Best practice guide for the design of new geothermal plants

Task 5.5 - GEOTHERM project

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Geothermal energy from sedimentary reservoirs
– Removing obstacles for large scale utilization

Innovation Fund Denmark: project 6154-00011B

Contents

The GEOTHERM project (2017-2019) is co-funded by Innovation Fund Denmark. The full title of the project is: GEOTHERM: Geothermal energy from sedimentary reservoirs – Removing obstacles for large scale utilization. Innovation Fund Denmark: project 6154-00011B.
Work Package 5 focused on examining the main problems related to the design and operation of geothermal plants. This best practice is a result of this work package. The authors would like to thank GEUS, Sønderborg Varme A/S, Hofor A/S, Thisted Varmeforsyning Amba and FORCE Technology for their input. Additionally, international partners have contributed to the project, i.e., BRGM, GFZ Potsdam and Lunds Universitet.

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1 Dansk resumé

Geotermi er som teknologi ved at blive industrialiseret til at indgå på lige fod med sol og vind i den grønne omstilling fra fossile brændsler. Teknologien har bredt set en række elementer, som komplementerer de andre grønne energikilder, og som derfor gør den interessant i et forsyningsmæssigt perspektiv.

Geotermi er som udgangspunkt en grøn energikilde, den er næsten CO_2 neutral, den er stabilt producerende hele året og man kan trække geotermivarme ud hele døgnet. Geotermi kan derfor indgå som et grundlast element på linie med f.eks. affaldsforbrænding.

Geotermisk energi er i en dansk kontekst udelukkende koncentreret omkring varmeleverance til fjernvarmenettet. Der findes på verdensplan forskellige måder at udnytte geotermisk energi på, herunder til elproduktion, men det er ikke relevant i Danmark og derfor ikke medtaget i denne guide.

Valg af geotermi som energikilde skal som andre energikilder vurderes på graden af systemindpasning, og der er en lang række kriterier (ikke nævnt her), som man skal evaluere efter. Alle projekter er opdelt i række faser, som løbende er med til at raffinere projektmodellen. Geotermi er speciel ved, at den udnytter naturligt forekommende varme i undergrunden. Når man har foretaget grundlæggende studie af de forretningsmæssige muligheder, laver man en efterforskningsfase bestående af en geologisk analyse og efterforskningsboring.

Design af geotermianlæg er kompleks, da det kræver indgående viden omkring geologi og reservoir til etablering af brønde og efterfølgende produktion af geotermisk brine, samt viden om varmeproduktionsanlæg med varmevekslere og varmepumper.

Bag designet af anlægget skal der tages en række operationelle, produktions- samt afsætningsmæssige beslutninger, og de påvirker anlægskonstruktionen og dets drift. Kerneparametre blandt mange er temperatur, tryk og flow. De definerer til sammen den totale varmeproduktion, og de er med til at beskrive den forventede totale levetid for brøndene og anlægget.

Beslutningerne, som tages under planlægningen, skal baseres på en risikovurdering, omkostningerne og operationelle procedurer. Materialevalg kan medføre en højere CAPEX, men også en lavere OPEX ved f.eks. at vælge komposit materialer, som kan holde hele brøndenes tekniske levetid.

Denne guideline er rettet mod at sikre en forståelse af teknologivalg taget <u>efter</u> efterforskningsfasen. Teknologivalgene har konsekvenser gennem hele projektets levetid.

Det er valgt at dele et geotermianlæg ind i 11 segmenter.

Segments	
1	Producent, reservoirdel
2	Producent, brønd
3	Dykpumpe, producent
4	Filtrering
5	Varmeveksler
6	Injektionspumpe
7	Injection, brønd
8	Injection, reservoirdel
9	Varmepumpe
10	Støttesystemer
11	Fjernvarmedistribution

Af de 11 segmenter er 5 rettet mod brøndene og 6 mod overfladesystemet og dets forbindelse til fjernvarmenettet. Segmenteringen er baseret på, hvordan et anlæg hænger sammen modulært, og hvilke snitflader man typisk opererer med teknisk og i forbindelse med SRO anlægget.

Støttesystemer inkluderer en bred vifte af de funktioner, som ikke er enkeltkomponenter, men samler modulerne til et hele som f.eks. SRO systemet, rørføring og kabling.

Det anbefales, at man tilgår projektet med et helikopterperspektiv, og et lettere konservativt metodevalg, for at vælge robuste løsninger.

Der er en række barrierer, som udvikling af geotermi som en af fremtidens energikilder står overfor, bl.a. finansiering og regulatoriske forhold. Geotermi kan ikke ses som en løsrevet komponent. Geotermi bygger på en lang og stærk tradition af viden og forståelse, som er skabt i andre industrier. Viden og ekspertise kan overføres og bygges videre på f.eks. olie & gas industrien, hvor boring, sikkerhed og miljøbeskyttelse i mange år har været integreret. Design og anlæg af produktionsanlægget bygger på den lange tradition med at skabe effektive faciliteter til de +400 fjernvarmesystemejere i Danmark. Fjernvarmeproduktionsfaciliteter har generelt i de senere år gennemgået en af de mest omfattende moderniserings- og renoveringsperioder med udfasning af olie og kul og en tilsvarende indfasning af biomasse, solvarme og varmepumper.

Geotermi er en del af fremtidens varmeforsyning.

2 Executive summary in English

Geothermal energy is under development and is becoming a relevant source of energy in the transition from fossil to green fuels. The technology can complement other green energy sources, such as solar and wind energy, and therefore becomes attractive from a supply perspective.

In general, geothermal energy is a green energy source. It is almost CO_2 neutral, it is stable throughout the year and geothermal heat can be extracted 24 hours a day. Therefore, Geothermal energy can also be included as a baseload element in line with e.g., waste incineration.

In Denmark, geothermal energy is exclusively used as a heat supply to district heating networks. Elsewhere in the world, geothermal energy is also used to generate electricity, but this application is not the focus in Denmark at the moment and, therefore, not included in this guide.

The choice for geothermal energy, like other energy sources, must be evaluated based on a large number of criteria. All projects are divided into several phases, which help to refine the project model on an ongoing basis. Geothermal energy utilizes naturally occurring heat in the underground, so once a basic study of the business opportunities is completed, an exploration phase consisting of a geological analysis and exploration drilling should be conducted.

The design of geothermal plants is complex, as it requires in-depth knowledge of geology and reservoirs for the establishment of well fields and the subsequent production of and re-injection of geothermal brine back into the reservoir, as well as knowledge of heat production plants with heat exchangers and heat pumps.

Behind the design of the plant, several operational, production and marketing decisions must be taken, and they affect the construction of the plant and its operation. Core parameters among many are temperature, pressure, and flow. Together they define the total heat production and help to describe the life expectancy of the wells and the plant.

The decisions taken during planning must be based on a risk assessment, cost and operational procedures. Material selection can result in higher capital expenditure (CAPEX), but also a lower operational expenditure (OPEX) for example.

This guideline is aimed at ensuring an understanding of technological choices made after the exploration phase and the consequences of these decisions throughout the life of the project.

It has been chosen to divide a geothermal plant into 11 segments.

Segments	
1	Producer, lower completion
2	Producer (well bore)
3	Production Electrical Submersible Pump (pESP)
4	Filtration
5	Heat Exchangers
6	Injection Pump (iP)
7	Injector (well bore)
8	Injector, Lower completion
9	Heat Pump
10	Auxiliary systems
11	Heating loop (distribution)

Of the 11 segments, 5 are related to the wells and 6 to the surface system and its connection to the district heating network. Support systems include a wide range of functions that are not single components but assemble the modules into a whole such as SCADA system, piping, and cabling.

There are several barriers to the development of geothermal energy as one of the future energy sources, as, for example, financing and regulatory matters. Geothermal cannot be seen as a detached component. Geothermal science is based on a long and strong tradition of knowledge and understanding created in other industries. Knowledge and expertise can be transferred and built on, for example, from the oil & gas industry, where drilling, safety, and environmental protection have been integrated for many years. The design and construction of the production plant are based on the long tradition of creating efficient facilities for the +400 district heating system owners in Denmark. In recent years, district heating production facilities have generally undergone one of the most extensive modernization and renovation periods with phase-out of oil and coal and a corresponding phase-in of biomass, solar heat and heat pumps.

Geothermal energy is part of the future heat supply.

3 Introduction

The development of geothermal projects involves risks and uncertainties that need to be carefully evaluated. Besides the comprehension of the legal and political aspects of each project, it is fundamental to go deep into the technical specifications and make the best assessment of the natural resources to develop the right approach and maximize its potential.

The greater the volume of information extracted from the reservoir and its fluids, the lower the investment risks and, consequently, the higher capital expenditure needed. Finding the ideal balance between risk and costs is a key parameter for the project feasibility.

Upfront investments in characterizing the reservoir, geothermal brine and district heating network during the early stages of a project support the proper evaluation and design of geothermal plants, which can enable a long-lasting and trouble-free operation, resulting in OPEX savings during the production phase.

With the knowledge acquired from the oil and gas industry and based on the experience of low enthalpy geothermal plants in Europe, it is possible to identify the main risks of geothermal energy production.

Some of the major challenges faced by low enthalpy geothermal plants around Europe include[1]:

- Scaling
- Corrosion
- Gas content
- Low injectivity
- Reservoir cooling
- Equipment failures
- NORM and contaminants
- Induced seismicity

Acknowledging and understanding the main risks and lessons learned from the industry can determine the success of a new project. In that way, based on GEOOPs expertise, knowledge acquired from GEOTHERM project and a bibliographic review, this document aims to describe the main equipment and decisions regarding low enthalpy geothermal heat production plants and wells, highlight the main design steps to implement new projects and provide recommendations of best practices for the operation of geothermal wells and plants.

Every project possesses a unique set of characteristics and constraints that will influence the design of the production facilities. Therefore, there is no strict formula to determine how a plant should be built and operated.

3.1 Best practice guide structure

Geothermal brine is extracted from geothermal reservoirs through production wells, drilled and completed based on the depths, flowrates, temperatures, pressures, geology and water chemistry predicted for the designed project.

In most of the cases, these wells do not possess sufficient pressure to flow the geothermal brine to the surface, so a lift system is required to provide flow assurance.

Once at the surface, the geothermal brine must pass through a series of equipment responsible for removing solids, potential entrained gas and aggressive components, extract and transfer the heat to the district heating loop and inject the brine back into the subsurface through the injection well(s).

Following the definitions proposed in the Work Package 6 of the GEOTHERM project, the plant can be divided in eleven major components:

1. Producer, lower completion
2. Producer (well bore)
3. Production Electrical Submersible Pump (pESP)
4. Filtration
5. Heat Exchangers
6. Injection Pump (iP)
7. Injector (well bore)
8. Injector, Lower completion
9. Heat Pump
10. Auxiliary systems
11. Heating loop (distribution)

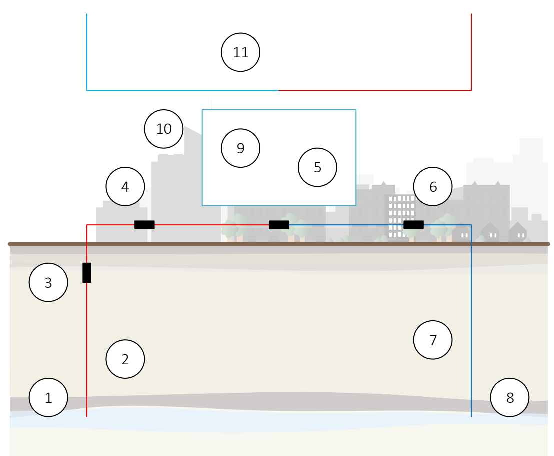


Figure 1. Geothermal plant main components scheme

This document adopts similar division to address the main topics related to the design of a new low enthalpy geothermal plant.

Best practice chapters:

1. Dansk resumé
2. Executive summary in English
3. Introduction
4. Best practice guide structure
5. Organization
6. Basis of the design
7. Production and Injection wells
8. Production Electrical Submersible Pump (pESP)
9. Filtration and water treatment
10. Heat Exchangers
11. Injection Pump (iP)
12. Heat Pump
13. Auxiliary Systems
14. Heating Loop
15. Conclusions
16. References

4 Organization

The planning and execution of a geothermal project requires an organization which fulfils the formal requirements of technical and financial capacity, according to the Danish Subsoil Act and the license granted by the Minister for Climate, Energy and Utilities / the Danish Energy Agency.

The company which is planning to execute a geothermal project in a district heating area needs to apply for a license. The relevant documents and procedures are available on the Danish Energy Agency's home page:

https://ens.dk/ansvarsomraader/geotermi/ansoeg-om-en-geotermitilladelse

The company or group of companies to whom the license is granted is called the licensee. An operator has to be appointed, typically one of the companies from the licensee group.

Once there is a project and the district heating company has contractually committed themselves to either buying the geothermal plant(s) or the geothermal heat, an organization must be established that covers all of the disciplines, e.g. project management, drilling, geology, reservoir engineering, completions and production technology.

