Multidisciplinary approach for the sustainable utilization of medium-low temperature geothermal resources

Approccio multidisciplinare per l'utilizzazione sostenibile di risorse geotermiche a medio-bassa temperatura

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E-mail: vaccaro maurizio@gmail.com
...Lucio che aveva 36 mucche nella stalla disse: «La scuola sarà sempre meglio della merda».
— Scuola di Barbiana, “Lettera a una professoressa”

*Tra il dire e il fare c’è di mezzo «e il»*

— Elio e le storie tese, “Carro”
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LIST OF ACRONYMS

AIT  Auxiliary Injection Tubing
AMIS  Abbattimento Mercurio e Idrogeno Solforato
ATES  Aquifer Thermal Energy Storage
BC  Boundary Condition
CLTPT  Closed Loop Two Phase Thermosyphon
DCH  Downhole Coaxial Heat Exchanger
DHE  Downhole Heat Exchanger
DHP  Downhole Pumps
EGS  Enhanced Geothermal System
EOS  Equation Of State
ESP  Electrical Submersible Pumps
GEESOR  Geothermal Energy Extraction System Organic Rankine
GHE  Ground Heat Exchanger
GCHP  Ground Coupled Heat Pumps
GHP  Geothermal Heat Pumps
GRT  Ground Response Test
GTC  Geothermal Convecto
GWHP  Groundwater Heat Pumps
HPT  Heat Pipe Turbine
HTMC  Hydraulic, Thermal, Mechanic and Chemical conditions
LCA  Life Cycle Assessment
LCI  Life Cycle Inventory
LCIA  Life Cycle Impact Assessment
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEC</td>
<td>Levelized Energy Cost</td>
</tr>
<tr>
<td>LSP</td>
<td>Line Shaft Pumps</td>
</tr>
<tr>
<td>NCG</td>
<td>Non Condensable Gas</td>
</tr>
<tr>
<td>NEL</td>
<td>Number of elements</td>
</tr>
<tr>
<td>NEQ</td>
<td>Number of equations</td>
</tr>
<tr>
<td>ORC</td>
<td>Organic Rankine Cycle</td>
</tr>
<tr>
<td>PI</td>
<td>Productivity Index</td>
</tr>
<tr>
<td>PP</td>
<td>Pinch-point</td>
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<tr>
<td>RHE</td>
<td>Recovery Heat Exchanger</td>
</tr>
<tr>
<td>SBES</td>
<td>Single Borehole Extraction System</td>
</tr>
<tr>
<td>SCC</td>
<td>Stress Corrosion Cracking</td>
</tr>
<tr>
<td>SSC</td>
<td>Sulphide Stress Cracking</td>
</tr>
<tr>
<td>TRC</td>
<td>Thermosyphon Rankine Cycle</td>
</tr>
<tr>
<td>TRT</td>
<td>Thermal Response Test</td>
</tr>
<tr>
<td>TSR</td>
<td>Thermosyphon Rankine Engine</td>
</tr>
</tbody>
</table>
LIST OF SYMBOLS

Roman letters

\( \dot{B}_{F,k} \) fuel stream component of the environmental impact
\( \dot{B}_i \) environmental impact (pts/Gj)
\( \dot{B}_{PF} \) pollutant formation component of the environmental impact
\( C_{\text{comp}} \) cost of the plant components
\( C_{D,k} \) cost associated to the exergy dissipation
\( C_I \) cost of the irreversibilities
\( C_{\text{inhib}} \) cost of the inhibitor
\( c_{\text{MW}} \) specific cost of the make-up wells
\( C_{\text{max}} \) maximum sustainable (or affordable) cost
\( c_{\text{O&M}} \) specific cost of the Operation and Management costs
\( c_p \) specific heat capacity
\( c_{p,geo} \) specific heat capacity of the geothermal fluid
\( C_{\text{pp}} \) annual cost of the plant
\( C^*_{\text{pp}} \) annual cost of the reference plant
\( c_p \) specific cost of the products
\( C_v \) volumetric heat capacity
\( c_Z \) specific investment cost
\( D_e \) external pipe diameter
\( d_{ij} \) distance between the blocks center
\( e \) transmissivity
\( e_{geo} \) specific exergy rate of the geothermal fluid
\( \dot{E}_D \) destroyed exergy
\( \dot{E}_f \) exergy flux associated to the fuel
\( \dot{E}_{in} \) Inlet exergy stream
\( \dot{E}_L \) lost exergy
\( \dot{E}_P \) exergy flux associated to the products
\( f_{b,k} \) exergoenvironomic factor
\( f_g \) thermoeconomic gain factor
\( f_{VPL} \) vapor pressure lowering factor
\( g \) acceleration of gravity
\( g_{ij} \) component of the gravity acting through the interface (blocks)
h  length
H  thermal energy of a reservoir domain
hf  convective heat transfer coefficient
hfg  latent heat of vaporization
hgeo  enthalpy of the geothermal fluid
h1  initial distribution of hydraulic head
Hrein  enthalpy of the reinjected fluid
hs  specific enthalpy of the geothermal fluid in the reservoir
during the exploitation (hs < hgeo)
i  slope (in the aquifer Δh/L)
I  total exergy losses
Icond  exergy losses in the condenser
Iexp  exergy losses of the turbine
IHE  exergy losses of the heat exchanger (geofluid/working fluid)
Irein  exergy losses due to the reinjection
k  permeability
K  hydraulic conductivity
K  hydraulic conductivity tensor
Kd  aqueous phase distribution coefficient
km  thermal conductivity of the solid liquid mixture
ma  aquifer renewed mass flow rate
ma1  short-circuited part of ma
ma2  totally fresh renewed water part of ma from the aquifer
mf  mass flow rate of geothermal fluid in the well
mgeo  mass flow rate of the geothermal fluid
mgeo*  modified extraction rate
mvol  volumetric flow rate
MW  molecular weight of water
mw  mass flow rate effectively expanding in turbine (e.g. flash power plants)
w  mass flow rate of the working fluid
m*  mass flow rate of the geothermal fluid from the reservoir
Ne  number of exergy fluxes
during the exploitation
pec  capillary pressure
pc  difference between aqueous and gas phase pressures
pen  specific energy price
pin  intermediate pressure
pin  pressure in the i-th block at the end of the n-th time step
\(p_{wh}\) pressure at the well-head
\(P^*\) reference plant output
\(\dot{q}\) volumetric flow rate
\(\dot{q}\) heat flux
\(Q\) heat power rate exchanged
\(q_{eij}^{n+1}\) energy production occurring in the block \(i\) evaluated at the end of the \((n+1)\)-th time step
\(Q_{\text{geo}}^{n+1}\) energy flux from block \(i\) to block \(j\)
\(Q_{geo}\) heat power rate from the reservoir
\(q_{mij}^{n+1}\) mass production occurring in the block \(i\) evaluated at the end of the \((n+1)\)-th time step
\(Q_{mij}^{n+1}\) mass flux from block \(i\) to block \(j\)
\(R\) recovery factor
\(r_m\) mixing ratio
\(s_{geo}\) specific entropy of the geothermal fluid
\(T_{geo}\) temperature of the geothermal resource
\(T_i\) average temperature of the \(i\)-th volume
\(T_i^n\) in the \(i\)-th block at the end of the \(n\)-th time step
\(T_i\) initial distribution of temperature
\(T_{rein}\) temperature of reinjection
\(T_{wh}\) temperature at the well-head
\(T_{wi}\) well inlet temperature
\(T_{wo}\) well output temperature
\(T_0\) reference temperature (environment)
\(T^*\) temperature of the geothermal fluid in the reservoir during the exploitation \((T^* < T_{geo})\)
\(T_\infty\) temperature of the unperturbed aquifer
\(U\) global heat transfer coefficient
\(u_\beta\) specific internal energy in phase \(\beta\)
\(V\) total volume
\(V_i\) \(i\)-th volume
\(V_n\) subdomain for the integration
\(V_v\) volume of the empty volumes
\(W_{\text{CS}}\) power consumption of the cooling system
\(W_{\text{gross}}\) gross power produced
\(W_{\text{net}}\) net power produced by the plant
\(W_{\text{pump}}\) power consumption of the pumps
\(W_t\) gross power extracted from the turbine
\( W^* \) modified power
\( x \) quality
\( \dot{Y}_k \) environmental impact of the k-th component
\( z \) geometric head (or height)
\( \dot{Z}_k \) sum of investment and O&M costs

Greek letters

\( \beta \) specific brine or geofluid consumption
\( \gamma \) specific weight force
\( \Gamma \) border of the numerical model domain \( \Omega \)
\( \Gamma_n \) boundary of the integration subdomain
\( \delta \) circulation ratio
\( \Delta p \) pressure variation
\( \Delta T_{lm} \) mean temperature difference
\( \varepsilon(T_{geo} - T_0) \) equivalent thermal capacity of the geothermal reservoir referred to \( T_0 \)
\( \eta_{el} \) electrical conversion efficiency of the plant
\( \eta_I \) First Law Efficiency
\( \eta_{II} \) Second Law Efficiency
\( \theta \) utilization factor (DHE)
\( \kappa \) label of the quantities in the balance equations (TOUGH2)
\( \kappa \) permeability tensor
\( \lambda \) heat conductivity
\( \mu \) viscosity
\( \mu_\beta \) viscosity of phase \( \beta \)
\( \xi_k \) exergetic efficiency of the k-th element
\( \phi \) porosity (total)
\( \phi_e \) effective porosity
\( \rho \) density
\( \rho_i \) density of the i-th rock volume
\( \rho_R \) grain density
\( \rho_w \) density of the water
\( \sigma \) short circuiting ratio
\( \sigma_{st} \) surface tension of the working fluid
\( \tau \) transmissivity
\( \Omega \) numerical model domain

Subscripts and superscripts

\( a \) aquifer
\( \text{cond} \) condenser
\( \text{CS} \) cooling system
\( e \) energy (or effective, in case of porosity)
el electrocal (e.g. conversion efficiency)
en energy (specific price)
exp turbine or expander
f fluid in the well or referred to the convective coefficient
F fuel
geo referred to the resource or to the geofluid
gross gross (e.g. power output)
HE heat exchanger
i referred to the i-th block
ij referred to the i and j blocks
inhib inhibitor
int intermediate value (e.g. pressure)
j referred to the j-th block
k referred to the k-th element
m mass (or mixing ratio r_m)
MW make-up wells
n subdomain
net net (e.g. power output)
O&M operation and management
P product
pp power plant
pump pump
r rock
rein reinjection
t turbine
v of the v volume
vol volumetric
w water
W from the turbine or expander
wf working fluid
wh well-head
wi well inlet
wo well output
Z investment
ABSTRACT

A growing interest in the applications of the medium-low temperature geothermal resources can be observed, but often a reference frame in this field does not exist. Different backgrounds are involved in the design and optimization of geothermal projects: Earth Sciences, Engineering, Economics, Environmental Impact. In the practice one aspect often tends to take priority on the others. In this work firstly the elements for a methodological interdisciplinary framework for geothermal projects analysis are given. A clear frame of the state of the art and possible technical-scientific developments are illustrated.

