina cycle	Pilot plants	100 - 300°C	MW	75			
Rankine cycle	Pilot plants	100 - 300°C	MW	75			
hybrid cycles					**1**	**1**	**1**
Gas turbine topping cycle	Commercial		MW	> 75			
co-firing (fossile/biomass)	Commercial		MW	75			
fuel cell topping cycle	R+D		kW	> 75			
stirling engine	Commercial	200 – 500 °C	kW	< 50	**3**	**3**	**3**
linear generator		80 - 200°C	kW	?	**3**	**3**	**3**
4 - magneto-hydrodynamic							
Liquid metal MHD	R+D	> 300°C	kW	?	**3**	**3**	**3**
5 - mechanical expansion	R+D	?	kW	?	**3**	**3**	**3**

Table 5: Short- medium and long-term relevance of selected conversion processes

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Part II

Practical experiences:
Planning and operation of geothermal power plants

Joachim Ködel, Karl-Heinz Schädle, Kathrin Ramsel

Gruneko AG, CH - 4002 Basel, Switzerland

1 Fundamentals / Technical Basics

1.1 Relevant Site Specific Conditions

The technical and economical feasibility of a geothermal power plant is highly influenced by the framework conditions given by the location of the site. They are divided into geological aspects, energy demand and infrastructural aspects. Most important for the selection of a location are the geothermal framework conditions as they can be restrictive constraints. The technical conditions can all be resolved and have an influence only on the economics.

1.1.1 Geological Aspects

For the description of the required geologic conditions, it is useful to differentiate between hydrothermal and hot-dry-rock (HDR) sources:

Hydrothermal Sources:

In case of having a hydrothermal source, following information about the thermal water is of main interest:

1. temperature
2. amount of water available
3. water quality & chemism

If the temperature of the thermal water exceeds 100°C electricity production is possible. For direct heating purposes temperatures > 70°C are suitable. If the temperature is below 70°C, it is still possible to use the heat for heating purposes when implementing a heat pump.

The durability of the aquifer should be about 40 years (two life cycles of the technical part of the geothermal plant). The durability depends on the

- volume (length, heights and width) of the aquifer,
- porosity
- distance between extraction and introduction borehole, and
- heat flow being extracted.

If it turns out, that it is possible to extract > 60l/s, the aquifer can be utilised for power production. With smaller extraction rates of about 20 l/s it would be economically more reasonable to satisfy only a heat demand.

Quality and chemism of the thermal water influences the choice of the implemented material and therefore investment- as well as maintenance costs of the technical part of the plant.

Hot-Dry-Rock / Deep Heat Mining

In case of having a Hot-Dry-Rock (HDR) source, the following information is of main interest:

1. depth & thickness of the granite layer
2. structure of granite layer

The depth of the granite layer determines the temperature of the source. For deep heat mining projects, it should be the aim to reach temperatures above 150°C, because with lower temperatures it has to be checked carefully if a positive net electricity production will be reached. To use the geothermal heat only for heating purposes is not advisable because of the high risk and high costs associated with deep drilling.

The thickness of the granite layer determines the heat exchanger volume. To reach a heat exchanger volume capable to heat an amount of water required for electricity production, a thickness of about 2-3 km is needed.

Knowledge about the structure of the porosity is crucial. Only in a regular arranged porosity, hydraulic fracturing is possible (hydraulic fracturing is the technique to build up a system that allows the water to flow through the granite between the boreholes).

1.1.2 Heat / Power Demand

For most geothermal power plants, it is economically crucial to sell the heat. Therefore, it is important to find an adequate heat demand in the vicinity. For electricity production, temperatures down to 70°C can be used in the energy conversion cycle. Because of that, the heat demand should be preferably at low temperatures (e.g. 35°C - 40°C for heating purposes) and steady around the year.

Usually the power demand has no influence on the economics of the geothermal power plant. The power is usually sold directly to the local utility and distributed to the next consumer load.

1.1.3 Infrastructural Conditions

There are several infrastructural issues to be taken into account. Usually they do not pose restrictive constraints but can influence the economics of a geothermal project essentially.

Roads: For the transport of the drilling equipment, roads should be apt for trucks of 40 t and cranes. Therefore, it would be an advantage if such roads would be close to the interesting location.

Electrical Grid: During drilling period, there will be high power demand, depending on the drilling-equipment. For smaller boreholes, made for heat production only, stand-alone systems with diesel engines are a reasonable option. For DHM drilling equipment, electricity consumption is in the range of 3-5 MW (Basel example) and usually, a connection to the local medium voltage grid will be realised for the electricity consumption during the drilling period as well as for the feed-in during operation of the geothermal power plant. Diesel engines for electricity production in the drilling site are an option, but noise and exhaust gas emissions have to be kept in mind. On a site with a weak grid, implementation of a bivalent system could be an option, that most of the time uses the grid and during periods of very high electricity demand a diesel engine is started up to support the grid. It would be an advantage to have a power line which fits the needs close to the interesting location because building up new power lines is expensive. It is necessary to check with the local utility or grid operator.

District Heating Grid: The economical feasibility of a project depends highly on the revenues achieved by selling of heat and electricity. Very important customers for heat are district heating grids. Therefore a site near by an accessible (in terms of temperature and capacity) district heating grid is favourable.

If the flow-temperature in an existing grid is too high for the use with a geothermal power plant, in some cases it could be an option to decrease the supply- and return-flow temperatures of the heat demand by technical or operational measures.

Water: Water is an important medium during the drilling period as well as during operation of the power plant. Mainly it is used as coolant for drilling and later as coolant for the power plant cycle. The cooling type during drilling depends on the temperatures reached underground and the type of soil. During the first part of the borehole, up to a temperature of < 60°C, usually a drilling fluid is circulated. In this stage, only water losses have to be replaced and the common water grid or a hydrant could be used.

Reaching a certain temperature (e.g. > 60°C), direct cooling is needed for drilling as well as for operation of the power plant. Water flows for cooling water can reach up to 100 - 150 l/s.

Cooling water sources could be rivers or air with a cooling tower.

Used cooling water must be conducted to a receiving watercourse (river, canalisation, sewage treatment plant, etc.). The following aspects are interesting for the decision where to lead the water and which kind of treatment has to be applied before disposal:

- temperature, (e.g. the temperature of a river course should not be increased more than 3°C),
- mass flow,
- quality (salinity, pH, chemism).

Usually the water needs treatment before disposal. To decrease the temperature to an acceptable value it could be mixed with cold water. To reach a water quality that allows disposal, the water could be treated chemically or be disposed into a sewage treatment plant.

Canalisation: The drilling site will be contaminated with oils, fats, dust and drilling fluid chemicals, therefore there will occur polluted surface water (e.g. when it rains) and therefore an oil trap must be implemented.

1.1.4 Permits / Administrative Constraints

The project has to comply with the applicable national & regional legislation and regulations with respect to environmental aspects. Dependent on the size of the plant and the legislation an environmental impact assessment (EIA) is required.

The following paragraphs give an overview over the most important possible disturbing factors.

The **acoustic emissions** during the drilling phase are considerable. Counteractive measures could include e.g. noise barriers like walls and windows (if the site is in a housing area). During the operation phase, there are less noise emissions; possible noise emitter are the cooling tower, turbine and pumps.

Usually the entire drilling energy remains within the ground; only during the first meters of drilling **vibration** can be expected.

In some cases, there is a proof demanded, that the hydraulic fracturing does not increase the risk of / does not provoke an earthquake.

Sources for **airborne pollutants** are

- transport of material to the site and waste from the site,
- flue gasses of diesel engines, if the site has no electric connection,
- steam and water drops from the hot drilling fluid,
- gasses (e.g. volatile sulphur compounds, methane)

The borehole with its relatively small diameter usually does not constrain the **ground water** flow.

Pollution of the ground water is unlikely / preventable. Drilling fluid does not enter the **ground water** if the casings are carefully sealed with a non-toxic concrete. The site should be sealed; accruing waters must be cleaned and correctly disposed.

Withdrawal and return of **surface water** (e.g. for cooling purposes) must comply with the regional legislation (temperature increase, concentration of components, pH, etc.)

If there are **contaminated soils** at the drilling site, a correct disposal of the wastes has to take place.

It has to be checked if there is any protected **biota** at the site that could be endangered by the project. In some cases, it is possible to realise compensations for damages (e.g. planting of new fauna at another site).

It has to be checked with the regional authorities, if the project on the selected site complies with the **land use or regional planning.** During the drilling phase, the drilling rig with its 50-60 m height is dominating the landscape. During operation phase, the cooling tower (if existent) would be the highest building.

Because of the risk of downfall of the drilling tower a safety distance of about 1.1 x tower length to the next residential area has to be complied with.

Table 1: Site Location / Summary

	housing area	industrial area	nature area
heat demand	+	++	--
infrastructure	+	++	--
noise control	--	+	-
water protection	-	-	-

1.2 Drilling Techniques

The borehole and drilling techniques for geothermal purposes derive from the drilling techniques for crude oil and gas. Still the technology is not very well adapted to the different conditions found when drilling for geothermal purposes. Main differences are:

- Production rate usually is higher, because the energy density of hot water is lower than the energy density of crude oil. Therefore, the diameter of geothermal boreholes must be larger.
- A geothermal power plant needs a second borehole for re-injection of the thermal water because on the one hand disposal of such amounts of saline water would be very costly. On the other hand, in case of a hydrothermal heat source, the aquifer would loose pressure quickly if water is not re-injected and in case of a HDR-source a huge demand of fresh water would arise.
- Drilling is usually more difficult because of harder stone (especially for HDR)
- Usually higher temperatures and therefore increased costs for measurements, increased strain on materials.
- Often drilling in housing areas (because of heat demand) - in this case noise protection is very important

Drilling Procedure

Rotary drilling is the most common drilling method in geothermal well drilling. There are several variations, e.g. rotary table drive or top head drive, each having their advantages and disadvantages. The basic elements of a conventional rotary mud rig are the rig, drill bit, drill collar and drill pipe, casing pipe, drilling fluid cycle consisting of a pump, cooling system, cleaning/ filtering system, storing space for drill pipes, electricity connection/ transformer / diesel engines and a water reservoir.

The rotary table (drive) applies torque to the hollow drill collar and drill pipe, which themselves rotate the drill bit. The heavy drill collar assembly applies enough weight on the bit and the travelling block holds the drill pipe in tension.

Rigs with top head drive do not use a rotary table. Instead, a hydraulic motor that travels up and down the mast supplies torque directly to the drill pipe. Often a much shorter and lighter drill collar is used, and the rigs have pull-down chains to utilize part of the rig's weight at shallow depths.

Drilling fluid circulates down the drill pipe and escapes at openings/ nozzles in the drill bit where it cleans cuttings from beneath the bit and cools it. The fluid carries cuttings through the annulus between borehole wall and drill pipe to the surface where vibrating screens, hydro cyclones and/ or centrifuges separate the cuttings from the water, before it is cooled and led back into the drilling fluid cycle. In most cases, the drilling fluid is mud (water with additives such as bentonite, polymer, etc.).

It performs the following functions:

- Cool the drill bit.
- Remove cuttings produced at the drilling face.
- Transport cuttings up the borehole.
- Stabilize the hole to prevent cave-ins.
- Minimize formation-fluid migration into the borehole and fluid losses to the formation (the additives clog up small holes and fissures).
- Lubricate mud pump, bit and the annulus between the drill string and the hole.
- Reduce drill string corrosion.
- Release cuttings in the mud tank.

In certain intervals, the borehole walls need additional support to avoid that

- stones fall out of the borehole wall,
- the borehole collapses or
- for separating two different soil horizons.

This support is realised by implementing casing pipelines and filling the gap between casing and borehole wall with cement. To realise this, the drill collar, drill pipe and drill bit have to be taken out and after implementation of the casing, inserted again (so called "round trip"), this time with a slightly smaller drill bit that fits into the piping. For this reason, the borehole begins with a large diameter that decreases until the deepest part of the borehole. For deep boreholes like DHM/HDR, this procedure is repeated 4-6 times.

Additionally the drill collar, pipe and bit have to be unplugged for changing the drill bit that has a lifetime of 20 - 100 h (values for granite). The drill pipes have a length of app. 10 m and are screwed together. Usually during this procedure, the drill pipes are disassembled and stored on the tower but newer technologies store the drill pipes horizontally on the ground. This shows the advantage, that the rig can be designed smaller because it does not need to store the heavy pipes and it increases the safety on the rig site, because the pipes if they are stored on the ground, cannot fall down. The procedure of a round trip is time consuming, in a depth of about 5000 m it can last up to 30 hours, but there is potential for optimisation.

For the realisation of a vertical borehole with a depth of 5.000 m, a period of 100-120 days is a good estimation, if no complications occur.

After reaching the planned depth, a set of tests is performed, e.g. surveying of the borehole, determination of temperature and pressure in the depth, geophysical (in case of HDR) /geochemical (in case of hydrothermal) tests, hydraulic tests to determinate where to situate the second borehole. Afterwards the completion of the first borehole is carried out and the second borehole is drilled.

With the second borehole the same tests are carried out but also the stimulation (acidic-stimulation or/and hydraulic fracturing), and afterwards circulation tests. The results of the circulation tests give a good basis for the design of the geothermal power plant.

1.3 Thermal Water Quality

Process, function and operation of a geothermal plant depend in several points of view on the properties of the geothermal water. Besides the properties of the geothermal water have a wide influence on the operation conditions and on the life cycle of the plant, restrictions on the operation by corrosion, erosion, fouling and clogging have to be taken in consideration. Hence, the planning and the design of a geothermal power plant depend highly on the quality of the water. Geothermal water from hydrothermal as well as from HDR-sources can have a varying quality. It is essential to find out the supposed quality in an early stage because the underground and the above ground installations, especially the choice of materials depend highly on this issue.

The main objective of a geothermal water flow is the continuous feed of hot geothermal water to a consumer and a safe disposal (usually by re-injection) of the cooled geothermal water. Hence the water quality of a geothermal plant has to be scrutinized on the following aspects of the physical an chemical properties

- dissolved salts and minerals
- dissolved gases
- alkalinity, pH and conductivity
- particulate matter
- composition

To avoid any restrictions on the flow rate of the geothermal water in the borehole casing, in the pipes and the heat exchangers the concentration and quality of particulate matter, of dissolved salts and of possible precipitations have to be taken in account. This makes necessary to investigate the geothermal water quality on following items:

1.3.1 Particulate Matter

Non-soluble minerals in the geothermal water may either be kept in high disperse condition in the water or it has to be removed by a filter.

There are no experiences with solid particulates of non-mineral character in geothermal water. In such a case, a treatment by coagulation and a subsequent filtration would be necessary.

A precipitation of dissolved components in the geothermal water has to be avoided as far as possible.

1.3.2 Dissolved Minerals and Salts, Hardness

The concentrations of dissolved salts and minerals become important due to following circumstances

- Dissolved substances in a concentration near to the saturation point of the solution may precipitate and crystallise in case of a change of the temperature.
  Particularly high soluble substance in high concentrations may result to huge quantities of precipitated minerals. Low soluble salts can be regarded as negligible for the physical properties of the geothermal water.
- Dissolved salts increase the tendency of corrosion (NaCl, $CaCl_2$, NaF, …).
- Concentrations of neutral salts may rise up to the saturation concentration. Concentrations of more than 50 g/l of NaCl or Na_2SO_4 may occur.
- In case of hydrogen carbonates the geothermal water has to be kept on a higher equilibrium pressure to avoid degassing of CO_2 and hence the precipitation of carbonates.

  Note: Already small concentrations of $Ca(HCO_3)_2$ in the geothermal water make it necessary to avoid any degassing of CO_2 by pressure relief of the geothermal water. According to the balance $Ca\ (HCO_3)_2 \rightleftharpoons Ca\ CO_3 + CO_2 + H_2O$ the calcium-carbonate would be formed as solid particles, instead of having the dissolved calcium-hydrogen-carbonate.
- Dissolved iron (Fe) can be used as a corrosion indicator. The initial Fe-concentration of the geothermal water therefore is required to be known.

1.3.3 Dissolved Gases

The solubility of gases in water depends on the kind of the gas, on the temperature and the pressure. Inert gases like Ar, He have a very poor tendency to dissolve in water, whereas gases like CO_2, NH_3, H_2S can be easily absorbed and dissolved in water. The absorption capacity of gases in water generally rises with increasing pressure and decreases with rising temperature.

A selective gas separation from the geothermal water can be required for a geothermal plant. While having different gases in the geothermal water it might be necessary to keep some gases inside the geothermal water (for example CO_2) whereas other gases (like CH_4) should be desorbed for a further use.

Gas separation processes have to be designed on the base of the physical properties of the specific gases. The possibility of a specific gas separation depends on the concentrations of the absorbed gases in the liquid phase and the partial pressure of the gases in correlation to the temperature.

Particularly in petroliferous zones, the presence of higher alkenes than CH_4 is possible.

The expected gases in geothermal water are He, H_2, Ar, N_2, CO_2, CH_4, H_2S.

O_2 was detected in geothermal water only in small traces.

1.3.4 Alkalinity, pH-Value and Conductivity

Geothermal water of hydrothermal sources has often a high concentration of neutral salts. The ph-values of saline geothermal water are typically between 6.0 and 7.5. The hardness of the geothermal water with a certain presence of Mg^{++} or Ca^{++} ions raises the buffering capacity. A high buffering capacity results to high demand of acid to be metered to the geothermal water for any reduction of the pH-value. Hence, the hardness has to be taken into account for an adjustment of the pH of geothermal water.

The geothermal water of HDR-systems will adopt a salinity that is given by solubility of the rocks. The conductivity of the geothermal water rises generally with the concentration and types of ions. Hence, the conductivity depends on the salinity.

A high conductivity and a low pH-value of geothermal water promote the tendency of corrosion of iron-based materials of construction. An adjustment of the pH for corrosion inhibition is not recommended due to the fact of any resulting precipitations and the buffering capacity of carbonated water.

1.3.5 Corrosion

The corrosion of metallic material of construction, particularly iron-based material is influenced by

- the presence of dissolved and free oxygen in the water
- the concentrations and types of salts. Particularly salts with P and halogens (Cl, F, I, Br) are essential for the corrosion of iron based materials of construction.
- the pH-value: low pH-values combined with halogens, O_2, P. and Co_2, increase the tendency of corrosion.

1.4 Materials

Dependent on water quality, temperature and pressure, certain material specifications have to be met and the planning has to be adapted to the given framework conditions.
Most important criteria for the decision for a material are the following:

- Corrosion
- Temperature / pressure
- surface finish / fouling
- Costs / availability

Corrosion: In many cases, the thermal water contains substances that promote corrosion. These are generally all oxidants as well as acids e.g. O_2, HCl (hydrochloric acid), H_2SO_3 (sulphuric acid), HNO_3 (nitric acid).

Temperature / Pressure: Temperatures are expected to be < 250°C with the highest temperature at the extraction side. During normal operation, the temperatures at the re-injection-side are much lower than at the extraction side but during system malfunction or during start-up and shutdown the temperatures can reach the same level as on the extraction side.
The highest pressure in the system, usually not above 150 bar, will occur close to the lower end of the re-injection borehole.

Assuming these temperatures and pressures, all underground-installations have to meet the requirements described in the PED (Pressure Equipment Directive) 97/23/EG.

Surface finish/ fouling: The condition of the inner pipeline-surface influences considerably the pressure loss of the cycle and therefore the needed auxiliary power. The better the surface finish the smaller the flow resistance. Moreover, a smooth surface provides the best protection against fouling, a process that deteriorates the surface finish. It is important to consider, that the surface finish should be good over the whole lifetime. Problematic in that context is also corrosion, because corrosion itself deteriorates the surface-finish and furthermore promotes fouling.

For rolled steel for example, 0.01mm can be assumed as a reference-value. Dimensioning a hydraulic system, a calculating-value of 0.03 mm is considered realistic.

Costs / availability: Apart from technical criteria, economical aspects should be considered when choosing a material. In this context, direct costs for purchase and construction are as important as indirect costs such as high quality standards, good availability and good service (and therefore short idle times).

Applicable Materials:

Ordinary steel (black carbon steel): Ordinary steel is a cheap material showing a good temperature and pressure stability. Dependent on the water quality this kind of steel shows bad corrosion behaviour and consequently the surface-finish worsens during operation.

Coated steel (e.g. epoxy phenol coating): Coated steel usually consists of ordinary steel as basic material, the parts of the pipelines that get in direct contact with the fluids, are coated with an epoxy-phenol-coating. This coating has to be temperature- and pressure resistant (up to 200°C). Major disadvantage is a more intricate handling during installation and operation compared to uncoated steel.

Coated steel pipes are industrial standard and therefore are easily and quickly available. However, a disadvantage is that the procedure of coating of the pipelines happens in specialized companies. Reworking of the parts at the site (implementation of sensors, lugs …) is almost impossible. Very careful and detailed planning is therefore essential when implementing this material.

The life span of coated steel pipes is equal to that of steel pipes used in conventional power plant devices if thermal and pressure stress is not alternating.

Glass-fibre reinforced plastic (GRP): Applicable in principle with temperatures up to 120°C. Considering the fact, that high temperatures and pressures influence highly the durability of GRP, prolonged exposure to temperatures above 90 °C is not advisable.

Alloyed steel: Some of the alloyed steels show a good corrosion resistance, but they are much more expensive than ordinary steel. Temperature and pressure stability is good and adequate for geothermal power plant purposes. Handling is simpler compared with the handling of coated steel.

Titan: Titan is a very temperature, pressure and corrosion-resistant material, but very expensive. The following table indicates values for surface finish/ fouling of different materials.

Table 2: surface finish of different piping materials

Plastic pipes	0.001 - 0.01 mm
GRP	0.007 - 0.1 mm
Titan, Nickel, alloy	0.005 - 0.05 mm
Coated steel pipes	0.001 - 0.01 mm
Duplex	0.01 - 0.01 mm
Ordinary steel	0.01 - 0.05 mm
corroded ordinary steel	3 - 5 mm

Table 3: Rating matrix / summary

	corrosion	temperature / pressure	surface finish / fouling	costs / availability
ordinary steel (black carbon steel)	- -	+	0	++
coated steel (epoxy phenol-coating)	++	+	++	+
GRP	++	- -	0	+
alloyed steel	+	++	+	- -

2 Planning of Geothermal Power Plants

Usually a geothermal power plant is divided into three parts:

- underground installations (boreholes with casing, extraction pump),
- above ground installations (primary / thermal water cycle & necessary instruments like heat exchanger, injection pumps, pressure maintenance system, etc.)
- power conversion installations (secondary cycle, turbine, generator, cooling system).

2.1 Conceptual Design & General Aspects

In a geothermal power plant project, many different disciplines are working together that are usually working for another purpose and are often not used to work together. There are the drilling company coming from crude oil drilling, geologists, geophysicists, geochemists, measurement-engineers, power plant manufacturer, power plant planner, civil engineers, etc. In a geothermal power plant project, all of these disciplines are faced with slightly changed conditions but these changed conditions can influence the whole project substantially. Most important for realising an economically feasible geothermal power plant is therefore an integral & interdisciplinary planning from the beginning, including all participating disciplines.

Figure 1 shows a simplified flow chart of the project-steps, inclusive potential abortion points during a geothermal power plant project.