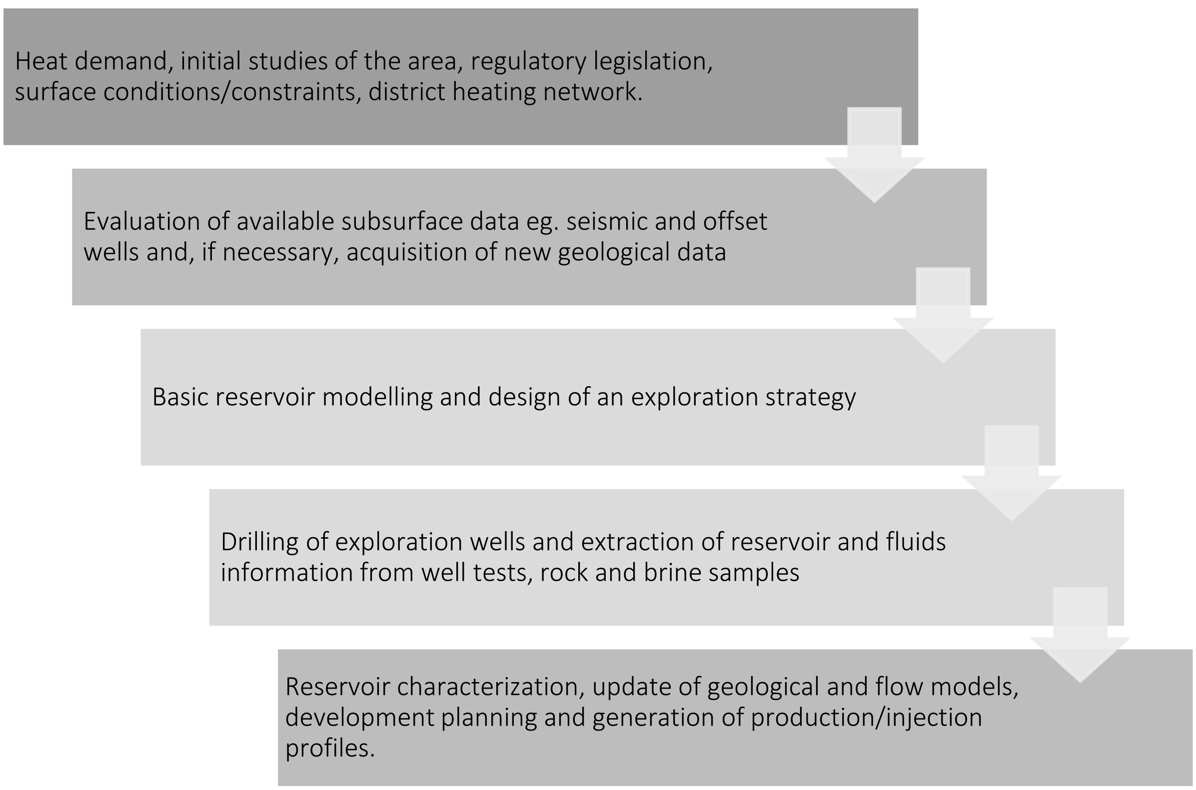
An organizational chart and a RACI (Responsible, Accountable, Consulted, and Informed) chart should be established to ensure all roles and responsibilities are described.

Once the geothermal plant is ready for production, an operations organization has to be in place.

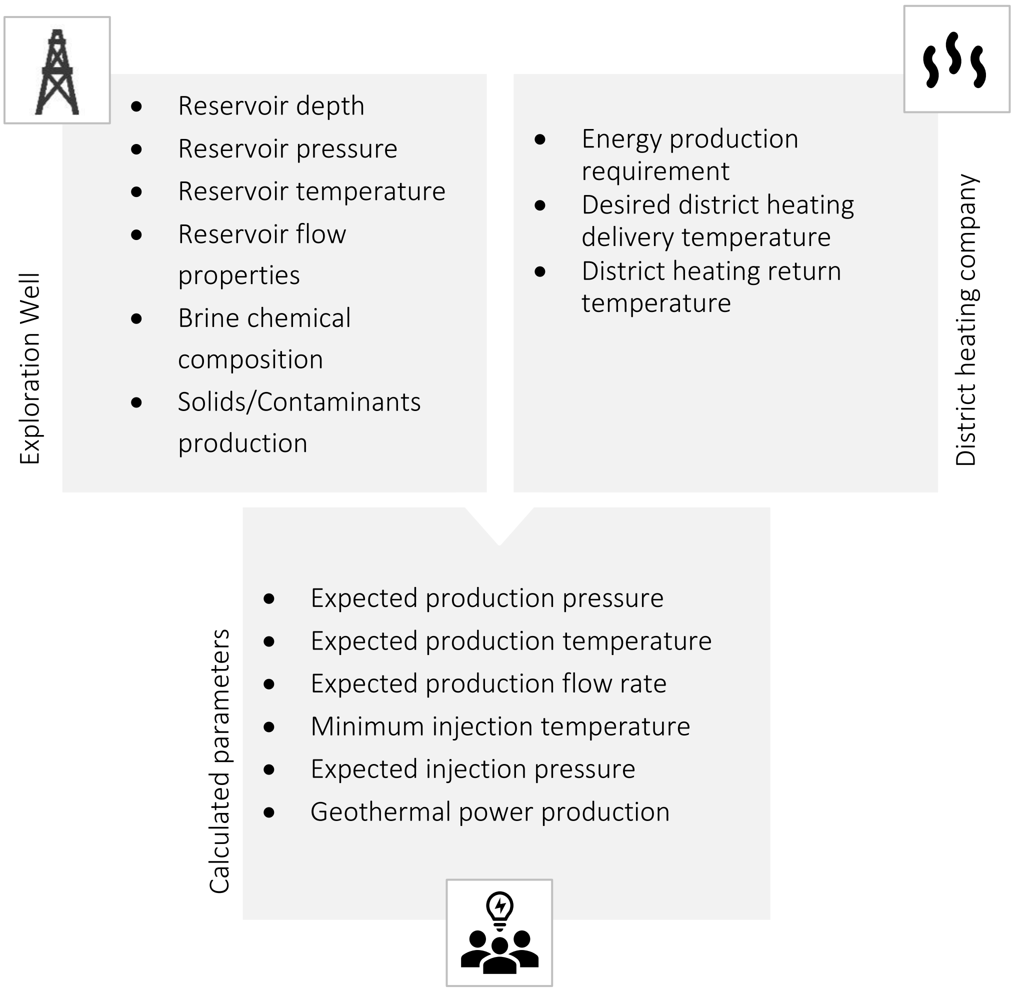
5 Basis of the design

Designing a new plant requires a complete assessment of its main objectives, its social-geographic environment and the surface/subsurface characteristics of the place where it will be located. During this project phase, a range of input parameters must be provided and the higher the accuracy of the information available, the better will be the design.

To obtain the desired input parameters some steps must be taken. This pre-design phase can be summarized as shown in the flowchart below:



Once all the studies and analyses are finished, it is possible to define the input information that will guide the design of a new plant. A summary of these primary inputs is shown below:



In order to optimize the plant design, most of the input parameters should not be viewed as static, but instead as being dynamic and subject to change during the lifetime of a plant. In order to generate accurate energy production forecasts, avoid the potential over- or under-dimensioning of production facilities, and develop effective operational guidelines, it is advisable to assess how the primary input and output parameters will vary through the seasons and production years.

For example, electric submersible pumps (ESPs) are designed according specific ranges of flowrates and pressures. If the production forecast indicates significant changes in the flowrate and pressure during the lifespan of the equipment (5-7 years), an ESP can be selected that accommodates a wider range of flowrates and pressure in order to accommodate these variations and prevent a well intervention to replace the ESP.

6 Production and Injection wells

The production well is the path for the geothermal brine to flow from the reservoir to the surface. The design, construction and material selected for a well will directly impact the quality of the produced water, flowrates and project costs.

The pressure in most low enthalpy geothermal reservoirs is sub-hydrostatic and therefore does not provide enough energy (pressure) for the reservoir brine to flow naturally to the surface, so an artificial lift method must be adopted. Due the high flow rates required, the common technology applied is an Electrical Submersible Pump (ESP). High volume ESPs have larger diameters, which needs to be taken in consideration during the design of production wells.

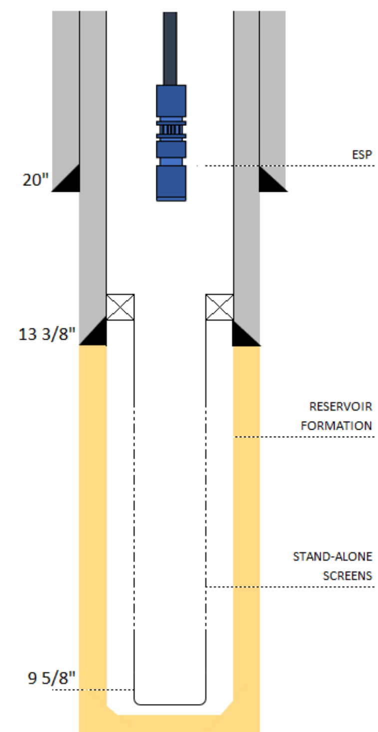


Figure 2. Production well example

Injection wells are the connection between the surface plant and the reservoir. After heat is extracted from the produced geothermal brine, the cooled brine is displaced back to the reservoir providing pressure support to the production wells.

Because of the formation characteristics, solids content and changes in the physical/chemical composition of the brine, the reservoir and the well offer flow resistance to the cooled injection stream. Over the operational time, as reservoir damage increases the resistance to flow also increases. Injection wells should be designed to operate over a wide range of pressures, and it is recommended that the injection capacity exceed the production potential (number of injection wells higher than production wells).

In many cases, the main operational issues observed in geothermal plants are related to injectivity difficulties. Therefore, injection wells should be designed so that they offer the lowest resistance to the flow and do not contribute to the reservoir damage caused, for example, by corrosion and scaling by products. Furthermore, proper wellbore conditioning and cleanup should be performed prior to completing the wells.

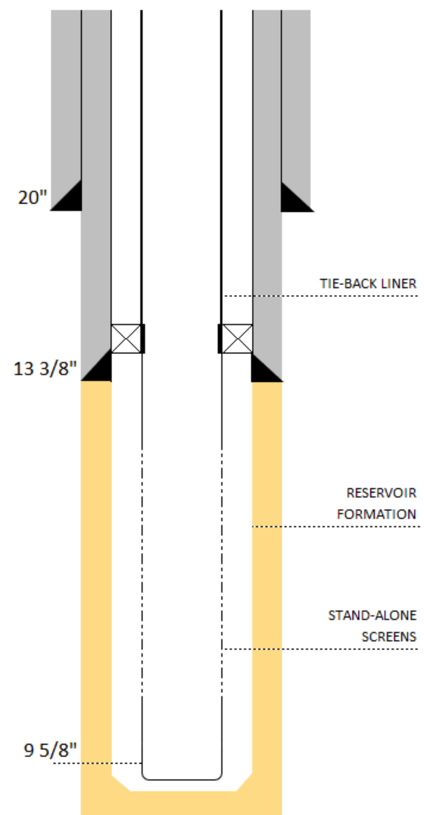


Figure 3. Injection well example

Completions can be divided into reservoir completion (the connection between the reservoir and the well) and upper completion (conduit between reservoir completion and surface facilities)[2].

6.1 Lower Completion

The major risks concerning the lower completion are related to the chemical and physical characteristics of the fluids and solids circulated from the production well to the injection well, the mechanical properties of the reservoir formation, flow conditions, and the pressure and temperature changes in the well and reservoir near the wellbore.

The main risks, causes and mitigating actions to consider when designing lower completion systems are:

Risks	Cause	Mitigating Action
Sand production: Concentration (ppm) and size distribution (mm)	Formation characteristics	Sand control methods, Filtration
Corrosion	Dissolved gases (CO_2, O_2, H_2S etc.) Bacterial count	Corrosion inhibitors, Biocides Material Selection, Oxygen ingress control
Scale Precipitation	Dissolved solids (salinity) (TDS): Concentration, water compatibility, pressure and temperature	Scale inhibitors, pressure/temperature control
NORM	Natural occurrence	NORM inhibitors, Reservoir Selection
Fines migration	Critical flow velocity	Well design Adjust flow rate or salinity, Periodic stabling treatments
Well instability	Formation characteristics	Completion selection
Gas production	Natural occurrence	Zone selection, separation and utilization, reinjection
Induced Seismicity	High pressure caused by fluids injection	Control of operational pressures and seismicity monitoring
Reservoir cooling	Proximity between producer (high temperature) and injector (low temperature and low temperature support from underground	Well placement and temperature control

All the risks listed above can result in a decrease in well productivity and/or injectivity, environmental issues, damage to downhole equipment and/or production facilities, formation damage and plugging of perforations/screens.

The assessment of these risks will define the design of the well and operational procedures.

6.1.1 Sand production

Unconsolidated (or poorly consolidated) sandstone reservoirs with permeabilities in the range of 0.5 to 8 Darcy are most susceptible to sand production. Sand production can occur with varying degrees of severity during early-time production startup or later in field life when the reservoir pressure decreases and can be temporary or continuous.

Although some degree of sand production can be accepted and managed, it is unwanted because it can plug wells, erode equipment, and reduce well productivity.

Sand production is associated with three main characteristics[3]:

- The strength and geomechanical properties of the rock
- Regional stresses imposed to the perforation or wellbore
- Local loads imposed to the perforation or wellbore due the presence of the hole, flow and reduced pore pressures

In certain cases, sand production can be avoided without special downhole completions by selecting mechanically strong reservoirs intervals to complete wells in, avoiding open hole completions and applying reservoir management strategies to maintain reservoir pressure.

Below certain acceptable limits, this production can be tolerated. In such a case the associated risks must be fully quantified and mitigating measures must be evaluated and implemented.

Once sand grains are produced from the reservoir, depending on the characteristics of the production flow and volume of solids, it can be carried by the brine to the surface, accumulate in the bottom of the wellbore or even cause the collapse of the wellbore (open hole completion).

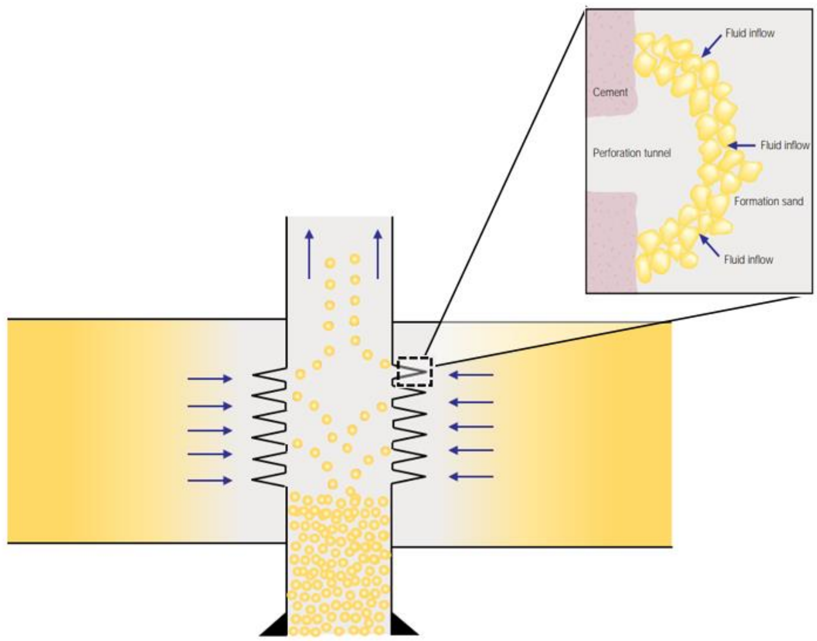


Figure 4. Sand production inside the well[4]

If the accumulated sand volume in the well is enough to cover the producing interval (lower completion), the production rate can significantly decline, requiring a clean-up intervention to remediate the problem and put the well back in normal operation.