The necessity of an “integrated” interdisciplinary approach is underlined, with reference to several case studies. The geothermal potential evaluation tasks and methods are illustrated, and some outlines for an assessment oriented to the resource utilization are described. The sustainability of geothermal projects is analysed under different perspectives and criteria.

The main technological issues of geothermal binary cycle power plants are discussed (mainly for small power size), together with technological solutions. The concept of upper limit to the extraction rate is introduced, with reference to an equilibrium point between power production and resource depletion. Direct heat uses are also briefly described and the common issues related to environmental impact and resource durability are then discussed, with a particular focus on the scaling phenomena and the reinjection strategy. An innovative solution for geothermal power production (SBES) is described: the application of the heat pipe principle, in the CLTPT concept, for power production purposes is proposed.

The numerical simulation of geothermal reservoirs is an important instrument for the synthesis between the different backgrounds involved in the geothermal energy study. General aspects and its potentialities (historical data matching and forecast of future utilization scenarios) are illustrated. Several numerical models from scientific literature are reviewed (about 21 geothermal fields and related 24 numerical models). The reservoir models of Momotombo (Nicaragua) and Sabalan (Iran) have been realised from literature data and widely discussed. One original model, Monterotondo Marittimo - Torrente Milia (Italy) has been realised in a very multidisciplinary framework and it is also presented. Different utilization scenarios for the case studies are analysed and their sustainability level is discussed.

A purely economic approach is considered to be counter-productive for geothermal utilizations, so the thermoeconomic analysis is here applied to geothermal power plants. Momotombo case study and other small size power plants are analysed in order to estimate their thermoeconomic sustainability (exergy balances and cost items are evaluated). The current Italian geothermal energy market situation is briefly described, in relation to the ORC technology diffusion. The small size plants technological and environmental issues treated in this work are then linked to the current way of diffusion in the Italian market.

The outlines coming from the global work of analysis are organised in order to give the main features of the proposed methodological approach. The multidisciplinary perspective is reviewed and extended in order to optimize the sustainability of the projects (environmental impact reduction, resource durability).
The main themes of this work of Thesis are: geothermal binary power plants, medium-low temperature geothermal resources sustainable utilization, numerical simulation of geothermal reservoirs (oriented to the exploitation), and the evaluation of the technical-economic feasibility of these plants.

An interdisciplinary approach to the geothermal energy utilization is pursued, and it reveals to be fundamental for enhancing sustainability of geothermal projects. An integrated approach must consider as the object of its study and optimization the “geothermal system”, composed by the power plant (or generic utilization), the resource, the environment, and all the links (in terms of mass and energy transfer) between them.

In the Chapter 1 the potential assessment of the resource is discussed. The main methods are illustrated and several issues related to the integration of this analysis with the specific utilization are discussed (“resource utilization” oriented assessment). The sustainability issues that are object of the further chapters are here introduced and the importance of the interdisciplinary framework is remarked and argued.

Chapter 2 deals with the utilization of the medium-low temperature geothermal resources. Mainly the technological issues related to the binary cycle power plants are described and possible solutions are discussed. A state of the art of this technological application for the geothermal energy exploitation is presented together with thermodynamic optimization issues. The concept of upper limit to the extraction (and production) rate is introduced. An equilibrium point between power production and resource depletion has to be matched, leading to appropriate and sustainable utilization levels (to be individuated for each plant).

Direct heat uses are also briefly described in order to have a complete view of the following issues. The common problems related to environmental impact and exploitation are then discussed. Particularly important issues are the scaling phenomena and the reinjection strategy.

In the same chapter, an innovative solution for power production (SBES) is illustrated. The application of the heat pipe principle, in the CLTPT concept, is proposed for the extraction of geothermal heat and power production. A review of the literature available applications of the HPT concept is presented, then and a preliminary thermodynamic efficiency study of the proposed system is illustrated.

Chapter 3 deals with the numerical simulation of geothermal reservoir. It has to be seen as an important instrument for the synthesis between the different backgrounds involved in geothermal energy study. The general aspects (literature indications) of this technique are given, in order to describe its potentialities (historical data matching and forecast of future utilization scenarios). Also a brief section dealing with the mass and heat transport phenomena (occurring into the geothermal reservoirs) and the mathematical-numerical background is presented (in Appendix A a more deep description referred to the main used softwares is given).
In chapter 4 several numerical models are presented. The review of about 21 geothermal fields and related 24 numerical models is illustrated and discussed. The two reservoir models of Momotombo (Nicaragua) and Sabalan (Iran) have been simulated from literature data and widely discussed. One original model, Monrotondo Marittimo - Torrente Milia (Italy) has been realised in a very multidisciplinary framework and it is also presented. The detailed properties of the models used and their features are given in the Appendix B. For these three models different utilization scenarios have been simulated and their sustainability level is discussed.

To have a more global approach to the geothermal energy utilization, in chapter 5 the thermoeconomic analysis is introduced. The aspect of economic sustainability is here seen from a more complete point of view respect to a purely economic perspective. A review of the cost items related to the small size power plants is firstly presented (drilling, investment, plant, scaling inhibitors). The application of thermoeconomic analysis to the Momotombo case study is presented and its production historical data are discussed under this approach. The analysis of four Turkish power plants is also presented, studying also their cost items in order to discuss the evolution of the maximum sustainable (or affordable) cost. Also the Miravalles (Costa Rica) geothermal production is analysed through the thermoeconomic approach. A brief introduction to the exergoeconomic and exergoenvironmental analysis is presented in Appendix C. The current Italian geothermal energy market situation is illustrated, in relation to the ORC plants diffusion (in terms of applications and concessions by the players). The small size plants issues treated in this work are then linked to the current way of diffusion in the Italian market.

To present a synthesis of all the problems and technological proposals of this work, in the chapter 6 the outlines for a methodological approach are illustrated. Firstly the sustainability aspects of the utilization analysed are reviewed. The outlines coming from the global work of analysis are organised and linked between them. A general idea of both the complexity of the approach and the focuses proposed is illustrated in this way. The multidisciplinary perspective is then reviewed and extended to analysis which better allow to optimize the sustainability of the projects and reduce their environmental impact. Some open issues are listed and discussed in the same chapter.

The chapter 7 is dedicated to the concluding remarks of this work and future developments.
Geothermal energy is considered in many countries a strategic resource for its characteristic of renewability, when a correct exploitation of the reservoirs is carried out. The possibility of long time continuous productivity distinguishes geothermal energy from the other renewable sources, intermittent or stochastic.

Many areas around the world have accessible geothermal resources. Only a few of them are dry steam dominated, while the majority is of the low enthalpy type. The worldwide distribution of geothermal energy as function of the resources temperature has been evaluated by Stefansson [1]. In Fig. 1 it is possible to see the distribution of geothermal energy in the world depending on the temperature of the resource. More than 70 % of the geothermal resources available in the world are estimated to be water dominated fields, at temperatures under 150 °C and pressure below 15 bar [1]. The total expected geothermal potential has been estimated being about 200 GW for power production [1, 2].

This stronger diffusion of medium-low temperature resources respect to the “classic” geothermal reservoirs is contributing to an expansion of the geothermal industry market worldwide. A stronger interest about the geothermal heating/cooling can also be observed. From a technological point of view, the binary power plants diffusion is contributing to increase the number of reservoirs that considered to be useful. ORC (Organic Rankine Cycle) or binary power plants units are considered the most efficient and convenient solution for water dominant resources with temperature lower than 180 °C. Their use is growing in other renewable energy sectors (e.g. biomass) or for waste heat recovery for power purposes. This technology is the object of the chapter 2.

In Table 1 a classification of the geothermal resources depending on temperature is given (from Dickson and Fanelli, [4]). A classification of geothermal resources by exergy has been proposed by Choon Lee (2001) [5].

In this chapter a general overview about the problem of the resource assessment and characterization is given. The same concepts will be valid both for power production and for heat extraction systems, unless some specific clarification. General concepts will be here introduced. In the next chapters a review of the technologies and their problems will be given, together with the developments in the field of potential assessment (numerical simulation) for an integrated and global approach to the geothermal resources utilization and sustainability. This initial concepts will be re-elaborated and referred to specific cases and technologies in this work.
Figure 1.: Distribution of geothermal energy in the world depending on the temperature of the resource (from Stefansson 2005, [1])

1.1 THE GEOTHERMAL POTENTIAL ASSESSMENT

The geothermal potential assessment can be considered a relatively recent field. The growing experience and technological advance in oil and gas industry (in the last century) lead to increase the knowledge of geothermal exploration too. As it happened for other renewable sources, geothermal energy development has followed peculiar historical peaks of interest and investments (as it happened during the oil crisis in the 1970s). The not uniform distribution of geothermal resources worldwide contributed to a reduced diffusion of knowledges and industrial interest in this field. Common and unifying approaches have not been pursued. Authors used to work and write reports about specific geographical areas, sometimes disregarding comparisons with other areas.

Since the beginning of the scientific field of geothermal potential assessment it has been stated that a general methodology for every kind of geothermal field does not exist. Although in the literature a lot of different methods and reliable principles have been treated and tested. However it is quite difficult to find a complete multidisciplinary view of the problem, in which the connections between the parameters of plant design, geological and geophysical characterization and reservoir engineering can be clearly evidenced. The major contributions came from geophysical analysis of the source or from technical optimization of the plant variables.

The geothermal resource evaluation is also affected by the personal opinion and discretional contribute of who is in charge for the assessment. This is true for the energy market and economic context evaluation too. Strategic observations can be subjective, and this is not good if they deal with energy policies and environmental impact. Laws and policy plans are different depending on the country, their implications they can be very difficult to “estimate”.