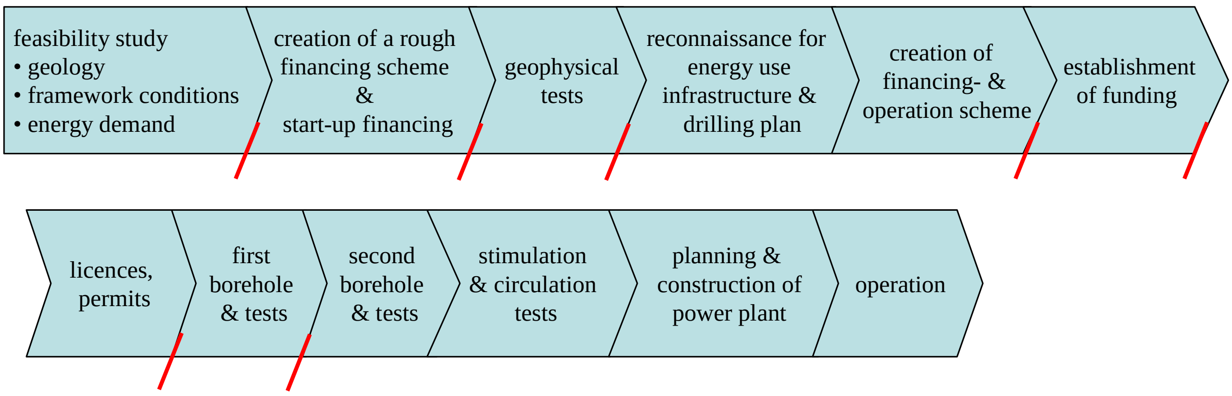

Figure 1: simplified flow chart of the project-steps, inclusive potential abortion points

2.2 Underground Installations

Hydrothermal:

The underground installations for geothermal power plants with a hydrothermal source consist of the following parts:

Boreholes: usually there is one extraction borehole and one or two re-injection boreholes. A very important issue to consider is that a replacement of the pipelines in the boreholes is not possible. If holes occur during life span of the casing, it is possible to fix them, which is a very expensive option. The other possibility is to insert a new piping within the old pipelines but this decreases the diameter and therefore the capacity of the power plant.

This shows that the choice of casing-material is a very important matter that is worth a discussion before beginning of drilling.

France is the first country that demands inspections of the casing in a five-year frequency and the operator is obliged to fix detected holes.

Measuring instruments: It is advisable to install measuring instruments on the ground of the boreholes to determine e.g. temperatures, pressures, pH-value, chemism. None of these instruments is required strictly, installation is optional, but they help to understand the processes happening within the borehole during operation. It is recommended to implement them at least in the extraction borehole.

Extraction pump incl. piping: the extraction pump transports hot thermal water from the aquifer to the power plant and provides the pressure necessary in the thermal water cycle. Therefore, the pump should be installed within the extraction borehole.

Design of the pump depends on planned flow rate, resistance within aquifer & borehole casing. With this information, it is also possible to calculate the subsidence of the surface of the thermal water during operation. It is necessary to install the pump deep enough that it is always in the water, that no cavitation, no precipitation and no degassing occur during operation. Dimensioning of the pump is difficult because the exact pressure situation within the aquifer (pressure and permeability) is unknown until commissioning of the plant.

In some rare cases, there is enough pressure in the aquifer and the re-injection pumps are able to maintain it, and for that reason, a submersible or a line shaft pump in extraction well is not necessary.

The operating energy needed by the pumps depends mainly on the pressure drop within the aquifer. In addition, the design of the well casing and the surface finish of the pipes have a serious influence on the necessary pump drive energy. Figure 2 shows the influence of the surface finish on the pressure loss and therefore on the operating energy of the pumps.

Surface finish of the pipelines in a device with coated steel pipes is supposed to have values between 0.01 und 0.1 mm during operation.

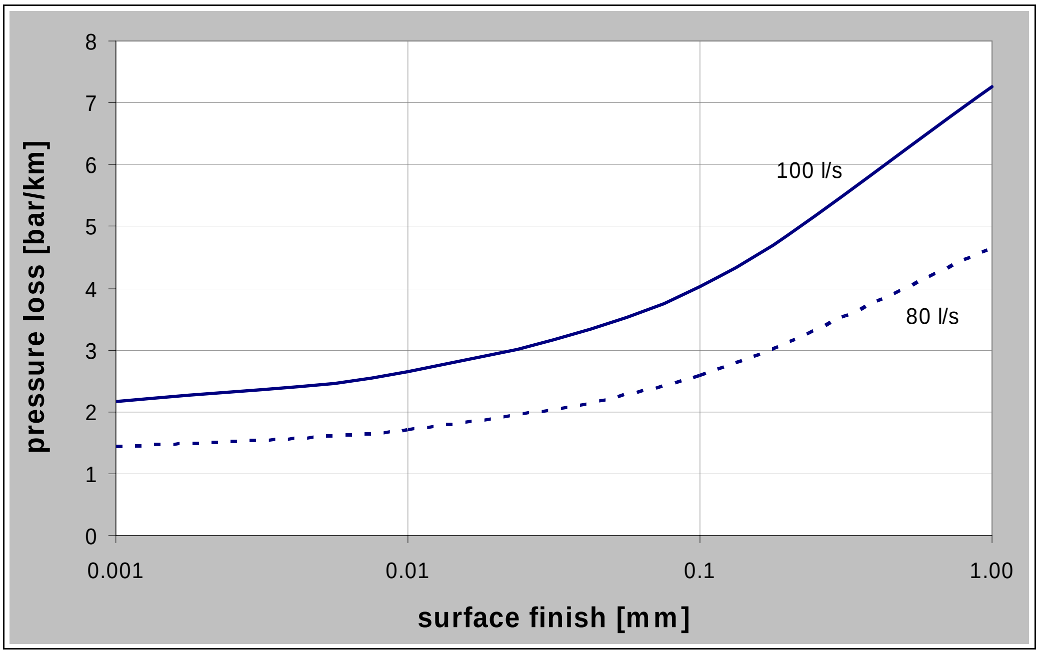

Figure 2: pressure loss over surface finish of the extraction borehole pipeline (Diameter 8", temperature 200°C)

Optional installations dependent on thermal water quality

Corrosion protection: In the extraction borehole, a corrosion protection can be necessary. It consists of the injection of inhibitors at the ground of the borehole. Especially if the borehole piping consists of black-steel and the geothermal water is aggressive, corrosion protection could be expedient.

HDR

There are only a few differences between underground installations for HDR and for hydrothermal systems:

– If the heat exchanger system built in the granite layer is sealed, no extraction pump is needed because the re-injection pumps maintain the pressure necessary for extraction of the thermal water. If a pump in the extraction borehole would be needed, this could rise a problem, because there are still no pumps available that can be operated with temperatures above 180°C and temperatures above 140°C already make the operation complicated/ unreliable. (Aquifers usually do not exceed temperatures above 160°C.)

– Admission of wellhead with inert gas is only necessary if the water surface can drop, e.g. during a shut down period, when the heat exchanger is not perfectly sealed and therefore has high water losses.

2.3 Aboveground Installations

The aboveground installations include the cycle of the thermal water by connecting the extraction borehole with the re-injection borehole. In this cycle, several installations are implemented: first, a filter, then one or two heat exchangers to exchange the heat from the thermal water to the power plant cycle, before re-injection another filter with a smaller mesh length cleans the thermal water to avoid contamination of the re-injection borehole.

Annex 1 shows a flow chart of the underground and above ground installations.

The pipelines usually are thermally insulated, laying directly in the ground and equipped with a leakage control.

The following paragraphs describe the main above ground installations:

Filter: The thermal water can contain dissolved substances as well as solid particles. To protect the power plant as well as the re-injection borehole against contamination and eventual precipitations, the application of a filter system is advisable. To avoid frequent shutdowns of the power plant, the filter should be self-cleaning during operation. The primary cycle is equipped with a coarse filter placed before the heat exchanger and a fine filter before the re-injection borehole.

Of course, the filter should be apt for the existing temperatures and pressures and the pressure loss over the filter should be kept to a minimum.

The mesh sizes of the filters depend on the heat exchangers as well as on the thermal water quality.

Heat exchanger: Usually a heat exchanger separates the thermal water cycle from the secondary, the energy conversion cycle. For electricity production, at least two heat exchangers are necessary: a pre-heater and an evaporator. The hot medium is the thermal water, here it is important to choose an appropriate material (possibly titan). The material on the cold side depends on the working fluid. Heat exchanger should be designed in a modular form for redundancy reasons. Tube bundle heat exchangers are easy in operation and cleaning but they have a high specific weight, therefore price and availability are not good.
Plate heat exchanger: low specific weight and therefore more expensive materials could be used. It is easier to design it in a modular way. But it does not provide complete pressure separation between the systems.

Pressure maintenance system: The pressure within the thermal water cycle must always be maintained on a minimum pressure, which depends on the quality of the thermal water as well as the temperature to avoid that:

- the thermal water evaporates
- precipitations of e.g. calcium oxide, salts occur
- degassing of e.g. CO_2 occur

During operation, the extraction- and re-injection pumps create the pressure within the above ground installations. After shutting down of the plant, shut-off valves at the wellheads have to be closed and an additional pressure maintenance system consisting of a thermal water buffer and pressure maintaining pumps will maintain the pressure to a minimum level.

During maintenance, repairing or downtimes, it can be required to add auxiliary water to the thermal water cycle. Dependent on the quality of the thermal water, the auxiliary water should not contain any oxygen to avoid reactions. Therefore, a **degasser for feed water** could be necessary.

Admission of wellhead with inert gas: This installation is only necessary, if the quality of the thermal water prohibits a contact with oxygen (air) and if during operation the water level drops.

E.g. in the case the well is not artesian, the pump provokes a subsidence of the water surface within the borehole and this will aspirate air into the wellhead and cause reactions of the oxygen content of the air with the dissolved minerals in the thermal water. The products of these reactions can cause precipitation and damage the following components of the primary cycle.

For this reason, it can be necessary to feed inert gases (usually nitrogen) with a higher density than air into the wellhead to avoid that air gets in contact with the thermal water.

Degasser: Between extraction- and re-injection borehole a bypass should be installed equipped with a degassing system, that bypasses all the aboveground installations. For starting up the geothermal circulation the thermal water is led through the bypass, where gasses that entered the thermal water during downtime are extracted and the boreholes and the pumps are warmed up.

Leakage control: To detect and avoid oxygen entering the thermal water cycle, leakage control is realised by pressure measurement or by electric coils around all systems (leakage provokes changes in resistance).

Re-injection pumps: the thermal water is re-injected by a centrifugal pump. Frequency converters control the rotational frequency of the centrifugal pumps and consequently the grouting pressure under varying conditions during operation. The re-injection pump is designed together with the extraction pump and the well casing dependent on the geologic/hydraulic conditions found during the circulation tests.

For the re-injection pumps, the choice of material especially for casing and impeller is important. During operation, temperatures will stay below 70°C but will reach 120°C peaks during operational faults.

Auxiliary components: instruments, measurement- & control systems, safety valves as well as the electrical engineering correspond to the state of the art of the power plant technology.

Optional components:

Methane-Degasser: If the thermal water contains a substantial amount of methane, it could be a financially feasible solution to degas the methane and use it, e.g. in a gas engine for electricity production.

A typical design of a degasser is a pressure vessel. Thermal water enters the pressure vessel through a spray tower. The pressure in the vessel is set on a value, where a large amount of Methane degasses but CO_2 remains dissolved in the thermal water. Methane degasses at the same pressure as N_2, dependent on the further use of the gas, it has to be separated, dried, cleaned, etc.

Hydrocarbon separator: If it can be expected that the thermal water contain crude oil it is necessary to install an oil separator before the first filter.

2.4 Installations for Energy Conversion

2.4.1 Description of suitable conversion technologies

The following paragraphs describe briefly the three main technologies suitable for geothermal power plants from the practical/ technical point of view only. In the second part of the report, EPFL gives a sound thermodynamic description.

Steam turbine

The steam process in its simplest design is a well-known Clausius-Rankine-Cycle, with steam as working fluid. The steam cycle used with low-temperature sources works at temperatures in the range of 150°C - 220°C and pressures between 3-5 bar. The classic steam cycle operates at much higher temperatures and pressures. Therefore, there is a lot of experience with the cycle itself but much less with cycles suitable for geothermal heat sources.

Assets & drawbacks:

+ many experiences in operation
+ working fluid not toxic, not inflammable
– relatively high temperatures necessary (the lower the temperature, the lower the efficiency)

Organic-Rankine-Cycle (ORC)

The Organic Rankine Cycle (ORC) is a Clausius-Rankine Cycle using an organic working fluid. There are several organic working fluids available with different boiling- and condensation-points. The optimal working fluid has to be chosen depending on temperatures and pressures in the cycle. The temperature range is from 70°C - 300°C.

The ORC is an approved cycle used since more than 20 years (with different low-temperature heat sources). There are turbines available in the range between 100 kW and > 5 MW.

Assets & drawbacks:

+ many experiences in operation
+ part load compliant
+ working fluid not corrosive
+ most of the working fluids are not toxic

– most of the working fluids are inflammable

Kalina-process

The Kalina-process is a binary cycle with an ammonia-water-mixture as working fluid. An absorber replaces the condenser and a desorber the evaporator. Boiling- and condensation-points of this working fluid depend on the concentrations of water and ammonia. Therefore, one has to choose the ammonia-concentration depending on temperatures of the process.
The temperature range is from 70°C - 300°C.

Up to today only a few cycles are realised (USA, 2xJapan, Island). Only one of them is powered by a geothermal heat source.

Assets & drawbacks:

– few experiences in operation
– working fluid toxic
– because of the behaviour of ammonia, high standards of design in view of materials and sealing (no non-ferrous metals, sealing preferably in EPDM, PTFE)
– more expensive than ORC
– needs larger heat exchangers than ORC
+ cheap working fluid (many experiences with ammonia from refrigeration engineering and chemistry)
+ adaptation of the working fluid to the given temperatures possible
+ theoretically higher efficiencies than with ORC possible

Table 4 shows exemplary operating data from manufacturers for four different ORC cycles and one Kalina cycle. ORC II to ORC IV are only simulated data for fictive framework conditions, ORC I and Kalina are calculated values.

Table 4: exemplary operating data for different cycles

		ORC I	ORC (sim) II	ORC (sim) III	ORC (sim) IV	Kalina
thermal water						
flow temperature	°C	115	200	150	100	150
return temperatur	°C	61	79	76	61	66
mass flow	kg/s	95	80	80	80	100
thermal capacity	MW	22	42	25	13	36
cooling water						
flow temperature	°C	13	20	20	20	21
return temperatur	°C	8	10	10	10	12
mass flow	kg/s	910				790
thermal capacity	MW	19				30
turbine / generator						
Stufen		2				1
total electrical capacity	MW	2.4				4.8
net electrical capacity	MW	2.3	5.6	2.0	1.0	4.1
miscellaneous						
required area	m2		500			400

Net electricity production: For all kinds of thermodynamic cycles, it is important to consider not only the efficiency of the power plant cycle but also the overall net electricity production. The pumps within the thermal water cycle have high electricity consumption. Dependent on the geothermal heat source (temperature and thermal water flow) this could result in a bad overall electricity production.

The following Figure 3 shows the operating energy needed by the pumps for powering the geothermal water cycle that depends on the pressure loss over the aquifer/ HDR-heat exchanger as well as the type of piping. It is important to check, if production of electricity is reasonable, or production is close to operation energy of pumps.

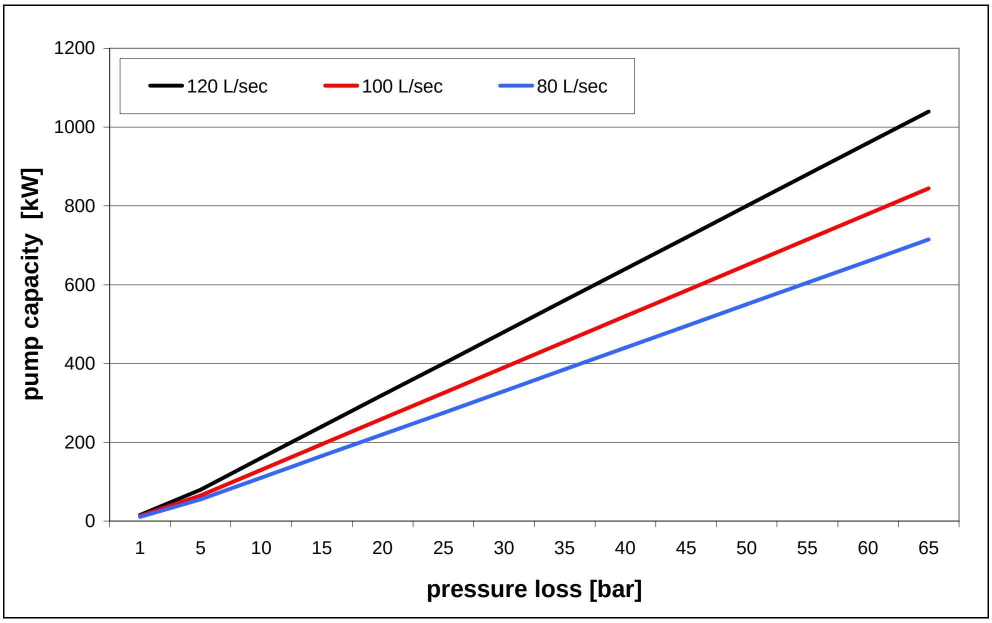

Figure 3: pump capacity over pressure loss in thermal water cycle

Heat production: There are several options where to take the heat out of the geothermal power plant. The options to produce heat without influencing the electricity production are

1. to implement an additional heat exchanger into the thermal water cycle, after evaporator and pre-heater of the thermodynamic cycle (electricity producing process).

2. to use the heat of the condenser/absorber of the thermodynamic cycle if the temperature (app. 70°C) is still high enough for heating purposes.

There are two additionally options that influence the electricity production negatively:

1. to realise heat & electricity production as two parallel processes in the geothermal water cycle, this is the least energy efficient option, because high temperature heat is used for heating purposes.

2. to take the heat from certain points within the thermodynamic cycle. One interesting difference between the processes is, that the heat extraction for the co-generation is realised in different parts of the cycle (for example from the internal recuperation).

Table 5: Summary - comparison of thermodynamic cycles

	Kalina	**ORC**	**Steam**
Tu - range	70°C - 200°C	70°C - 200°C	from 200°C
investment costs	--	-	0
efficiency at low temperatures	++	+	-
efficiency at high temperatures	0	0	+
operation	-	0	+
experiences with technology	-	+	+

Cooling System

The above described energy conversion technologies need cooling for condensation (absorption in the case of Kalina) of the working fluid after expansion in the turbine. In all three cases, the efficiency of the power cycle increases with decreasing condensation temperature.

There are three cooling systems available:

- wet tower,
- dry tower and
- water cooling.

In **dry cooling towers,** the hot medium flows through a heat exchanger within the tower. Heat transmission between the hot medium and the ambient air is realised by convection only and the temperature achieved is always above ambient air temperature. Therefore, in summer, only high temperatures are reached and in winter, the temperatures reached are very low.

To increase the efficiency, huge ventilators are installed within the cooling towers implicating high noise emissions. Especially in summer the efficiency of dry towers is relatively bad, hence large exchange areas are needed. This influences the efficiency of the power plant cycle significantly.

Wet cooling towers operate on the principle of evaporation. The hot medium is sprayed into the air within the cooling tower and the hot medium cools down primarily by the evaporation energy of the water and for a minor part because of the temperature difference between the hot and the cold medium. The part of the medium that evaporates has to be substituted. Because of the evaporation energy, wet cooling towers have a higher efficiency than dry towers and are therefore smaller. In a wet cooling tower, the warm water can be cooled to a temperature lower than ambient, if the ambient air is relatively dry. Especially when the air is dry, wet towers form a plume, which could cause lower public acceptance.

Direct water-cooling shows good efficiencies and constant framework conditions because usually the temperature of the water source used for this type of cooling does not change as much during the year as the ambient air temperature. Electricity consumption is low, but dependent on the cooling water source, there occur significant costs for filter cleaning. The acceptance of this type of cooling is high because there is no plume, no noise and no huge cooling tower. However, it is highly dependent on the local site conditions (availability of water, etc.) whether direct water-cooling is a feasible option.

2.4.2 Combined Processes with Additional Heat Source

Under some circumstances, the option of combining the geothermal power plant with an additional heat source such as a boiler, gas turbine, gas engine, etc. should be examined.

Reasons for using a combined process:

1. Geothermal power plant cannot cover the existing heat demand
2. Raising of temperature to reach better efficiencies
3. Synergy effects through other energy sources in the vicinity (combustion of sewage sludge, biogas, etc.)

<u>1. The geothermal power plant cannot cover the existing heat demand</u>

If the geothermal power plant alone cannot meet the heat demand, it could be an option to combine another power plant (boiler, gas turbine, gas engine, etc.) to satisfy the demand. The choice of technology depends on the annual load duration diagram. Figure 4 shows a typical annual load duration diagram and a reasonable example for a combined process: the geothermal power plant provides the heat base load, a gas turbine or gas engine provides middle load (< 4000 h) and an additional boiler provides the peak load (< 1000 h).

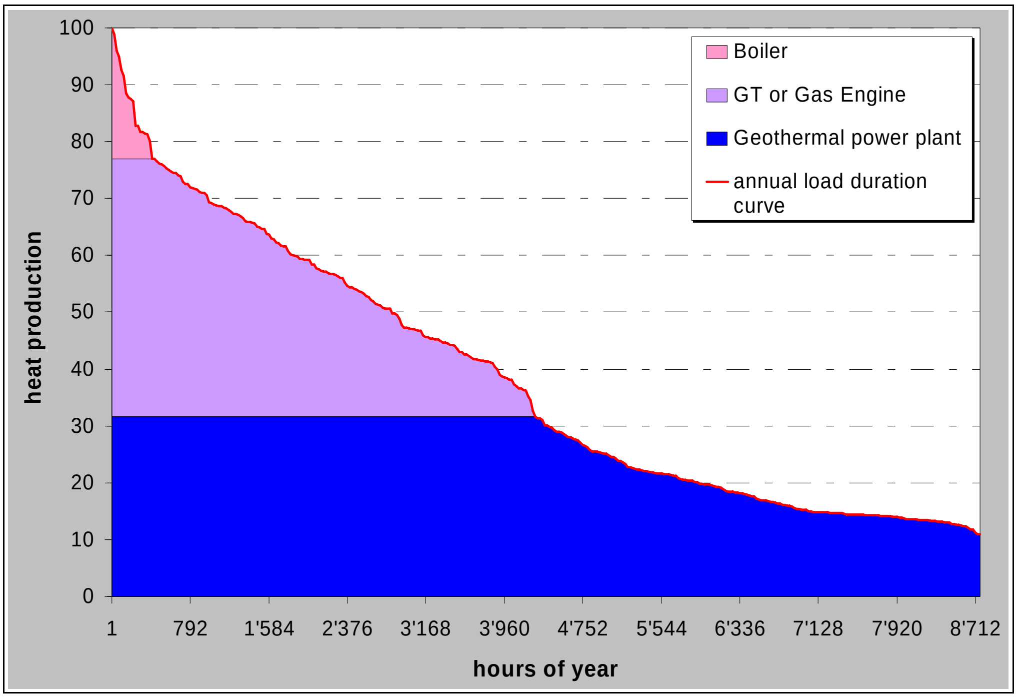

Figure 4: Typical annual load duration curve with an example for a combined process

In this combination, the gas turbine or engine will be coupled with the geothermal process; the waste heat from the gas turbine/ gas engine first goes through the geothermal power plant cycle and then the waste heat from the geothermal power plant cycle is used to satisfy the heat demand.

For economy reasons, the boiler would be used stand-alone to provide the peak demand only.

Gas turbine vs. Gas engine:

For the decision weather a gas turbine or a gas engine should be implemented, the following aspects must be considered:

Small gas turbines in the range of 0.5 - 5 MW usually show poor efficiencies. The following Figure 5 shows a trend line for the efficiencies of typical gas turbines.