When sand is produced with the geothermal brine, it may erode downhole and surface equipment or accumulate in production facilities, restricting the flow.

The consequence of these events is the risk of HSE issues, early equipment failure and the need for replacement, lower energy production and non-operational periods (shut-ins) to remove sand from production facilities.

Because of the potential damages caused by sand production to the wells and production facilities, the ideal solution is to control it downhole with a properly designed lower completion[5].

Figure 5. Blockage and erosion problems caused by sand production[6]

Predicting the sand production risk requires detailed knowledge of the formation´s mechanical strength and the in-situ earth stresses. This information can be acquired from an exploration well or from offset wells[7]. There are different techniques to determine if sand control is required, but none of them has proven to be universally acceptable or completely accurate[8].

Core analyses and field techniques like micro fracturing may be used to gather rock strength data and far-field earth stresses to help predict the differential pressure that will cause formation failure and sand production.

In exploration wells, a sand flow test is often used to detect sand production and correlate the volume of solids observed to the applied drawdown and flow parameters[9].

6.1.2 Corrosion

Corrosion results from the interaction between three elements: An unprotected metal, an electrolyte (e.g. moisture/water) and an oxidizing agent (e.g. oxygen, acid or CO_2).

In geothermal systems, the interaction between the brine, the equipment´s material and system exposure to oxidizing agents, such as oxygen, will determine the type and severity of potential corrosion processes.

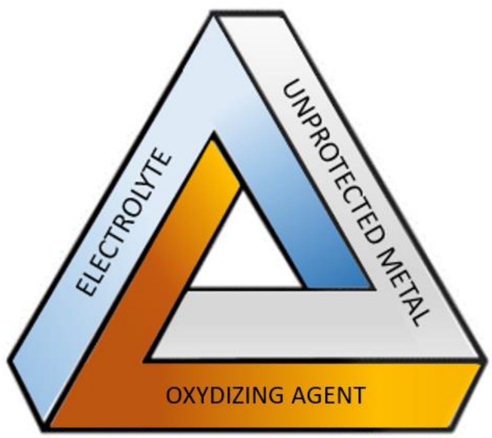


Figure 6. Aqueous corrosion elements representation

There are different forms of corrosion, each of them induced by different agents such as temperature, gases, oxygen, microbial activity and material selection. Corrosion causes the degradation of wells, completions and production facilities and damage to the reservoir.

The main types of corrosion related to the geothermal plants, its characteristics, critical factors and prevention/mitigation actions are described in the *Best practice guide for the operation of geothermal plants to avoid corrosion - Task 5.6 GEOTHERM project,* and presented in the following table[10]:

Corrosion Type	Mechanism	Critical Factor	Prevention/Mitigation
Carbon Dioxide Corrosion	The reaction between the CO_2 present in the geothermal brine and water results in the formation of carbonic acid. The acid lowers the pH of the water and depending on the concentration can cause corrosion.	CO_2 content Flow velocity Temperature Brine chemistry	Corrosion allowance Inhibition treatment Resistant materials
Oxygen Corrosion	Corrosion caused by the interaction between dissolved oxygen and carbon steel.	O_2 content Flow velocity Temperature	Minimize oxygen ingress Maintain positive pressure with inert gases during shut-in periods Selection of right sealing systems and avoid materials permeable to oxygen on the surface plant. Operational procedures Oxygen scavenger Resistant materials
Erosion and Erosion-Corrosion	Corrosion caused by the mechanical removal of metal content by solids produced from the reservoir or introduced into the system by corrosion or scaling processes	Solids content Flow velocity	Control of corrosion, scaling and sand production processes Avoid excessive velocities caused by restricted flow areas

Microbiologically Influenced Corrosion (MIC)[11]	Process where bacteria activity is related to the chemical degradation of the material. There are different kinds of bacteria associated with MIC such as Sulphate-Reducing Bacteria (SRB), Metal-Reducing Bacteria (MRB), Metal Depositing Bacteria (MDB) and Acid-Producing Bacteria (APB).	Stagnant or low flow conditions Microorganisms presence energy source (light or chemical substances) carbon source (CO_2 or organic substances) Electron donator (inorganic or organic substance) Electron acceptor (Oxygen, NO_2^-, NO_3^-, SO_4^{2-}, CO_2) Protection provided by scale deposition	Biocides Maintain minimum flow velocities Procedures to avoid contamination of equipment Periodic lab analyses with samples from the water and solids
Crevice Corrosion[12]	Crevice corrosion is a localized form of corrosion usually associated with a stagnant solution in the micro-environmental level. Such stagnant microenvironments tend to occur inside crevices, under gaskets, washers, insulation material, fastener heads, surface deposits, threads, lap joints and clamps.	Air/O_2 content Existence of crevices Presence of chlorides	Minimize oxygen ingress and use of oxygen scavengers Material selection Protection/Isolation of crevices Design of free flow systems, avoiding the creation of low flow/stagnant areas.

Under Deposit Corrosion	Refers to different kinds of corrosion process that can be physically entrapped and stimulated by solids/scale deposition, reducing the effectiveness of corrosion treatments.	Solid deposition in low flow or stagnant areas	Solids control Scales/Corrosion inhibition Design of free flow systems, avoiding the creation of low flow/stagnant areas.
Pitting Corrosion	Corrosion morphology characterized by the formation of cavities/small holes. Its occurrence is related to the localized mechanical/chemical removal or defect of protective surface films of passive alloys such as stainless steel. Once the process starts, it can develop in a high velocity due the formation of a strong galvanic cell.	Use of passive alloys protected by a passive (oxide) surface film Chloride content, pH, O_2 and aggressive species such as S, H_2S and organic acids Mechanical damage or manufacturing defect of pipes and equipment	Material Selection Oxygen Minimize oxygen ingress and use of oxygen scavengers Careful handling and installation of stainless-steel tubing and equipment Avoid ferrous contamination by the contact with carbon steel.

Sour (H2S) Corrosion	Corrosion caused by the H_2S presence in the geothermal brine. Depending on the concentration of H_2S, an insoluble iron sulphide film may form on the steel surface, which can greatly reduce the rate of general corrosion (Smith and Joosten 2006). However, in some circumstances this protective film can break down and localized corrosion attack occurs, i.e. pitting corrosion. H_2S also promotes various hydrogen related cracking mechanisms.	H_2S content pH temperature Flow velocity High chloride Concentrations Metallurgy, hardness and high mechanical stress	Chemical inhibitors Material selection Minimize oxygen ingress and oxygen scavenger usage
Galvanic Corrosion	Corrosion process caused by the electrochemical reaction resulting from the contact of two different metals, or between a metal and graphite, in the presence of an electrolyte. A special form of galvanic corrosion may also occur from deposition of noble metal ions in the brine, e.g. Cu^{++} or Pb^{++}	Presence of an oxidizing agent. Two different materials (metal/metal or metal/graphite) connected in the presence of an electrolyte	Avoid the formation of galvanic cells resulting from the contact of different class alloys. Avoid corrosion process using inhibitors and prevent oxygen ingress. Break electrical contract between metals Apply non-metallic coating on noble metal

Corrosion is one of the main challenges for geothermal plants and its effects can have a significant impact on project economics. Strategies to mitigate corrosion should be addressed in the design phase upon definition of the operational scenario and the assessment of the main corrosion threats and potential damage.

In general, two scenarios are technically possible to mitigate corrosion:

The first one is to invest in premium (corrosion resistant alloys) or composite materials/coatings for equipment and surface/subsurface facilities that will be in contact with the geothermal brine. This will provide resistance to degradation even in corrosive environments.

The second scenario is to design a chemical treatment system and protect the plant against the ingress of corrosive elements such as oxygen.

Chemical inhibitors protect exposed surfaces and slow the rate of corrosion reactions. Besides the composition and dosage of the treatment, the right location to inject these fluids should be defined and can, for example, influence the well design (if an injection line should be installed downhole).

Regarding oxygen ingress, it is advisable to select an efficient sealing system for the surface facilities, avoid permeable piping material (such as composites), maintain positive pressure in the plant with inert gases (e.g. N_2) during shut-in periods and create operational procedures to keep the system isolated.

The decision between these two options or a combination of them, will depend on the corrosion potential of the geothermal brine and the lifecycle cost analyses of both strategies.

In both cases the periodic control of the corrosion rates using monitoring equipment and lab analyzes of the brine and solid materials is advisable.

6.1.3 Scaling

Geothermal brines experience large changes in pressure, temperature and chemical conditions during the flow path from the reservoir, the production well, the geothermal plant and finally re-injection back into the reservoir. These changes along with the interaction between the geothermal brine, solid materials and microorganisms can result in the precipitation of dissolved minerals and scaling.

Precipitated solids can adhere to different surfaces and restrict flow, or remain suspended in the brine, representing a risk of clogging surface equipment, tubing, screens, perforations or even the reservoir porous media[13].

Typical scales are calcium carbonate, calcium sulfate, barium sulfate, strontium sulfate, iron sulfide, iron oxides, iron carbonate, the various silicates and phosphates and oxides.

Scaling issues are widely reported in geothermal plants in different countries. In addition to the industry expertise and historic site information, the scaling potential of a specific location can be investigated through laboratory analysis of the brine chemical composition and its interaction with reservoir rock and metallic samples from wells and equipment. Obtaining sufficient sample material (reservoir rocks and geothermal brine) from the reservoir during the well test to allow extensive analysis is considered a vital part of the exploration programme.

Scaling tests, conducted in specialized laboratories, aim to emulate the operational conditions of the wells and plant to understand how different environments impact the equilibrium of dissolved minerals.

After this assessment and taking in consideration the limitations of the process, it is possible to determine a mitigation action to control the scale formation, which can include pressure and temperature control, chemical treatments, controlled precipitation or the selection of materials with low adherence surface.

When designing a new plant, it is also advisable to create mechanisms to identify and control the scale occurrence, for example periodic water analysis and automated flow parameters monitoring and control.

6.1.4 NORM

Naturally Occurring Radioactive Materials (NORM) can be found in the earth's crust and with the exploitation of geothermal brines, hydrocarbon resources and mining can be brought to the surface.

Depending on its concentration, NORM contamination can cause severe damages to humans and environment and increase operational costs because of the protection, handling and disposal of this radioactive waste.

Once the equilibrium conditions of the dissolved radioactive metal are disturbed, due to electrochemical reactions and solubility, these radionuclides can corrode and precipitate. These solids accumulate in production facilities or are injected with the low temperature brine, potentially damaging the reservoir and consequently reducing the injectivity.

Lead is one of the most common radioactive contaminants in geothermal plants with occurrence reported in countries such as Netherlands, Denmark and Germany[14].

When reservoir selection is not an option, the prevention measures during the design phase to avoid or control the radioactive precipitation are like the regular scaling and consist of NORM precipitation control, chemical inhibition, galvanic cell avoidance and material selection.

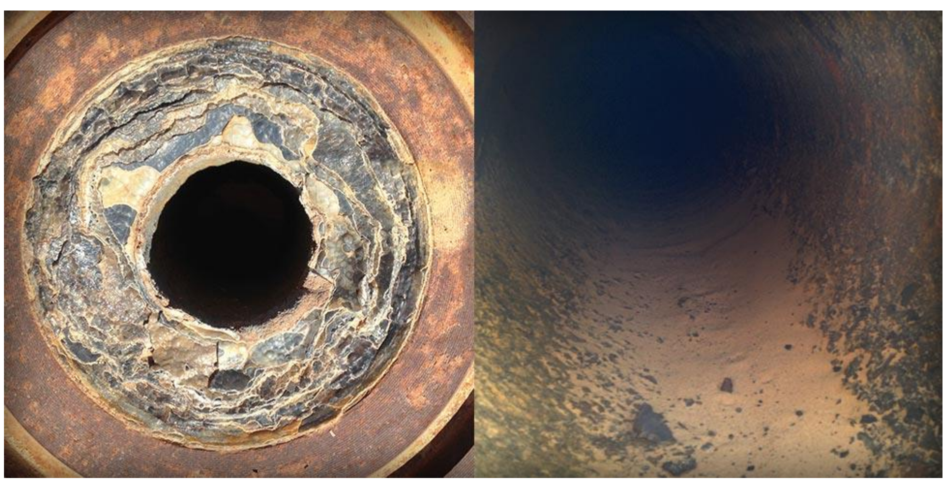
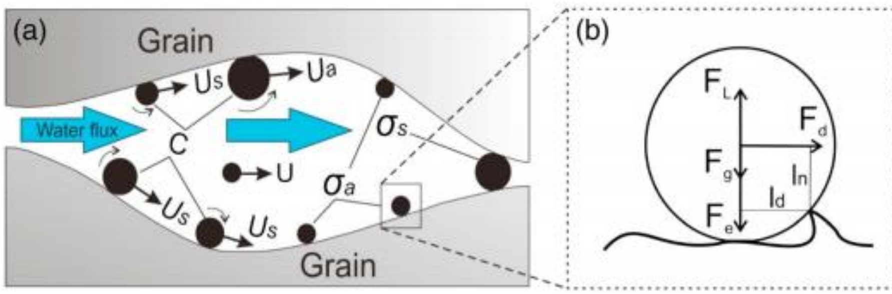


Figure 7. NORM scaling deposited on pipes[15]

6.1.5 Fines Migration

Fine solid material consisting of clays, quartz, feldspars, micas and plagioclase can be found inside reservoir porous media in a free state. Due to electrostatic, drag, gravitational, and lifting forces, these solids can remain attached to the rock surface in a stable state, but once this mechanical equilibrium is disturbed, the particles are displaced together with the produced brine and tend to accumulate in different locations, such as near wellbore areas, gravel pack completions in production wells in injection wells and the reservoir[16].