Giving a detailed definition of the geothermal potential assessment is not a trivial task. In general one can assume that a geothermal utilization project cannot take place in a convenient way without a complete and accurate characterization of the resource and without a study about the evolution of the field exploited during time
[3]. As clearly stated by Cataldi and Muffler, 1978 [6], one of the main problems is not only to evaluate the “base” resource, but also to elaborate a method to assess the portion of it that could be exploited under specific economic and technological conditions (present or future context). Today a lot of instruments are available today to improve the detail of the informations needed to design plants for energetic purpose in a geothermal area.

A correct geothermal exploration project involves different stages [7]:

1. appropriate localization of potential areas in which a geothermal field is known to exist or there are physically consistent data about its existence;

2. an accurate evaluation of the size of the reservoir and resource capability;

3. an appropriate identification of the main physical transport processes involved to build a conceptual model.

In general several factors characterize the determination of the geothermal potential. They can be categorized as follows:

- geological and geophysical factors :
  - distribution of temperature and heat capacity
  - total and effective porosity
  - permeability
  - circulation model of the fluid
  - phase of the geofluid
  - depth of the reservoir

- technological factors :
  - drilling technology
  - techniques of geofluid extraction
  - energy conversion factors and efficiencies
  - availability factor and utilization factors
  - possibility of “cascade” and multi-purpose utilizations
  - systems for waste liquids and gas

- economic factors :
  - energy values (direct uses or power production)
  - Operation and Maintenance Costs
  - capital costs
  - investment risk
  - drilling costs (dependant on the depth of the well)

- general factors :
  - regulations and laws
– national or regional energy policy
– social acceptance
– environmental limits and social issues

The main aspects to be assessed in order to elaborate a production strategy can be here briefly listed:

• Energy stored in the reservoir and energy available from the wells
• Temperature, pressure and mass flow rate of the fluid
• Chemical composition of the fluid and gas phase
• Time interval after which extraction temperature decreases under a critical value (at a given production rate)
• Wells to be drilled: number, mutual distances and interference effects
• Reinjection strategy
• Compensation wells

Some of the main practical properties that a certain geothermal resource have to accomplish to be considered suitable for the exploitation are here listed (modified from [12]):

• temperature and heat sufficient to guarantee high conversion efficiencies and a long useful plant lifetime;
• availability of sites for the drilling of the reinjection wells as designed and derived from the numerical simulation of the reservoir;
• systems to avoid or reduce scaling and corrosion phenomena
• high reservoir permeability, to guarantee a good productivity of the wells and groundwater circulation;
• road accessibility and proximity to electric transmission grid facilities.

1.1.1 Spatial and temporal scale in geothermal potential assessment

The geographical (national or local) scale is another issue to be linked to the potential assessment. The detail of the exploration and analysis changes when passing from a local to a wider scale, particularly for geological and hydrogeological data distribution. Space discretization (not only time) has a key function in the first evaluations, and particularly during the numerical model set up [3].

Different methodologies are taken into account to assess the geothermal potential, also depending on the phase (temporal or operational) of a certain geothermal project. As it is evident, in a geothermal project different and gradual steps has to be followed, particularly during exploration. The detail of informations acquired about the reservoir structure and energy content will be higher when building a database of all the exploration and evaluations results. A progressive approach to
the exploration data interpretation is generally followed, considering the opportunity of pursuing the project itself. For this reason several levels of analysis exist for the energy potential assessment:

- “first order” methods
- statistical approaches
- numerical simulation of the reservoir

This methods and techniques will be treated and discussed in the next section.

Table 1.: Classification of the geothermal resources depending on temperature (°C) (from Dickson and Fanelli, [4])

<table>
<thead>
<tr>
<th>Method</th>
<th>low (°C)</th>
<th>medium (°C)</th>
<th>high (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hochstein (1990) [8]</td>
<td>&lt; 125</td>
<td>125 — 225</td>
<td>&gt; 225</td>
</tr>
<tr>
<td>Benderitter &amp; Cormy (1990) [9]</td>
<td>&lt; 100</td>
<td>100 — 200</td>
<td>&gt; 200</td>
</tr>
</tbody>
</table>

1.2 APPROACHES AND METHODOLOGIES

Significative examples of the techniques and approaches used in the evaluation of the geothermal energy potential are here briefly described and discussed, with a particular attention for the medium-low enthalpy resources. “First order” methods and statistical approaches are usually the first attempt to assess the geothermal potential.

When exploration is in an advanced stage and reservoir structure is known, then the numerical simulation can be applied for the study of the behaviour of the reservoir under exploitation. Numerical modelling allows to simulate production/reinjection scenarios instead of evaluating only the thermal content and the portion of it that could be available for extraction in useful conditions.

1.2.1 “First order” methods

When the available data on a certain geothermal area are weakly defined, a complete study of the behaviour of the resource is not possible. The group of the so-called “first order methods” can be used when a primary evaluation is needed, to evaluate the order of magnitude of the thermal energy stored in a certain reservoir.

An interesting classification can be found in the fundamental paper by Cataldi and Muffler, *Methods for regional assessment of geothermal resources*, 1978 [6]. The most important are here listed (for the specific references see [6]): surface heat flux method,
volume methods or stored heat methods, planar fracture method, magmatic heat budget method.

Generally they consist in the estimation of the thermal energy content in a reservoir, considering the different contribution from the solid and liquid phases, or from the main underground heat sources in a certain geometric domain. It is now interesting to show some of the main features and characteristics of these methods.

The most used and simple approach is the one that can be referred to the volume methods: different volumes of rock or fluid are individuated, their average temperature is estimated and used to calculate the heat stored, compared to a reference temperature (environment). The thermal energy of a reservoir domain \( H \) referred to a \( i \)-th volume can be calculated from the following equation:

\[
H_i = C_v V_i (T_i - T_0)
\]  

(1)

where \( C_v \) is the volumetric heat capacity of the volume \( V_i \), \( T_i \) is the average temperature of the \( i \)-th volume and \( T_0 \) is the reference temperature (e.g. environment). The volumetric domains containing rock or fluid phase are considered when defining the total porosity \( \phi \) as the ratio between the volume of the empty spaces (\( V_v \)) and the total volume \( V \) (the void or empty volumes are supposed to be partially filled with fluid):

\[
\phi = \frac{V_v}{V}
\]  

(2)

But in general not all the empty spaces in a rock domain are full of liquid or connected, but the underground water flow is possible only between the interstitial inter-connected empty volumes, so the effective porosity \( \phi_e \) should be considered. \( \phi_e \) takes into account the effectively interconnected voids, and for this reason it is generally less than \( \phi \).

It is evident that the contributes to the thermal energy content \( H \) can be distinguished between the rock (subscript \( r \)) and fluid (subscript \( w \)), considering the porosity:

\[
H_i = H_{ir} + H_{iw}
\]  

(3)

\[
H_i = (1 - \phi_i) C_r \rho_i V_i (T_i - T_0) + \phi_i C_w \rho_w V_i (T_i - T_0)
\]  

(4)

being \( C_r \) the volumetric heat capacity of the rock and \( C_w \) the volumetric heat capacity of the fluid (geothermal water), while \( \rho_i \) and \( \rho_w \) are respectively the density of the \( i \)-th rock volume and the density of the water in the pores.

The errors made in this case can be then mitigated by the introduction of a recovery factor \( R \), which can be defined as the ratio

\[
R = \frac{H_r}{H}
\]  

(5)

where \( H_r \) is the resource which is extractable in the current technological and economic conditions and \( H \) is the total resource available in the reservoir (see equation 1). The definition of this factor is similar to indexes used in the oil and gas indus-
try. The early geothermal potential assessment concepts have been derived from this field.

The definition of the thermal energy available for the extraction $H_r$ comes from a relation between geological, physical and also industrial factors, they are here listed:

- $H_i$: th energy content of a single $i$-th volume,
- $\phi_e$: effective porosity,
- $T_i$ and $p_i$: respectively temperature and pressure of the reservoir,
- $T_{wh}$ and $p_{wh}$: respectively temperature and pressure at the well-head,
- production model adopted (Extraction strategy and energy conversion system).

The recovery factor is then a function of both the reservoir characteristics and the utilization and extraction methods. In the estimation of $R$ an industrial lifetime scale must be considered (e.g. 10 ÷ 50 years), instead of a geological time scale. Values of 25 % or less are usual.

A substantial difference exist, for the evaluation of $R$ between water dominated and steam dominated fields. The depth and the effective porosity affect the recovery factor but the temperatures $T_i$ and $T_{wh}$ appears to have some effects on $R$. In particular $R$ decreases when the average depth of the reservoir increases and it is higher for very permeable reservoirs (also high $\phi_e$ values).

This approach is the base for the implementation of successive numerical solutions to the simulation of the heat and mass transport in porous media, for example considering the finite volumes or finite difference methods.

Another “first order” approach is the surface heat flux method. A conductive heat flux $q$ and the natural heat emissions from a defined surface area $A$ are considered. The “natural heat power” $W$ can be calculated as the sum of these two contributes

$$W = W_1 + W_2$$

$$W_1 = A q$$

$$W_2 = G C_w (T_w - T_0)$$

$G$ is the mass flow rate of the natural emissions, $C_w$ is the specific heat capacity, $T_w$ is the temperature of the naturally wasted heat in the environment and $T_0$ is the reference temperature (environment). In a fixed geological time $t$ the thermal energy can then be calculated from $W$ as

$$H = W t$$

The two very simple methods here cited have strong limitations, for example the natural recharge in the reservoir is not considered. In the second approach just a minimal potential is estimated, in particular in case of little natural dispersion of heat and geothermal water.

Other “first order” methods have been elaborated, also considering similar techniques from the oil and gas extraction industry.
1.2.2 Statistical approaches

In literature there exist methods in which the uncertainty about the thermophysical and hydrogeological data are involved in the calculation of the thermal energy stored and available. The result will be a probability distribution of the energy and the recovery factor.

These methods are also treated by Cataldi and Muffler [6]. In particular one can refer to the approach proposed by Parini and Riedel [15]. These approaches often implement the Monte Carlo method.