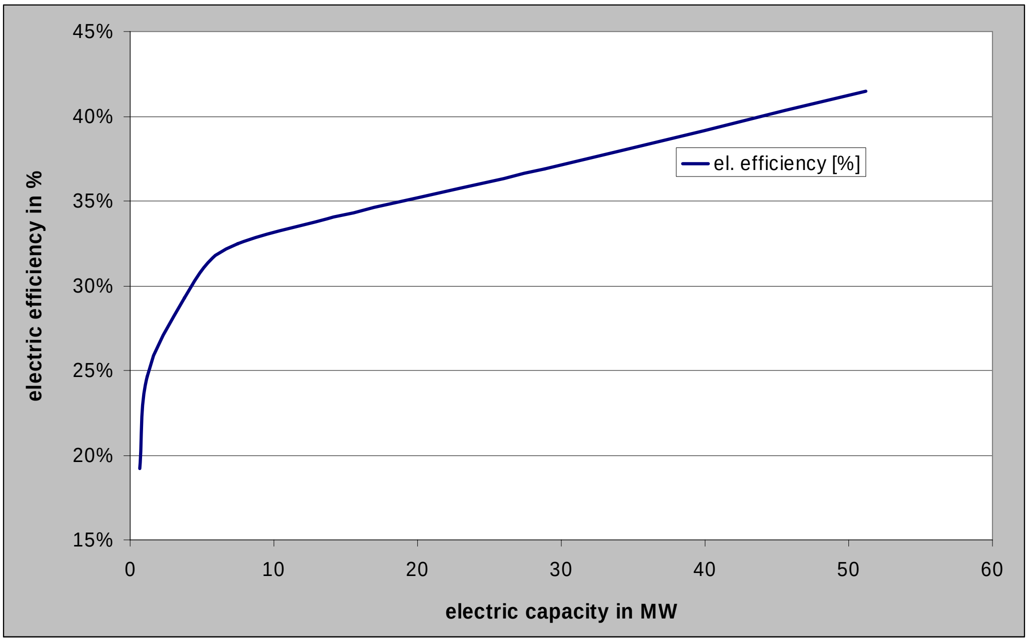

Figure 5: electric efficiency over electric capacity

Efficiencies > 40 % can be reached by gas turbines > 40 MW only. The temperatures of the waste heat are in the range of 440°C - 520°C; the content of oxygen in the exhaust gas is in the range of 14 – 17%.

Usually gas engines with small capacities can reach higher efficiencies than gas turbines. Already in the range of 1 MW_{el} they show efficiencies of about 40%. The waste heat of this process derives on the one hand from the flue gas with temperatures about 180°C, and on the other hand from engine, -oil- and compressor-cooling which accrues on a low temperature level of about 70-100 °C.

Table 6: typical temperatures of waste heat from a gas engine

electricity production	**Thermal energy with T > 180°C**	**Thermal energy 100°C > T > 70°C**	**waste heat**
41%	19%	28%	12%
7.5 MW	3.5 MW	5.1 MW	2.2 MW

Conclusion: If the temperature levels (180°C respective 70-100°C) as well as the mass flows reached by the gas engines is sufficient, and the capacity needed is small, then gas engines are the preferable option. If high temperatures are needed and the capacity is high, a gas turbine should be implemented.

2. Rising of temperature

If after completing the boreholes the real temperature is lower than expected, it could be an economically feasible option to increase the temperature of the geothermal water with an additional heat source to be able to run a thermodynamic cycle.

4. Synergy effects through other energy sources in the vicinity (combustion of sewage sludge, biogas, etc.)

Under certain circumstances, e.g. if other energy sources like sewage sludge or biogas are available in the vicinity it could be an energetically optimised option to use these energy sources to power the geothermal process and increase the electricity output of the geothermal power plant cycle than to produce only heat. In the Basel example, there is a sewage sludge combustion plant near the geothermal site, producing heat on a temperature level of 250°C, which will be used to increase the process temperature of the geothermal power plant and increase the CHP-coefficient.

Examples of combined processes

Framework conditions:

Geothermal mass flow:	80	kg/sec
Temperature wellhead:	190	°C
Temperature geothermal return flow:	100	°C
Geothermal capacity:	30	MW
District heating flow temperature:	120	°C

ORC-combinations:

process	thermal capacity into process	electric capacity	efficiency of ORC
only DHM	30.4	4.8	15.8
DHM + Gas turbine with 4.6 MW	38.9	6.35	16.3
DHM + Gas turbine with 7.5 MW	41.2	7.2	17.5
DHM + Gas engine with 7.5 MW	34.8	5.7	16.3

Kalina-combinations:

process	thermal capacity into process	electric capacity	efficiency of Kalina-cycle
only DHM	30.4	4.6	15.1
DHM + Gas turbine with 7.5 MW	41.2	6.5	15.7
DHM + Gas engine with 7.5 MW	34.8	5.5	15.7

Steam-combinations:

process	thermal capacity into process	electric capacity	efficiency of steam-cycle
only DHM	30.4	2.8	13.6
DHM + Gas turbine with 7.5 MW	41.2	4.7	15.2

3 Operation & Maintenance

3.1 General Aspects

To avoid long repairing or maintenance periods, most of the plant components should be designed in a way that they can be replaced or maintained during operation, e.g. with bypasses, etc.

Some of the plants component should be designed redundant: e.g. the pre-heater, evaporator and the re-injection pump should be designed in a modular way, so that the plant only must reduce capacity, and not shut-down completely if one of these components fails.

The only component that cannot be designed neither redundant nor with a bypass is the extraction pump, because there is not enough space in the borehole. High temperatures, high salinity of the thermal water, etc usually cause a short life-time of the extraction pump. There are two alternatives how to operate the extraction pump: to wait until a crash before replacement or to replace it during every maintenance shut-down, revise the "old" pump and install it again during the next shut-down. Which alternative to choose must be checked carefully based on a cost calculation.

The following paragraphs describe briefly the different operational states of a geothermal power plant:

Down time: Extraction- und re-injection pumps are shut down. The shut-off valves of both wellheads are closed. The nitrogen-device maintains the well pressure and the pressure maintenance system maintains the pressure of the thermal water cycle.

Start-up of the plant: The first step when starting -up the geothermal power plant, is to remove all gasses from the pipelines. For this reason, the thermal water is first pumped over a bypass between the boreholes and existing gasses are led off the system. Leaking thermal water will be cooled down and led into the canalisation or stored in a buffer tank.
The pressure maintenance system has to be checked, missing thermal water refilled and afterwards closed.

Now the re-injection pump starts and temperature, pressure and flow rate of the cycle are powered-up slowly until they reach minimal operating conditions for the power plant operation. The temperature difference between down time and operation time is quite high, for this reason, starting-up should be realised very slowly.

Operation of the geothermal power plant: A geothermal power plant with co-production of electricity and heat should be operated continuously. The reasons for a shut down are the common reasons: fault, reparation and maintenance.

Shutting-down the power plant: The shut down is carried out in reverse order to the start up. In a first step, the extraction- and re-injection pumps are stopped and the shutting-valves at the wellheads are closed. Afterwards the pressure maintenance systems are given way.

4 Economics

During the last few years, the first geothermal power plant projects started and therefore there is no real data available yet. Therefore, the figures given in this chapter derive from studies and or data available from other fields of use (bore costs for crude oil drillings, ORC-costs from other low temperature heat sources, etc.), partially verified by pricing offers.

The investment costs for a HDR geothermal power plant can be divided into the following parts (source: Institut für Energetik und Umwelt):

70 % drilling
20 % conversion power plant
3 % primary (thermal water) cycle
3 % planning
2 % stimulation
2 % pumps

The **drilling costs** take the main part of the total investment costs. The following Figure 6 shows the expected drilling costs over the depth of the borehole. The huge bandwidth is explained by the drilling costs that depend on many factors as will be described in the following paragraph.

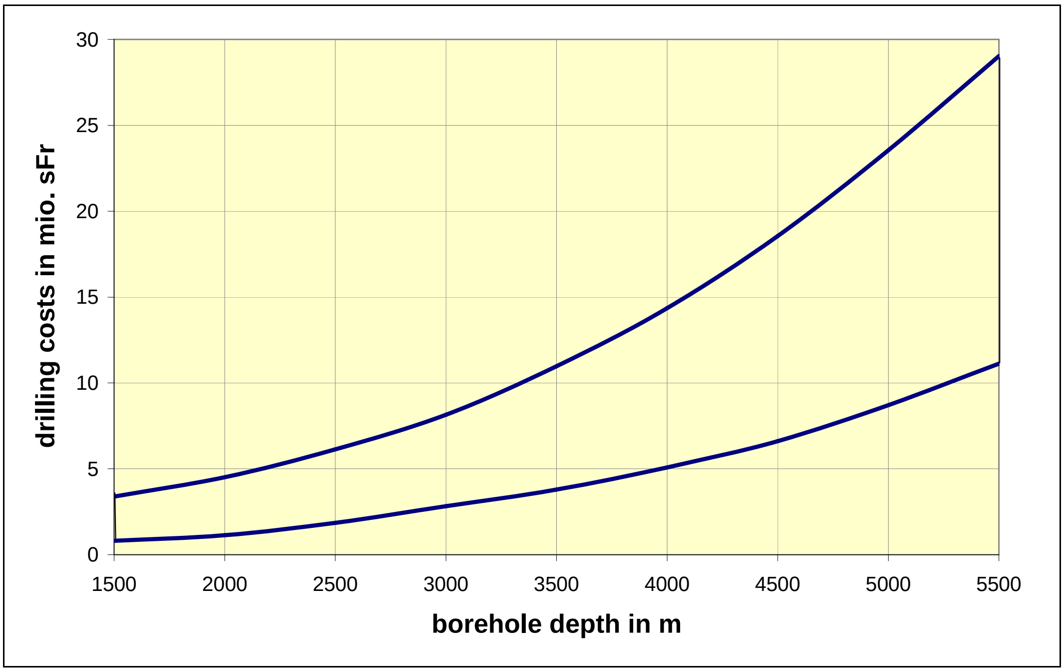

Figure 6: drilling costs over borehole depth

The **geology** influences the ability to drill the ground (type and number of bits needed & progress) as well as the mode of piping applied.

The **borehole diameter** influences the size of the drilling rig and therefore the rig cost as well as the material consumption.

If a borehole is drilled vertically or diverted influences the costs because diversion is more expensive than vertical drilling. For the same depth, more drilling meters are needed and diversion is more challenging.

The **size of the rig site and drilling device** influences the costs because of higher daily expenses, and the **construction of rig site** influences the time needed for drilling (time needed for a round trip, etc.)

Because of the high energy consumption the **energy costs** play a role during drilling.

The drilling costs can be divided into items that do only depend on the time and not on the drilling activity (e.g. the rig & the personnel costs). These take more than 1/3 of the total costs. Costs that arise only during drilling periods, (e.g. drilling fluid, bits & coring) take another 1/3 of the costs. The completion of the borehole with the casing and the cementation take ¼ -1/3 of the costs.

The **thermal water cycle** costs between 2.5 and 4.0 million. sFr (for water flows between 70-100 l/s). The price difference results from different sizes on the one hand and the different material costs for different thermal water quality on the other hand.

The investment costs for the **conversion cycle** depend on the size of the power plant as well as on the type of conversion cycle chosen. For cycles between 1 - 6 MW investment costs of about 2'000 to 4'800 sFr/kW can be expected. Prices will decrease in the future because of further development and increasing demand for the technology. The Kalina-cycle is more expensive than the ORC-cycle because of more complex technology.

Part III:

Methodology for the optimal integration of energy conversion system in geothermal power plants.

Luc Girardin, François Marechal

Laboratory for industrial energy system, Ecole polytechnique fédérale de Lausanne, CH-1015 Lausanne, Switzerland.

Contents

Nomenclature

$\delta\dot{Q}$	Heat-power variation	[W]
P	Power	[kW]
p	Pressure	bar
$\dot{m}$	Geothermal water flow rate	[kg/s]
c_p	Water specific heat	[J/(K kg)]
dT	Temperature variation	[K]
$P_{ex}, \dot{E}_{ex}$	Exergy-Power	[W]
$\dot{Q}$	Heat-Power	[W]
$\Delta T_{\ln}$	Log-mean Kelvin temperature difference $(T_{in} - T_{out}) / \ln(T_{in} / T_{out})$	[-]
$\delta\dot{E}_x$	Local variation of Heat-Exergy-Power	[W]
$\delta\dot{Q}$	Local variation of Heat-Power	[W]
$T_a = 25[°C]$	Ambient temperature	[K]
$\theta = 1 - T_a / T$	Carnot factor (temperatures in Kelvin)	[-]
$\eta_{c,ex} = P_{mec} / \left(\dot{Q} \cdot (1 - T_a / \Delta T_{\ln})\right)$	Carnot efficiency (temperatures in Kelvin)	[%]
$C_{Drilling,spec}$	Borehole specific cost	[$/m]
η_e	Energetic efficiency	[%]
$\eta_{ex} \in [0,1]$	Exergetic efficiency	[%]
$\dot{E}_{el}, P_{el}$	Electro-mechanical power	$[W]$
C_{HX}	Heat exchangers coefficient	[-]
$\Delta T_{\min}$	Minimum heat transfer temperature difference	[°C]
$\Delta T_{\min,ref}$	Reference heat transfer temperature difference	[°C]
$\Delta T_{ORC,hot}$, DT_{hot}	Temperature difference between the temperature of the geothermal water produced and the super heated working fluid temperature	[°C]
$\Delta T_{ORC,cold}$, DT_{cold}	Temperature difference between the condensation temperature of the working fluid and the hottest temperature reached by the cooling fluid	[°C]
U_{ref}	Reference heat transfer coefficient.	[W/(m^2°K)]
U_i	Overall heat transfer coefficient.	[W/(m^2°K)]
U_2	Peripherical speed of the rotor	[m/s]
C_0	Speed of the isentropic flow	[m/s]
N	Regime of the turbine/pump	[rpm]
N_s	Specific speed of the turbine / pump	[]
D	Principal Diameter of the rotor	[m]
η_s	Isentropic efficiency of the turbine/pump	[%]
g	Gravitational constant	[m/s^2]
A	Heat exchanger area	[m^2]
T_{cold}	Coldest temperature of the working fluid	[°C]
ΔT_{Cold}	Temperature increase of the cooling fluid	[K]

P_{high}	Working fluid high pressure	[bar]
$\dot{m}$	mass flow rate	[kg/s]
ORC	Organic Rankine cycle	-
ex	Exergetic	-
h	Borehole deepness	[m]
T_{deep}	Temperature of the water in the deep field of the earth crust.	[C]
$T_{geo,surf}$	Temperature of the geothermal water at the surface, borehole production temperature	[C]
IC	Investment costs	[$]
ORC	Organic Rankine cycle	-
ex	exergetic	-
geo	Geothermal	-
feed	Feed or input	-
th	Thermal	-
el	electric	-
mec	mechanical	-
T+G	Turbine and generator	-
DH	District heating	-
COOL	Cooling fluid	-
V	Vapor phase	-
EVAP	Vaporization level	-
COND	Condensation level	-
L	Liquid phase	-

1. Introduction

This report relates the methodology and results for the optimal valorization of the thermodynamic potential contained in deep geothermal fields. A pinch-analysis approach is applied to choose suitable conversion systems to be integrated into constrained geothermal processes. The optimal integration of the geothermal conversion system is achieved by the use of a multi-objective optimisation technique. The results relate the trade-offs between installation costs and efficiency, and give the expected heat and electricity services delivered for the corresponding optimal systems.
The topics contained in this report are:

- Problem statement and Scenarios description.
- Conversion potential of geothermal resources
- Energy conversion of geothermal resources
- Modelisation of geothermal power plants
- Methodology proposed to solve the integration problem.
- Results for the Basel, Lavey and Geneva case studies
- Conclusion and future works.

1.1. Problem statement

The deep layers of the earth's crust constitute a geothermic source of energy-heat with enormous potential. This potential is extracted from hot dry rock by injection of pressurized water from the surface through bore holes into hot granite rock at about five kilometers underground.
Geothermal energy from hot dry rock is one of the renewable energies that could underpin a nonfossil fuel based economy. However, power generation from hot dry rock is still in its infancy. The goal of this study is to implement a methodology and the tools to analyze, generate and evaluate designs of systems achieving efficient conversion of geothermal energy into heat and power. The proposed methodology is applied to three scheduled geothermal power plant: Basel, Lavey and Geneva.

1.2. Scenarios description

Three scenarios, namely “Basel”, Lavey” and “Geneva” were considered as representative geothermal processes. Each process is well defined as soon as the temperature and power specifications are known for the geothermal hot source, the district heating, the cooling cold source and, if it is present, the gas turbine or the boiler.
The situations covered by these scenarios are:

1. Basel:
   The geothermal source delivers heat at high temperature (170 - 190°C) with a district heating demanding heat at comparatively low temperature (120°C). The accent is then put on power generation from geothermal heat.
2. Lave:
   The geothermal source delivers heat at low temperature (100°C). The size and design of low cost conversion systems has to be proposed and integrated.
3. Geneva:
   The geothermal source can deliver heat at high temperature (200°). The profile demand peaks from the district heating network can be greater than the available geothermal heat. Thus the integration of a supplementary heat source, presently a gas turbine, is required, and the varying nature of the heating demand defines a multiperiod problem.

The available data for each scenario are given in table 1.3 below.

Table 1.3: Data specific to each scenario

Sub-process	Parameters	**Basel**	**Geneva[13]**	**Lavey[14]**
Geothermal production borehole	Deepness [m]	5000	6000	3000-4000
	Production Temperature [°C]	190-170	200	130-100
	Reinjection Temperature [°C]	70	140	80
	Water flow rate [kg/s]	80	-	50-100
	Geothermal Power [MWth]	30	20	8-20
Conversion system	Electricity production [MWe]	-	0.7-2	-
District heating	Feed Temperature [°C]	120	120-80	90-65
	Return Temperature [°C]	55	73	50
	Heating Power Demand [MWth]	1-20	5-62	20
	Number of connected inhabitants	-	20'000	-

In order to realize the energy conversion, a cooling system may be necessary to allow the thermodynamic transformation of geothermal heat into electricity. This system will use air and/or water as natural coolant with constraints given in table 1.4.

Table 1.4: Cooling constraints.

Scenarios	Cold source Temperature [°C]	Max temperature increase [°C]
River Water	10-25	10
Air	0-35	-

If the demand of district heating is higher than the available heat from the geothermal production borehole, a gas turbine (or a boiler) is integrated into the geothermal process (table 1.5).

Table 1.5: Specification of the integrated boiler/gas turbine

Scenarios	Exhaust gas temperature [°C] (K)	Stream DT min [°C]
Gas turbine	575 (848.15)	25

In some cases using a gas turbine in order to increase the thermal output of the plant could be an economical feasible option. The size and the characteristics of the gas turbine can be determined using a thermo economic equipment database [5] representative of the technology state of the art on the market.

2. Conversion potential of geothermal resources.

2.1. Geothermal power plant fluxes

The geothermal power plant of figure 2.1 can be decomposed into two sub-systems, namely the geothermal process and the energy conversion system. By definition, the geothermal process include the geothermal subsurface plant, the auxiliary gas turbine or boilers, the district heating network and the cooling system whose hot (cooling down) and cold (heating up) fluxes are listed in table 2.1.
The conversion system contains all the sub-systems doing the transformation of the geothermal process thermal fluxes into useful heat and electricity.

Table 2.1: Flux of the geothermal process.

Material fluxes of the geothermal process	Thermal fluxes symbol	Thermal fluxes Type
Gas turbine exhaust gas	GT	hot
Geothermal water at surface	GEO	hot
District heating water	DH	cold
Cooling water/air	COOL	cold

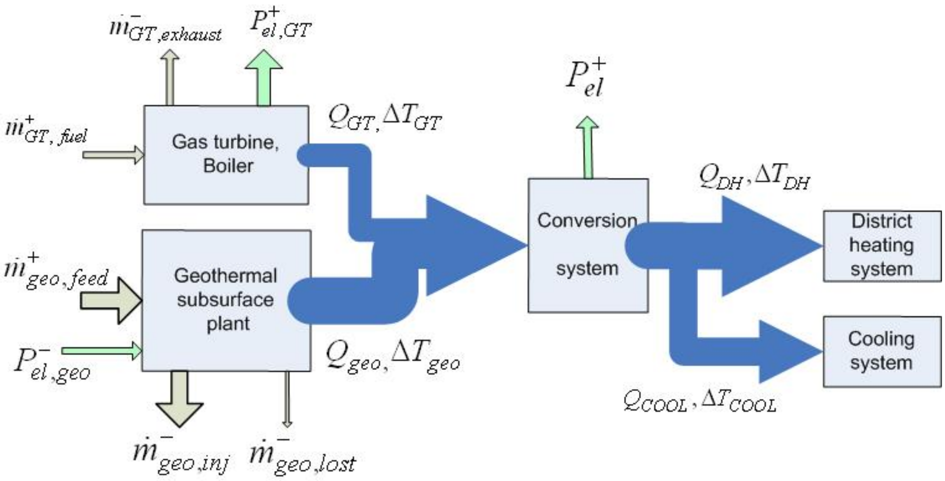

Figure 2.1: Geothermal power plant flowsheet.

2.2. Potential of the Geothermal process

The geothermal plant potential is the maximal amount of mechanical work, and thus electricity, that can be obtained from the geothermal plant. It is expressed by the thermodynamic concept of exergy. Exergy represents the maximum mechanical work, which could ideally be obtained, from each energy unit being transferred or stored, using reversible cycles realizing exchange only with the ambiance. By comparing the exergy available in the geothermal source and the effective work that is produced, one may calculate an efficiency that defines the optimality of the conversion system. Moreover, the concept of exergy presents the advantage of producing system-independent efficiency definitions, formally defined by the quotient 2.1 below.

$$\frac{\sum exergetic\ services\ delivered\ by\ the\ system}{\sum exergetic\ contributions\ received\ by\ the\ system} \qquad (2.1)$$

This definition allows comparing different types of conversion systems receiving exergy from a geothermal heat source cooling down from T_{in} to T_{out}. By definition, the mechanical exergy equal the mechanical work, and the exergy of the heat is calculated by integration from inlet to outlet temperatures by formulae 2.1:

$$\dot{E}_x = \int_{T_{out}}^{T_{in}} \left(1 - \frac{T_a}{T}\right) \delta\dot{Q} = \dot{Q} \cdot (1 - \frac{T_a}{\Delta T_{\ln}}) \qquad (2.2)$$

2.3. Graphical representation of the geothermal process potentials

In the pinch theory, hot and cold composite curves are used to represent the heat exchange between hot streams that are cooled down and cold stream that are heated up. In the heat – temperature diagram of figure 2.2, the hot composite curve in red represents the heat available in the system as a function of the temperature. The cold composite represents the heat required by the cold streams of the system. Assuming a minimum approach temperature between streams ([2]), the composite curves allow to compute the maximum heat exchange between the hot and the cold stream and to estimate the area and the cost of the heat exchanger network. In our study, this method has been used to model the heat exchangers between the conversion equipment and the hot and cold geothermal process fluxes.

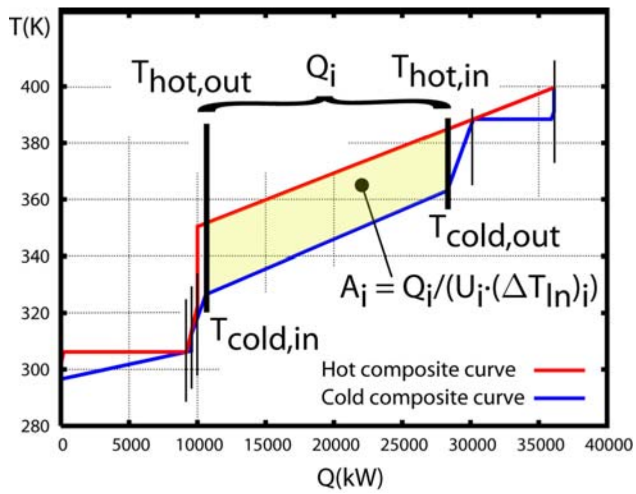

Figure 2.2: Hot (red) and cold (blue) composite curves.

The grand composite curve $\theta(Q)$ describes for each temperature T and related Carnot factor $\theta=1-(T_a/T)$, the total amount of heat to be supplied or removed from the system. The area enclosed by the geothermal process grand composite curve (figures 2.4 to 2.7) represents the geothermal process exergetic potential. The exergetic potentials of the geothermal source for different production/reinjection water temperature are shown in figure 2.3.

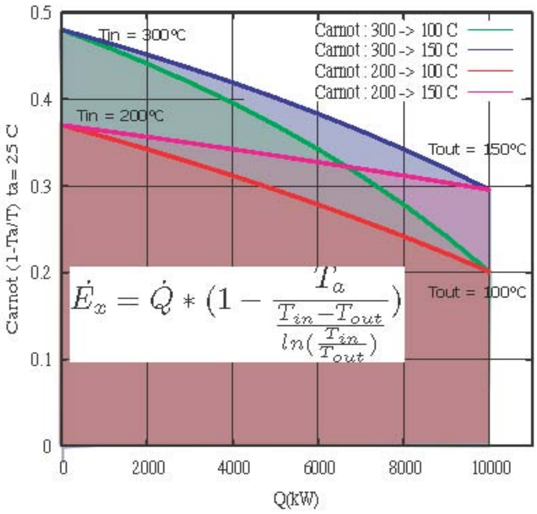

Figure 2.3: Geothermal source exergetic potential for some production(T_{in}) and reinjection(T_{out}) temperatures.