C, σa, and σs are suspended, attached, and strained concentrations, respectively; U and Us are velocities of fluid and particles, respectively; Fd, Fe, Fg, and FL are drag, electrostatic, gravitational, and lifting forces, respectively; ld and ln are lever arms for drag and electrostatic forces, respectively.

Figure 8. Cross section of a pore throat (a) and illustrating forces acting on the attached fine particle (b)[17]

With time, the accumulation of fines can reach a critical level and block the flow channels, resulting in the reduction of productivity and/or injectivity.

Different conditions stimulate fines migration, the main ones are related to high production flowrates, low salinity brines, pH increases, high temperatures and matrix acidizing. Despite the high salinity, geothermal reservoirs are vulnerable to fines migration due to the high temperatures and flow rates.

Acid treatments to stimulate production from sandstones, if incorrectly designed, can achieve the opposite effect, by increasing the liberation of fine material. The prevention of fines migration includes acid treatments, designed to dissolve fines and enlarge the porous media, and treatments using ultra-thin tackifying agents (UTTA) to stabilize loose particles in a high flowrate environments.

6.1.6 Well Instability and Lower completion selection

Lower completion design will determine the ability and efficiency of a given well to perform the role it is designed for, either to produce or inject. Decisions related to well trajectory, bottom hole completion and sand control methods are examples of choices that should be made to guarantee/enhance productivity and injectivity, provide wellbore stability and prevent the circulation of solids in the system.

- Well trajectory and inclination

Well trajectory and inclination will influence the area and the efficiency of the contact surface between the reservoir and the wellbore.

Vertical wells are easier to drill than deviated wells and can be completed in and produce from different pay zones. Horizontal wells provide a greater area of contact between the wellbore and reservoir than vertical wells, but with higher drilling risks and costs.

Well trajectory also influences the wellhead positioning. While directional wells can have their wellhead installed close to each other and exploit separated locations of the same reservoir, vertical wells should be spread in distant surface positions to reach these targets and need to be connected to the plant by longer surface flowlines.

In summary, as simpler projects, vertical wells offer less risk and drilling costs, but promote a less efficient contact with the reservoir formation and need larger pipe network to connect the wells. In this way, the advantages, risks and costs of each trajectory type should be carefully evaluated.

- Open hole versus Cased hole

The term open hole covers a variety of completion techniques such as bare foot completion, pre-drilled and pre-slotted liners, open hole sand control techniques (standalone screens, gravel packs and expandable screens). Open hole completions can significantly reduce the costs of the project, by avoiding perforating and cementing costs, especially in long producing intervals, but can offer higher risks in terms of well stability.

Cased and perforated completions are mainstay of many fields and there are several advantages over the open hole completion, for example: higher well stability, selectivity of production areas, simpler techniques to isolated undesirable sections of the reservoir, ability to reperforate in damaged zones or add new production zones, reduced sanding potential and easy application of chemical treatments[18].

- Sand control requirement and type of sand control

High sand production rates can become a problem depending on the characteristics of the reservoir being produced. Different techniques can be applied to control the sand production. The solutions can range from changes in operating practices to mechanical and chemical measures.

Sand production can be a problem in both production and injection wells.

Sand production in production wells is typically the result of high drawdown pressures and high flow rates in the near wellbore environment. Sand production and the loss of injectivity in injection wells can be caused by back production during shut in periods, cross-flow between different reservoirs intervals in the well and pressure pulses caused by abrupt shut-ins (water hammer). The main techniques to control sand production are listed and briefly described below[19]:

- Operational procedures to reduce sand production
- Standalone Screens
- Open hole gravel packs
- Cased hole gravel packs
- Frac packs
- Expandable screens
- Chemical consolidations

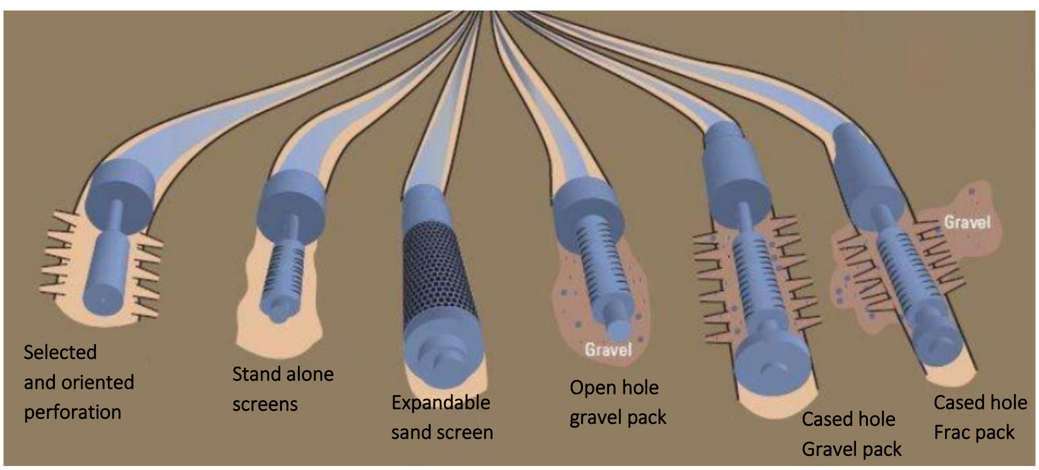


Figure 9. Sand control completions[20]

Sand control method	Description	Pros	Cons
Operational procedures to reduce sand production	Operational techniques to control sand production without using screens, gravel pack or chemical agents. Lower sand production can be achieved by maintaining the flow pressure above the bottom hole critical pressure, perforate only consolidated intervals and through techniques such as oriented perforation.	Possibility to reduce sand production without major investments. Eliminate risks related to complex operations to install sand control equipment.	Limited methodology not applicable to every case, can impose limitations to flowrates, higher risk of sand production.
Standalone Screens (SAS)	Sand control screens installed in open hole wells without using solid porous media inside the annulus between the screen and the reservoir formation. Different kinds of screens can be used such as wire wrapped, pre-packed and premium screens.	Simple method. Easier installation and relative lower investment costs. Can offer good productivity, if the rock formation is stable and if the right screen is selected. Good option when gravel pack installation has high risks like in very long horizontal or multilateral wells.	Although the advances on installation techniques, the historical reliability of this method is poor. High chance of screen erosion magnified by screen plugging Not suited to highly heterogeneous reservoirs.

Open hole gravel packs	Sand control screens installed in open hole, but, different from standalone, the anulus between the screen and the formation is filled with specially selected porous media, or gravel.	Good reliability provides good mechanical support to the formation, high productivity.	Higher costs, Skin increase, screens and gravel vulnerable to plugging due fines invasion, risks during gravel displacement/ screens installation, reduction of the wellbore radius.
Cased hole gravel packs	Screens and gravel installed in a cased and perforated well. The gravel should fill the interior of the perforations and the annulus between casing and sand screen	Good reliability, possibility of zone isolation.	Higher costs, Skin increase, screens and gravel vulnerable to plugging due fines invasion, risks during gravel displacement/ screens installation, reduction of the wellbore radius.
Frac packs	Combined technique of hydraulic fracturing and cased hole gravel pack. Bypassing formation skin and creating high permeability channels, the induced fractures increase the production rates. Gravel and screens prevent sand production.	High reliability even in high fines and high stress environment. Good productivity in heterogeneous formations	Poor productivity in high permeability reservoirs, very high cost, fracturing risks.

Expandable screens	Sand control screens installed in open hole or cased completions. The screens are expanded inside the wellbore to eliminate the annulus space between the screen and the reservoir face and provide mechanical support to the wellbore.	Good reliability, low skin factor, wellbore mechanical support, fast installation, larger open area to flow, better wellbore access	Costs higher than standalone screens, some sand production through the screens can be expected
Chemical consolidations	Usage of chemical products like epoxy, furan, phenolic resins and alkoxysilane to harden and bond formation sand. Usually applied as a remedial measure, can be used as a sand control method in some cases. Before the consolidation, the formation must be treated. This treatment should not affect the permeability of the sand and must be effective over time.	Lower costs. Avoidance of high-risk operations.	Advisable only for short intervals with low likelihood of sand production and lower cost intervention wells

- Types of sand control screens

The effectiveness of the completion of unconsolidated reservoirs depends not only on the design of the most appropriate sand control method, but also the selection of the proper sand control screens.

Screens types can be divided in three main groups: wire wrapped screens, pre-packed screens and premium screens.

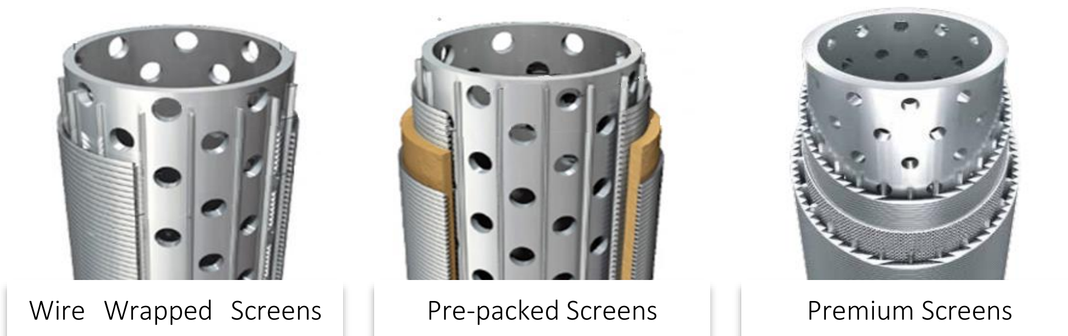


Figure 10. Screens types[21]

Wire wrapped screen (WWS) consist of a wire-wrapped jacket welded around a perforated pipe. The wires wrapped around the vertical ribs are keystone shaped, which is designed for decreasing the chances of sand plugging the screen. WWS have a larger flow area in comparison to a slotted liner and it provides good strength and accurate slot opening area[22].

Pre-packed Screens (PPS), are similar to WWS, but constructed with two concentric screens filled with gravel in the annulus between them, providing an extra filtering media. Premium screens are an all metal design with a protective outer metal shroud and a metal mesh filtration. The main advantages of premium screens over other screens are screen plugging resistance and ability to flow back drilling fluid through the screens[23].

In addition to the aforementioned screens, slotted liners can be also used to control sand production, but although the low cost, their efficiency is questionable as the slots tends to allow some degree of sand production[24].

6.1.7 Gas production

Depending on the reservoir fluids composition and pressures variations during the geothermal production, free gas phases can be liberated (methane, nitrogen, CO_2, H_2S). Under some conditions, it is possible to operate above the saturation pressure of the gases and not have to contend with free gas

When it is not possible to operate above the saturation pressure, the gas should be separated in a degassing facility. Once the gas is separated, it can be used in different applications. For example, methane can be utilized to run auxiliary equipment and CO_2 in greenhouses and beverages companies.

The gas phase separation can lead to changes of the brine chemistry and cause the precipitation of carbonate scale, requiring the usage of inhibitors to avoid this process.

Figure 11. Gas Separation facility in a geothermal plant in Slovenia[25]

6.1.8 Induced seismicity

Geothermal activities can affect the balance of subsurface pressures and trigger/generate seismic events. The mechanism of fluid induced seismicity can be divided in three categories[26]:

1) Increase of pore-fluid pressure in faults
2) Fluid compression and poroelastic deformation within pore spaces
3) Thermoelastic deformation due to temperature differences between injected and formation fluids

It is recommended to understand the geophysical characteristics of the reservoir and the historical seismic activity of the area, but this action alone will not prevent the occurrence of new seismic events. The effects of the combination between the injection parameters such as flowrate, temperature, cumulative injected volume, pressure and reservoir conditions such as pore pressure, temperature, stress field, rock strength, pre-existing faults and their orientation, are difficult to predict.

Beyond the geophysical assessment, is recommended to monitor the seismic events and use this information to control the injection parameters if and when seismic variations are detected.

Control the pressure applied to the reservoir and avoiding abrupt changes in the pressure regimes inside the wellbore (soft starts and shut ins) are key factors to avoid induced seismicity.

6.1.9 Reservoir cooling

The geographical proximity and high permeability between production and injection wells, added to a scenario of insufficient thermal influx from the underground, can lead to the decrease of the temperature of produced brine. This situation causes the reduction of the amount of heat that can be extracted from the brine and reduces the efficiency of production facilities designed for the original temperature conditions. It is advisable to, through reservoir simulation, ascertain the ideal distance between the production and injection wells to prevent thermal breakthrough during the projected plant operational lifetime.

6.2 Wellbores

The main decisions concerning the wellbore are the well design, wellbore mechanical properties, casing isolation and the interaction between the subsurface materials and the produced brine.

In that way, the main issues to take in consideration when designing wellbore systems are:

Risks	Cause	Control
Well instability, poor isolation and restricted diameter	Well design misspecification	Well design review and validation, stress analyses, and industry best practices
Corrosion	Dissolved gases (CO_2, O_2, H_2S etc.) Bacterial count	Corrosion inhibitors, Biocides Material Selection, Oxygen ingress control
Scale Precipitation	Dissolved solids (salinity) (TDS): Concentration, water compatibility, pressure and temperature	Scale inhibitors, pressure/temperature control

6.2.1 Well instability, poor isolation and restricted diameter

The objective of the casing design is to ensure the well's mechanical integrity, providing a design basis that accounts for all the anticipated loads that can be encountered during the life of the well[27].