The applications of statistical methods are often referred to the volume methods. Probability distributions for the reservoir parameters have to be defined (usually triangular or Gaussian distribution are considered). Some “key parameters” are used, which are the typical control factors of a geothermal reservoir, but also the non condensable gases (NCG) specific value, the spacing between fractures and the exploitation strategy. It appears evident that they are an evolution of the “first order” methods, in terms of error control, accuracy and integration between geological and technical factors. The critical conditions of “field abandonment” have to be defined in the Parini and Riedel approach to give more reliable results [3, 15].

1.2.3 Developments and numerical simulation

The geothermal potential assessment is a relatively “young” field of research. In the last years a lot of enhancements have been elaborated and tested. These researches are often geographically delimited to particular areas.

New approaches to the geothermal resource assessment involve geophysical techniques enhancements, improvements and public access to the databases, numerical simulation of the fields [17]. In this work only the aspects of the numerical models and integration of the different approaches are considered.

The basic idea is that physical and hydrogeological interpretation of the exploration data can be synthesized in a conceptual model. Then a numerical simulation of the model, in relation with the expected exploitation strategy can be run in order to foresee the evolution of the scenario. In this way several strategies can be tested, in order to optimize the resource utilization, maximize the renewability and minimize the environment impact of the geothermal project. In the chapter 3 this topic is treated and discussed (p. 73).

Heat is transported in the Earth by two main phenomena: (a) conduction and (b) advection by convective flow [7]. Each of them has its own characteristics and it needs different initial data to be simulated. One of the main problems involving geothermal phenomena simulation is the building of a proper conceptual scheme, in which all the transport phenomena (mass, heat, chemicals) are clear before the setting up of the model. The study of the underground heat transport mechanisms is important in order to evaluate the appropriate boundary and initial conditions to the model.

As a basic feature the “undisturbed” (or unperturbed) state of the field has to be studied. The conditions before the exploitation should be first reproduced into the model, to make sure that the forecast scenario is physically consistent and proven about the present (or not disturbed by utilization) field state.
Geological properties naturally change according to the geographical siting of a field. A wide range of variation of the thermophysical properties of rocks exists. Uncertainty changes with depth and chemical and hydrothermal alterations.

It is important to remark until now that a stable solution of a numerical model can be not physically consistent (see chapter 3, p. 73).

1.3 THE ASSESSMENT ORIENTED TO THE “RESOURCE UTILIZATION”

When talking about power and heat utilization of the geothermal resources it is important to clarify the industrial tasks. The sustainability of a geothermal project deals with three main aspects:

- technology feasibility
- environmental impact
- economic feasibility

In the industrial practice the main level evaluations and critical decisions are often taken basing mainly on the economic suitability, and this can be considered to be common to all the renewable energy sources projects. But sustainability, as it is known and obvious, is not only related to economic profitability, the three elements listed above should be equally considered both in the early stage and in the design steps.

Geothermal energy can not be considered a renewable energy source “lato sensu”: it is renewable (in a practical time scale) only under particular conditions. So the durability of a plant is directly connected to the way the resource is explored and then exploited.

In the past, the potential assessment has been related only on the thermal energy content of a reservoir, calculating the useful variation of enthalpy of the geothermal fluid flow extracted. But also in one of the early important scientific papers (Cataldi and Muffler 1978, [6]) the issue of the definition of the effectively suitable portion of the thermal energy content of a reservoir has been treated. Approaches like this have been used for long time.

The feasibility, technical sustainability and economic performance of geothermal power plants, particularly in case of ORC, is the result not only of a technical optimization but also of a matching between the reservoir characteristics and technical solution, particularly in case of power plants that use low temperature heat sources [13].

A critical element is the difficulty in finding a correct matching between reservoir capability and technical solution. For dry steam high enthalpy geothermal field a reduction of pressure and temperature of the source during the lifetime of the plant can be compensated by an increase of the mass flow rate. In case of binary plant, an increase of the extraction rate can cause a variation of the thermal properties of the reservoir, leading to the end of life of the plant. From this point of view, the first and most important activity is an accurate investigation about the geothermal potential
assessment, that is the prediction of reservoir response at given industrial exploitation configurations. This can be obtained both with experimental and theoretical analysis. Exploration, geophysics and geological database building, evaluation of the possible utilizations through simulation of the behaviour of the reservoir are the main step of the geothermal potential assessment.

The first and most important activity is an accurate investigation of the “behavior” of the geothermal reservoir considering different ways of operation and exploitation scenarios. This can be obtained both with experimental and numerical analysis. Reservoir modeling is a powerful tool available for this purpose [2, 14] (see chapter 3 and chapter 4).

Numerical modeling of the geothermal fields can be useful for predicting reservoir performances by allocating production and reinjection wells at specified sitings, considering different exploitation scenarios in order to match durability and sustainability for the future years and to analyse the effects of reinjection (and design the possible make-up wells to keep productivity constant).

The importance of a strategic interconnection between the assessment of the geothermal potential of the reservoir with the optimized design of the power plant is particularly remarked in this work.

1.4 SUSTAINABILITY ASSESSMENT

An open problem here discussed is the sustainability of a geothermal utilization project. As it is known, the renewability of the geothermal heat and fluid circulation is possible only under particular conditions. In some way the environmental impact of both geothermal power plants and geothermal heat direct utilization is still a discussion topic.

The diffusion of a large number of ORC plants worldwide is in progress. Not only the installation of new ORC plants, but also new explorations and studies are active, a new market appears to be growing. In the past, this high activity periods brought to a large amount of data and knowledge about many geothermal fields all over the world. In this case also sustainability should be pursued in the projects implementation.

According to one of the most classical definitions, sustainability assessment involves:

- Environment
- Technology
- Economics
- Society

A geothermal project is seen in different ways by the different active players and factors involved: Government, Institutions and society; investors and enterprises; power plant efficiencies; resource capacity and environmental impact.

Globally considering all these statements it is clear that geothermal energy can not be considered too much similar to the other renewable energy sources. In par-
ticular for the strict connection between the exploitation strategy and the resource renewability. This is one of the main topics of this thesis.

1.4.1 The “geothermal system”

When taking into account the global sustainability assessment of a geothermal plant the boundaries of the domain considered should be appropriate. An important evolution that should be pursued in the field of the geothermal potential assessment is to consider globally the system constituted by the plant, the reservoir, the environment and all the links between them in terms of mass and energy exchanges (Fig. 2). When the aim is the durability of the resource and the technical/economical feasibility this should be the appropriate approach. The reservoir behaviour depends on the exploitation strategy, while the plant efficiencies depend on the environment temperatures $T_0$ and on the resource temperature $T_{geo}$ (see chapter 2).

This complex problem, related to the thermodynamic balances of the plants and wells systems, can be studied only under a wide perspective. This proposal of scheme for all the evaluations about a resource exploitation and sustainability is a key concept of this work.

The same statements could be extended to the direct heat utilization, being these systems also very influenced by resource variations. The scheme of the “geothermal system” proposed is still valid. The major sustainability issues, in case of “open loop” systems deal also with mass flow withdrawal.

The main characteristic of this conceptual sketch is that it gives an idea of the complexity of the problem to be faced. The necessity of an interdisciplinary approach then appears to be clear.

![Diagram of the geothermal system](image)

**Figure 2:** The “geothermal system” to be considered for a sustainability assessment of a geothermal project (plant, reservoir, environment and all the links between them in terms of heat and mass transfers).
1.5 MULTIDISCIPLINARY APPROACH

For all the reasons and issues reported above, it is clear that a sustainable geothermal project (which must necessarily match economic/technological and environmental aims) becomes possible only under a strongly interdisciplinary perspective. Three main backgrounds are involved, as shown also in Fig. 3:

- **Thermodynamics - Energy Engineering**: thermal energy conversions, efficiencies, power plant optimization, heat and power distribution and utilization;

- **Geophysics - Geology - Geochemistry**: geothermal exploration, geologic database and mapping, geofluid analysis, reservoir structure and composition, reservoir hydrogeology, heat flux and temperatures;

- **Reservoir Engineering**: appropriate siting of the wells, reinjection strategy, balance between extraction and reinjection of the geothermal fluid, simulation of the reservoir for an appropriate time scale in order to avoid overexploitation and match productivity goals.

Figure 3.: Conceptual scheme of the multidisciplinary approach proposed, with the connections between the three areas involved.

One can consider that this concept is known or basic. It is a simple statement, but its implementation in a real project development is not easy. In industry for example a lot of players only consider the geological/geophysical aspects to be important, forgetting the environmental impact and in particular the power plant efficiency variations. Or it can happen that economics turns to be prevalent respect to the other aspects. Only one of the background is often considered dominant, particularly in the case of new industry and market players. This is partially happening in the case of ORC plants diffusion. Binary power plants are considered to be economic, low-impacting on the environment, but this is true only if the size and the mass flow rate extracted/reinjected are appropriate to the reservoir considered. The consequences of a bad sized or non optimized plant layout are discussed in the next chapters, but they could be in some way catastrophic or they can bring to economic losses.

The potential assessment assumes then a leading role in a geothermal project framework.

The optimization of the plant has a key role in particular in the case of the medium-low resources that are the object of this work. As it is known (and as it will explained in the next chapters) the efficiencies of the power plants and heat extraction systems decline dramatically when the resource temperature decreases.
For this reason the mass flow rate extracted (which is the linking parameter between the plant and the reservoir) and consequently the size of the plant must be the result of an accurate characterization of the resource and then optimization of the plant. In this perspective the need for a multidisciplinary way to face the problem is clear. This is even more important when the quality of the resource is low.
In this section a critical review of the most used and innovative technical solutions for the utilization of the geothermal energy from medium-low resource is given.

The use of the medium-low temperature resources, which is such a large part of the worldwide geothermal fields (see Fig. 1, [1]), is bringing to new technical challenges. As stated in the previous chapter, the sustainability of a geothermal project is not only a technical problem, it involves other backgrounds besides Energy Engineering.

2.1 Binary Cycle Power Plants (ORC)

The binary cycle technology using Organic Rankine Cycle (ORC) is the most efficient solution for power production from medium-low temperature geothermal fields. The size and peculiarity of such plants is often different from the industrial practice of traditional power production from geothermal energy sources.

Small size power plants (100 kW ÷ 5 MW) are innovative since in traditional geothermal power industry almost only greater sizes (5 ÷ 200 MW) have been used (flash systems, dry steam plants). The exploitation of medium-low temperature reservoirs introduce the possibility of small size units.