For each geothermal process, the shape of the grand composite curve defined by the known heat flux exhibit a typical aspect. From this curve, we can deduce the **geothermal process exergetic potential** giving the maximum amount of energy that can ideally be converted into heat and/or electricity.

2.3.1. Basel Scenarios

The heat and cold fluxes for typical winter time operating conditions of the Basel case study are given in table 2.2.

The corresponding grand composite curve is shown in figures 2.4 and 2.5. The exergy contained in this system is equal to 8130 kW (figure 2.5). It represents a upper bound for the amount of mechanical work, and thus electricity that can be obtained in this situation.

Table 2.2: Basel, typical flux

Flux	Inlet temperature [°C]	Outlet temperature [°C]	Heat load [MW]	Dtmin/2 [K]
GEO	190°C (463.15 K)	70°C (343.15 K)	30	4.3
DH	55°C (328.15 K)	120°C (393.15 K)	15	2

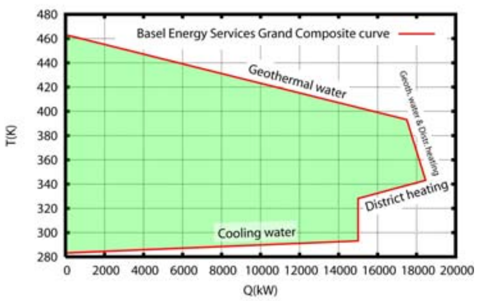

Figure 2.4: Basel grand composite (Q-T).

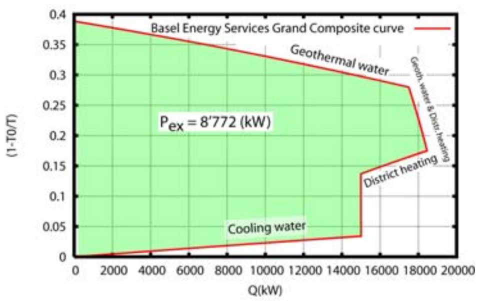

Figure 2.5: Basel exergetic potential and grand composite curve (θ-T)

2.3.2. Lavey Scenario

The heat and cold fluxes for typical operating conditions of the Lavey case study with a district heating consumption of 10 MW_{th} are given in table 2.3.

The corresponding grand composite curve is shown in figure 2.6. The exergy contained in this system is equal to 5453 kW.

Table 2.3: Lavey, typical flux

Flux	Inlet temperature [°C]	Outlet temperature [°C]	Heat load [MW]	Dtmin/2 [K]
GEO	110°C (402.15 K)	80°C (353.15 K)	26.018	3.4
DH	65°C (323.15 K)	90°C (359.15 K)	14.937	3.4
COOL	10°C (283.15 K)	20°C (293.15 K)	11.081	3.4

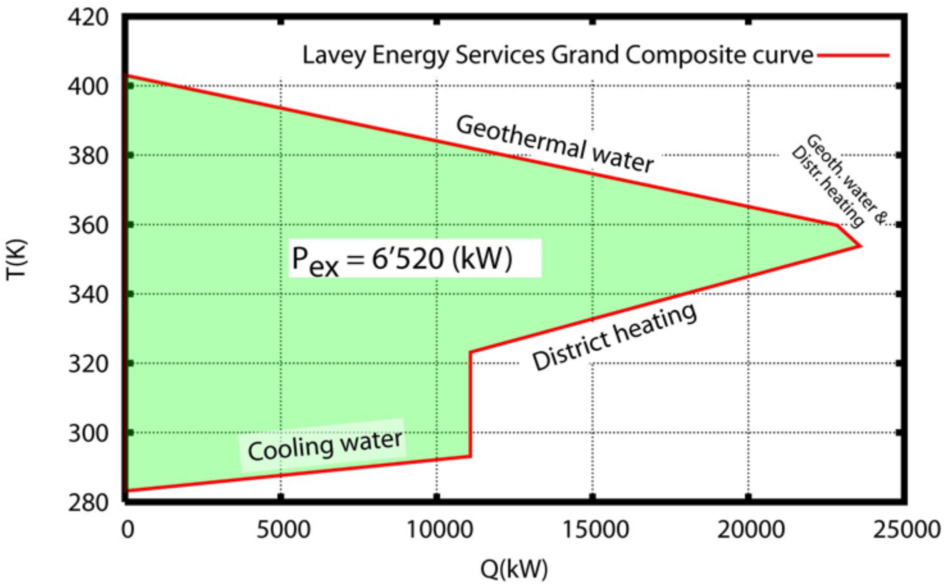

Figure 2.6: Lavey potential and the grand composite curve (Q-T)

2.3.3. Geneva Scenario

For the Geneva scenario, the variation of the district heating consumption is taken into account, and the analysis is performed on the highest (40 MW_{th} in winter) and lowest (5 MW_{th}) value of the demand. During winter (table 2.4), the heat required by the district heating is higher than the geothermal thermal capacity. The district heating operates as a geothermal flux coolant and the additional heat is supplied at high temperature (575°C) by a gas turbine or a boiler (figure 2.7). The maximal amount of mechanical work that can potentially be extracted out of the system is 15'513 kW.

In summer (table 2.5) a cooling power up to 15 MW_{th} is required if one wants to exploit the exergetic potential of the process. The exergetic potential fall to 6'098 kW provided that the gas turbine is kept unused.

Table 2.4: Geneva, typical flux (Winter)

Flux	Inlet temperature [°C]	Outlet temperature [°C]	Heat load [MW]	Dtmin [°K]
GT	575°C (848.15 K)	125°C (398.00 K)	18	25
GEO	200°C (473.15 K)	140°C (413.15 K)	22	4.3
DH	55°C (328.15 K)	120°C (393.15 K)	40	2

Table 1.5: Geneva, typical flux (summer)

Flux	Inlet temperature [°C]	Outlet temperature [°C]	Heat load [MW]	Dtmin [°K]
GEO	200°C (473.15 K)	140°C (413.15 K)	20	4.3
DH	55°C (328.15 K)	120°C (393.15 K)	5	2
COOL	10°C (283.15 K)	20°C (293.15 K)	15	4.3

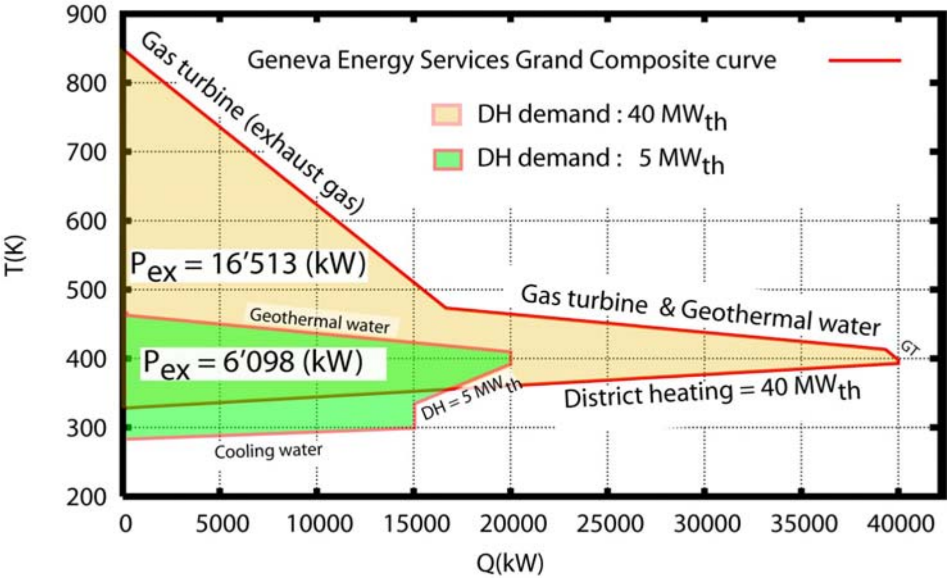

Figure 2.7: Geneva potential and the grand composite curve (Q-T).

3. Energy conversion of geothermal resources

There exist several ways of converting a geothermal energy resource in useful energy. The first distinction has to be made concerning the energy services to be supplied: electricity and heat. While the first may be distributed through a network and can be considered as a base load power, the second depends on the location and the way it may be distributed. In some situation, heat may be used locally, for example in thermal centers applications, in other situation heat has to be distributed through a district heating network to satisfy the needs of the heating requirements of a district or a city. In this case, the evaluation of the geothermal energy valorization has to account for the variations of the heat demand as well as of the temperature level at which the heat is distributed. To account for the difference of temperature between the geothermal heat resource temperature and availability and the corresponding demand, combined heat and power production systems are usually envisaged.
The conversion of geothermal heat into electricity and heat is realized by three major types of thermodynamic cycles:

- Flash cycles: where the working fluid is the water of the underground systems and is flashed before being expanded in a condensing turbine
- Steam cycle.
- Rankine cycle: where the heat of the geothermal source is used to evaporate a pressurized fluid that is expanded in a condensing turbine, the outlet of the turbine being condensed in a condenser by exchange with a cold source that may be the environment or the one used to cogenerate some heat. Due to the relatively low temperature of the geothermal source, organic fluid is used instead of water in the cycle.
- Kalina cycle: where the fluid is a mixture of water and ammonia and where the partial pressure effect of the mixture separation is used to increase the efficiency of the cycle.
- Other cycles like trilateral cycles that directly expand liquid fluids that evaporate in the turbine, or thermo-electric cycles applying the Seebeck effects. However, the state of the art of the technologies is not showing attractive efficiencies for these technologies.

Our study was therefore focused on the first three cycles. It is worth mentioning that the implementation of each of these cycles require a cold source to operate. The following figure 3.1 shows the value of electricity and cold source requirement as a function of the temperature of the hot and cold sources which are assumed to be at constant temperature.

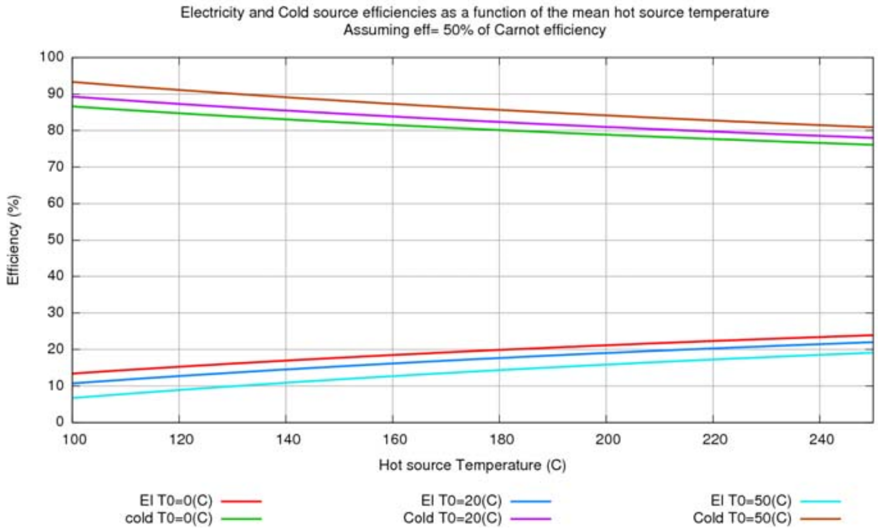

Figure 3.1: Electrical efficiency (El) and cold source requirement (Cold) as a function of the hot and cold source temperature, (Carnot efficiency assumed to be 50 %)

3.1. Flash Cycles

The principle of a flash cycle is given in figure 3.2. The high pressure hot water at the outlet of the geothermal well is expanded to an appropriately selected pressure (p_{in}) to produce a certain amount of steam to be expanded in a condensing steam turbine that operates under atmospheric pressure. The optimal pressure (p_{in}) is computed to optimise the power conversion as shown on figure 3.3. This calculation has been made assuming a source temperature of 200°C and 17 bar and a water flow of 84 kg/s at the outlet of the geothermal well, a reinjection temperature of 100°C and 115 bar, assuming water losses of 10 kg/s.

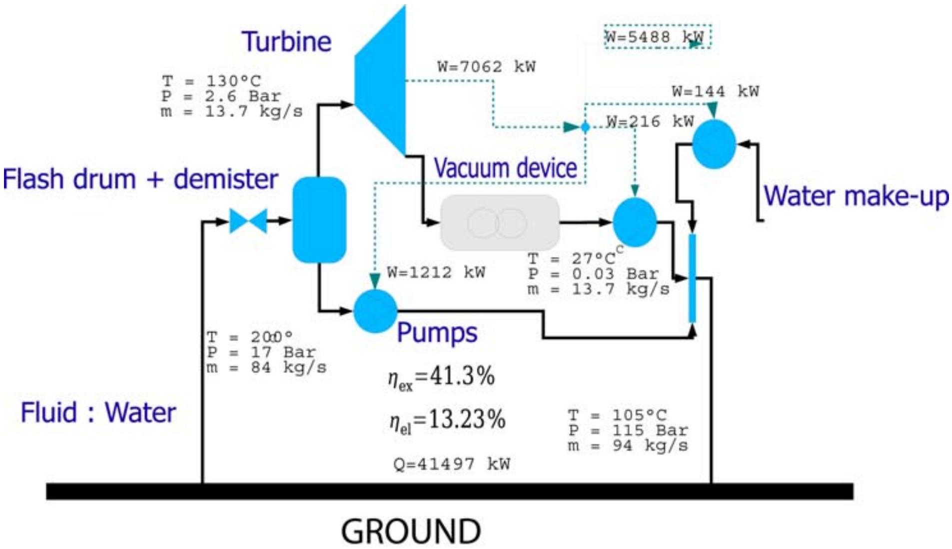

Figure 3.2: Flowsheet of a flash cycle

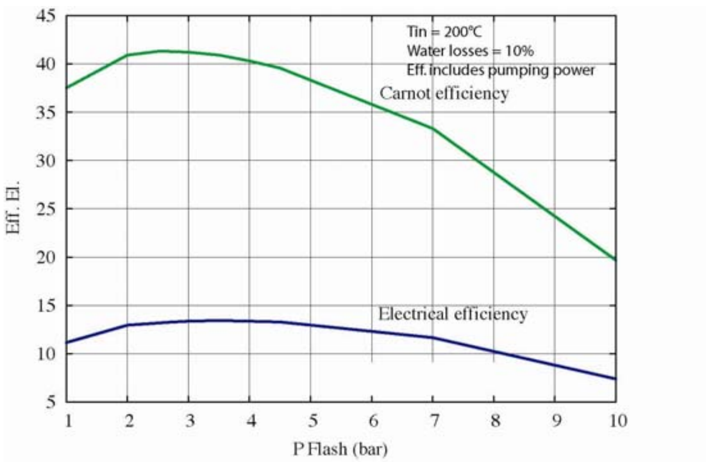

Figure 3.3: Calculation of the optimal pressure of a flash cycle

Based on the data given on figure 3.2, the Carnot efficiency of the cycle amount 41 % and includes the pumping power of the condensed water.

Adding a second stage in the water expansion and reinjecting the water at a medium pressure allows to increase the efficiency of the cycle (figure 3.4). Assuming the same conditions for the geothermal sources a Carnot efficiency of 55% may be reached once the pressures in the cycle are optimised.

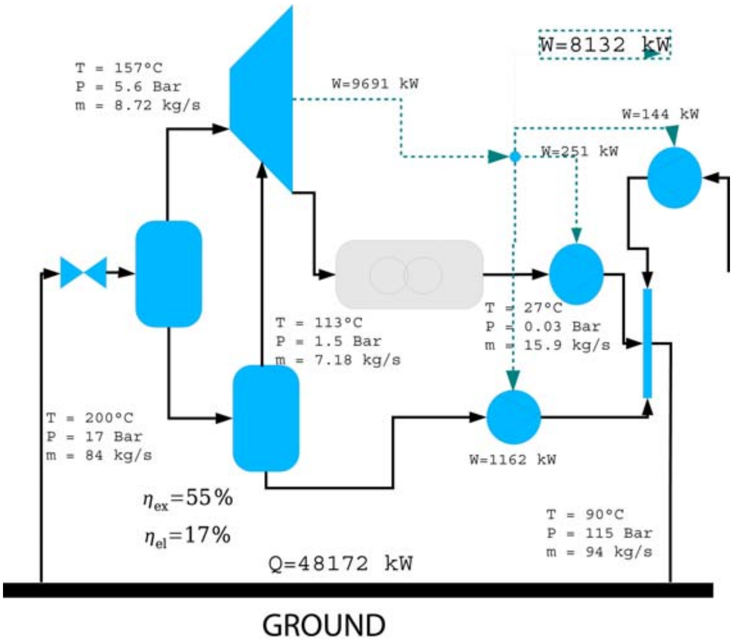

Figure 3.4: Flow sheet and conditions of a 2 stages flash cycle

It is possible to increase the efficiency of the cycle by integrating the use of a gas turbine (figure 3.5) in order to increase the temperature at the inlet of the steam turbine (super heating). In this case, the power of the gas turbine is about 1/2 of the steam turbine, and Carnot efficiency of the system amounts around 48 % with a single pressure flash cycle. The marginal efficiency of the natural gas used in the gas turbine amount 46 %. This value is computed as being the ratio between the additional production of mechanical power in the conversion system (using the flash cycle without surperheating as a reference) and the lower heating value of the natural gas used in the gas turbine. In our example, the gas turbine has an efficiency of 30%.

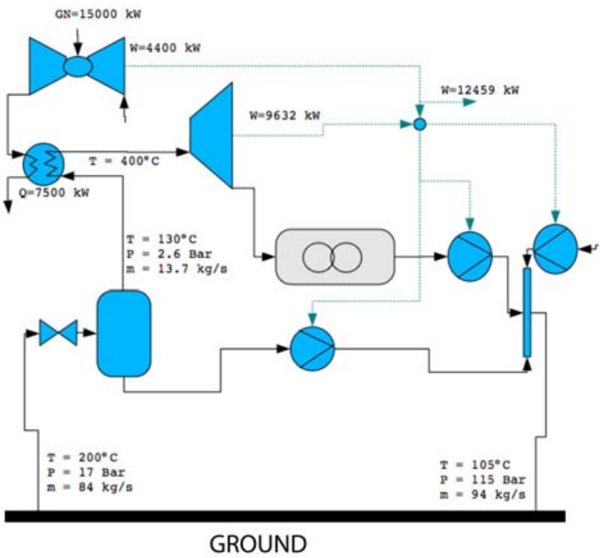

Figure 3.5: Flow sheet and conditions of a gas turbine integrated with one flash cycle

As the flash cycle produces a large amount of hot water (saturated liquid), flash cycles are therefore good candidates for the integration of combined heat and power production. A flowsheet of such a cycle is given on figure 3.6. Due to the fixed temperature imposed at the reinjection, the flash drum pressure has to be optimised according to the temperature and the heat flow required by the district heating system. The efficiency as well as the maximum temperature of the district heating system and the share of heating and electricity of a flash system is drawn as a function of the flash pressure on figure 3.7. Exergy efficiencies are computed considering the electricity and the exergy of the heat delivered to the district heating system.

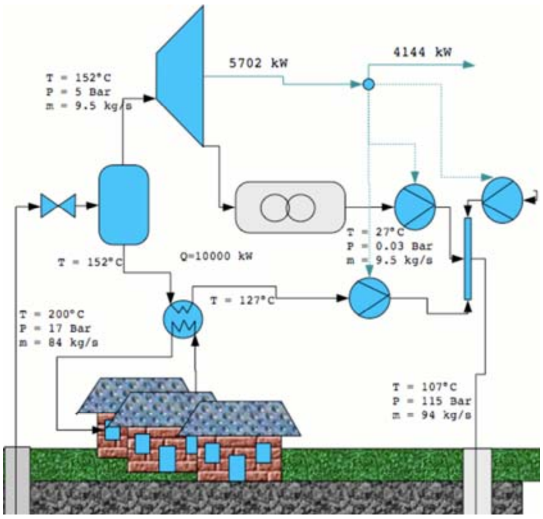

Figure 3.6: Flow sheet and conditions of a flash cycle integrated with a district heating system

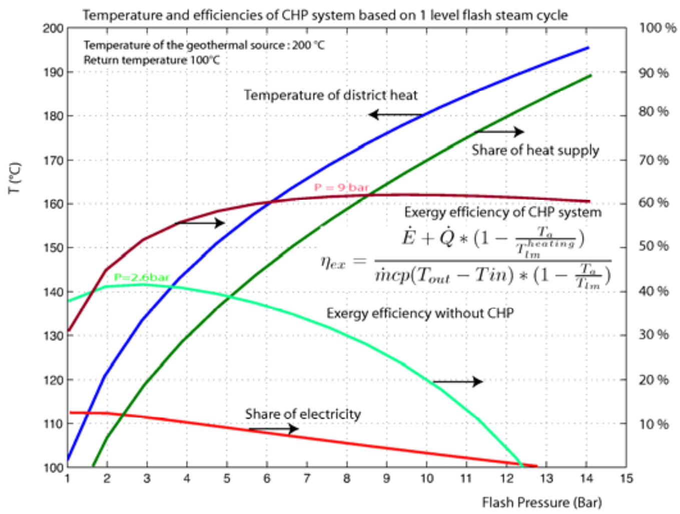

Figure 3.7: Efficiencies as a function of the flash pressure for single pressure flash systems with and without combined heat production

3.1.1. Flash cycles: conclusions

When designed with pressure flash drums, flash cycles may reach high conversion efficiencies and are suitable for combined heat and power applications especially in cases of low temperature heat distribution systems. In such situations however, the design of the turbine to follow the varying demands of heat production may be critical, since the flash drum pressure should be adapted to track the maximum efficiency of the system.

The major drawback of the flash systems is that these operate using the geothermal fluid whose flash steam is directly injected in the turbine. It seems that in Switzerland it won't be possible to use the geothermal fluid directly in the turbine because of expected bad water quality. Another disadvantage of

such systems is its operation below atmospheric pressure which requires the use of vacuum equipment, as well as large equipment able to handle huge volume of vapor stream.
Some applications of flash cycles have been cited by Dipippo [6] and are summarized in table 3.1.

Table 3.1: Examples of flash cycle applications

Site	Guanacaste	Beowawe
Exergy eff	29.5%	46.7%
Size (MW)	55	16.7
Cost ($/kW)	NA	1900
year	1994	1985
Source T(°C)	230	215
Operating pressure (bar)	6.0	4.21/0.93
Condensing (bar)	0.123	0.044
nb flash	1	2
Country	Costa Rica	USA (Nevada)

3.2. Rankine cycles

The Rankine cycles are the most widely used cycles to converted heat into electrical power. Due to the relatively low temperature of the hot source, organic fluids are usually preferred to steam. Such cycles are named Organic Rankine Cycles (ORC). The selection of the most appropriate fluid depends on the temperature of the source and of the application of the cycle. In this report, an analysis of the different fluid will be considered. The principle of the Rankine cycle is illustrated on figure 3.8. In ORC systems a heat exchanger is used to transfer heat from the geothermal source to the organic fluid. Flowsheet optimisation is discussed later in the report. The major flowsheet options used to increase the efficiency are briefly explained below with one example. It should be mentioned that the operating conditions have to be optimised to reach the optimal integration.