The well design must specify casings that can withstand a variety of forces, such as collapse, burst, and tensile failure[28]. At the same time, the casing and the cement barrier must provide the isolation between the formation and wellbore, especially in wells exposed to high injection pressures, high drawdowns and drinking water reservoirs.

The design and stress checks are usually made using commercial software such as *WellCat* and *StressCheck* allied with industry best practices and local knowledge.

Besides well integrity, casing internal diameter should be large enough to accommodate different downhole equipment such as pumps, logging tools, production string and sand control completion.

The internal diameter of casing and tubing, together with material roughness, will also impact the pressure losses in the well, i.e. larger diameters and smoother surfaces offer lower flow resistance, in other words, less pump power required.

6.2.2 Corrosion and Scaling

Corrosion and scaling can affect the mechanical stability of casing, contribute to the solids production and restrict the flow area, in addition to the issues discussed in the lower completion section.

The material selection and production chemical treatments will determine the vulnerability of this equipment to corrosion and scaling.

Special alloys, composite materials and coatings can increase the initial cost of the project. However, they may be a more economical alternative over the lifetime of a project by providing better resistance to corrosion and scaling and eliminating the need to use chemical inhibitors.

In that way, the benefits of increased performance from special materials should be weighed against the higher acquisition cost of this equipment during the economic analysis.

A list of the typical materials used in different water systems equipment can be found below[29].

Equipment	Materials
Wellhead equipment	Carbon steel or low alloy steel with alloy 625 on all wetted surfaces
Piping	Carbon steel, Type 316, Type 22Cr duplex, Type 6Mo, GRP
Vessels and equipment	Carbon steel with and without internal organic coating a, Type 316, Type 22Cr duplex.
Pumps and valve body/bonnets	Carbon steel, Type 316, Type 22Cr duplex, carbon steel internally clad with alloy 625.

7 Production Electrical Submersible Pump (pESP)

Electrical Submersible Pump are the prime candidates for an application in geothermal wells as they can produce large volumes of liquids, be installed in deviated wells and handle high temperatures.

Although very efficient, these pumps represent a significant cost and the misspecification or operational best practices neglection can lead to unpredictable expenditure that can compromise the project. As such, the main risks for the ESPs operation are:

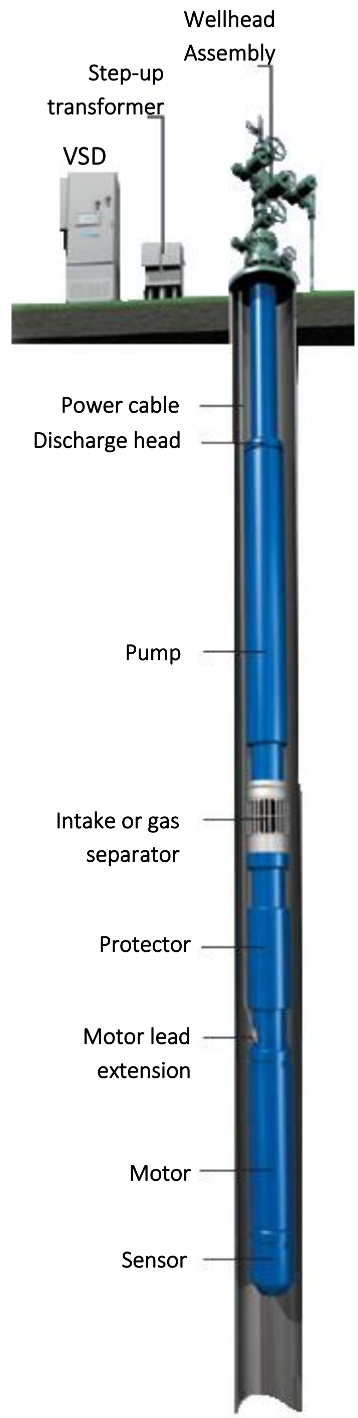
- Misspecification
- Improper installation and handling procedures
- Power supply quality
- Well deliverability and temperatures
- Solids production
- Gas production
- Corrosion and Minerals deposition

The ESP system delivers an effective and economical means of lifting large volumes of fluids from deep wells under a variety of well conditions. ESPs are a versatile form of artificial lift and are in operation all over the world in oil, gas and geothermal wells[30].

Installed inside the production wells, ESPs require minimal surface equipment, can be used in deviated wells and are capable of handle high temperatures and a wide range of flow rates. On the other hand, ESPs perform poorly in the presence of sand production, are sensitive to gas and require periodic interventions due to their limited lifespan (from 5 to 7 years) or unexpected maintenance.

A typical ESP system consists of an electric motor, seal section, gas separator, multi stage centrifugal pump, power cable, surface control mechanism and transformers. The centrifugal pump is driven by an electric motor that receives power from the surface.

The major ESP components are described below[31]:



- VSDs

VSDs offer greater flexibility than a switchboard to operate ESPs. Instead of operating the ESP at a constant 50 or 60 Hz, the ESP can operate at speeds greater or less than the grid power frequency. Changing the operating speed of the ESP can optimize the equipment performance and well productivity during the life of the well

- Wellhead assembly

The wellhead assembly, which allows the tubing and power cable to pass through the well to the surface, includes the following items:

  - Feed-through mandrel for power cable
  - Lower connector on the main cable

- Power cable

The power cable, which supplies electricity to the ESP motor, is available in various configurations, both flat and round profiles, to match the cable to specific wellbore conditions. The cable is banded or clamped to both the production tubing and the ESP components to support its weight. Cable clamp protectors are used in deviated wells or in wells with tight equipment clearances.

- Discharge head

The discharge head is the connection between the pump and the production tubing. It bolts to the pump and is threaded to the tubing.

- Pump

The pump adds lift to the wellbore fluid by converting kinetic energy from the rotation of pump impellers to potential energy in the form of hydraulic head. Pumps are available in a wide range of sizes and configurations.

- Intakes and gas devices

The wellbore fluid enters the pump through the intake section. To help reduce the negative effects of gas in the pump performance, it is possible to install gas separators and gas-handling devices, in addition to standard intakes

- Protector

The Modular Protector provides the ultimate protection available for keeping well fluids from entering the motor. It also serves as a motor oil reservoir, provides pressure equalization between the motor and the wellbore, and carries the thrust load of the pump.

- Motor

An electric motor provides rotational energy to the pump section. As with pumps, various sizes of motors are available.

- Sensors

Artificial lift monitoring systems enable advanced monitoring and control of the ESP performance.

7.1 ESP selection

Selecting the proper ESP and maximizing its lifespan starts with a good well data that represents the well fluid properties and inflow performance of the well, anticipation of harmful conditions and the selection of the appropriate metallurgies and equipment configurations to handle those conditions effectively.

Basic inputs for ESP design[32]:

Well Physical description

- Casing size and weight
- Tubing size, type, and thread
- Equipment setting depth
- Depth of perforation
- Restrictions
- Unusual mechanical conditions

Production data

- Static fluid level or static bottom-hole pressure
- Pumping fluid level or flowing bottom-hole pressure
- Expected production rate
- Bottom-hole temperature
- Gas content
- Tubing head pressure

Well fluid data

- Specific gravity of water
- Temperature

Power supply

- Surface voltage, phase, and frequency
- Line capacity

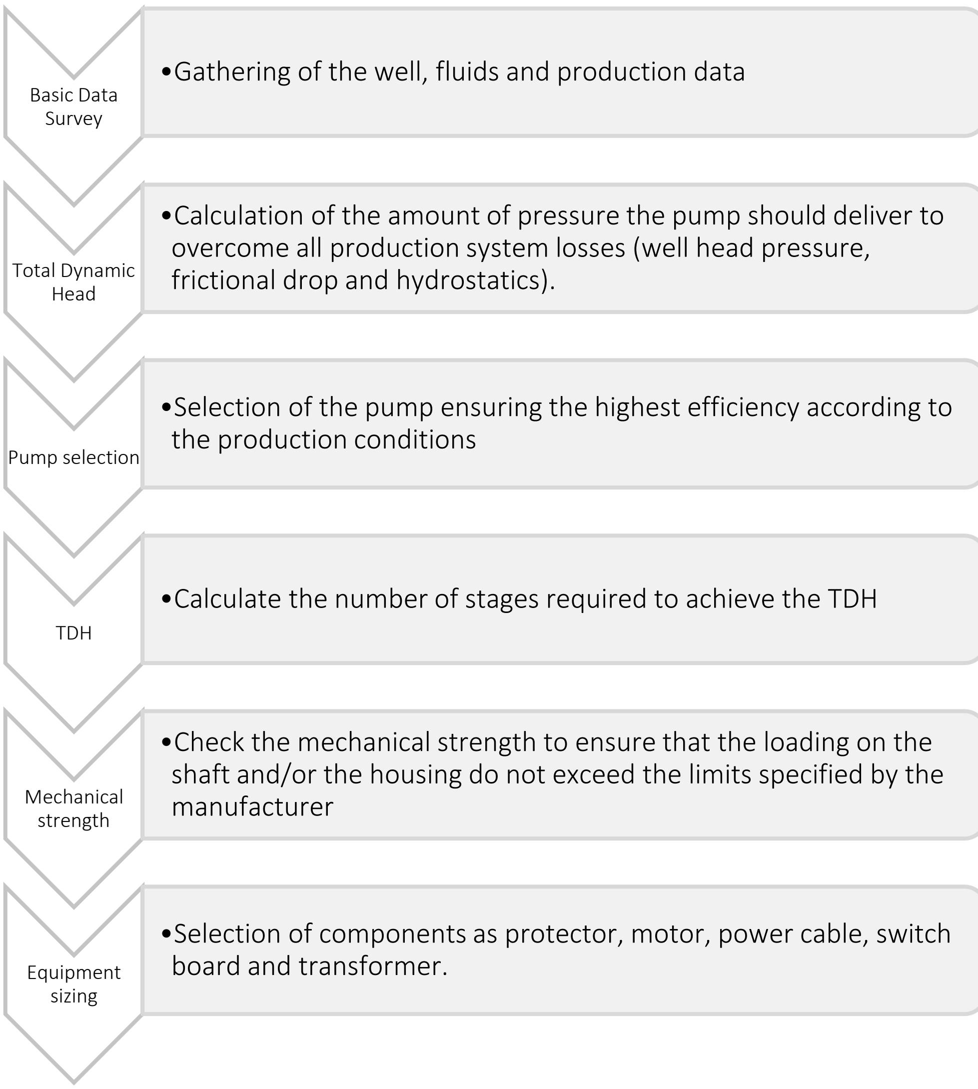
Unusual conditions

- Abrasives
- Corrosion
- Scale-forming tendencies

Performance monitoring

- Communication protocol
- Data management
- Monitoring and surveillance needs

After the definition of the basic input parameters, the ESP selection is commonly executed through commercial software, follow the summarized steps below:



In conclusion, the proper selection and operation of the ESP must take in consideration:

- Expected local reservoir performance/well deliverability during the lifespan of the equipment
- Borehole architecture/completion
- Produced fluid composition and thermochemical, free gas presence, aggressive components, solids production
- ESP equipment robustness, considering the usage of variable-speed drivers or dual installation design
- Competent ESP system assembly, installation, and commissioning
- Power quality to supply the pump system
- Project dynamic fluid level above the intake of the pump
- Use of downhole sensors and implementing a monitoring and surveillance system
- Measure, record and communicate lifespan performance
- Maintain stable operational parameters to improve the efficiency and operational life of the pump
- Establish start up and shut down procedures to protect the system from abrupt pressure and rate variations.

8 Filtration and water treatment

Water chemistry has a major influence on the efficiency of injection wells. Brines with high solid content can compromise the injectivity of even high-quality sandstone or carbonate formations[33].

Source water used for injection often contains solids, originated from the water production (e.g. sand) or by-products of corrosion and scaling, which can reduce permeability of the formation around the wellbore.

Solids-particle damage depends on particle size of the solids, the average pore-throat diameter of the formation and the injection rate[34].

According to Bellarby (2009), particles diameters larger than $^1/_3$ of the pore throats sizes form external filter cake and are easily back produced. Particles diameters between $^1/_3$ and $^1/_7$ of pore throats sizes tend to plug (internal filter cake) and are difficult to remove. Particles diameters less than $^1/_7$ of the pore's throats will pass through the formation and are easily back produced.

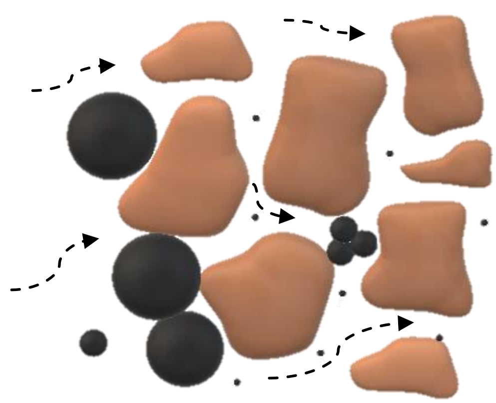


Figure 12. Solids displacement inside porous media

As solids concentration in the injection water increases, the permeability rate declines and consequently injection pressure becomes higher.

Solids present in the produced water will also impact on the functionality of surface and downhole equipment as they can erode different materials and restrict flow.

In addition to the particles produced from the reservoir, the precipitation of dissolved minerals and the byproducts of corrosion can contribute to an increase of the solid contents at different stages of the process. For this reason, filtering systems in geothermal plants are usually installed at two locations: one upstream of heat exchanger (to protect plant equipment) and another upstream of the injection pumps (to protect the injection wells).

Various water clarification devices are available, and the choice of the most suitable system should be based on the characteristics of the geothermal brine and process plant and the operational measures (e.g. periodic cleaning need) that every equipment requires.

Every equipment can be defined by its filtration parameters:

- Absolute filtration rate
- Nominal filtration rate
- Beta ratio
- Efficiency ratio

The absolute filtration rate of a filter refers to the diameter of the largest spherical glass particle, which will pass through the filter under laboratory conditions (very low-pressure differentials and no pulsating condition), in other words, it indicates the maximum theoretical particle size that can pass through the filter media.