In the world there exist about 200 binary power plants units, anyway their number is difficult to evaluate and continuously growing [18]. The power produced is estimated to be more than 1150 MW, while the total energy is more than 6 TWh (2010 data). Generally speaking the number of small plants (less than 10 MW power output) in 2010 has been about 259, with an average power size of 3,2 MW, only about 196 of them were binary cycle power plants, 22 back pressure, 22 single flash and 17 double flash [18].

The thermodynamic principle of binary plants is basically the same of the conventional power plants (based on Rankine cycle or its modifications) for fossil or nuclear fuels. In its most applied configuration it is known as ORC (Organic Rankine Cycle). As it is shown in the sketch of Figure 4, a working fluid (or secondary fluid) receives heat from the geothermal water in a heat exchanger, then it expands in a turbine, producing energy in a generator. After the expansion the fluid condenses, transferring heat to the environment (wet/dry cooling is possible) and then it is re-circulated with a feed pump to the heat exchanger [16].

The working principle scheme is also represented in Figure 5 on a T-s diagram of the R600a (isobutane). The transformation 2-3 is the evaporation of the secondary fluid, while the geofluid is cooled from $T_{geo}$ to $T_{rein}$ in the heat exchanger. The line 3-4 represents the expansion in the turbine of the Organic Rankine Cycle, which
gives the mechanical power to a generator, producing electricity. The secondary fluid is then cooled and condensed, and pumped again to the heat exchanger (4-5-1).

Figure 4.: Simplified scheme of a basic geothermal binary power plant.

Figure 5.: Thermodynamic cycle of a binary power plant using R600a (isobutane), T-s diagram.
Technological variations and thermodynamic optimization methods can be adopted and a wide literature does exist about binary power plants. In Fig. 5 a binary cycle scheme on a T-s diagram is shown for the isobutane as a working fluid. Other configurations are possible, with the different fluids used in the current industry of ORC systems (Fig. 6). In Fig. 7 a simple Rankine cycle on the T-s diagram of the refrigerant R134a is shown. In this case the fluid at the end of the expansion is a mixture of liquid and vapour, with a quality less than 1. As in the traditional steam power cycles, this happens when the vapour saturation curve has a negative slope on the T-s diagram.

In Fig. 8 a superheated vapour cycle with refrigerant R600a is shown on a T-s diagram. When the geothermal resource is available this cycle can be obtained to better utilize the heat and improve the plant efficiency.

In Fig. 9 the same superheated vapour configuration of Fig. 8 has been complicated with two pressure levels of the working fluid, which is R600a. This kind of improvement can be used to enhance the heat transfer performances in the exchanger (to better move closer to the temperature profile of the geofluid).

In Fig. 10 a supercritical cycle is considered, with R134a as working fluid. It is an interesting cycle, although it needs a more accurate design and it is generally more expensive, because of the higher pressures.

It is important to point out that the geothermal fluid only is used to transfer heat, without direct contact with the atmosphere or soil. Keeping the geofluid in pressure by using down-hole pumps contributes to control the scaling problems. The reduced environmental impact is a crucial aspect leading to the ORC units diffusion worldwide. The environmental impact due to chemicals from the geofluid is totally avoided during the running of the plant, only the heat is transferred to the secondary fluid. All the problems of fluid flashing (e.g. irreversibilities, scaling)
are avoided, but a great part of the exergy losses in this case are linked to the heat exchanger [16].

These geothermal plants have no emissions to the atmosphere except for water vapour from the cooling towers (only in case of wet cooling) and no losses of working fluid. Thus, environmental problems that may be associated with the exploitation of higher temperature geothermal resources, like the release of greenhouse gases (e.g. CO$_2$ and CH$_4$) and the discharge of toxic elements (e.g. Hg and As), are avoided. Another advantage of the binary technology is that the geothermal fluids (or brines) do not contact the moving mechanical components of the plant (e.g. the turbine), assuring a longer life for the machinery. The geofluid is always kept (from the extraction well to the reinjection) at pressures (usually very high) at which flashing or breakout of Non Condensable Gas (NCG) does not occur. A limit to the cooling of the fluid is given by the scaling in the last pipelines and in the reinjection well. These are some of the aspects that are elaborated in this work, particularly in this chapter.

In the Figure 6 some of the most used working fluids for binary cycle power plants are shown on a same T-s diagram. They can be refrigerants (e.g. R134a, R152a) or cryogenic (hydrocarbons like isobutane, n-pentane). The selection of the working fluid has been object of a wide literature [19, 20, 21, 22, 23, 24, 25, 26, 27, 28], since binary cycle plants are used also with other heat sources than geothermal. A growing interest from industry and research about ORCs for biomass, solar and waste heat applications has to be here cited [29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39] together with the huge literature about geothermal applications for ORCs [40, 41, 42, 43, 44]. Also multicomponent mixtures used as working fluid, for which evaporation occur with variation of temperature, as for example in the Kalina cycle, could increase the thermodynamic efficiency and should be taken into account [45].

As this technology is well known from a general point of view, the coupling with the geothermal resource is the real point to be studied. As it is discussed in this
work, the resource characteristics vary with time during the exploitation and the efficiencies and performances of the plant can rapidly decline.

2.1.1 Efficiencies and plant variables

ORCs raise considerable interest as they allow to produce electricity from medium-low enthalpy geothermal resources (typically within the range 100 ÷ 150 °C, exceptionally down to 90 ÷ 95 °C, depending on the availability of a cold enough lower thermal source).

Let us consider a geothermal plant with one extraction well and one reinjection well, this would reproduce a typical ideal binary plant. The heat power rate $\dot{Q}_{\text{geo}}$ extracted from the reservoir and processed in the heat exchanger can be calculated as

$$\dot{Q}_{\text{geo}} = \dot{m}_{\text{geo}} c_{p,\text{geo}} (T_{\text{geo}} - T_{\text{rein}})$$

(10)

where $\dot{m}_{\text{geo}}$ is the mass flow rate of the geothermal fluid, $c_{p,\text{geo}}$ is the specific heat capacity of the geothermal fluid, $T_{\text{geo}}$ is the temperature of the resource and $T_{\text{rein}}$ is the temperature of reinjection. Let us call

$$\Delta T = (T_{\text{geo}} - T_{\text{rein}})$$

(11)

the “useful” $\Delta T$ of the geofluid extracted. In the range of temperature and pressure considered, neglecting the pressure component of the enthalpy we could assume that:

$$h_{\text{geo}} - h_{\text{rein}} \approx c_{p,\text{geo}} (T_{\text{geo}} - T_{\text{rein}})$$

(12)
The energy balance at the heat exchanger, referring to the scheme of Fig. 7, is then described by

\[ \dot{m}_{wf} (h_3 - h_1) = \dot{m}_{geo} (h_{geo} - h_{rein}) \]  

(13)

where \( \dot{m}_{wf} \) is the mass flow rate of the working fluid and \( (h_{geo} - h_{rein}) \) is the heat needed to make the secondary fluid evaporate (Fig. 7).

The most immediate efficiency parameter of a power plant is the First Law Efficiency \( \eta_I \) which is defined as the ratio between the net power produced by the plant \( W_{net} \) and the total heat power entering the plant from the underground:

\[ \eta_I = \frac{W_{net}}{\dot{m}_{geo} (h_{geo} - h_{rein})} \]  

(14)

where \( h_{geo} \) and \( h_{rein} \) are respectively the enthalpy of the geothermal fluid and the enthalpy of the reinjected fluid [19, 46]. The Second Law Efficiency is defined as the ratio between the net power produced by the plant and the exergy content of the heat power of the geothermal fluid entering the heat exchanger:

\[ \eta_{II} = \frac{W_{net}}{\dot{m}_{geo} e_{geo}} = \frac{W_{net}}{\dot{m}_{geo} (h_{geo} - T_0 s_{geo})} \]  

(15)

where \( s_{geo} \) is the specific entropy of the geothermal fluid, and the denominator represents the exergy rate entering the plant by the geothermal fluid.

The Second Law Efficiency (Equation 15) is inversely proportional to the specific brine consumption \( \beta \), defined as

\[ \beta = \frac{\dot{m}_{geo}}{W_{net}} \]  

(16)
which gives an estimation of the mass fluid rate to be circulated to the heat exchanger to give a single power unit from the plant. Its units are (kg/s)/MW or kg/MJ.

In Table 2 some average range of efficiency parameters values are listed (power plants sizes from 0,1 to 1 MW or more) to give an idea of the order of magnitude of these parameters. If no adequate water source is available, a dry cooling system must be used.

The efficiencies of binary cycle plants are very sensible to the external thermodynamic parameters (ΔT of fluid, environment temperature, fluid pressure, permeability changes). For this reason, as stated in the chapter 1, the characterization of the resource available is a fundamental step.

Referring to the scheme of thermodynamic Rankine cycle of Fig. 5 and Fig. 7 the total power balance of a binary plant could be summarized into the following equations (according to [19]):

Table 2.: Typical range of values of $\eta_1$, $\eta_{II}$ and $\beta$ for geothermal binary power plants (0,1 – 1 MW)

<table>
<thead>
<tr>
<th>Efficiency values of geothermal binary power plants</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>First Law efficiency</td>
<td>$\eta_1$</td>
</tr>
<tr>
<td></td>
<td>5 – 10 %</td>
</tr>
<tr>
<td>Second Law efficiency</td>
<td>$\eta_{II}$</td>
</tr>
<tr>
<td></td>
<td>20 – 45 %</td>
</tr>
<tr>
<td>Specific brine consumption</td>
<td>$\beta$</td>
</tr>
<tr>
<td></td>
<td>20 – 200 (kg/MJ)</td>
</tr>
</tbody>
</table>

Power consumption by auxiliary systems (% of gross power)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Circulation pumps</td>
<td>2 – 10 %</td>
</tr>
<tr>
<td>Cooling tower fans</td>
<td>10 – 40 %</td>
</tr>
</tbody>
</table>
\[ W_{\text{net}} = W_{\text{gross}} - W_{\text{pump}} - W_{CS} = \]
\[ = \dot{m}_{wf} \left[ (h_3 - h_4) - \frac{v_{wf}(p_{eva} - p_{cond})}{\eta_{pump}} \right] - W_{CS} \tag{17} \]

where \( W_{\text{pump}} \) is the power rate consumed by the circulation pumps of the plant, \( W_{CS} \) is the power consumption of the cooling system. \( W_{\text{net}} \) is the net power produced by the plant, which is directly connected to the gross power produced \( W_{\text{gross}} \) by the electric conversion efficiency \( \eta_{el} \):

\[ W_{\text{net}} = \eta_{el} W_{\text{gross}} \tag{18} \]

\( \eta_{el} \) summarizes all the electrical conversions from the generator to the electrical grid (it is usually high, more than 95%).