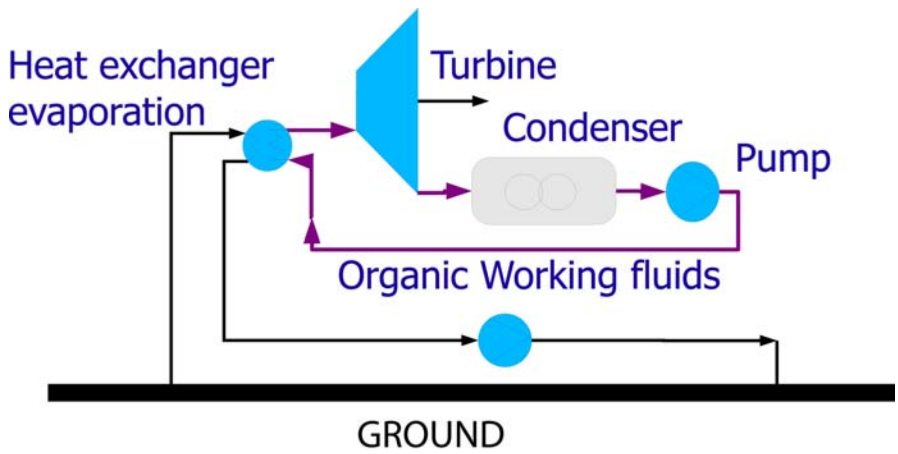

Figure 3.8: Principles of the Organic Rankine cycle

Table 3.2: ORC application example from the literature

Plant	Svartsengi ([7])	Mammoth Pacific([6])	Amedee([6])
Exergy eff	35% (est.)	22.7	13.9
Size (MW)	1	3.5	0.8
Cost US$/kW)	2400 (est.)		
Source Tin (°C)	103	169	103
Source Tout (°C)	95	66	71
Evaporation P (bar)	6.2	33.79	9.9
Condensing P (bar)	NA		2.76
Fluids	isopentane	isobutane	R-114
Location	ICELAND	USA (Ca)	USA (CA)
	ORMAT	ORMAT	Barber Nichols

3.2.1. Heat integration

In order to optimise the conversion efficiencies, and when the temperatures allow for it, the cycle flowsheet is adapted by adding a heat exchange recovery between the outlet of the turbine and the pressurized liquid to preheat it, as shown on figure 3.9. The method used for the integration is based on the pinch theory and results in the optimal integration that is represented by the integrated composite curves of figure 3.10.

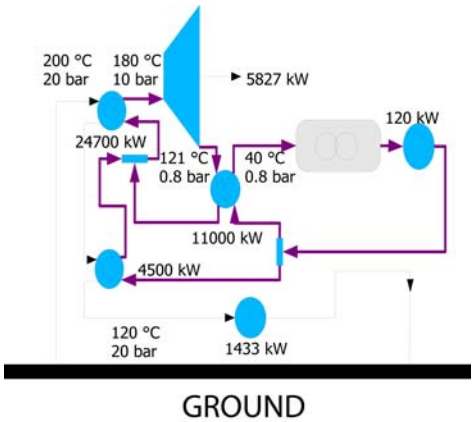

Figure 3.9: Principles of the Organic Rankine cycle with feed preheating

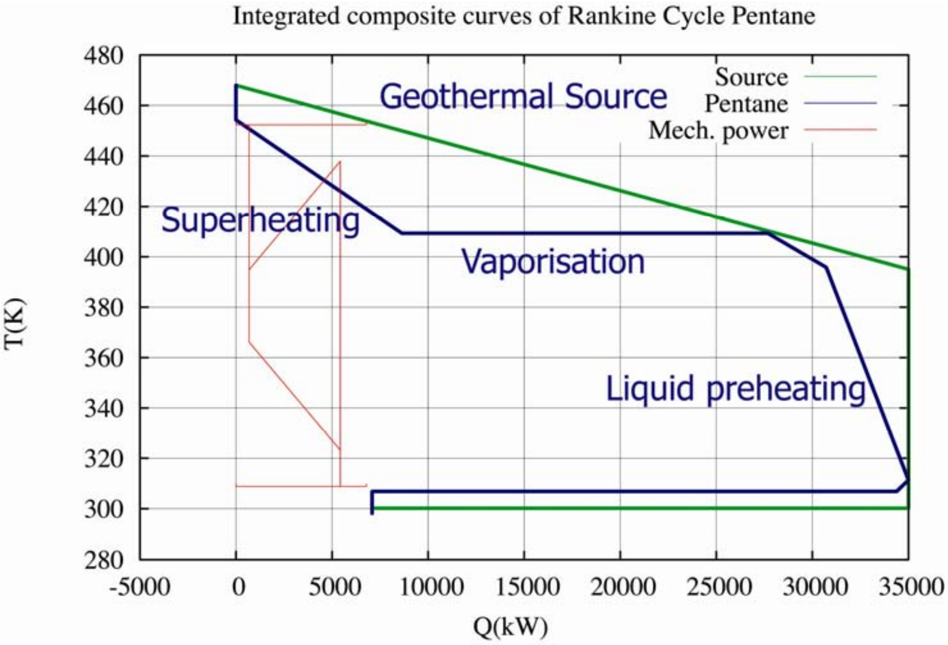

Figure 3.10: Integrated composite curves of an ORC

3.2.2. Using fluid mixtures

The use of fluid mixtures allows to reduce the exergy losses in the evaporator by introducing a glide in the vaporisation temperature profile. In this case, it is important to define the appropriate fluid mixture composition as a function of the hot and cold source temperatures. The following table (3.2) shows two applications of fluid mixtures reported in the literature [9]. The fluid mixture optimisation is discussed in more details in the following.

Table 3.1: Example of the mixtures proposed in the literature as a function of the source temperature

Source temperature	Mixture
130 (C)	98 % propane - 2% pentane
200 (C)	93 % isobutane - 7%hexane

Table 3.3: Exemple of mixture proposed in the literature as function of the source temperature.

Source temperature	Mixture
130 (°C)	98 % propane - 2% pentane
200 (°C)	93 % isobutane - 7% hexane

3.2.3. Two pressure levels

Producing superheated fluid at different pressure levels allows to reduce the losses in the evaporation by staging the evaporation. The fluid at an intermediate pressure level is injected in the turbine after being superheated. In this case, the heat exchanger network becomes much more complex as shown on figure3.11.

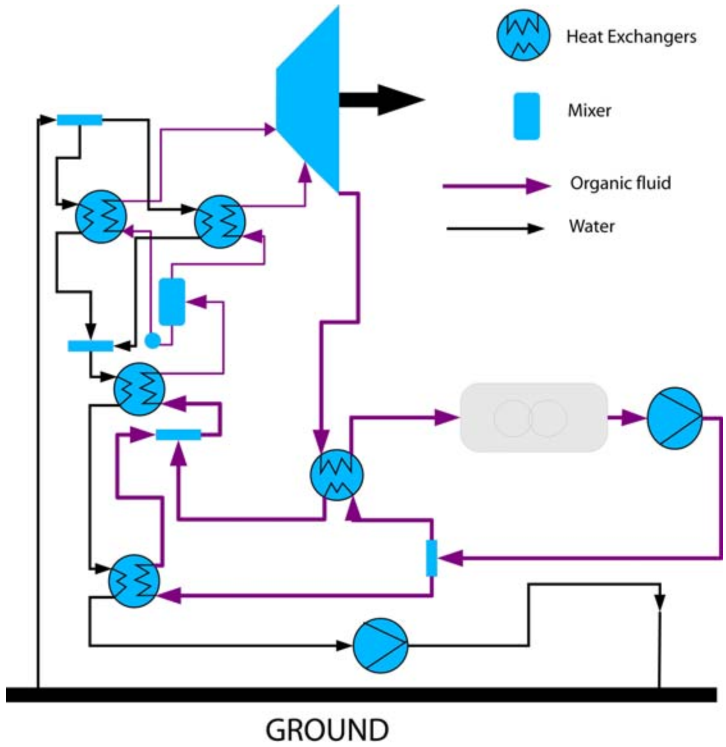

Figure 3.11: 2 stages ORC cycle with regeneration exchange

In this scheme, all the pressures and the temperatures have to be optimised.

3.2.4. Two pressure levels and preheating extraction

In order to further increase the efficiency it is also possible to add a draw off to the turbine. This draw off will be used to preheat later the pressurized liquid. The draw off supplements the turbine outlet stream to preheat the liquid up to the geothermal reinjection temperature. The resulting cycle has therefore a minimum exergy loss in the heat exchanges as shown on figure3.13. In this case, the Carnot efficiency of the cycle reaches 72 %, major characteristics of the cycle are given in table 3.4. The fluid is n-butane.

Table 3.4: Results of the integration of a 3 stages ORC

ORC [kWe]	9177
HP (33 b)- Cond (2.37 b) [kWe]	7106
HP (33 b)- draw of (10 b) [kWe]	542
MP (22 b)- Cond (2.37 b) [kWe]	1959
Geothermal source [kW] (463 K - 381 K)	43136

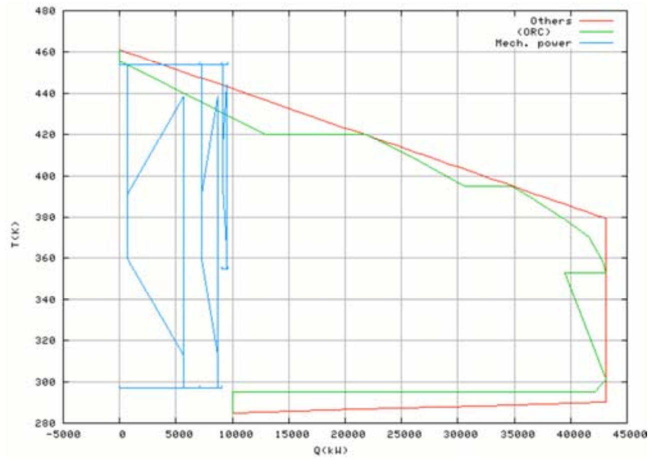

Figure 3.13: 3 Stages (2 pressure levels) ORC cycle with regeneration exchange

3.2.5. Gas turbine integration

Adding a gas turbine together with an organic Rankine cycle is also feasible, the gas turbine being used to superheat the organic fluids. However, when comparing with the flash cycle, it can be seen that the heat exchanger network system will be different since both the geothermal fluid and the flue gases of the gas turbine have to be cooled down to approximatively the same temperature. The heat exchanger system will therefore be more complicated.

Using the same data than the calculation above, it can be shown that the exergy efficiency of the system is of 51% accounting for both the geothermal fluid and the gas turbine efficiency (due to the size of the turbine an electrical efficiency of 28 % has been considered). table 3.5 shows the major results of this calculation and figure 3.14 shows the integrated composite curve of the ORC. In this application, the Carnot efficiency of the Rankine cycle is of 65.4 %. This explains by the fact that the losses in the flue gases are higher due to a higher inlet temperature. Considering the exergy value of the natural gas, the system has an overall exergy efficiency of 50.74 %. It is possible to calculate the marginal efficiency of the natural gas by comparing the 3 level system that uses only the geothermal source and the one that uses the gas turbine. Starting with an efficiency of 28 %, the additional electricity produced with the integration of the gas turbine amount 44.6 %.

Table 3.5: Results of the integration of a 3 stages ORC integrated with a conventional gas turbine

Mechanical power produced [kWe]	24393
ORC [kWe]	15048
GT [kWe]	9345
GT Natural Gas [kW]	34106
GT Heat [kW] (848 K - 398 K)	20877
Geothermal source [kW] (463 K - 381 K)	43136

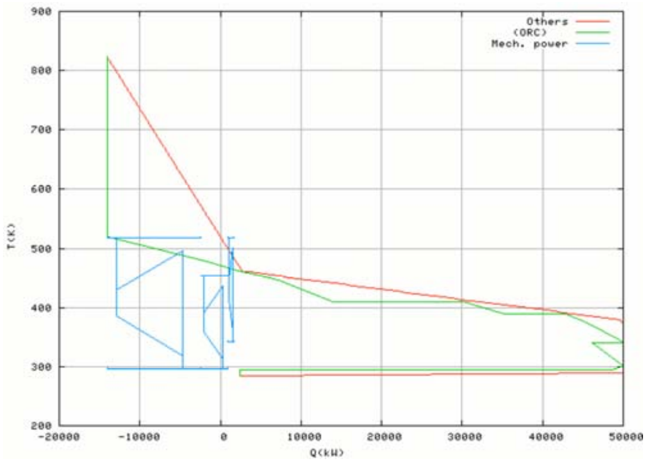

Figure 3.14: Integrated composite curve of the ORC for the configuration 3 stages (2 pressure levels) ORC cycle with regeneration exchange and gas turbine integration

The same scheme may be used as well to integrate a combined heat and power production, as discussed later in the report.

3.3. Kalina Cycles

Kalina cycles have been already studied by Brand [10]. One of the results corresponding to a Carnot efficiency of 56 % is shown on figure 3.15. To allow a more detailed analysis with the methodology described in this report, rigorous thermodynamic models have to be integrated in the analysis (the mixture ammonia-water can not be handled by conventional thermodynamic methods). Integration of specific methods for ammonia water cycles is under development at LENI. Therefore only partial results can be cited here.

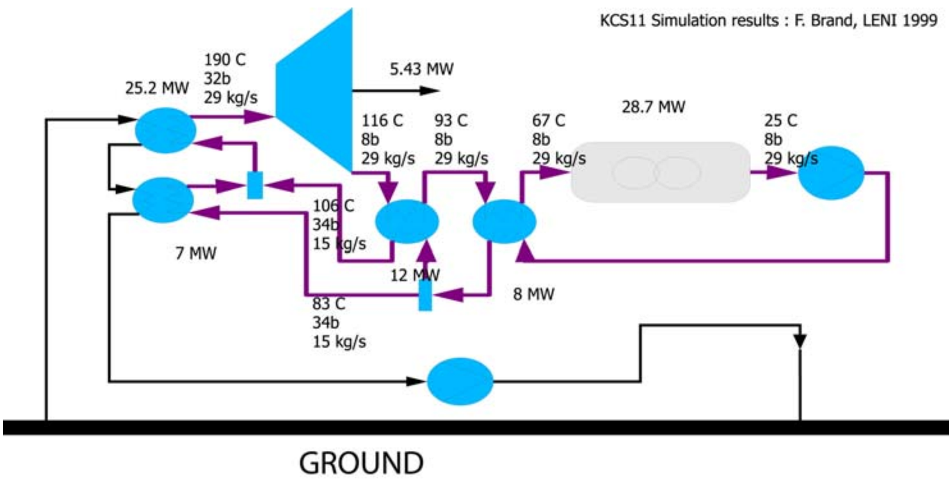

Figure 3.15: Flowsheet of a Kalina cycle

4. Thermo-economic model for the geothermal power plant.

The first part of this chapter describe the model of the geothermal process, and the second the model of the conversion system.
The geothermal plant is composed of the following components: heat exchangers, centrifugal pumps, steam turbine, gas turbine or boiler, district heating system and geothermal subsurface plant.
The thermodynamic constants used are listed in table 4.1 and the economical parameters in tables 4.2 to 4.4 below.

Table 4.1: Conversion system constants

Name	Value	Unit
$\frac{U_2}{C_0}$	0.72	-
N_{Pump}	3000	[rpm]
C_{HX}	0.7948	-
U_{ref}	1602	W/(m^2 K)
U_L	560	W/(m^2 K)
U_V	380	W/(m^2 K)
U_{EVA}	3600	W/(m^2 K)
U_{COND}	1600	W/(m^2 K)

Table 4.2: Exchange rates

currency	USD currency
1 €$_{2005}$	1.1879 \$$_{2005}$
1 CHF$_{2005}$	0.8 \$$_{2005}$

Table 4.3: M&S indices

Year	Value
M&S$_{2005}$	1224.5
M&S$_{1996}$	1037

Table 4.4: Cost coefficients for the pumps

name	value
K1	3.5793
K2	0.3208
K3	0.02850
C1	0.1682
C2	0.3477
C3	0.4841
B1	1.80
B2	1.51

4.1. Geothermal process

The cost models of the geothermal subsurface plant include the investment to drill the borehole, the cost for the geothermal water pumps and the auxiliary gas turbine reported in table 4.1. The drilling cost was modeled as function of the borehole deepness with a specific cost of $C_{Drilling,spec}$= 3000 CHF/m. A deep layer temperature predictive model identified from data in [13] and reported in table 4.2, was used to relate the drilling costs to the underground temperature.

Table 4.1: Geothermal process cost function [\$$_{2005}$]

Element	Investment Costs
Borehole	$CI_{Drilling}(T_{deep})=0.8\cdot C_{Drilling,spec}\cdot(T_{deep}-22)\cdot 100/3.6$
Stainless steel pumps	*see table 4.3 with F_M=2.4*
Gas turbine	$1.1879\cdot(1564\cdot W^{08523})$

The subsurface plant flowsheet is visible in figure 4.1. The injection pump injects water in the deep layers of the earth's crust a 114.5 bar [10]. The water absorbs heat from the hot rocks at the temperature $T_{geo,deep}$, which is a function of the borehole deepness as shown in figure 4.1 and table 4.1. During its way back to the surface, the water is assumed to loss 10% of the injected mass flow and decreases its temperature by 10°C. At the surface, the geothermal water enters the heat exchangers at a temperature of $T_{geo,deep}$-10 °C and a pressure of 16.5 bar [10]. Then it is mixed at with 15°C feed fresh water pumped from 1 to 16.5 bar, and is reinjected again in the borehole.

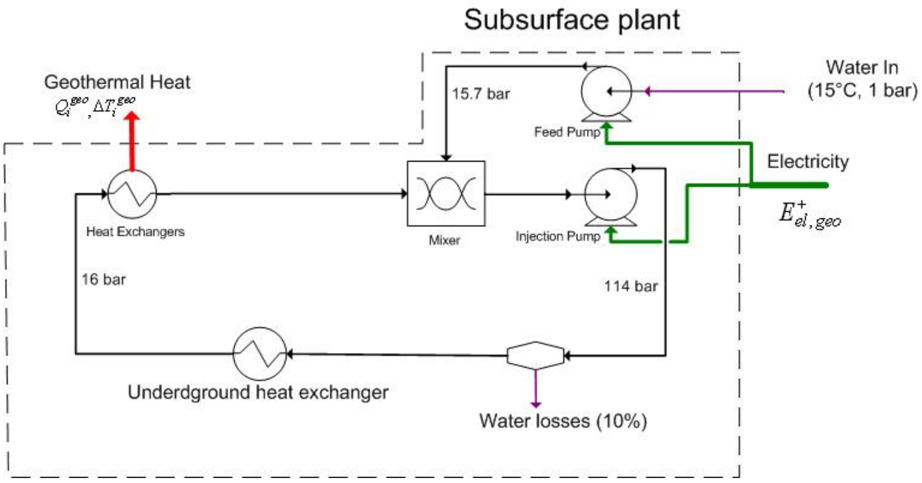

Figure 4.1: Geothermal subsurface process flowsheet

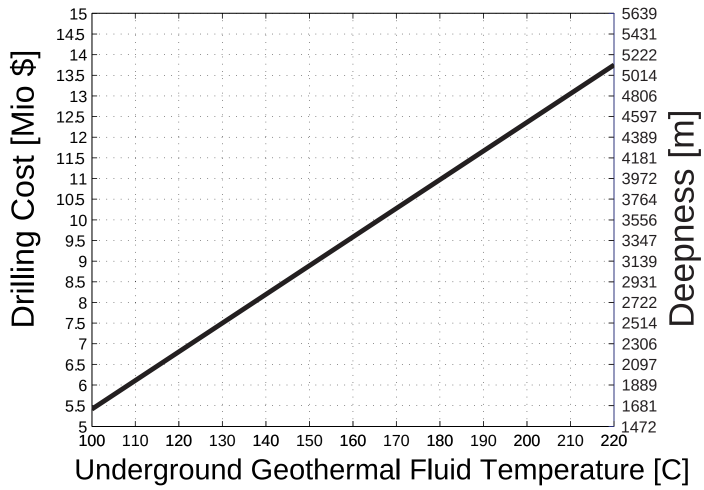

Figure 4.2: Drill hole deepness and cost vs. underground fluid temperature

Table 4.2: Geothermal process model

Elements	Equations
Subsurface plant	*Deep fluid temperature* $T_{deep}(h) = \frac{3.6}{100} \cdot h + 22$ *Surface fluid temperature* $T_{surf}(h) = T_{deep}(h) - 10$ *Mass balance* $\dot{m}_{geo,in} = \dot{m}_{geo,losses} = 0.1 \cdot \dot{m}_{geo}$ *Geothermal pumps model: equations table 4.5 with fixed (80%) isentropic efficiency.*
District heating System	$\dot{m}_{water} = \frac{c_{p,water}(T) \cdot \left(T_{feed} - T_{return}\right)}{\dot{Q}_{DH}}$
Gas Turbines	$\dot{W}_{mec} = \eta_{heat} \cdot \eta_{mec} \cdot \dot{Q}_{heat,\max}(\dot{m}_{fuel}, LHV_{fuel})$

4.2. Conversion plant
The investment cost function used for the heat exchangers, pumps, turbines and generators are resumed in table 4.3.

Table 4.3: Conversion process cost function [$\$_{2005}$]

Elements	Investments costs
Cast Steel Centrifugal Pumps [1]	$CI_P(P) = \frac{MS_{2005}}{MS_{1996}} \cdot \left[b_1 + b_2 \left(c_1 + c_2 \cdot \log(p_{out} - 1) + c_3 \log(p_{out} - 1)^2 \right) \cdot F_M \right] \cdot 10^{k_1 + k_2 \log(P_{mec}) + k_2 \log(P_{mec})^2}$ *Cast steel:* $F_M = 1.8$
Turbine & Generator [8]	$CI_{T+G}(P_{mec}) = (82872.8204 - 1163981.4884 \cdot \log(P_{mec}) + 487436.7695 \cdot \log(P_{mec})^2)$
Heat Exchangers [11]	$CI_{HX}(A) = (MS_{2005} / 1069.9) \cdot 7038 \cdot A^{c_{HX}}$

4.2.1. Pumps
The investment cost of the pumps is expressed as a function of the pumps power, the output pressure and the pumps material. It is explicited in figure 4.4 for cast steel pump for some fixed output pressure. The thermodynamic model for the pump is based on the implicit isentropic efficiency equation of table 4.4. The figure 4.3 shows the dependence of the isentropic efficiency to the specific speed (N_s) which is a non-dimensional design index used to classify pump impellers as to their type and proportions.

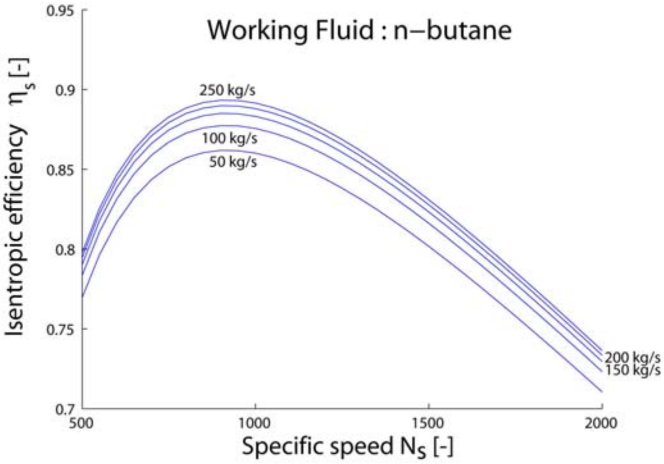

Figure 4.3: Pump specific speed-isentropic efficiency

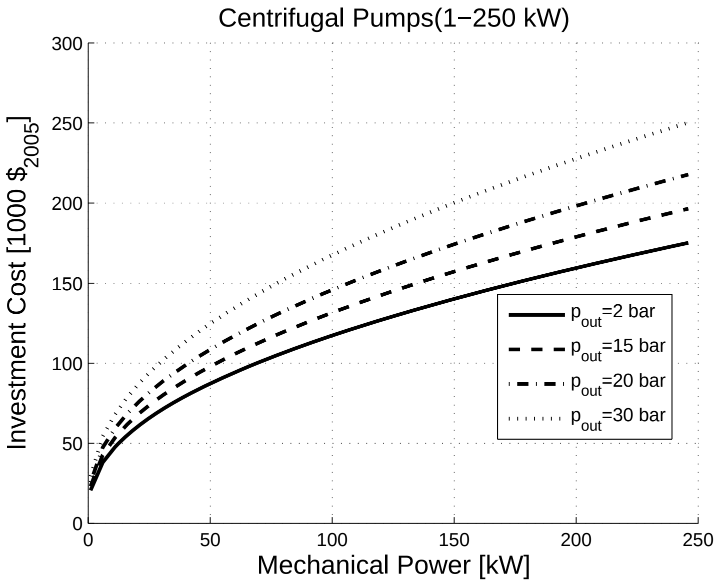

Figure 4.4: Cast steel centrifugal pump investment cost (p_{out} = … bar).

4.2.2. Turbines and generators

The rate of conversion of geothermal power into electricity depends on the turbine and generator efficiency. The efficiency equations for turbines are taken from a validated model [8] based on Balje [15] relations of table 4.5.