The nominal filtration rate refers to the ability of preventing passage of a minimum percentage (by weight - usually between 60% and 90%) of solid particles greater than the stated pore size[35].

The Beta Ratio is calculated using the ISO multi-pass test standard 16889:1999. The test consists of adding particles of a known size to the test fluid until the fluid reaches a saturation point, and then bringing the filter online to remove particles in one pass through the element[36].

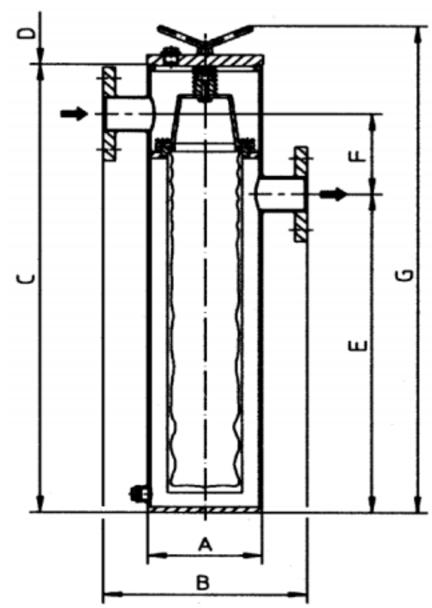
The ratio between the particle content (greater than the specified size) upstream and downstream the filter media is the Beta Ratio.

The efficiency ratio of the filter can be calculated directly from the beta ratio, by the formula: *((beta-1)/beta) x 100*. It means that, a filter with a beta of 10 at five microns is thus said to be 90 percent efficient at removing particles five microns and larger[37].

During operation, the pressure levels, filter media configuration, and solids geometry can vary, so these filtration rates may not represent the actual particle size filtered under operational conditions but serve as technical indicator of the filter potential.

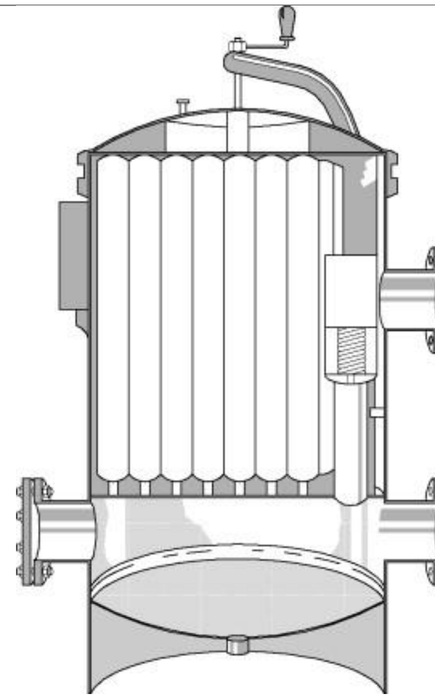
The main types of filtering systems applied to geothermal projects are:

- Bag filter
- Cartridge filter
- Self-cleaning filter
- Multimedia filter
- Hydrocyclone

Filter type	Description	Scheme
Bag Filter	Device composed by a metallic filter housing, support strainer and filter bag(s). Depending on the model, one single housing can accommodate more than one filter bag. The filter bag material and surface area determine the capacity and filtration rate of the equipment. The water flows from the top of the housing, passes through the bag and comes out at the bottom. As the solids are retained inside the bags, periodic filter replacement and solids disposal are required.	

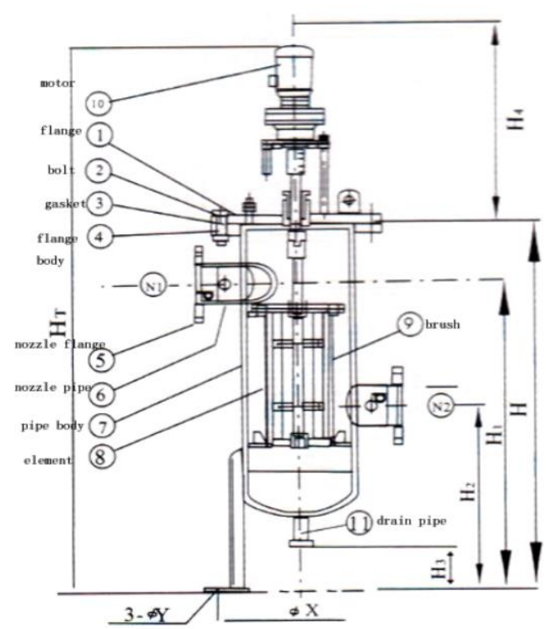
Cartridge filter

Applicable to the removal of fine particles or even chemicals, cartridge filters are composed of a metal housing equipped with supporting tube and cartridges tubes and are capable of filtrating not only on its surface but through the tube media. As with bag filters, the water flows from to the top to the bottom of the filter housing, which retains the solid material as the water flows through the cartridges. The cartridges can be made from different materials with a range of performance starting from 0.2 μm[38]. Once the solid retention capacity is achieved the cartridges need to be replaced.



Self-cleaning filter

In Self-cleaning filters, the water flows through a cylindric filter element located inside the filter housing, and sediments accumulate on the inside surface of the filtering screens. Once the volume of sediments achieves a determined volume, the pressure drop caused by this accumulation activates automatic blades/brushes, that move longitudinal inside the filter pushing the sediments to the bottom of the equipment, where later, they can be drained.



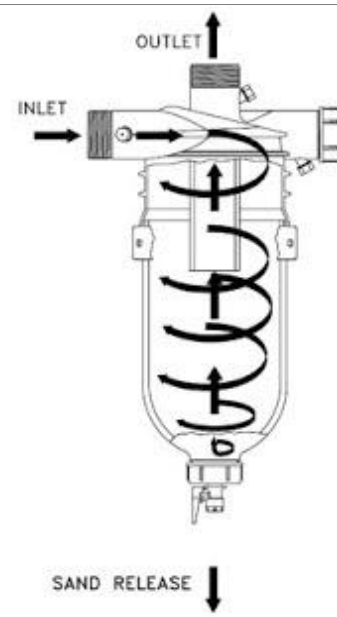
Multimedia filter

A multimedia filter is used to reduce the level of suspended solids (turbidity) in process water. Suspended solids can consist of small particles such as silt, clay, grit, organic matter, larvae, zooplankton, algae and other microorganisms. The filtration degree of a multi-media filter depends on the filter media and flow velocity through the filter.

A typical multimedia filter setup contains three layers of filling: anthracite, sand and gravel.

Hydrocyclone

The hydrocyclone filter consists of a cylindrical chamber connected to a conical body that uses fluid pressure to generate centrifugal force and a flow pattern which can separate particles or droplets from a liquid medium[39]. Brine and solids are injected into the hydrocyclone in such a way as to create a vortex and, depending upon the relative densities of the two phases, the centrifugal acceleration will cause the dispersed phase to move away from or towards the central core of the vortex.



The graphic below compares different technologies of filters based on their particle size retention range.

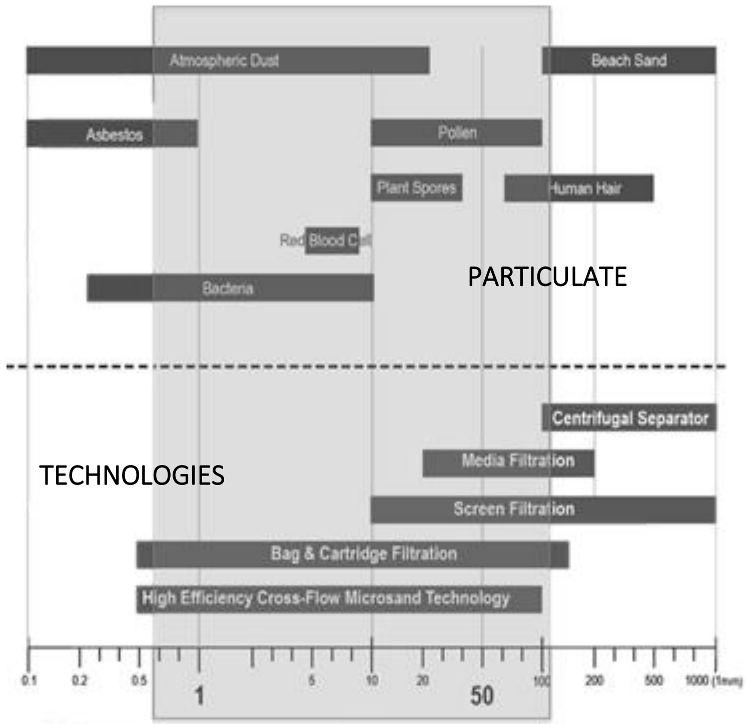


Figure 13. Filter types x filtration level

For geothermal plants, at the first filtration stage (before the heat exchangers), the objective is to remove coarser particles (over 10 µm).

This can be done with the use of Hydrocycles, bag filters and self-cleaning filters and this stage can be divided in two steps, using different filtering technologies and filtration levels.

At the second filtration stage, located before the injection pump and well, finer materials (0.5 – 10 µm) are removed usually by cartridge filters[40].

Start-up operations in wells with high sand content may require an additional filtering step, just after the production well, to remove high volumes of solids until the well is cleaned and the produced solids content is stable.

The concerns that need to be taken in consideration when designing a filtering system are[41]:

- Production/Injection flow rate
- Production and injection temperature
- Pressure
- Total amount of suspended solids particles (TSS)
- Particle size distribution
- Physical/chemical composition of the water
- Injection well properties (porosity, permeability)
- Solid content allowed in the system
- Equipment size and redundancy
- Solids handle and disposal
- Investment and operational costs

9 Heat Exchangers

Heat Exchangers are the equipment responsible for enabling the transfer of heat between two (or more) low streams with different temperatures. Although based on the same physical principles, there are different types of heat exchangers and according to their configuration they can be applied in many process and industries such as oil and gas, food, chemical and power.

For geothermal plants, heat exchangers can be used to:

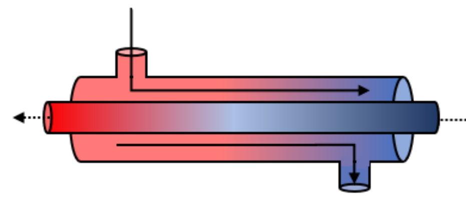
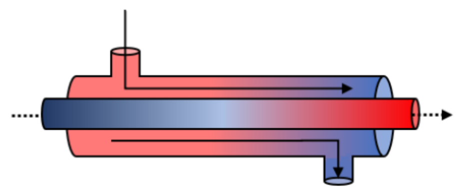
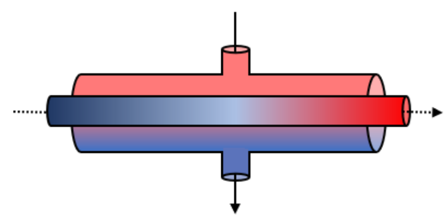
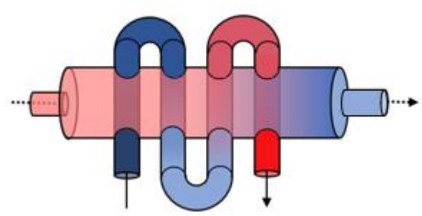
- Promote direct heat exchange between the geothermal brine and the district heating water, when the geothermal brine temperature is higher than the district heating water
- Transfer the heat between the geothermal water and a geothermal plant loop (clean water), avoiding the flow of aggressive components and solids (present in the brine) through the heat pump evaporator.
- Heat transfer at the evaporators and condensers of the heat pumps

Heat Exchangers can be characterized according to their flow configuration, construction and heat transfer mechanism. These characteristics are described below:

- Flow Configuration

Heat exchanges should provide a media where the thermal energy can flow from one flow stream to another. The direction and configuration of the flow streams inside the heat exchanger impacts the way the heat is transferred. There are four types of flow configuration in heat exchangers[42]:

- Counter Flow
- Co-current Flow
- Crossflow
- Hybrids

Type of flow	Description	Scheme
Counter Flow	Currents flows parallel and in the opposite direction. This configuration enables the highest heat transfer efficiency.	
Co-current Flow	Currents flows parallel and in the same direction. Although the lower efficiency, this configuration allows the greatest thermal uniformity.	
Crossflow	Currents flows perpendicularly to one another. The efficiency of this type of heat exchanger is higher than co-current but lower than counter flow.	
Hybrids	This type of heat exchanger mixes the techniques of the previous described types of flow, e.g. Cross Counterflow and Multi Pass Flow.	

- Heat exchanger Construction

Heat exchangers can be divides in two categories regarding their construction: Recuperative and Regenerative.

In the recuperative type, each current (cold and hot) flows simultaneously. This type of heat exchanger can be sub divided in two categories, Indirect and Direct contact.

In direct heat exchangers the hot and cold currents are mixed to maximize the heat exchange. In indirect heat exchangers, the hot and cold streams remain separated and the heat exchange occurs by conduction through a solid surface.

In regenerative heat exchangers the warm and cold streams flow through the same path alternately and can be subdivides in static or dynamic. Both types of regenerator are transient in operation and unless great care is taken in their design there is normally cross contamination of the hot and cold streams[43].

- Heat transfer mechanism

There are two heat transfer mechanisms: single and two-phase. The difference between them is the occurrence of a phase change of the fluids involved on the process and the liberation/consumption of latent or sensible heat.

- Heat exchanger types

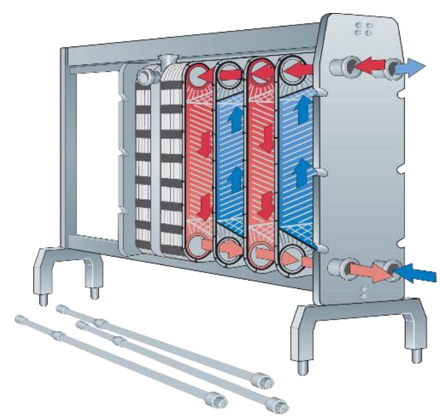
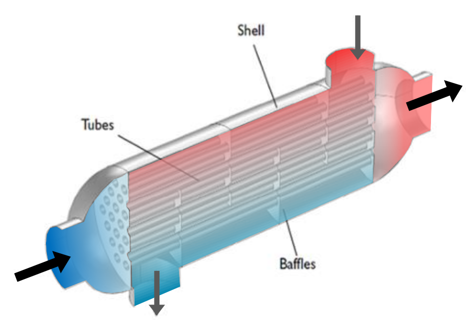
There are different types of heat exchangers available, in addition to the characteristics mentioned above, they can be differentiated by their construction materials (e.g. copper, titanium, and stainless steel) and the shape of the channels where the heat transfer occurs (e.g. shells, tubes, spiral tubes or coils, plates, fins, and adiabatic wheels).