A summary of the total exergy losses (I) of a binary power plant (referring to the simple schemes of Fig. 5 and Fig. 7) can be expressed as:

\[ I = \dot{m}_{geo} e_{geo} - W_{\text{net}} = I_{HE} + I_{\text{cond}} + I_{rein} + I_{\text{exp}} \tag{19} \]

where \( I_{\text{exp}} \) represents the irreversibility of the turbine (expander), \( I_{HE} \) the exergy losses in the heat exchanger (geofluid/working fluid), \( I_{\text{cond}} \) are exergy losses in the condenser and \( I_{rein} \) are the irreversibilities due to the reinjection of the geofluid (which is still relatively hot). These irreversibilities can be calculated as follows:

\[ I_{HE} = \dot{m}_{geo} (e_{geo} - e_{rein}) - \dot{m}_{wf} (e_3 - e_1') \tag{20} \]

\[ I_{\text{cond}} = \dot{m}_{wf} (e_4 - e_1') \approx \dot{m}_{wf} |\Delta h_{\text{cond}}| \left( 1 - \frac{T_0}{T_{cond}} \right) \tag{21} \]

\[ I_{rein} = \dot{m}_{geo} e_{rein} \tag{22} \]

The exergetic availability of the geothermal fluid to be used in a ORC plant can be evaluated with the definition of two ratios [19]:

\[ \frac{Ex}{Ex_0} = \frac{(T_{geo} - T_{rein}) - T_0 \ln (T_{geo}/T_{rein})}{(T_{geo} - T_0) - T_0 \ln (T_{geo}/T_0)} \tag{23} \]

\[ \frac{Ex}{Q_0} = \frac{(T_{geo} - T_{rein}) - T_0 \ln (T_{geo}/T_{rein})}{(T_{geo} - T_0)} \tag{24} \]

Eq. 23 represents the ratio of the theoretical work that can be extracted from the geofluid for a given \( \Delta T = T_{geo} - T_{rein} \) and the maximum theoretical work that can be extracted for given \( T_{geo} \) and dead-state temperature \( T_0 \). It provides an upper limit to the Second Law efficiency.

Eq. 24 represents the ratio between the theoretical work that can be extracted from the geofluid for a given \( \Delta T = T_{geo} - T_{rein} \) and the maximum theoretical heat rate that can be extracted for given inlet \( T_{geo} \) and dead-state temperature \( T_0 \). The reference value \( T_0 = 298 \text{K} \) represents a theoretical lower limit value for reinjection temperature. In both ratios the geothermal brine is assumed to have a constant specific heat.
In Fig. 11 and Fig. 12 the dependence of the ratios $\frac{E_x}{E_{x0}}$ and $\frac{E_x}{Q_0}$ on the temperature of the resource $T_{geo}$ and on the rejection temperature $T_{rej}$ is shown\(^1\).

**Figure 11.** Reference values for Second Law efficiencies of geothermal ORCs as a function of the available temperature difference $T_{geo} - T_{rein}$, according to Eq. 23, for different typical values of $T_{geo}$.

**Figure 12.** Reference values for First Law efficiencies of geothermal ORCs as a function of the available temperature difference $T_{geo} - T_{rein}$, according to Eq. 24, for different typical values of $T_{geo}$.

In Table 3, Table 5 and Table 4 several data about some small and medium size geothermal binary power plants are listed (data from [46, 19, 2]). The data about the worldwide diffusion of ORC plants are continuously changing and a dynamic industry market is developing [50, 46] (see section 5.6, p. 191). In the present work there is not a complete report or review of all the existing and to be installed ORC plants worldwide, some of them are only cited to describe the issues and problems here treated\(^2\).

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\(^{2}\) For a plants review see [14] and also [50].
2.1.1.1 Regenerative Rankine Cycle

One important technical solution for the practical optimization of the ORCs plants is the use of the internal heat exchanger to recover the heat of the secondary fluid after the expansion has occurred. This configuration of the binary cycle is called “Regenerative ORC” [47, 48, 46], it is shown in Fig. 13.

The use of a recuperator is particularly interesting in case of working fluids coming out from the expander at relatively high temperature. The vapour from the turbine is used to preheat the working fluid before it enters in the heat exchanger. The use of recuperative heat exchanger allows to reduce the size of the cooling system and consequently to reduce the parasitic losses. It is possible when using “dry expansion” working fluids, namely a fluid where the expansion in the turbine ends in the dry superheated zone and the expanded vapour has still a relatively high enthalpy content, that has to be dissipated. In this case the temperature after expansion in the turbine is often higher than the condensation temperature. This heat rate would be transferred with the environment into the condenser. The use of the internal recuperator allows to keep smaller the condenser and use the remaining heat to preheat the secondary fluid. The pre-heating or heat recovery occurs according to the balance

\[
\dot{m}_{wf-liq} \Delta h_{liq} = \dot{m}_{wf-vap} \Delta h_{vap}
\]  

(25)

Although under a theoretical point of view the vapor could be cooled down to the temperature of the liquid, in practice an efficiency of the recuperator should be considered. This is to be referred to the fact that the vapour has a lower specific heat capacity than the liquid. According to [46] one can define this efficiency as

\[
\varepsilon_{rec} = \frac{T_{in-rec} - T_{out-rec}}{T_{in-rec} - T_{out-pump}}
\]  

(26)

where \(T_{in-rec} - T_{out-rec}\) is the \(\Delta T\) of the cooling down vapour, while \(T_{in-rec} - T_{out-pump}\) is the maximum \(\Delta T\) in the recuperator (being \(T_{out-pump}\) the temperature at the exit of the feed pump). This ratio has 1 as theoretical upper limit. Also a finite minimum temperature difference between the vapor at the exit of the recuperator and the liquid at the outlet of the feed pump can be considered.

The “regenerative ORC” appears to be particularly interesting in the perspective of small size units for the exploitation of geothermal sources at moderate temperature, since the recuperator (or pre-heater) can reduce the sensitivity with respect to the variation of reinjection temperature and environmental temperature (which can have sensible annual and seasonal changes).

2.1.2 Effects of condensation, reinjection and reservoir temperature

If condensation temperature and environment temperature are too close a lot of power would be needed to dissipate the heat power. Environment temperature can change with time, with annual and seasonal variations but also hourly. This would affect the global efficiency of the plant (see Table 2). The parasitic power consumption of cooling auxiliary system is relatively high because of the need for forced ventilation. A dry cooling system can absorb from 10 – 12 % of gross power
Figure 13: Simplified scheme of a geothermal binary power plant in which a recuperator (heat exchanger) is used.

(under ideal conditions), to as much as 40 – 50 % if the environment temperature is very close to the condensation temperature of the cooling fluid. The capital cost can be also quite high: e.g. 30 – 35 % of the total cost of the plant. The cooling devices for the condensation heat (particularly in case of dry systems) contributes to a huge soil occupation, that brings to environmental impact problems and social acceptance issues.

In Fig. 19, 18, 20, 21, 22 the photos of geothermal binary power plants installed in different countries are shown (photos courtesy of Ormat Technologies Inc.). The relative sizes of cooling systems respect to the power unit can be evaluated.

As for the condensation temperature, also the reinjection can be a critical point in the design of binary cycle power plants. The reinjection temperature can not be chosen arbitrarily. It depends on different factors, mainly due to the chemical composition of the geofluid. Scaling and chemical deposition can cause fouling, reduction of the heat transfer coefficient and corrosion (see section 2.3.1). Many of these chemical reaction occur when the temperature and pressure decrease, so the reinjection pipeline and the last part of the exchanger could be interested by these critical phenomena.

An increase of $T_{\text{rein}}$ (leading to $\Delta T$ reduction) causes a decline of the heat rate extracted and transferred to the secondary fluid in the exchanger.

A reduction of the extraction temperature $T_{\text{geo}}$ can occur during plant lifetime due to natural decline or because the reinjection is done in a wrong way (e.g. reinjection well too close to the extraction well, reinjection temperature too low to restore the reservoir potential in an adequate time interval).

One effect of the decline of $T_{\text{geo}}$ on the plant is shown in Fig. 14, in which the points 1,2,3 are the same thermodynamic states of Fig. 5. A pinch point reduction (due to to a reduction of $T_{\text{geo}}$) would lead to unacceptable thermodynamic working point of the heat exchanger (e.g. negative or null pinch point).
Previous studies [2, 49], show that the specific brine consumption and the efficiency strongly depend on the difference between reservoir temperature $T_{\text{geo}}$ and reinjection temperature $T_{\text{rein}}$, varying from 25 ÷ 40 kg/s for each MW produced in case of source temperature of 150 ÷ 160 °C, up to over 100 kg/s for each MW produced in case of $T_{\text{geo}} = 110^\circ\text{C}$. Due to the medium-low specific enthalpy entering the heat exchanger, this typical values of flow rate have to be considered in terms of design parameters and costs, particularly for small size power plants.

If the the useful $\Delta T = T_{\text{geo}} - T_{\text{rein}}$ is used as a parameter, the values of $\beta$ for five different and optimized plant configurations (and $\Delta T$ values) are shown in Fig. 15.

In Fig. 16 some values of temperatures of small size geothermal binary power plants are shown (from [2]). The reinjection temperature appears to be approximately in a range from 55 °C to almost 90 °C, which can be considered an average value. The evaluation of the appropriate $T_{\text{rein}}$ value is related to the causes here described. Each reservoir has its own chemical, thermodynamic and hydrogeological conditions, which have to be synthesized together with the industrial utilization parameters to elaborate the reinjection strategy. One can not evaluate the $T_{\text{rein}}$ without any experimental data from the field. This would bring to uncorrect sizing or failure.

If scaling and chemical deposition problems occur and the reinjection temperature of a binary plant has to be increased, this will bring to an increase of the mass flow rate extracted. The exploitation rate of the resource will change with a more severe exploitation of the reservoir. Both the durability of the resource and the sustainability, also technological and economic, will rapidly decrease.