A sensitivity analysis of the efficiency of a single stage orc turbine in function of the input pressure, for operating conditions given in table 4.4, is shown in figure 4.5. The maximal power is generated at an input pressure of 7.8 bar, and the model predict a significant degradation of the efficiency for input pressure greater than 10 bar (figure 4.6).

Table 4.4: Constant for the turbine model sensitivity analysis

Name	Value	Unit
Working fluid	n-pentane	-
Turbine inlet temperature	185	C
Condensation temperature	33	C
Condensation pressure	1	bar
Geothermal water production/injection temperature	200/100	C
Cold source temperature	10	C

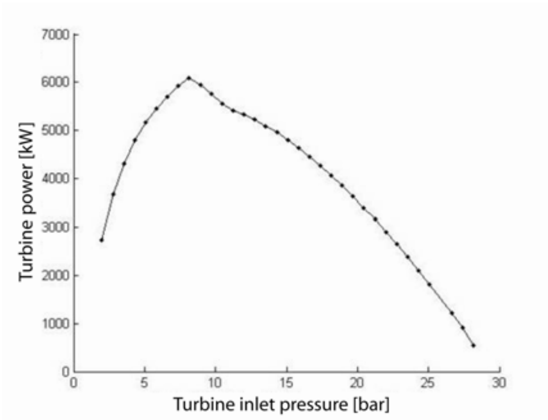

Figure 4.5: ORC turbine (p_{in}-$P_{turbine}$)

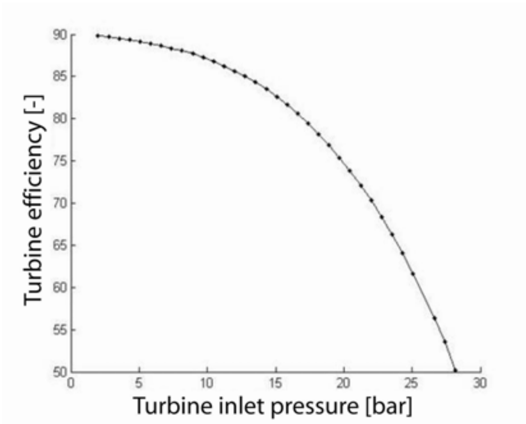

Figure 4.6: ORC cycle (p_{in}-η_s)

The investment cost function for the turbine and generator groups, shown in figure 4.6, come from a formulation of [1] reconciled with cost datas found in [8].

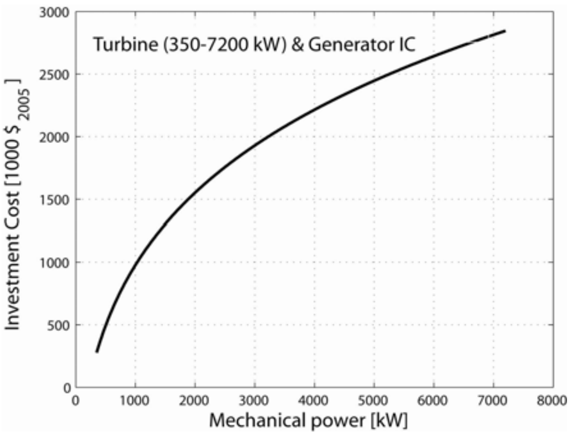

Figure 4.6: Turbine and generator investment cost model.

Table 4.5: Pumps equations

Centrifugal Pumps equations
Mass balance $\dot{m}_{in} = \dot{m}_{out}$
Energy balance $\int_{in,s}^{out,s} \delta e^{+} = \int_{in,s}^{out,s} v dp = \int_{in,s}^{out,s} dh = h_{out,s} - h_{in,s}$
Isentropic efficiency $E^{+}_{mec} = \eta_s \cdot \left(h_{out,s} - h_{in,s}\right)$
Discharge head relation $gH = E^{+}_{pump}$
Isentropic efficiency (implicit) $\eta_s = 0.94 - \left(13.2 \cdot Q\right)^{-0.32} \cdot (1 - f(\eta_s))$ $f(\eta_s) = 0.29 \cdot \left[0.32 - \log_{10}(\frac{1.5 \cdot N_s(\eta_s)}{1000})\right]^2$
Specific speed $N_s(\eta_s) = \frac{N \cdot \sqrt{Q}}{\left(\frac{1}{n} \cdot H(\eta_s)\right)^{3/4}}$
Number of pump stage $n = \left[\frac{H}{125} + 1\right]$
Mechanical power $W^{+}_{mec} = \dot{m}_{in} \cdot \eta_s \cdot \left(h_{out,s} - h_{in,s}\right)$
Mechanical losses $W^{-}_{losses} = W^{+}_{mec} \cdot 0.07$
Electrical power $W^{+}_{el} = \frac{W^{+}_{mec} + W^{-}_{losses}}{0.98}$

Table 4.6: Steam Turbine and generator equation

Steam Turbine and generator equation
Mass balance $\dot{m}_{in} = \dot{m}_{out}$
Energy balance $\int_{in,s}^{out,s} \delta e^{-} = gH = \int_{in,s}^{out,s} -dh = h_{in,s} - h_{out,s}$
Isentropic efficiency $\Delta h = \eta_s \cdot \left(h_{in,s} - h_{out,s}\right)$
Speed and diameter relation $C_0 = \sqrt{2 \cdot \Delta h_s}$ $N = \frac{N_s \cdot Q_3^{1/2}}{H^{3/4}}$ $D = \frac{U_2}{C_0} \cdot \frac{60 C_0}{\pi \cdot N}$
isentropic efficiency $\eta_s = \eta\left(n_s, D, \frac{p_{in}}{p_{out}}\right)$
Adimansionnal speed $n_s = \frac{w \cdot \sqrt{Q_3}}{\Delta h_s^{3/4}} = \frac{N_s \cdot \pi}{30 \cdot g^{3/4}}$
Number of pump stage
Mechanical power $W^{+}_{mec} = \dot{m}_{in} \cdot \eta_s \cdot \left(h_{in,s} - h_{out,s}\right)$
Mechanical losses $W^{-}_{losses} = W^{+}_{mec} \cdot 0.07$
Electrical power $W^{+}_{el} = \frac{W^{+}_{mec} - W^{-}_{losses}}{0.98}$

4.2.3. Heat Exchangers

The amount of heat exchanged between the hot and cold streams of the process through the heat exchanger network is given by

$$Q = \sum_{\text{Heat Exchangers}} U_i \cdot A_i \cdot \Delta T_{\ln,i} \qquad (4.1)$$

The heat exchanger network design is influenced by the minimum temperature differences allowed in the exchangers:

$$\Delta T_{\min,i} / 2 = \Delta T_{\min,ref} / 2 \cdot \left(\frac{U_i}{U_{ref}}\right)^{-C_{HX}} \qquad (4.2)$$

The overall heat exchange coefficients U_i used are given in table 4.1. The sensitivity of this minimum temperature difference DT_{min} for evaporators, condensers, vapor-vapor and liquid-liquid exchangers is shown in figure 4.7 as a function of a reference minimum temperature difference. The $DT_{min}/2$ lower bounds value($DT_{min,ref}/2=1$) is shown in table 4.7

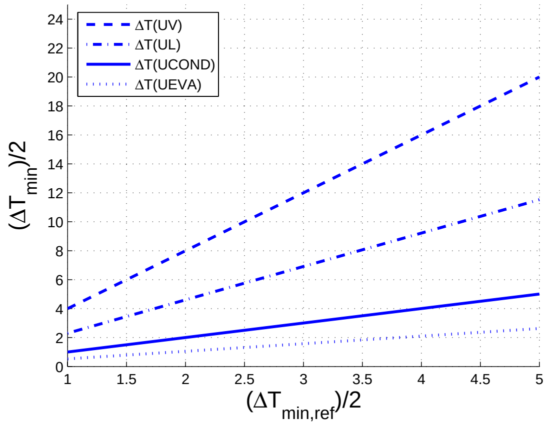

Figure 4.7: Heat Exchanger Dt_{min} versus $DT_{min,ref}$

Table 4.7: Calculated temperature difference: U_{ref} = 1602 W/(m^{2}K), $DT_{min,ref}$ = 1 °C.

Minimum temperature difference	Liquid	Vapor	Evaporator	Condenser
DTmin/2 [°C]	2.3057	4	0.52543	1

The heat exchanger investment cost function shown in figure 4.7, was proposed by [10]. It is a function of the exchanger's area and is reported in table 4.3.

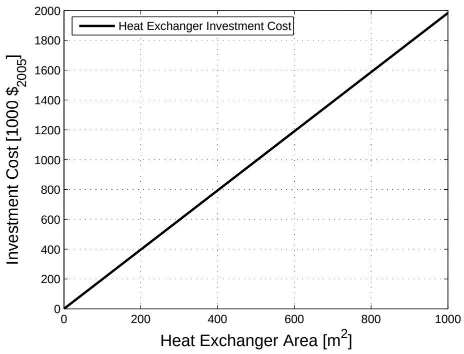

Figure 4.8: Heat Exchanger investment cost

5. Methodology used to solve the integration issue.

5.1. System integration

The task of process integration is to find the optimal sizes and the thermodynamic states of the sub-systems of the process. The complexity of this highly non linear and multivariable problem can be reduced by isolating linear sub-problems, instead of considering all the individual unit operations. This can be achieved by identifying the **heat fluxes utilities** of the system, which are the thermal fluxes those associate material flow rates are able to vary. The optimal integrated system is visualized in the diagram of the grand composite curves (figure 3.10). In this study, the utilities are composed by the conversion system heat fluxes and, if it has to be sized, by the geothermal process heat fluxes. The optimal integrated system is obtained when the pre-defined minimal temperature difference DT_{min}

between the geothermal process grand composites curve and the conversion system grand composite curve is attained. If it is the case, the two curves corrected in temperature by subtracting their respective $DT_{min}/2$ contribution, are in contact at the so called **pinch point**.

5.2. Thermo-economic optimization

In this study, the thermo-economic optimisation approach aims at minimizing the investment cost and maximizing the exergy efficiency:

$CI(x), \eta_{ex}(x) \rightarrow Min$

Under operating equality and inequality constraints $g(x,y)=0,\ h(x,y)\leq 0$ (5.1)

where x are the decisions variables and y define the dependant states of the system.

5.2.1. Solving methodology

An **equation solver** ([12]) determines the thermodynamic state of the system and sends the computed cold and hot heat fluxes to the **process integration solver ([2]).** This solver finds the pinch point of the hot and cold fluxes and determine the total area of the heat exchanger network. It returns size factors for each utilities sub-system, which defines the optimal integrated system (figure 5.1). The thermodynamic states of the integrated system are found by solving the problem again with the mass flows updated by the sizing factors. Finally, indicators of performance are computed based on the previously determined states of the system.

To find optimal operating points and provide well integrated systems, suitable decision variables and objectives functions are chosen, and a **multi-objective evolutive algorithm** is applied to solve the optimisation problem.

For every studied system, the result is given by a characteristic **Pareto frontier**, expressing the optimal trade-off between the exegetic quality and the quantity of investment costs. The Pareto frontier delimits a feasible but non optimal operating zone, and an unfeasible operating domain.

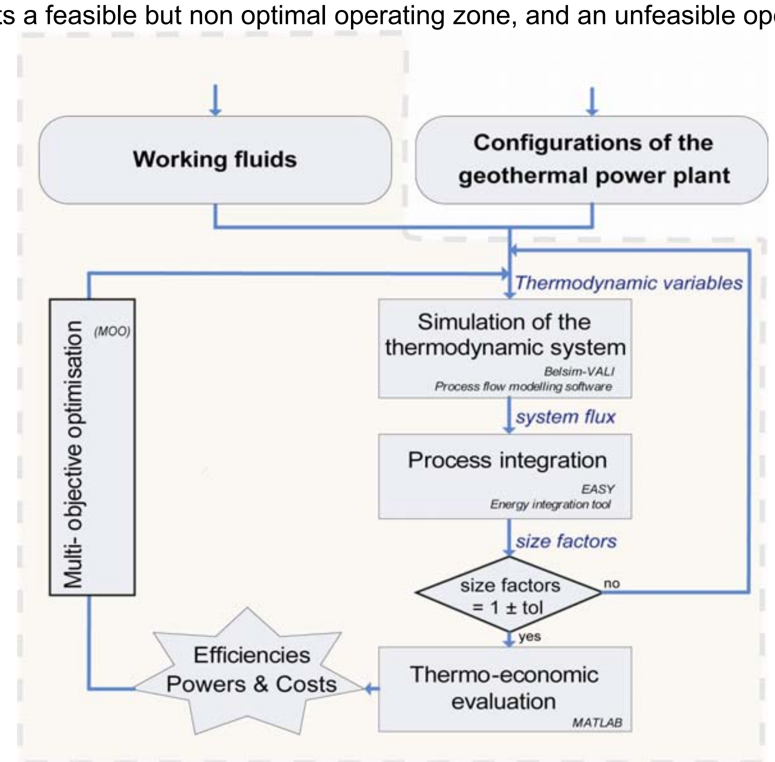

Figure 5.1: Solving procedure for the optimal integration of energy systems.

5.3. Working fluid selection

The first consideration in constructing binary plants is choosing the working fluid. The key parameters for suitable fluids are:

1) Saturation pressures at maximum and minimum temperatures should be within a given range, neither involving high pressure as to cause strength-of-material problems, nor low pressure as to give rise to sealing problems against atmospheric infiltrations;
2) Chemical stability and inertia during temperature changes in the cycle;
3) Vapour saturation line approximately close to the turbine expansion line; this will avoid excessive humidity at the turbine exit, eliminating superheating, and also all or nearly all of the heat rejection to take place at minimum temperatures;
4) The fluid should be inexpensive and not difficult to find and,
5) Not toxic.

For organic Rankine cycle, the choice of the working fluid depends on its boiling point, which should allow heat exchange with hot pressurized water. The thermodynamic properties of selected fluids extracted from the simulation software ([12]) database are given in table 5.1 (mind the temperatures given in Kelvin). The simulated saturation curves of figure 5.2 show the candidates selected in this study, that are able to operate in the window between 10-220°C of geothermal deep heat mining application.

Table 5.1: working fluids properties (taken from Belsim database)

Fluids	Denomination	Formula	**Molecular weight** [kg/kmol]	**Critical temperature** [K]	**Critical pressure** [bar]	**Boiling temperature** [K]
12-CL2-1122-F4-Ethane	12C2F4CL		170.922	418.9	32.6266	276.9
n-Pentane	N-C5	C5H12	72.151	469.78	33.7514	309.2
cyclo-Butane	CYC4	C4H8	56.108	460	49.8519	285.66
Iso-butane	I-C4	C4H10	58.124	408.13	36.477	261.32
Isopentane	I-C5	C5H12	72.151	460.4	33.3359	301
Benzene	BZ	C6H6	78.114	562.1	49.244	353.3
Ethylene	C2-	C2H4	28.054	282.36	50.318	169.45
Methane	C1	CH4	16.043	190.55	46.0421	111.658
Ethane	C2	C2H6	30.07	305.43	48.7981	184.52
Toluene	TOLUENE	C7H8	92.141	592	42.1512	383.8
Propylene	C3-	C3H6	42.081	364.9	46.2042	225.5
Difluoroethane(R152a)	1C2F2	C2H4F2	66.0508	386.6	44.9883	248.4
n-butane	N-C4	C2H10	58.124	425.16	37.9665	272.67
tetra-fluoro-Ethane	R134A	C2H2F4	102.032	374.21	40.5928	247.076

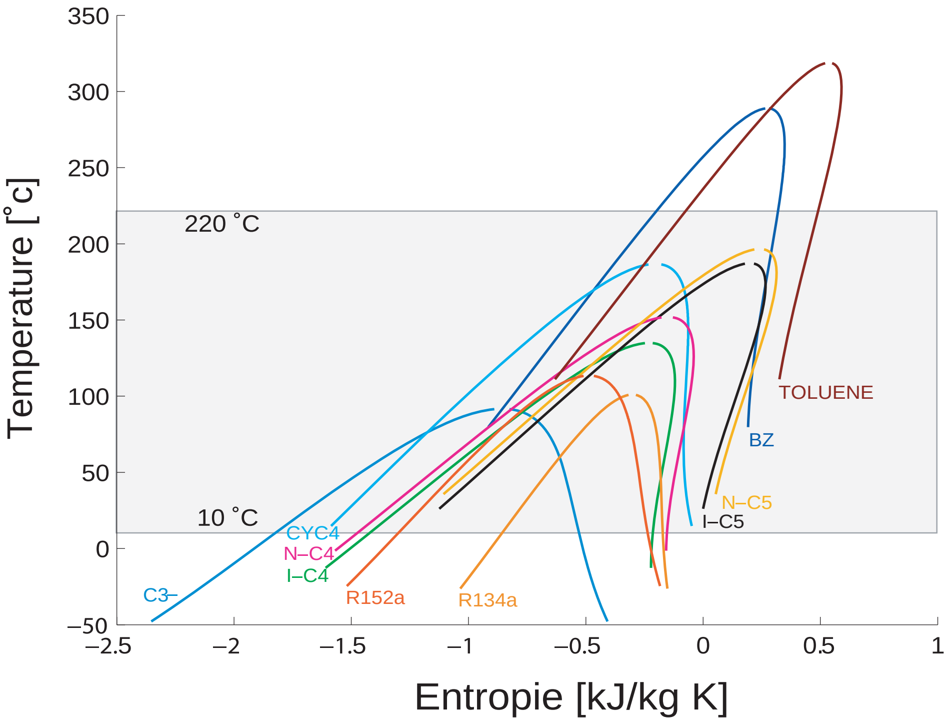

Figure 5.2: simulated saturation curves of working fluid candidates

Simulation procedures have been done for the Basel case study to investigate the influence of organic fluid mixture for a single stage orc cycle with fixed turbine(80%) and pumps(0.85%) efficiencies, using the underlined fluids of table 5.1. This preliminary optimisation was performed with integer value for the molar fraction of components. With this limitation, it has not been yet possible to find powerful mixtures. Nevertheless, the results plotted in figures 5.3 and 5.4 and reported in table 4.2, shows that n-butane is an appropriate fluid for application with temperatures similar to those encountered in the Basel case study.

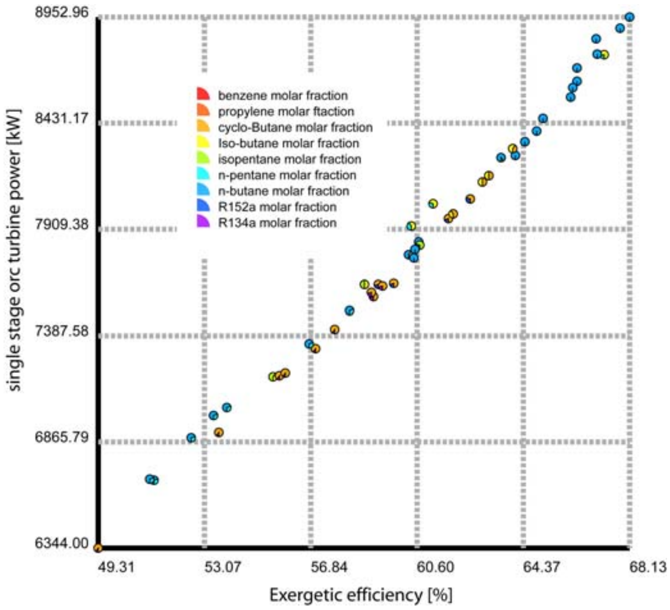

Figure 5.3: exergetic efficiency versus turbine power for different fluid mixture

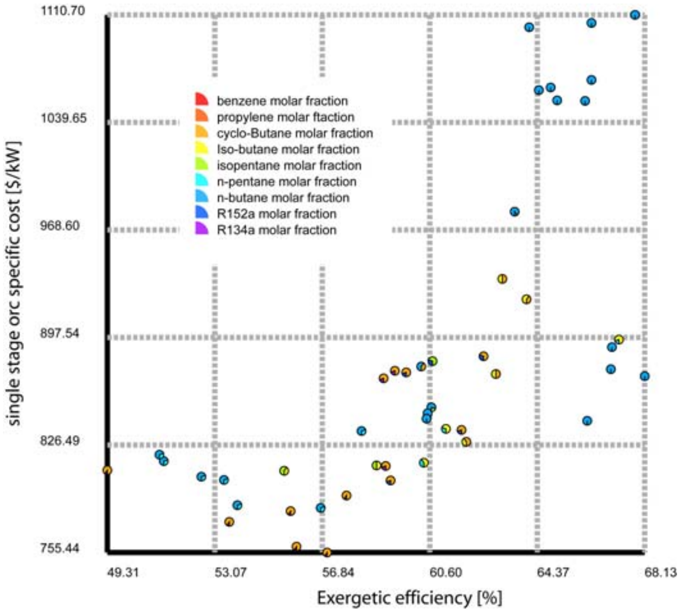

Figure 5.3: exergetic efficiency versus orc specific cost for different fluid mixture

Table 5.2: Preliminary fluid mixture optimisation results

Fluid mixture	Molar fraction 1[-]	Molar fraction 2 [-]	Exergetic efficiency [-]	Specific costs [$/kW]	Mechanical power [kW]	Hot DT [°C]	Cold DT [°C]	Superheating DT [°C]	High Pressure [bar]
n-butane	1.0	-	66.98	891.26	8770.16	9	47.28	3.46	28
n-butane	1.0	-	66.95	876.73	8845.29	6	38.66	3.46	34
n-butane	1.0	-	66.11	842.53	8605.67	7	65.83	3.46	21
isobutane-n-pentane	0.8	0.2	67.23	896.02	8766.99	7	51.19	9.72	26
cyclobutane-isobutane	0.4	0.6	63.99	922.73	8306.13	19	51.08	6.09	22
Cyclobutane-isobutane	0.5	0.5	63.14	936.14	8171.86	18	49.07	8.86	22
cyclobutane-isobutane	0.5	0.5	62.91	873.41	8142.34	19	48.07	8.86	22
cyclobutane R152a	0.8	0.2	61.72	836.55	7962.38	8	52.05	14.95	23
isobutane-npentane	0.7	0.3	61.16	837.2	8035.27	6	37.34	15.86	30
isobutane-n-pentane	0.6	0.4	60.39	814.89	7925.27	18	20.53	21.07	29
cyclobutane R134a	0.9	0.1	57.01	755.44	7206.04	12	17.67	54.95	23
cyclobutane R152a	0.9	0.1	55.93	759.44	7325.87	8	17.67	43.16	20

6. Results

6.1. Thermo-economic model validation

The thermo-economic model of a single stage ORC cycle describe in chapter 4 was validated with data from two orc plants hereafter “test case”. The partial data collected were not sufficient to identify the plant’s operating point: nor the working fluid, nor the cycle evaporation and condensation pressure/temperature were known. The validation was therefore performed by means of data reconciliation on the electrical capacity at the generator and the conversion plant investment cost, in order to identify the orc cycle.

The results of test case 1, which has a similar behavior compared to the studied cases Basel and Geneva (borehole production/reinjection temperature of 190/100°C), are reported in table 6.1. They are in good agreement with the provided datas, with relative deviations less than 1.15%.

The reconciled thermodynamic values of the orc plant of test case 2 (table 6.2) are in accordance with the provided datas with deviations less than 0.16%. However, in the situation of a high geothermal water temperature (260/155°C) coming from an ORC operation with a Gas Turbine, the model overestimates the referenced investment costs.

Table 6.1: Validation results, test case 1

Geothermal &ORC Plant parameters	Data from suppliers	Reconciled	Error
Borehole production/injection temperatures	190/100 [°C]	190/100 [°C]	
Cold source temperature	20 [°C]	20 [°C]	
Thermal capacity	30400 [kW]	30400 [kW]	
Working Fluid	-	n-butane	
Electrical efficiency	**13.9 %**	**14.0%**	**0.72%**
Electrical capacity at generator	**4225 [kW]**	**4273.7[kW]**	**1.15%**
Conversion plant cost	**6.96 [Mio $]**	**6.959 [Mio $]**	**0.01%**
Conversion plant Specific cost	**1647.3 [$/kW]**	**1628.5[$/kW]**	**1.14%**

Table 6.2: Validation results, test case 2

Geothermal & ORC Plant parameters	Data from suppliers	Reconciled	Error
Borehole production/injection temperatures	260/155 [°C]	190/100 [°C]	
Cold Source temperature	20 [°C]	20 [°C]	
Thermal capacity	6600 [kW]	6600 [kW]	
Working Fluid	-	n-pentane	
Electrical efficiency	**19.3 %**	**19.3 %**	**0.01%**
Electrical capacity at generator	**1275 [kW]**		**0.16%**
Conversion plant cost	**1.76 [Mio $]**	**1.99 [Mio $]**	**13.5%**
Conversion plant specific cost	**1020 [$/kW]**	**1569 [$/kW]**	**13.7%**

The simulated operating conditions for both test cases are reported in more details in the table 6.3 bellow, where the hot DT and cold DT refers to the temperature difference between the super heated working fluid and the hot geothermal water, respectively between the condensation temperature and the cooling fluid hottest temperature.