The choice of the type of heat exchanger employed will depend on the process and industrial application, characteristics of the fluids, the expected heat transfer efficiency, available area for installation, OPEX and CAPEX costs and maintenance requirements.

The main types of heat exchangers available are:

- Shell and Tube
- Double Pipe
- Plate
- Condensers
- Evaporators/Boilers/Condensers
- Air Cooled
- Adiabatic Wheel
- Compact
-

For the geothermal plants, the energy transfer should occur without the mixture of the fluids, so metal plates or tubes acts as contact surfaces between the different temperature fluids, enabling the conduction of heat. Two main designs of heat exchangers are employed by the geothermal industry are plate and shell and tube..

Type of Heat Exchanger	Description	Scheme
Plates	The plate heat exchanger consists of a frame with a varying number of plates pressed together. Each plate has a sealing gasket, so the plates form a closed system of parallel flow channels, through which the two different temperature streams flow. The system can provide high thermal efficiency, easy maintenance, high range of heat transfer area (adaptable during operation)[44]. The standard plate design is also available with some variations, such as in plate fin or pillow plate heat exchangers, plate and frame, plate and shell, and spiral plate heat exchangers.	 45
Shell and Tube	This is the most common type of heat exchanger and is suitable for high pressure applications. It consists of a tube bundle enclosed in a cylindrical casing called a shell. To transfer heat, one fluid runs inside the tubes, and another fluid flows over the tubes (through the shell). The currents can be single or double phase and can flow in a parallel or a cross/counter flow arrangement. The tubes may be straight or bent in the shape of a "U", in that way is possible to enlarge the heat transfer surface and the efficiency of the process.	

There are often baffles directing flow through the shell side, so the fluid does not take a short cut through the shell side leaving ineffective low flow volumes.

In general, shell and tube exchangers are made of metal, but for special applications (e.g., involving strong acids of pharmaceuticals) other materials such as graphite, plastic and glass may be used[46].

The selection of a heat exchanger and its design should be based upon the following inputs:

- Temperature, flowrates and pressures of the currents
- Expected output temperatures and process efficiency
- Fluids composition, aggressive components and solids presence
- Available installation area
- Industry and process characteristics (e.g. possibility to mix fluids or not, requirement of periodic cleaning, protection against oxygen ingress)
- Available budget

The main risks associated with Heat Exchangers are:

- Fouling
- Scaling
- Corrosion
- Leaking
- Air ingress
- Clogging
- Installation problems

Over time, sediment and grime resulting from the presence of solids, scaling and/or corrosion process can build up on plates or tubes and cause clogs, retard heat transfer and reduce efficiency. This issue observed in heat exchangers is called fouling.

It is advisable to protect heat exchangers from fouling by installing an upstream filtering system and by understanding the chemical and physical characteristics of the produced brine to avoid the precipitation of minerals inside the heat exchangers.

Corrosion is a threat to the surface area of equipment and the gaskets. It can cause leaks and damage the sealing material of the equipment, allowing oxygen ingress.

Corroded gaskets, uneven plate pack clamping, pressure losses, blockage and fouling are all issues that can eventually plague the heat exchanger systems.[10] Thus, period maintenance and cleaning measures should be planned to guarantee the integrity and optimal function of the system.

10 Injection Pump (iP)

In order to inject the produced geothermal brine r back into the subsurface, it is necessary to overcome all pressure resistance offered by injection pipes, wells and the reservoir formation. In most of the cases, hydrostatic pressure is not enough to displace the geothermal brine back into the reservoir , so a pressure support system should is needed.

Water injection pumps are installed at the surface plant right before the injection well and must be able to deliver the amount of power needed to overcome the pressure drop in the wellbore, lower completion and in the reservoir.

There are different kinds of pumps available on the market and the right equipment should be designed and selected based on the project injection flowrate, required pressure, brine temperature, fluids composition, equipment and formation pressure limits.

The inputs and steps to select an injection pump are similar to the ones described for ESP systems:

Surface and Well Physical description
- Flowlines, casing and tubing properties
- Suction and discharge pressures
- Depth of perforation
- Restrictions
- Unusual mechanical conditions
- Pressure limits

Injection data
- Static bottom-hole pressure
- Expected injection rate
- Reservoir Temperature
- Gas content
- Fracturing pressures

Well fluid data
- Specific gravity of water
- Temperature
- Viscosity
- Vapor pressure
- Brine composition and solids content

Power supply
- Surface voltage, phase, and frequency
- Line capacity

Unusual conditions
- Abrasives
- Corrosion
- Scale-forming tendencies

Performance monitoring
- Communication protocol
- Data management
- Monitoring and surveillance needs

Basic Data Survey	• Gathering of the well, fluids and production data
Total Dinamic Head	• Calculation of the amount of pressure the pump should deliver to overcome all production system losses (well head pressure, frictional drop and hydrostatics).
Pump selection	• Selection of the pump ensuring the highest efficiency according to the production conditions
TDH	• Calculate the number of stages required to achieve the TDH
Mechanical strength	• Check the mechanical strength to ensure that the loading on the shaft and/or the housing do not exceed the limits specified by the manufacturer
Equipment sizing	• Selection of components as protector, motor, power cable, switch board and transformer.

It is advisable to select a flexible/modular system, which is able to easily adapt to variations of pressure demand due formation plugging, commonly occurred during the production life of the well and facilitate the maintenance/replacement of specific pump components.

Major horizontal pump components:

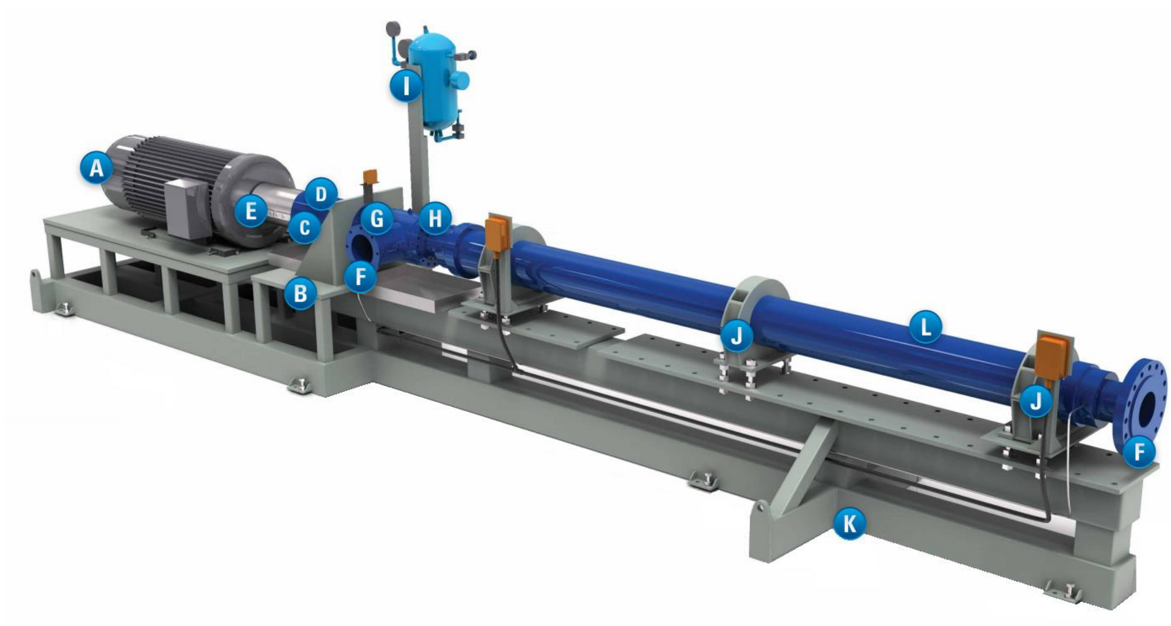


Figure 14. Injection pump scheme[47]

a) Motor
b) Motor adjustment lugs
c) Bearing assemblies
d) Thrust chamber
e) Spacer Coupling
f) Discharge flange and suction flange
g) Back pullout seal
h) Mechanical Seal
i) API flush plan pressure containment system
j) Adjustable pump clamps
k) Skid
l) Pump

The selection and operation of the surface injection pump must take in consideration the following:

- Expected local reservoir injectivity during the lifespan of the equipment
- Produced fluid composition and thermochemical, free gas presence, aggressive components and suspended solids
- Equipment robustness, considering the usage of variable-speed drivers or dual installation design
- Competent pump system assembly, installation, and commissioning
- Attention to seal selection to prevent oxygen ingress
- Ensure power quality to feed the pump system
- Pressure, temperature and flowrates monitoring and surveillance system
- Measure, record and communicate run-life performance
- Maintain stable operation parameters to improve the efficiency and run life of the pump
- Establish start up and shut down procedures to protect the system from abrupt pressure and temperature variations

11 Heat Pump

The heat pump is the equipment responsible for transfer heat from a lower temperature source to one of a higher temperature, using external power to accomplish the work of transferring the heat in the opposite of the natural flow.

The operating principle of a heat pump is based on the physical properties of a volatile working fluid known as refrigerant.

During the heating or cooling cycle, the refrigerant is exposed to different pressure and temperature conditions resulting in phase changes and heat transfer.

Different refrigerants can be chosen and include natural and synthetic fluids. The fluids selection criteria include parameters such as working pressure, critical temperatures, energy efficiency, investment costs, required size of the installation and safety and environmental risks.

The efficiency of heating systems is denoted by its Coefficient of Performance (COP). The COP is defined by the ratio between the heat delivered and the energy cost of the heat extraction.

The COP increases as the temperature difference (known as *lift*) between heat source and destination decreases.

There are several types of heat pumps available on the market:

- Mechanical
- Gas engine
- Absorption
- Adsorption
- Transcritical CO2
- Hybrid heat pump
- Thermoacoustic heat pump

The two main types of heat pumps used in geothermal projects are the mechanical and absorption. Mechanical heat pumps are typically driven by electricity, while absorption heat pumps use heat as an energy source.

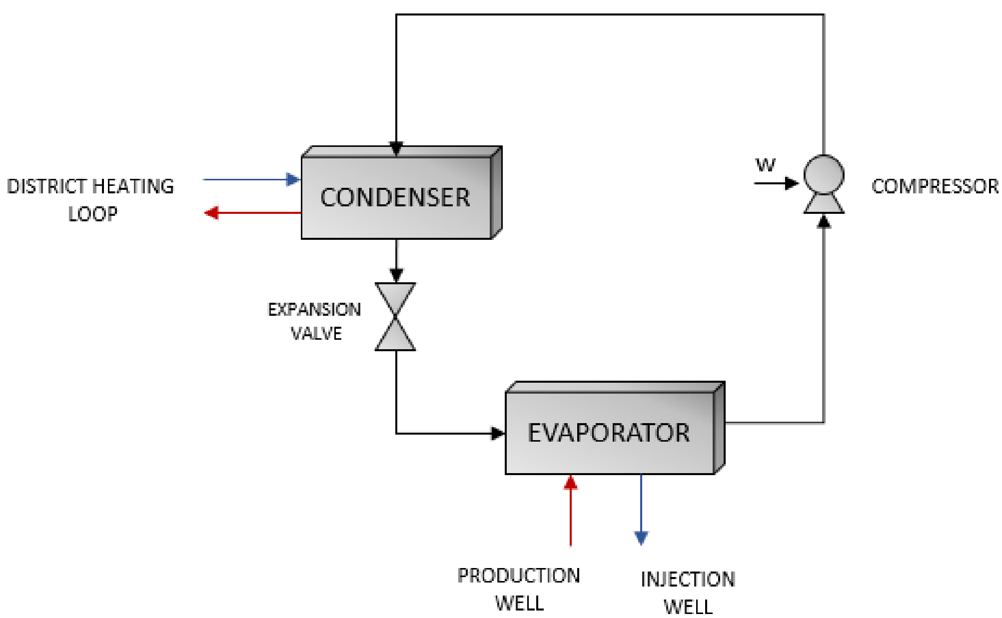
Type	Description
Mechanical	Mechanical heat pumps have four main components: evaporator, compressor, condenser and expansion device.

Running through these four components, a refrigerant fluid promotes the heat transfer between two streams when exposed to pressure, temperature and phase changes, induced during the process.

In the evaporator, heat is extracted from a heat source, in the geothermal case, the hot brine from the production well. The refrigerant absorbs heat and boils. The resulting gas is pressurized and circulated through the system by a compressor driven by electric energy.

On the discharge side of the compressor, the now hot and highly pressurized vapor is circulated into a heat exchanger, called a condenser, until it transfer its heat to the geothermal loop water and condenses into a high pressure, moderate temperature liquid.

The liquid refrigerant then passes through a pressure-lowering device, such as an expansion valve, and returns to the evaporator as a low-pressure liquid refrigerant, reinitiating the cycle.As they don't require an external source of heat (not available at every site), mechanical heat pumps are considered flexible systems.