The necessity of estimate on equilibrium working point for the “geothermal system” appears then to be clear.
2.1.3 Geothermal potential assessment and geofluid extraction/reinjection rate

2.1.3.1 Extraction/Reinjection rate

Let us consider the sensitivity of a traditional geothermal flash-steam power plant respect to the sensitivity of a small size ORC plant. It can be useful to explain some of the key points of this chapter. In case of flash-steam plants, in geothermal field with quite high temperature and pressure of the geofluid, a reduction of temperature or pressure could cause a reduction of the productivity of the plant. Let us consider the thermodynamic cycle of a flash steam power plant of Fig. 17 (T-s diagram of water). For a fixed intermediate pressure $p_{\text{int}}$ the quality of the steam to be expanded can be calculated as

$$x_2 = \frac{h_2 - h_4}{h_3 - h_4}$$  \hspace{1cm} (27)

being $h_2 = h_1$. The mass flow rate of steam to be expanded in the turbine (3-5) $\dot{m}_3$ is then

$$\dot{m}_3 = \dot{m}_{\text{geo}} x_2$$ \hspace{1cm} (28)

while the useful gross power extracted from the turbine is

$$W_t = \dot{m}_3 (h_3 - h_5)$$ \hspace{1cm} (29)

As it is evident, a reduction of $h_1$ lead to a reduction of $x_2$, which means that the mass flow rate going to the turbine ($\dot{m}_3$) is reduced. The consequences can be:

- the reduction of the plant output or
- an increase of the extraction ($\dot{m}_{\text{geo}}$) to keep constant the power output.

But in both situations the production can continue (if more serious effects do not occur). This would not directly lead to failure or damages.

For a binary plant the power output can be expressed (approximately) as discussed for the Eq. 17 and Eq. 18. A reduction of the temperature of the geothermal
Figure 16.: Prospects of temperature values (particularly production and reinjection) in some geothermal plants (from [2]).

source from $T_{geo}$ to $T^* < T_{geo}$ (if limited) can be compensated by an increase of geofluid extraction, if the balance equation

$$\dot{m}^* (h^* - h_{rein}) = \dot{m}_{geo} (h_{geo} - h_{rein})$$

(30)

is kept satisfied, being

$$h^* - h_{rein} \approx c_p (T^* - T_{rein})$$

(31)

A temperature reduction of the geothermal source could then cause the end of life of the plant because it could be impossible to maintain a correct pinch-point value (PP) in the heat exchanger. Fig. 14 (b) shows the decrease of the rejection temperature profile (decline of the source temperature), which causes a decrease of pinch point from the value PP1 to the value PP2. This problem is important for each typology of ORC, but in particular for advanced heat recovery solutions, like Rankine with superheater, Kalina and Supercritical cycles and for $T_{geo} < 120 \div 130 \, ^\circ C$.

Moreover an excessive extraction induced by increasing mass flow rate needed by the plant leads to prejudice the renewability of the resource. In the next chapter of this work this topic is also treated and critically discussed. The time interval in which the restoration of both fluid and energy occur depend on natural phenomena which can be hardly determined. These elements have to be taken into account in the potential assessment, because they deal with a dynamic evaluation of the “geothermal system” (see section 1.4.1).
2.1.3.2 Upper limit to the extraction and potential assessment

It is possible to define an upper limit to the extraction, which depends on a complex function of the whole geothermal system. Similarly to Eq. 30 and according to Eq. 31 one can write, for the geothermal system under exploitation:

\[ \dot{m}^* (h^* - h_{rein}) = \dot{m}^* c_p (T^* - T_{rein}) \]  

(32)

This enthalpy rate is always less or equal to a “potentially extractable” thermal energy (and consequently a geofluid rate) of the reservoir

\[ \dot{m}^* c_p (T^* - T_{rein}) \leq \dot{m}_{geo} \varepsilon (T_{geo} - T_0) \]  

(33)

where \( \varepsilon (T_{geo} - T_0) \) is an equivalent thermal capacity of the geothermal reservoir referred to \( T_0 \). Being always \( T_{rein} \geq T_0 \), in this case \( T_0 \) can be considered as a theoretical lower limit for the \( T_{rein} \). Assuming that the potential is constant in a time scale larger than the operative timescale of the plant lifetime, \( \dot{m}^* \) is necessarily limited, and inversely proportional to the “useful” \( \Delta T \)

\[ \dot{m}^* \propto \frac{1}{T_{geo} - T_{rein}} \]  

(34)

\( \dot{m}_{geo} \varepsilon (T_{geo} - T_0) \) can be considered as the upper theoretical limit to the extraction from the reservoir. The value of \( \dot{m}_{geo} \) which determines this limit can be considered as the result of a complex function which clearly depends on a lot of parameters and factors (both natural and technological): permeability distribution; hydraulic linking between the production and the reinjection areas; siting of the wells; natural recharge (meteoric water) to the reservoir. It would represent the synthesis of what

Figure 17.: Scheme of the thermodynamic cycle of a flash steam geothermal power plant (T-s diagram of water).
introduced and discussed also in the previous chapter. This upper limit for $\dot{m}_{geo}$ is such a kind of potential to be determined by a function, let us call it $\Pi$

$$
\Pi = f (\text{geothermal system}, t) 
$$

being a complicated function of the particular geothermal system and of time.

Summarizing what is expressed in this section about extraction rate in relation with the geothermal potential assessment:

- ORC systems have very low efficiencies in case of off-design working point, for example a reduction of the $T_{geo}$.

- the balance in the recovery heat exchanger of the binary plant is given by Eq. 13. If $T_{geo}$ decreases to a value $T^* < T_{geo}$ (being also $h^* < h_{geo}$) this can be compensated by a limited increase of the mass flow extracted (reaching the value $\dot{m}^*$), to keep maintained the balance of Eq. 30.

- Excessive extraction rates (together with a wrong reinjection strategy) could lead rapidly to the impoverishment or cooling down of the reservoir (fast advancing of the cool fluid front to the production wells, see chapter 3).

- $T_{geo}$ reduction could lead also to an incorrect pinch point in the heat exchanger (Fig. 14), causing the end of the life of the plant.

2.1.3.3 Reservoir pressure and Downhole Pumps

Considering the preliminary characterization of the geothermal resources, another peculiar theme from the related literature is the importance of the pressure in the reservoir. Geothermal fields are usually classified basing on temperature or enthalpy values (see Table 1). But the definition of a real global potential of a reservoir, also hydraulic head and pressure field variations have to be taken into account. The pressure at which the fluid is available is important in connection with the productivity of the well and the scaling phenomena.

Talking in terms of thermodynamic efficiency of a plant-wells system (as a subsystem of the “geothermal system” considered in this work), the reservoir pressure is important also because it affects the chemical deposition phenomena. Generally the geofluid arrives in the RHE (Recovery Heat Exchanger) of the binary power plant at a high pressure. Since the main environmental advantage of ORCs is the absence of geofluid contact with the atmosphere, the heat transfer occur with the geofluid kept in liquid phase. A pressure decline under critical values or a flash separation of a vapour phase would cause for the discharge of non-condensable gases (NCG) or polluting gases. When pressure decreases (and also gases are discharged), chemical deposition of solid or scaling can occur, causing damaging and fouling into the pipelines and the RHE. For these reasons the pipelines in which the geothermal fluid flows are kept over a certain pressure value, in order to keep it liquid (in case of water dominant field) and avoid scaling phenomena and deposition.

Downhole Pumps (DHP) are used, but the technological solutions for this task are also not trivial. DHP work in very severe conditions: high temperatures, chemical aggressiveness, corrosion, boiling, thermal expansion, cavitation. Their operating cycle can be very short and this is an important aspect to consider when making
economic decisions. Pumps selection and optimization (for liquid dominated fields) have been treated by N. Aksoy [52], distinguishing the two main configurations

- Line Shaft Pumps (LSP), powered by a long shaft driven by a motor installed at the wellhead;

- Electrical Submersible Pumps (ESP), in which a combination of an electric motor and pump set inside the well is used.

According to Culver [53] and Aksoy [52], geothermal LSPs operating parameters are limited at temperatures above 200 °C and depths to 600 m, due to well deviations, vibration, durability of the long shafts and bearing problems. ESPs can better face these problems but they are more expensive than LSPs, since they require special bearings and cables, and a sealed motor shaft. In case of ESP the motor has to be cooled, and the coolant is the geofluid itself, so the maximum working temperature for ESP is also determined by the geofluid temperature.

The dissolved salts in the geofluid increase the boiling point, while the NCGs decrease it [52]. When the pressure into the pump drops below the boiling or flashing point, cavitation will occur, reducing the efficiency and damaging it in a short period of time. In order to avoid both flashing and scaling the pump has to be set at a depth at which the fluid is always kept in the liquid phase. The well annulus can be pressurized with an inert gas such as nitrogen, which ensures that the fluid remains in the liquid phase from the reservoir to the pump inlet. DHPs also have to maintain the wellhead pressures required for the surface equipment (plant) to operate properly. It is also possible to add pumps in series in case of pressure drop in the pipeline and RHE before the reinjection.

Talking about this topic it is also interesting to describe a parameter which is very useful when evaluating the wells operativity. The Productivity Index (PI) is defined as the ratio between the volumetric flow rate \( \dot{q} \) to pressure change \( \Delta p \) [52]

\[
PI = \frac{\dot{q}}{\Delta p}
\]

and its units are \((m^3/Pa\cdot s)\). In oil and gas industry it is also expressed in \((bbl/psi\cdot d)\). It is generally used to express how a reservoir is able to deliver fluid to the wellbore. It can be also defined as the inverse\(^3\) of what defined in Eq. 36. It is derived from production tests on the well.

2.1.4 A technology standardization perspective

The problem of binary plants design and optimization involves a lot of different variables: selection of working fluids; heat recovery system and heat transfer surfaces; thermodynamic cycle (Rankine, Rankine with superheater, Kalina, Supercritical); and auxiliary systems consumption.

From a technological point of view binary technology potentially has a great variability of thermodynamic solutions and heat exchanger surfaces and this topic has been considered in a lot of papers and books in the scientific literature in the last

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3 This means for example that another possible definition is \( PI = \Delta p/\dot{q} \).
years. The key point is that a “standardization” of this energy conversion technology is actually difficult, due to the number of different types of available reservoir (temperature, pressure, chemical composition) and to the strong dependence of $\beta$, $\eta_1$ and $\eta_{II}$ on external parameters (reservoir and environment) [2].