Table 6.3: Test case simulated operating conditions

	Geothermal & ORC Plant parameters	Reconciled values Case 1	Reconciled values Case 2
Efficiencies	Exergetic efficiency	47.25 [%]	48.3 [%]
	Turbine efficiency	89.5 [%]	84.2 [%]
	Pump efficiency	84.28 [%]	73.2 [%]
Operating Parameters	Working fluid flow rate	71 [kg/s]	14.57 [kg/s]
	Hot DT	22.65 [°C]	62 [°C]
	Cold DT	10.57 [°C]	22.8 [°C]
	Working fluid Higher Pressure	15 [bar]	24.6 [bar]
	Working fluid Lower Pressure	1.5 [bar]	1.73 [bar]
	Reference DTmin	1.3959 [°C]	1 [°C]
	Pump electrical power	177.35 [kW]	81.3 [kW]
Investment Costs	Turbine Investment Cost	2’381’220 [$]	1’245’159 [$]
	Pump Investment Cost	145’189 [$]	103’330 [$]
	Heat Exchanger Investment Cost	4’433’588 [$]	649’302 [$]
	Borehole Investment Cost	11.86 [Mio$]	16.53 [Mio$]

6.2. Basel Scenario

Basel is the first planned enhanced geothermal system pilot plant in Switzerland.

In the Basel scenario, the temperature difference between the geothermal heat source (near 170°C) and the district heating feed temperature(120°C) is assumed to be high and the district heating demand is supposed to be constant at 15 MW (winter time operating conditions) with supply and return temperatures of 120/55 °C. The constant values used are listed in table 6.5.

Given the ranges for the variables of the geothermal heat source shown in table 6.4, the geothermal process potential is the range of 3’370 kW up to 12’450 kW, that can be used for electric power conversion by integration of conversion systems. In this case study the integration of a 2 stage orc is investigated with butane (r600) as working fluid.

Table 6.4: Decision variables of the Basel scenario

Name	Range	Unit
$T_{geo,feed}$	[135 ; 220] [408.15 ; 493.15]	°C K
$T_{geo,inj}$	[70; 120] [343.15 ; 393.15]	°C K
$\dot{m}_{geo}$	[50 ; 100]	kg/s
k_a	[0.05 ;0.95]	-
k_b	[0.05 ;0.95]	-
k_c	[0.05 ;0.95]	-
k_d	[0.05 ;0.95]	-

Table 6.5: Constants of the Basel scenario

Name	Value	Unit
T_{cold}	10 283.15	°C K
ΔT_{cold}	5	°C
$T_{DH,feed}$	120 393.15	°C K
$T_{DH,return}$	55 328.15	°C K
P_{DH}	15	MW
ORC working fluid	butane	-

The decision variables of the Basel case study are the geothermal water flow rate, the production/reinjection temperatures, and the conversion system temperature levels expressed with the variables k_i of equations 6.1.

Superheating level: $T_{geo,\,feed} - k_a (k_d (T_{geo,\,feed} - T_{geo,inj})$

Evaporation level: $T_{geo,\,feed} - k_d (T_{geo,\,feed} - T_{geo,inj})$

Condensation level: $T_{cold} + k_c (T_{DH,return} - T_{cold})$

Turbine extraction level: $T_{DH,return} + k_b (T_{geo,\,feed} - k_d (T_{geo,\,feed} - T_{geo,inj}) - T_{DH,return})$ *(6.1)*

Given these decision variables and problem constants, the result of the optimisation of the exergetic efficiency and the investment cost:

$CI(x) = CI_{orc,Turbines\&Generators} + CI_{orc,Pumps} + CI_{Exchangers} + CI_{Drilling} + CI_{geo,pumps} \quad \rightarrow min$

$\eta_{ex}(x) = (P_{el,ORC\ Turbine} + P_{ex,DH} + P_{ex,COOL}) / (P_{el,ORC\ Pump} + P_{ex,GEO}) \quad \rightarrow max$

gives two distinct types of configuration (cluster 1 and 2). The first cluster make an abundant use of geothermal power (28.7 to 45 MW_{th}), and require high consumption of cooling water (12.7 to 23 MW_{th}) to reach high efficiency through electrical power generation (1.5 to7.7 MW_{el}). The second cluster uses about 17.7 MW_{th} geothermal power and less than 1.8 MW_{th} coolant, but cannot produce more than 0.84 MW_{el}. The most efficient integrated systems of each cluster are shown in figures 6.1 and 6.2.

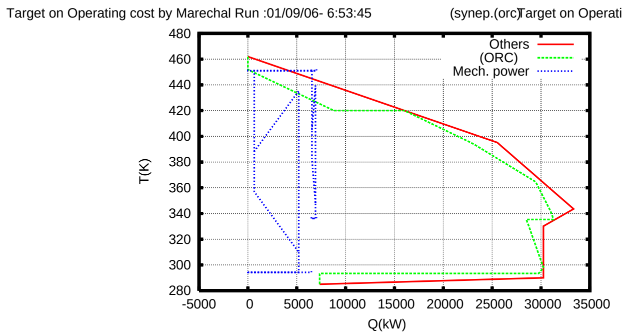

Figure 6.1: cluster 1 point with 82% exergetic conversion efficiency

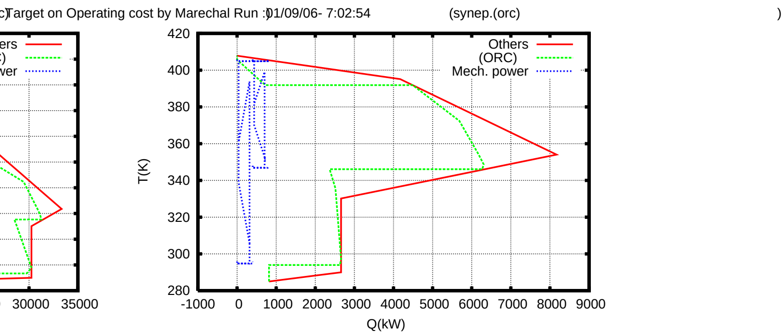

Figure 6.2: cluster 2 point with 86% exergetic conversion efficiency

The plot of the exergetic efficiency versus total investment cost is given in figure 6.3. For Cluster 1, a trade-off is visible between the efficiency and the investment cost, and cluster 2 seems to have an optimal configuration with a capacity of electricity production limited by the specification of the district heating temperatures.

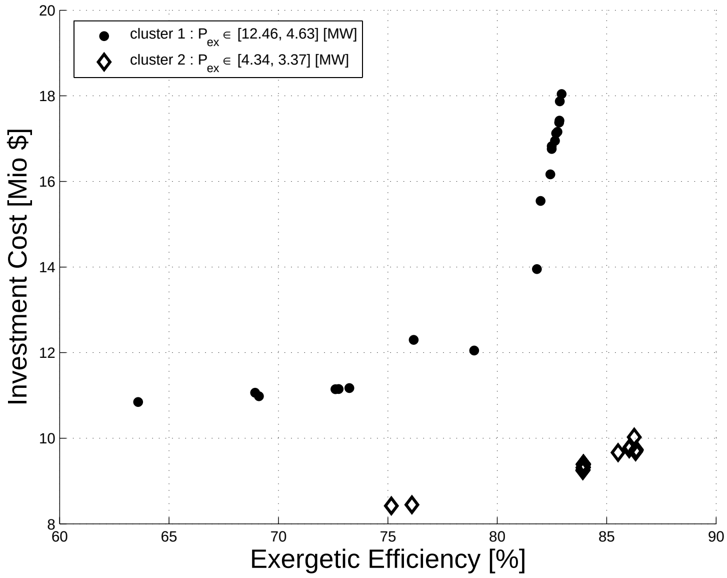

Figure 6.3: exergetic conversion efficiency versus investment cost

The figure 6.4 shows the trade-off in the axis of efficiency versus turbine power. It is manifest that the slope of cluster 1 is steeper for high power between 4 an 7.7 MW_{el}, and if one wants to deliver 7.7 MW_{el} instead of 4 MW_{el}, he will have to invest an additional amount of 6 Mio$ (0.62 Mio$/$MW_{el}$). This investment will be used to drill deeper on the ground in order to increase the geothermal exergetic potential by augmenting the borehole production temperature. The sensitivity of the exergetic efficiency in function of the borehole production temperature is given in figure 6.5.

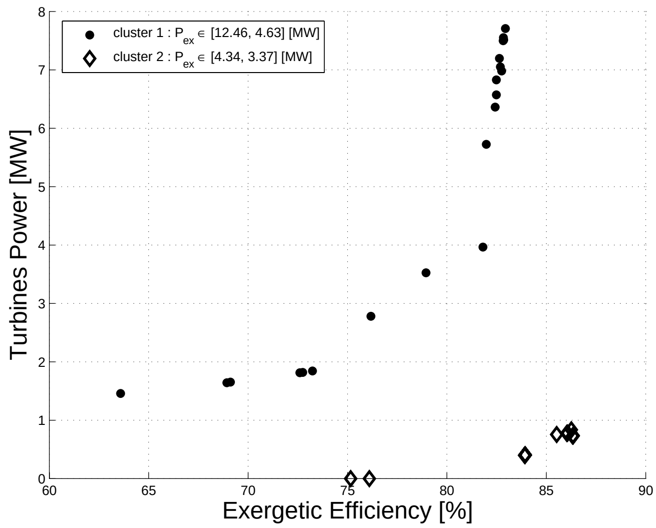

Figure 6.4: exergetic conversion efficiency versus turbines power

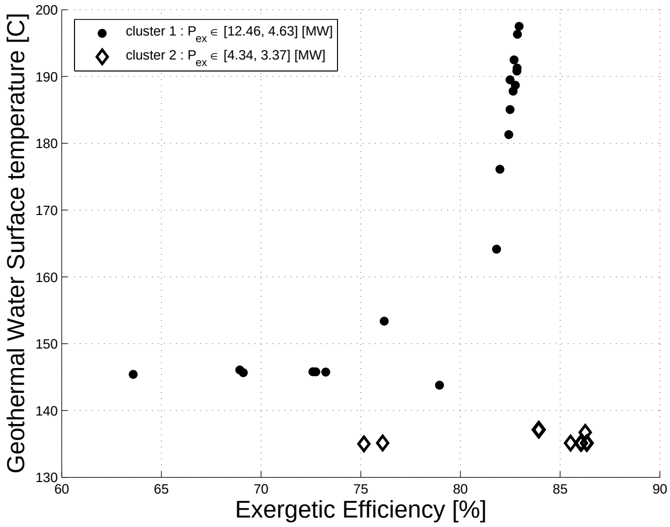

Figure 6.5: exergetic conversion efficiency versus borehole production temperature

One can observe that the geothermal water flow rate stands between 70 and 80 [kg/s] for all cases with a reinjection temperature reaching its bound of 70-75 °C for cluster 1 and of 83-90 °C for cluster 2.
The results are summarized in the table 6.6 which list the minimal and maximal values encountered in each cluster. The investment costs reported comprise the costs of the orc cycle including the heat exchanger network, the drilling cost, the cost of the geothermal injection pump and fresh water injection pump.

Table 6.6: Min-Max value for configurations of cluster 1 & 2.

	Geothermal power [MW]	Cooling power [MW]	Electrical power [MW]	Geothermal mass flow [kg/s]	Reinjection temperature [°C]	Borehole Deepness [m]	Borehole Cost [Mio$]	ORC Cost [Mio$]	Investments cost [Mio$]
Cluster 1	28.7 45-0	12.7 23.0	1.50 7.70	75	76 70	3’705 5’105	8.89 12.36	5.67 1.95	18.0 10.4
Cluster 2	15.0 17.7	0.0 1.8	0.40 0.84	70	83 86	3’450	8.20	5.19 0.97	9.3 10.0

6.3. Lavey Scenarios

A new project has been presented recently by a group of geologists for a geothermal plant in Lavey-les-Bains/VS [14]. The aim is to build a low temperature power plant driven by geothermal hot water. The geologists are expecting a mass flow of 50 to 100 kg/s a t a temperature of 100 – 130°C.
In this scenario, only the district heating return temperature and the cooling source temperature assume constant values which are listed in table 6.8. The geothermal water flow rate and temperature, the district heating flow rate and supply temperature, as well as the conversion system design parameters are varied in the ranges given in table 6.7.
With the low temperature ranges specified for the geothermal source and the district heating network, the geothermal process exegetic potential defined in chapter 2 is in the order of 1 MW to 6.3 MW. A heat exchange with a small temperature difference may occur between the geothermal fluid and the district heating water, resulting in a heat transfer with an exergetic efficiency ranging from 63% up to 82%. Thus, if one wants to minimize the investment cost while maximizing the delivered exergetic conversion efficiency:

$$CI(x) = CI_{orc,Turbines\&Generators} + CI_{orc,Pumps} + CI_{Exchangers} + CI_{Drilling} + CI_{geo,pumps} \quad \rightarrow min,$$

$$\eta_{ex}(x) = (P_{el,ORC\ Turbine} + P_{ex,DH} + P_{ex,COOL}) / (P_{el,ORC\ Pump} + P_{ex,GEO}) \quad \rightarrow max$$

no electrical conversion systems will be integrated. The curve representing this optimisation is shown in figure 6.6. The last point of the curve represents a geothermal plant producing water at 100°C and reinjecting it at 60 °C, 114.5 bar and 59 kg/s, thus supplying 10 MW_{th} power with 82% exergetic efficiency to the district heating network (90°C) for an initial total investment cost of 7.91 Mio$ (719.4$/$MW_{th}$). The improvement of the efficiency along the frontier is made by augmenting the area and cost of the heat exchangers (figure 6.7).

Table 6.7: Decision variables of the Lavey scenario

Name	Range	Unit
$T_{geo,feed}$	[100 ; 130] [373.15 ; 403.15]	C K
$T_{geo,inj}$	[60; 100] (optim1) [75;100] (optim2)	C C
$\dot{m}_{geo}$	[50 ; 100]	kg/s
$T_{DH,feed}$	[65 ; 90] [338.15 ; 363.15]	C K
$\dot{m}_{DH}$	[30 ; 100]	[kg/s]
$\Delta T_{ORC,hot}$	[1 ; 50]	C
$\Delta T_{ORC,cold}$	[1 ; 50]	C
$P_{ORC,high}$	[5; 30]	Bar
$DT_{\min}^{ref}/2$	[1 ; 5]	C

Table 6.8: Constants of the Lavey scenario

Name	Value	Unit
$T_{DH,return}$	50 323.15	C K
T_{cold}	20 293.15	C K
ΔT_{cold}	10	C
ORC working fluid	n-butane	-

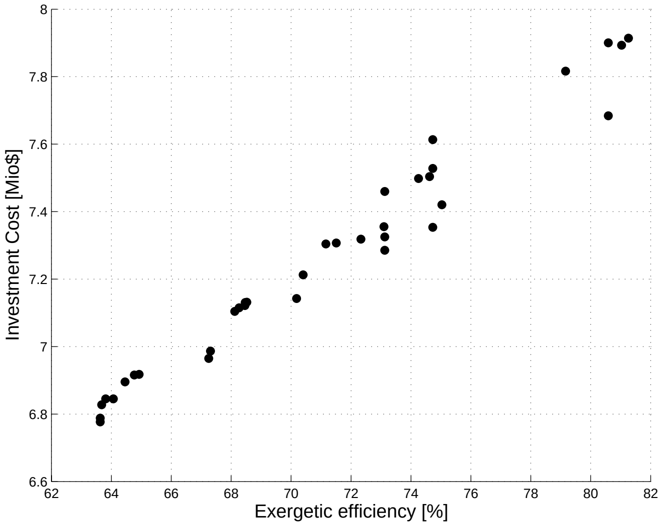

Figure 6.6: exergetic efficiency versus investment costs

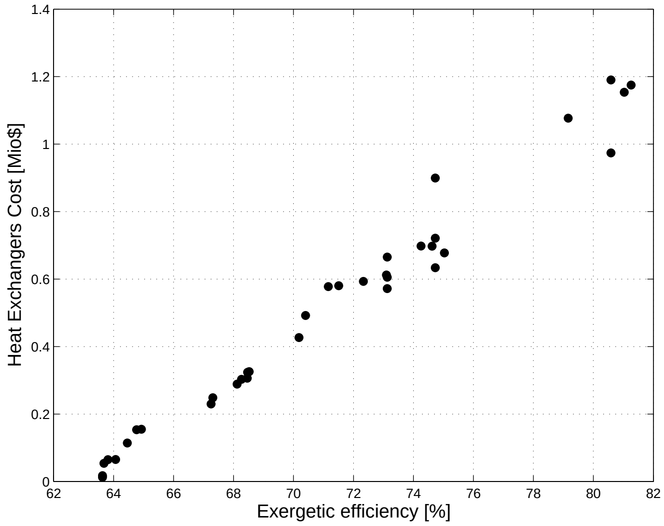

Figure 6.7: exergetic efficiency versus heat exchangers network cost

To generate also some electricity, one has to reach higher temperature differences between the geothermal hot water and district heating supply water. The trends between electricity and the district heating power supply was obtained by maximizing both the electrical power $P_{el,ORC}(x)$ and the power supplied to the district heating $P_{DH}(x)$.

$P_{el,ORC}(x) \quad \rightarrow max,$

$P_{DH}(x) \quad \rightarrow max,$

Each optimal point of figure 6.8 represent an optimal configuration with a given size and operating point for the conversion system integrated in the geothermal process. One can show that these configurations can be grouped together in four distinct integration options:

1. district heating only: the geothermal energy is not used to generate electrical power.
2. heat and electrical conversion with emphasis on district heating: the orc cycle temperature levels are included between the got geothermal water temperature and the district heating water return temperature.
3. heat and electrical conversion with emphasis on electrical power: the condensation temperature level of the orc cycle is lower than the disrict heating return temperature.
4. power generation only: the geothermal energy is not used for district heating.

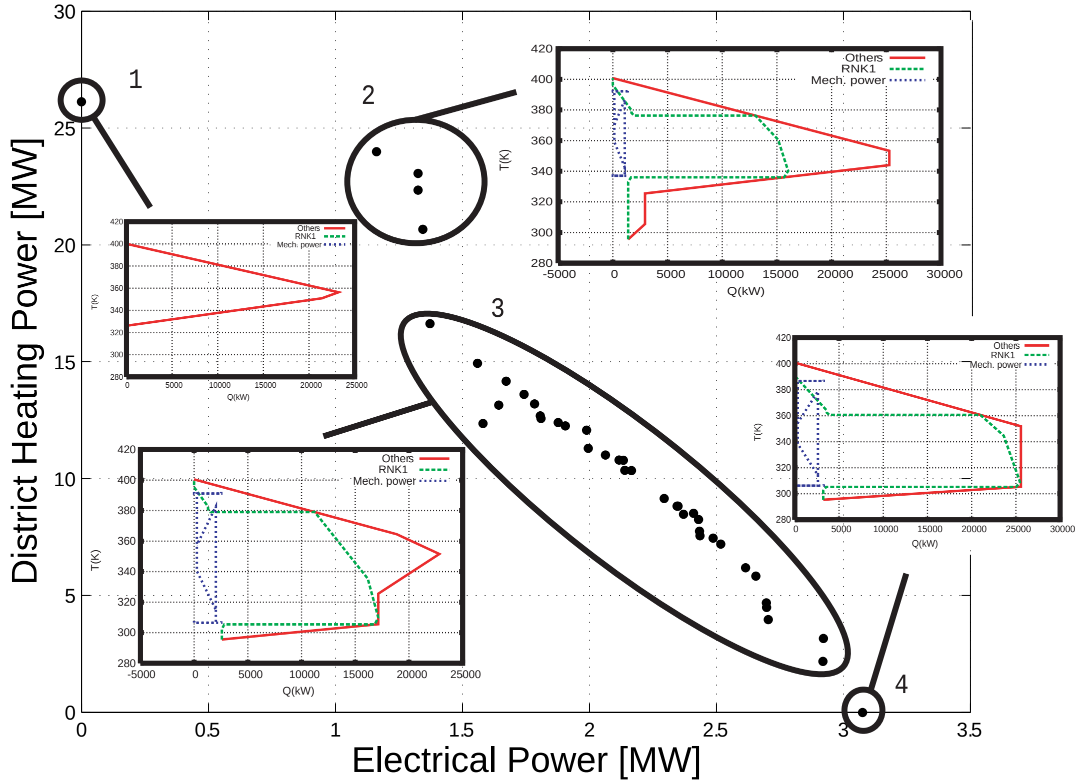

Figure 6.8: Resulting configurations when optimizing $P_{el,ORC}$ and P_{DH} in the case of Lavey.

The investment cost for each configuration are given in figure 6.9 and 6.10. Each configuration make full utilization of the geothermal potential, and the geothermal source decisions variables reaches the bound initially defined by:

- 100 kg/s water mass flow
- production temperature of 130°C with a borehole deepness of 2773 m (7.86 Mio$).
- reinjection temperature near 75°C.

The exergetic efficiencies vary from the lowest value of 37% if only electricity is delivered to the highest value of 57.6% if only heat is delivered. The difference between this higher bound efficiency compared to those (80%) previously predicted by the thermo-economic optimisation, is due to the constrained reinjection (75°C) and district heating supply (90 °C) temperatures.

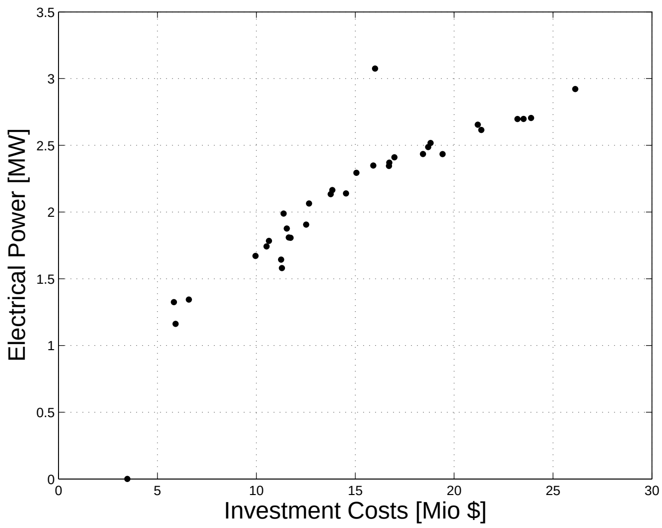

Figure 6.9: Lavey investment cost versus electrical power

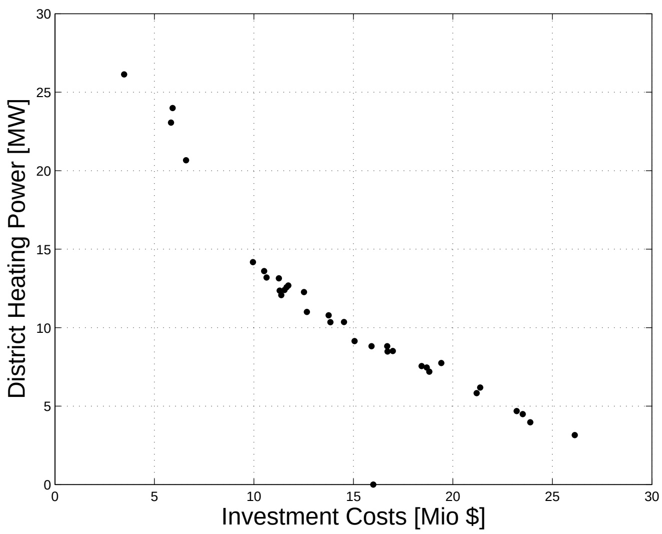

Figure 6.10: Lavey investment cost versus heating power.