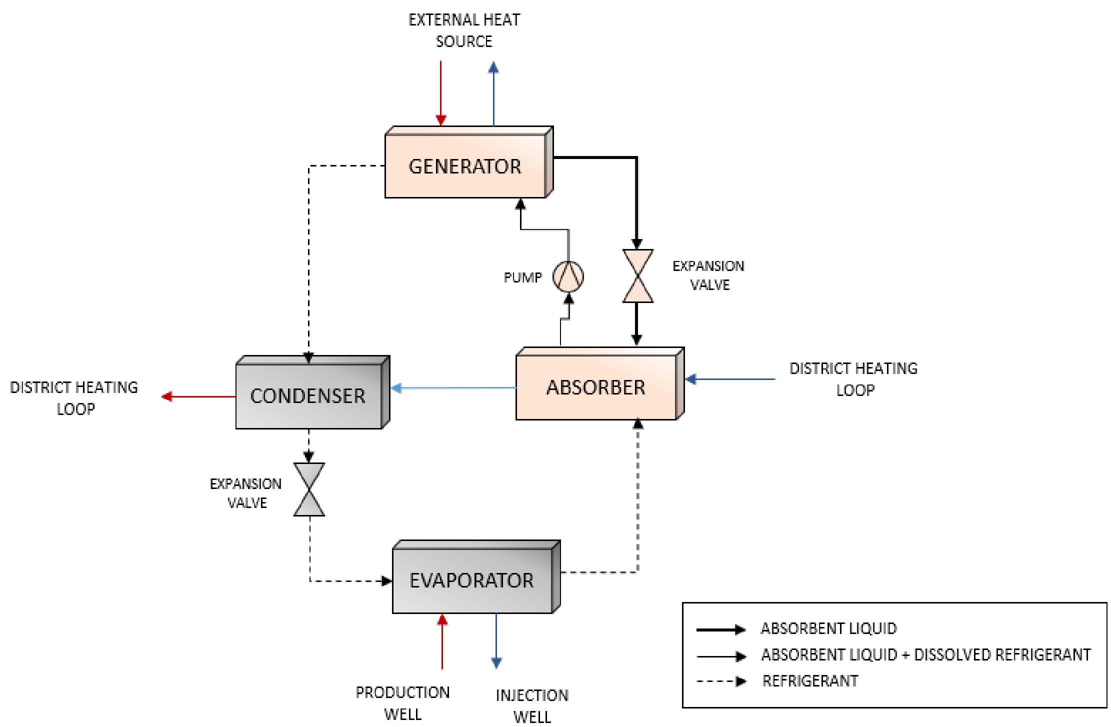


Absorption In absorption heat pumps, the refrigerant is condensed, expanded and finally vaporized in the evaporator, like the vapor-compression cycle. However, instead of compressing the vapor using an electric gas compressor, the vapor refrigerant is absorbed into a liquid solution (at the absorber) and this mixture is pressurized using a pump, making it possible to increase the pressure using a lower amount of power.

Once the high pressure is achieved, an external source of thermal energy is used to separate the refrigerant gas and the liquid solution (at the generator). The high-pressure refrigerant is then displaced to the condenser, while the liquid solution returns to the absorber reinitiating the cycle.

By replacing the mechanical compressor with this "thermo chemical compressor", the amount of work required for the cycle is reduced considerably.

Well known combinations of refrigerant and absorbing medium are Lithium-Bromide and Water and Ammonia and Water[48].



Hybrid Heat Pumps combine absorption and compression heat pump technology and use a mixture of media (e.g. NH_3 and water). Hybrid Heat Pumps can deliver a higher temperature lift while operating at low pressure compared to conventional heat pumps. The combination of these two factors results in higher COP values.

Despite the higher installation complexity and costs, Hybrid Heat Pumps are gaining popularity and being offered by a larger number of manufacturers (e.g. Siemens, Carrier, Danfoss). They can be an attractive alternative to conventional heat pumps, especially when a sink temperature above 100°C is required.

The first step in selecting a heat pump system is to assess the available and desired properties from the heat source and sink streams. The following basic inputs should be known[49]:

Type of data	Item	Comments
Temperature and Flowrate (source and sink streams)	Averages Maximum Minimum Start-Up/Shut Down Full Load/Part Load	Are variations large and frequent? Do variations in the source side temperatures coincides with consumers side temperatures?
Fluid Properties	Main Components Phase(s) Specific Heat Capacity Latent Heat Corrosive Components Fouling Components Pressures Available Pressure Properties Heat Transfer Coefficients	For vapors/two phase mixtures
Time Related	Annual availability Daily/weekly load profiles Seasonal Variations Frequency of start-up/shut Down	If availability is variable, will this be difficult to be handled by the heat pump?
Site Information	Heat Pump Location Piping Routes Location of Services	Civil/Structural Details and Access Fuel/Power/Water, Etc.

Heat pumps are considered to have a high efficiency as compared to gas heated systems, can promote large energy savings and significant reductions in CO_2 emissions. However, to get the most of a heat pump the limitations and risks should be well known upfront when designing a new system.

Once these parameters are mis specified or non-predicted changes are observed within the process, the efficiency of the system will be impacted. Correcting faults in a heat pump system is much more expensive after it has been built than in the design stage.

Target temperature and COP values

The target heating temperature required by the district heating loop will determine the type of heat pump and refrigerant that can be applied.

Theoretically, mechanical heat pumps using ammonia as its refrigerant, can deliver maximum temperatures of 90 to 100°C, but in practice, a maximum temperature of 80°C is typical. Temperatures of 90 to 120 °C can be reached with absorption heat pumps [50].

In addition to the target temperature (the lower, the higher the COP of the system), the efficiency of a heat pump depends on the temperature level of the waste heat source (in geothermal case, the produced brine). When high temperatures are desirable, the waste heat source should have a relatively high temperature to increase the COP of the system.

Hazardous refrigerant materials

Refrigerant substances can cause problems if not well selected and handled. Through time, different kind of materials were used in heating and cooling systems. In the past, CFCs (halocarbons) and HCFC (hydrohalocarbons) were the most commonly used refrigerants, but due their ozone depletion and global warming potentials, other materials were developed.

HFCs were created (in some contexts they are referred to as F-gases or Flourinated gases) as substitutes for CFCs, but although they do not deplete the ozone layer, they still contribute to global warming.

Natural refrigerants serve as alternatives to the CFCs, HCFC´s and HFC´s refrigerants. They are not synthetic chemicals and generally have Global Warming Potential (GWP) and Ozone Depletion Potential (ODP) at a zero or close-to-zero level.

However, in some applications they are related to other risks or challenges that must be handled. Ammonia (NH_3), hydrocarbons (HCs), carbon dioxide (CO_2), air and water are commonly used natural refrigerants. Ammonia, for instance, is highly toxic and flammable. There is also a risk of over pressurization in these systems and risks of leakage, which means strict safety inspections need to be carried out and regulations strictly followed[51].

Energy supply

Heat pumps require a stable supply of electricity (mechanical heat pumps) or waste heat (absorption heat pumps) to operate. In this way, it is recommended to evaluate if these energy sources are available and can be utilized during the hole project life time.

Materials and construction

Heat pumps system uses different equipment such as heat exchangers (evaporator, condenser, generator and absorber), compressors, pumps, expansion valves and pipes. All these systems need to be investigated separately and be able to interact with the chemical composition of the streams and refrigerant fluids, maintain that the system is isolated from oxygen ingress and refrigerant or fluids leakages, and promote efficient heat transfers.

12 Auxiliary Systems

Auxiliary Systems refer to all auxiliary equipment supporting the geothermal heat production. It includes infrastructure assets like the land, building and power, plant and production collecting/injecting pipes, pressure support equipment, production monitoring, control and measurement systems.

12.1 SCADA System

The SCADA system is responsible to monitor and control the plant and equipment. The control may be automatic or initiated by operator commands. It can provide real-time data during production operations, implement more efficient control paradigms, improve plant and personnel safety, and reduce operational costs.

For Geothermal Plants, the SCADA system is typically responsible for:

- Monitoring and recording flowrates, pressures and temperatures
- Controlling equipment such as injection pump, production pump and heat pump
- Actuating remote controlled valves
- Alarm and safety logic systems

The greater the volume of monitoring data collected for the system, the better is the management of the reservoir, control of the plant and the capacity to predict operational constraints.

As different equipment interacts within the system, during the acquisition phase, it is required to check the compatibility of every equipment to the rest of the network.

SCADA system equipment and software need to be periodically updated and tested to guarantee the system security and functionality.

12.2 Piping, Valves and Meters

Geothermal plants contain pipes, connections, valves and meters.

The pipes and connections are responsible for providing a path where the fluids from reservoir and district loop can flow and should be able the handle the pressures, temperatures and water composition of the plant, without losing its mechanical integrity and not allowing leakages nor oxygen ingress.

Valves are responsible for controlling the fluid flows in the plant and have an important role in the safety of the system.

Pressure, Temperature and Flow Meters, extracts all the data from the plant and allied with the SCADA system allow the control of the production stream.

To maintain the system operational and safe, all equipment should have a maintenance and inspection programme covering issues related to, for example, corrosion and scaling effects, erosion, sealing and calibration, in order to maintain a system operations and safety.

12.3 Electricity Supply

Mechanical heat pumps, injection pumps and ESPs are responsible for large electricity consumption, making it one of the main cost drivers of a project.

In addition to the acquisition costs, the quality of the electric supply will also have an impact on the project costs. The supply quality impacts directly on the operationality and lifespan of the pumps and consequently on the economics of the project

Therefore, the pumps should be specified taking in consideration the optimization of electric power usage and the system should rely on a robust and stable electric supply.

12.4 Pressure support system

To prevent oxygen ingress to the facilities equipment during shut-in periods, pressure support systems using inert gases as nitrogen, are used. Once the production is interrupted, the system releases the gas and maintains positive pressure, mitigating oxygen ingress.

The nitrogen can be supplied in bottles or generated on site. A technical-economic analysis should be conducted to determine the best option.

13 Heating Loop

The heating loop is the connection to distribution system, an interface with the network of insulated pipes where the heat is distributed to the customers. At the customer level the heat network is usually connected to the central heating system of the dwellings via heat exchangers.

The conditions on the surface should be favorable to the construction of geothermal plants and tie-in to the heating loop.

The geographic location of the district heating loop will determine the thermal power and temperature demand for the geothermal plant, limit the possible places for the construction of the plant and affect the exploration, installation and operation costs of the project.

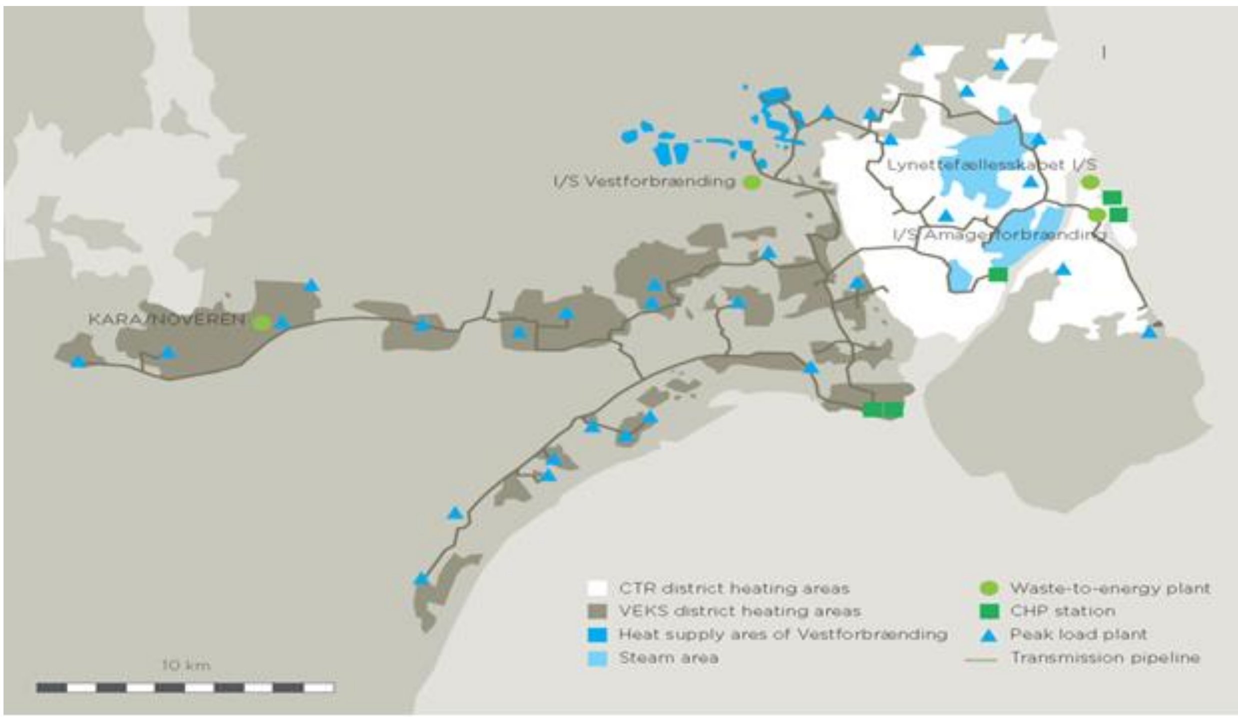


Figure 15. Heating loop simplified scheme from Copenhagen/Denmark[52]

14 Conclusions

The design of a geothermal heating plant is a complex task and requires multidisciplinary knowledge from different industries and a firm project management.

A complete technical assessment of the subsurface and surface characteristics is the first step in the design of a new geothermal production facility. The quality of the information extracted during this phase, allied to the understanding of how operational parameters (such as power demand, temperatures, flowrates and pressures) can vary through the time will determine the success of the whole project.

The assumptions taken and decisions made during the planning design phases will directly impact the operational costs and production procedures of a geothermal wellfield and plant. Upfront investments in characterizing the reservoir, geothermal brine and district heating network during the early stages of a project support the proper evaluation and design of geothermal plants, which can enable a long-lasting and trouble-free operation, resulting in OPEX savings during the production phase.

In that way, it is recommended to adopt a holistic view of all project phases to make the best decisions.

Geothermal district heating is still in its early stages of development and the potential to become a significant clean source of thermal energy is notable.

Financial and regulatory uncertainties faced by the main stakeholders are barriers to the implementation of new projects. However, as technologies are developed, knowledge is acquired from pilot projects, expertise transferred from industries such as oil and gas and the cooperation with other clean sources of energy (such as solar and wind) are stablished, the tendency is to reduce risks and costs.

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