The bounds of the operating parameters for each configuration options are resumed in the following table 6.9.

Table 6.9: Min/Max value for the Lavey single stage orc integration option.

Options	Geothermal power [MW]	Cooling power [MW]	Electrical power [MW]	District. Heat power [MW]	Exergetic conversion efficiencies [%]	ORC Cost [Mio$]	Investments Cost [Mio$]
1	26.30	0.00	0.00	26'128	57.6	0.00	3.49
2	25.23	0.13	1.16	20.66	38.6	5.34	5.92
		3.32	1.34	24.00	44.4	6.03	6.59
3	25.70	8.25	2.92	16.63	52.8	5.80	9.97
	26.30	20.44	1.37	2.18	57.8	8.79	26.12
4	25.56	22.35	3.08	0.00	37.0	8.14	16.00

The figure 6.11 shows that the augmentation of the electrical power production in the configuration 3 and 4 is followed by a diminution of the conversion efficiency (1800 kW_{el} per percent) for the points of configuration 3. This is explained by the augmentation of the exergy losses, represented by the surface between the geothermal(red) and conversion(green) composite curves of figure 6.6-3, for increasing temperature and pressure differences between the turbine inlet and outlet. This suggests improvements such as:

- introduction of a second turbine stage with a by pass, (studied in the Basel case chapter 6.2).
- use of fluid mixtures in order to render the evaporations and condensations levels no more isotherm.

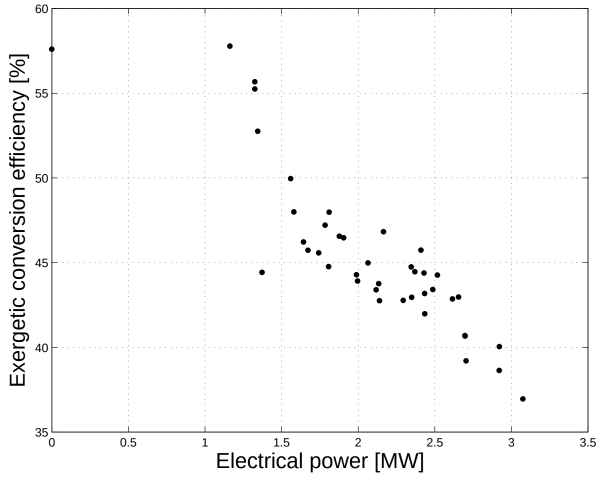

Figure 6.11: Lavey electrical power versus exergetic efficiency

6.4. Geneva Scenario

The predicted annual varying demand of district heating in Geneva, taken from [13], is reported in figure 6.11. In a first step, the year was discretized in 6 periods and a gas turbine was integrated to supply heat to the district heating network in the coldest period of the year. The results of the integration are shown in figure 6.12.

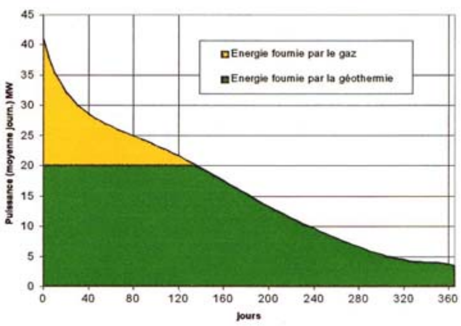

Figure 6.11: Geneva expected district heating demand [13] with geothermal- (green) and boiler(yellow) repartition.

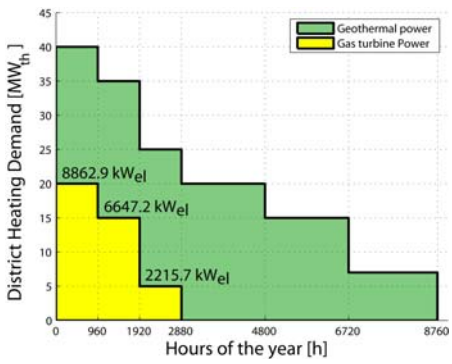

Figure 6.12: Multi-period integration of a gas turbine.

In a second step, the integration of an orc cycle was performed by maximizing the annual electrical energy conversion and minimizing the investment costs of the equipments:

$E_{el}(x) = \sum P_{el,ORC,i}(x) \cdot \Delta t_{periode,i} \qquad \rightarrow max,$

$CI(x) = CI_{orc,Turbines\&Generators} + CI_{orc,Pumps} + CI_{Exchangers} + CI_{Drilling} + CI_{geo,pumps\ s} \qquad \rightarrow min,$

The values of the decisions variable and the constants are reported in table 6.10 and 6.11. The configuration of the most productive conversion system during period 6 is shown in figure 6.14.

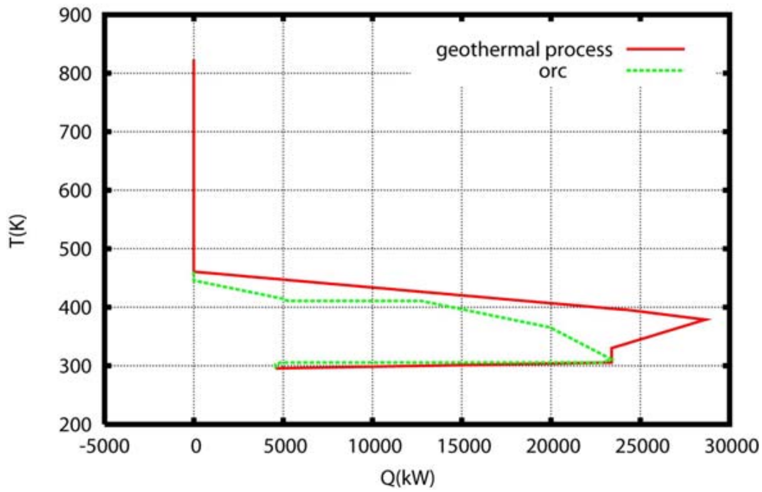

Figure 6.13: composite curves of the system during the period 6

Table 6.10: Decision variables of the Geneva scenario

Name	Range	Unit
$\Delta T_{ORC,hot}$	[1 ; 50]	C
$\Delta T_{ORC,cold}$	[1 ; 50]	C
$P_{ORC,high}$	[5; 30]	Bar
$DT_{\min}^{ref}/2$	[1 ; 5]	C

Table 6.11: Constants of the Geneva scenario

Name	Value	Unit
$T_{geo,feed}$	200 473.15	C K
$T_{geo,inj}$	100 373.15	C K
$\dot{m}_{geo}$	70	kg/s
$T_{DH,feed}$	120 393.15	C K
$T_{DH,return}$	73 346.15	C K
$\dot{m}_{DH}$	50	[kg/s]
T_{cold}	20 293.15	C K
ΔT_{cold}	10	C
ORC working fluid	n-butane	-

The optimal configurations are shown in figure 6.14 below. The orc cycle produces 19345 MWh/an (2208 kW_{el}) for an investment cost of 20.62 Mio$.

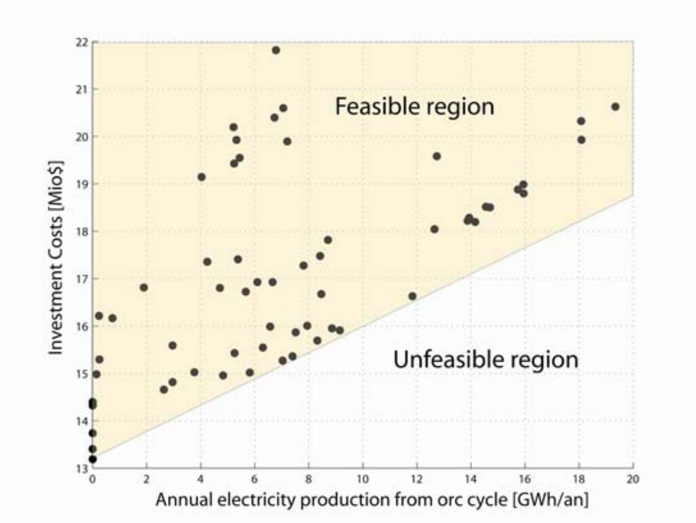

Figure 6.14: Geneva electricity produced versus investment cost

6.5. Energetic optimisation

The behavior of the maximum electricity production capacity of a single stage and a two stages ORC cycle with coproduction of 0%-100% heat are reported here for 7 reference cases which are defined in Table 6.12. The reinjection temperature is supposed to be constant at 70°C and the district heating system has a supply temperature of 100°C and a return temperature of 50°C.

Table 6.12: Data for process calculation

Case	Source Temperature [°C]	Flow rate	Differential pressure	Geothermal power
1	Hydrothermal source 110°C	40 kg/s	20 bar	8’543 MWth
2	Hydrothermal source 135°C	60 kg/s	30 bar	20’766 MWth
3	Hydrothermal source 135°C	120 kg/s	30 bar	41’531 MWth
4	Hot dry rock, source 160°C	80 kg/s	50 bar	38’225 MWth
5	Hot dry rock, source 190°C	80 kg/s	70 bar	50’823 MWth
6	Hot dry rock, source 220°C	80 kg/s	85 bar	63’468 MWth
7	Hot dry rock, source 220°C	160 kg/s	100 bar	126’936 MWth

6.5.1. Optimisation of a single stage ORC cycle.

A simplified model of the turbine with a fixed isentropic efficiency of 85% was used and the working fluid was included in the set of the decision variables of the problem.
The objectives considered are the electricity capacity at generator and the district heating thermal power:

$E_{el}(x),\ Q_{DH}(x) \quad \rightarrow max,$

with values of the decisions variable and the constants given in table 6.13 and 6.14.

Table 6.13: Decision variables of the energetic optimisation scenarios.

Name	Range	Unit
$\Delta T_{ORC,hot}$	[1 ; 80]	C
$\Delta T_{ORC,cold}$	[1 ; 80]	C
$P_{ORC,high} / P_{sat}$	[0.1; 0.99]	-
$DT_{\min}^{ref} / 2$	[1 ; 5]	C
Q_{DH} / Q_{GEO}	[1 ; 1]	-
Working Fluid (Table 5.1)	[1 ; 9]	-

Table 6.14: Constants of the energetic optimisation scenarios.

Name	Value	Unit
$T_{geo,feed}$	Table 6.8	C
$T_{geo,inj}$	70	C
$\dot{m}_{geo}$	Table 6.8	kg/s
$T_{DH,feed}$	100	K
$T_{DH,return}$	50	C
T_{cold}	20	C
ΔT_{cold}	10	C
$\eta_{s,Turbine}$	85	%

The results of the performed energetic optimisation are visible in figure 6.15. The dependencies of the electrical efficiency $\eta_{el}=P_{el}/P_{GEO}$ of the conversion system is reported in figures 6.16 and 6.17. The doted lines in figure 6.15 and 6.17 represent the design limitation of 12 MW_{el} that can be delivered by a single stage axial turbine.

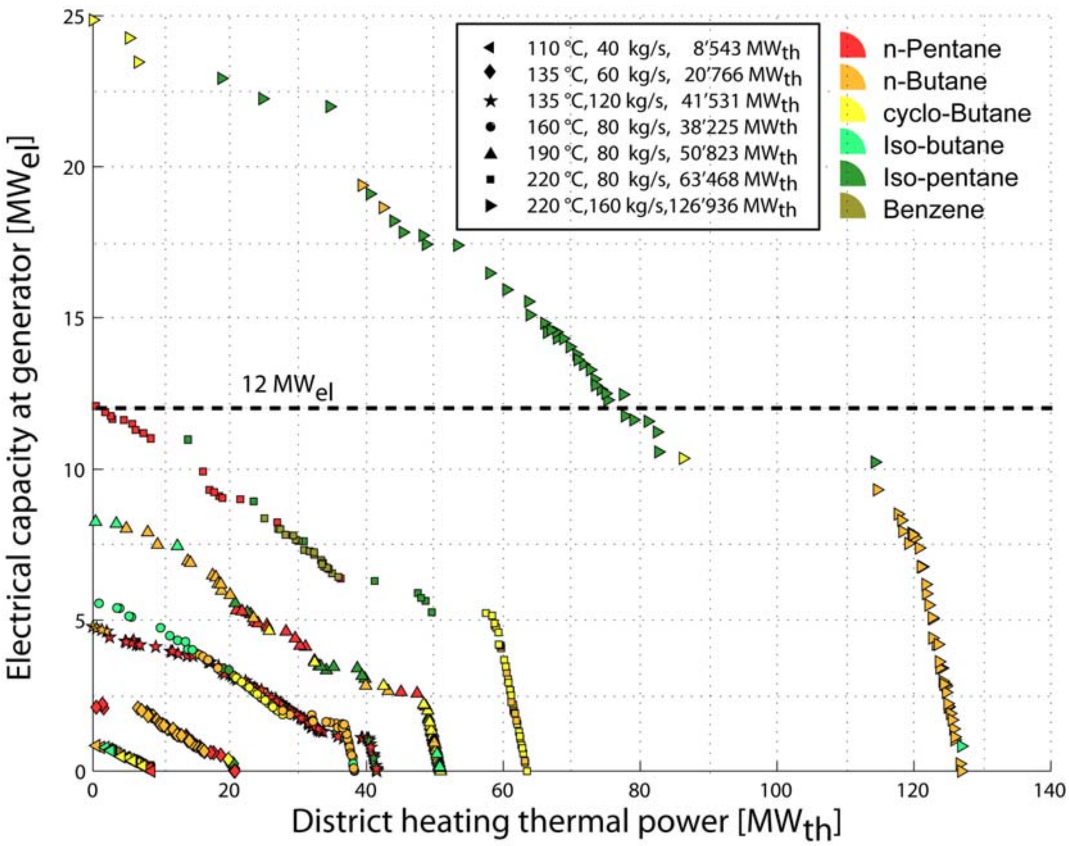

Figure 6.15: District heating power versus 1 stage ORC electrical power.

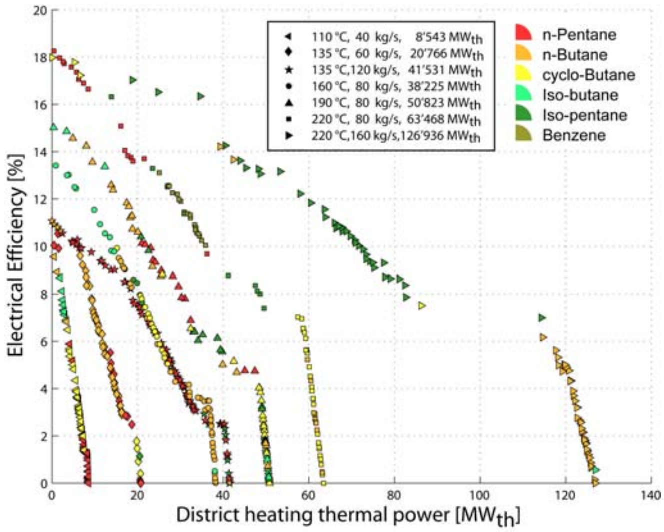

Figure 6.16: District heating power versus electrical efficiency.

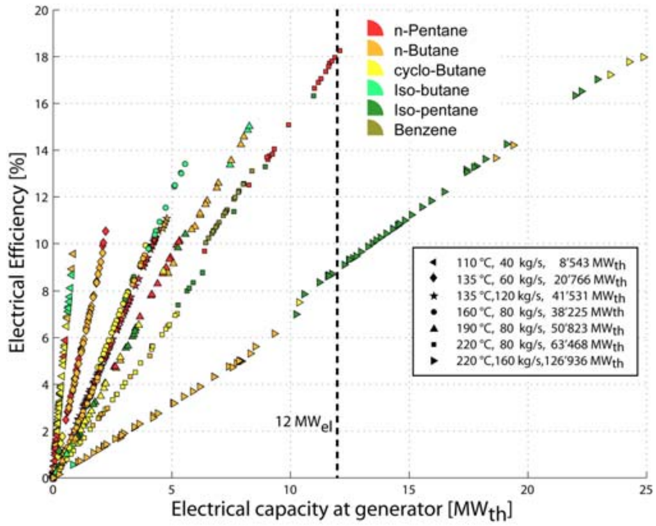

Figure 6.17: 1 stage ORC electrical power versus electrical efficiency

6.5.2. Comparison with a 2 stages ORC cycle

An energetic optimisation was also performed for a two stage ORC cycle. The comparative results of the delivered electrical power versus the supplied district heating power are visible in figure 6.20 and 6.21.

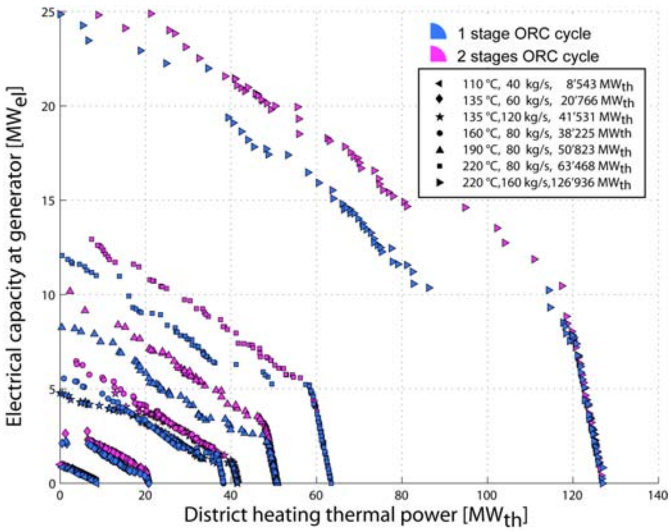

Figure 6.20: District heating power versus electrical power for 1 and 2 stages ORC cycle.

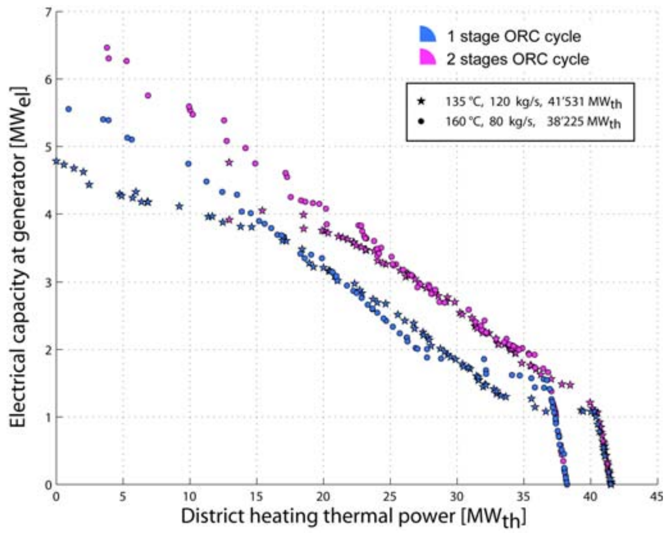

Figure 6.21: District heating power versus electrical power for 1 and 2 stages ORC cycle (detailed view).

The integration profile along the optimal frontier has similar behavior for each reference cases of table 6.12. It is reported for case 4 (160°C, 40 kg/s) in figure 6.22. The optimal frontier for 1 stage ORC conversion system shows 3 regions:

1. The single stage cycle is integrated between the geothermal source and the district heating sink without additional cold utility.
2. The single stage cycle is integrated between the geothermal source and the district heating sink with additional cold utility.
3. The single stage cycle is integrated between the district heating sink and the cold utility.

4. The first cycle is integrated between the geothermal source and the district heating sink. The second cycle stands between the district heating sink and the cold utility.
5. The first cycle is integrated under the geothermal source and above the district heating sink. The second cycle stands between the district heating sink and the cold utility.

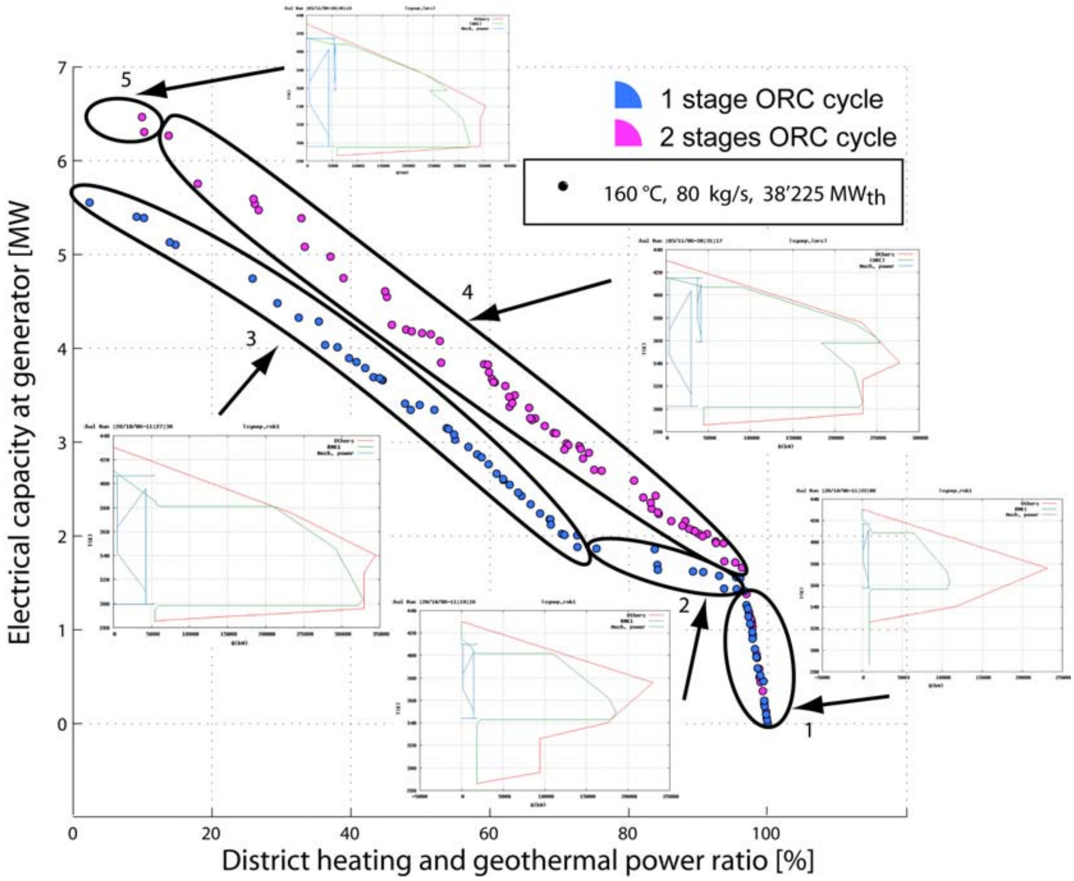

Figure 6.22: Integration profile along the optimal frontier (extracted from case 4)

7. Conclusion and future work

A technology survey of the possible energy conversion methods to be used to convert the geothermal energy into useful energy was conducted and the most suitable systems have been identified and evaluated. The priority has been given to organic rankine cycle (orc) technologie that are well developed, and are at least in demonstration phase.

The application of a thermo-economic optimisation methodology has been demonstrated for the optimal integration of energy conversion system in geothermal power plants. Thermo-economic models of the system have been elaborated. Each model includes the thermodynamic characterization of the cycles and a cost estimation of the equipment in the system. The thermo-economic study of three geothermal projects, namely Basel, Lavey and Geneva were considered. This analysis has identified the possibility of a combined usage of the geothermal resource to supply both electricity and heat with the possible extreme conditions of operating to provide only heat or only electricity.

The characterization of the geothermal resources has been used to identify the trade off between the mining costs, the conversion efficiency and the investment cost of the energy conversion system. In all cases, the influences of both the production water temperature from the underground heat exchanger and the return temperature has been analyzed.

However it will also be necessary to respect the expected long term cooling of the rock during the lifetime of the plant when making economic evaluations.

The possible combined usage of different cycles and the possibility of combining the use of external sources like, for instance, natural gas or waste combustion for increasing the efficiency of electricity production can be investigated in more details in future works. The possibility of getting further improvement with cycle using some binary mixture (e.g. Water-Ammonia), which require more sophisticated model of fluid state, are still to be done.

The optimisation of the thermodynamic performance of a multi-period geothermal integrated system was performed, but a methodic approach for that multi-period problem for the geothermal power plants has not been developed at the moment.

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