There is a huge literature about geothermal ORCs, often based on specific and local industrial applications. Till now each installation is designed for the conditions at a given location and the various systems have been tailored to specific geothermal fluid characteristics. The major manufacturers in this field, like Ormat, Mafi Trench, Siemens and UTC Power have adopted this approach.

At present the technology is not at a stage of development capable of readily providing “standard machinery”, but recently some manufacturers have proposed the use of standard systems (e.g. UTC Power proposed The PureCycle® Power System)\(^4\). This approach could be the key element for a large diffusion of small size geothermal plants. R245fa is the working fluid of this system. The gross power output is up to 280 kW, with an inlet temperature range of the hot fluid of 90 $\div$ 150 $^\circ$C, according to the standard size (from 100 kW up to about 300 kW).

A larger diffusion of such systems would be possible only if adequate provisional instruments will be developed. For a correct sizing of a plant, mainly of an ORC plant, two elements are of primary importance: the definition of the geothermal potential assessment and the reinjection strategy. Due to the reduced standardization of machinery, the sizing of the plant (power output and fluid rates) and the siting of the wells are the main global and synthetic tasks for a sustainable geothermal project.

Manufacturers of ORC systems designed suitable units for different applications of heat recovery and power production: biomass plants, hot exhaust combustion gases, waste heat, geothermal energy. It is evident that every renewable energy source has its own characteristics of availability and utilization. It is a challenge for this “multi-purpose” units to be fit for both constantly available heat sources (e.g. combustion hot gases) and geothermal source with all the concerns about the sustainability of the “geothermal system”.

This argument is crucial for the future development of small geothermal plants, mainly in Europe, where a wide expansion of this industrial market is being pursued. For example in Italy, at the present time, about 43 applications for geothermal exploration are active according to the Ministry for Economic Development website\(^5\), almost all in Latium (25), Tuscany (7), and Sardinia (7), while 43 geothermal exploration concession have been granted. About 10 “experimental plants”\(^6\) instances of permission [54] are in progress, and 13 are the received applications\(^7\). This could determine a meaningful expansion of geothermal power plants in Italy, which is historically one of the most important countries for geothermal energy exploitation and tradition.

A strategy for the sustainable design of small size geothermal power plants (below 1 MW of net power output) and reservoirs at temperatures below 150 $^\circ$C through an interdisciplinary approach is proposed in this work.

\(^4\)http://www.utrc.utc.com/pages/ResearchInnovation/ORC.html
http://www.thirdwave.de/3w/tech/power/PureCycleThermocouple.pdf
\(^5\)http://umig.sviluppoeconomico.gov.it/umig/geotermia/titoli/titoli.asp
\(^6\)“Impianti pilota” in Italian.
\(^7\)http://umig.sviluppoeconomico.gov.it/umig/info/impianti_pilota.asp.
Figure 18.: Galena III, Steamboat Complex, USA, 23,5 MW, 2008 (Photo courtesy of Ormat Technologies Inc.).

Figure 19.: Amatitlan, Guatemala, 23,5 MW, 2007, Air-cooled OEC (Photo courtesy of Ormat Technologies Inc.).
Figure 20: Mokai Complex, New Zealand, 109,7 MW, 2000-2005-2007 (Photo courtesy of Ormat Technologies Inc.).
Figure 21.: Upper Mahiao, Philippines, 132 MW, 1996 (Photo courtesy of Ormat Technologies Inc.).

Figure 22.: Zunil, Guatemala, 24 MW, 1999 (Photo courtesy of Ormat Technologies Inc.).
Table 3. Small binary power plants using moderate temperature geothermal resources or non-conventional working fluids (data from various papers and open-file sources on the web, see [46, 19, 2]):

<table>
<thead>
<tr>
<th>Plant Location</th>
<th>T geo °C</th>
<th>Cycle Working Fluid</th>
<th>Power Size kW</th>
<th>β kg/(s)/MW</th>
<th>Cooling Device</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birdsville Australia</td>
<td>98</td>
<td>Rankine</td>
<td>Isopentane</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>Bruchsal Germany</td>
<td>120</td>
<td>Kalina</td>
<td>NH₃</td>
<td>610</td>
<td>518</td>
</tr>
<tr>
<td>Empire USA</td>
<td>118</td>
<td>Rankine</td>
<td>Isopentane</td>
<td>1200</td>
<td>90</td>
</tr>
<tr>
<td>Fang Thailand</td>
<td>116</td>
<td>Rankine</td>
<td>Isopentane</td>
<td>300</td>
<td>47.4</td>
</tr>
<tr>
<td>Husavik Iceland</td>
<td>124</td>
<td>Kalina</td>
<td>NH₃</td>
<td>2030</td>
<td>53</td>
</tr>
<tr>
<td>Nagqu China</td>
<td>110</td>
<td>Rankine</td>
<td>Isopentane</td>
<td>1300</td>
<td>69</td>
</tr>
<tr>
<td>Unterhaching Germany</td>
<td>122</td>
<td>Kalina</td>
<td>NH₃</td>
<td>4000</td>
<td>44.2</td>
</tr>
<tr>
<td>Wabuska USA</td>
<td>104</td>
<td>Rankine</td>
<td>Isopentane</td>
<td>750</td>
<td>90</td>
</tr>
<tr>
<td>Wendel Germany</td>
<td>103</td>
<td>Rankine</td>
<td>R114</td>
<td>2000</td>
<td>128.2</td>
</tr>
<tr>
<td>Wineagle USA</td>
<td>110</td>
<td>Rankine</td>
<td>Isobutane</td>
<td>750</td>
<td>105</td>
</tr>
</tbody>
</table>

Table 4. Small binary power plants using moderate temperature geothermal resources (data from various papers and open-file sources on the web, see [55]):

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>T geo °C</th>
<th>T rein °C</th>
<th>˙m geo kg/s</th>
<th>W net kW</th>
<th>β (%)</th>
<th>η I</th>
<th>η II (%)</th>
<th>Ex/Ex₀</th>
<th>E/F</th>
<th>Q/Ø₀</th>
<th>T₀ °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pico Vermelho USA</td>
<td>151</td>
<td>87</td>
<td>117.1</td>
<td>10.5</td>
<td>11.15</td>
<td>13.9</td>
<td>40.8</td>
<td>0.72</td>
<td>10.95</td>
<td>22</td>
<td>Ormat</td>
</tr>
<tr>
<td>Ormat</td>
<td>108</td>
<td>82</td>
<td>30.1</td>
<td>4.33</td>
<td>111.8</td>
<td>8.0</td>
<td>17.9</td>
<td>0.48</td>
<td>4.33</td>
<td>17</td>
<td>Ormat</td>
</tr>
<tr>
<td>Ormat</td>
<td>110</td>
<td>88.5</td>
<td>30</td>
<td>0.18</td>
<td>166.7</td>
<td>6.6</td>
<td>9.7</td>
<td>0.35</td>
<td>3.75</td>
<td>9</td>
<td>Ormat</td>
</tr>
<tr>
<td>UTC Power</td>
<td>74</td>
<td>57</td>
<td>40.28</td>
<td>0.42</td>
<td>95.94</td>
<td>14.7</td>
<td>46.3</td>
<td>0.48</td>
<td>2.1</td>
<td>5</td>
<td>UTC Power</td>
</tr>
<tr>
<td>Turboden</td>
<td>106</td>
<td>70</td>
<td>81.7</td>
<td>1.0</td>
<td>81.7</td>
<td>8.1</td>
<td>23.3</td>
<td>0.6</td>
<td>5.63</td>
<td>13</td>
<td>Turboden</td>
</tr>
<tr>
<td>GMK</td>
<td>98</td>
<td>70</td>
<td>25.9</td>
<td>0.165</td>
<td>156.8</td>
<td>6.1</td>
<td>12.7</td>
<td>0.48</td>
<td>6.1</td>
<td>12.7</td>
<td>GMK</td>
</tr>
</tbody>
</table>

See [55]
Table 5.: Medium size binary power plants using moderate temperature geothermal resources or non-conventional working fluids (data from various papers and open-file sources on the web, see [46, 19, 2])

<table>
<thead>
<tr>
<th>Plant</th>
<th>Location</th>
<th>Power size MW</th>
<th>Cooling device</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blundell</td>
<td>Utah, USA</td>
<td>11</td>
<td>dry</td>
</tr>
<tr>
<td>Casa Diablo (Mammoth)</td>
<td>California, USA</td>
<td>42</td>
<td>dry</td>
</tr>
<tr>
<td>East Mesa</td>
<td>California, USA</td>
<td>89,4</td>
<td>wet</td>
</tr>
<tr>
<td>Heber (SIGC)</td>
<td>California, USA</td>
<td>40</td>
<td>wet</td>
</tr>
<tr>
<td>Olkaria III</td>
<td>Kenya</td>
<td>12</td>
<td>dry</td>
</tr>
<tr>
<td>Pico Vermelho</td>
<td>Azores, Portugal</td>
<td>11,5</td>
<td>dry</td>
</tr>
<tr>
<td>Rotokawa</td>
<td>New Zealand</td>
<td>13,5</td>
<td>wet</td>
</tr>
<tr>
<td>Salt Wells</td>
<td>Nevada, USA</td>
<td>14</td>
<td>dry</td>
</tr>
<tr>
<td>São Miguel</td>
<td>Azores, Portugal</td>
<td>16</td>
<td>dry</td>
</tr>
<tr>
<td>Soda Lake</td>
<td>Nevada, USA</td>
<td>12</td>
<td>dry</td>
</tr>
<tr>
<td>Steamboat Spring</td>
<td>Nevada, USA</td>
<td>34</td>
<td>dry</td>
</tr>
<tr>
<td>Stillwater</td>
<td>Nevada, USA</td>
<td>15,3</td>
<td>dry</td>
</tr>
<tr>
<td>Stillwater 2</td>
<td>Nevada, USA</td>
<td>48</td>
<td>dry</td>
</tr>
<tr>
<td>Zunil</td>
<td>Guatemala</td>
<td>28,6</td>
<td>dry</td>
</tr>
</tbody>
</table>

Bottoming plants of combined cycles, medium size (power size > 10 MW)

<table>
<thead>
<tr>
<th>Plant</th>
<th>Location</th>
<th>Power size MW</th>
<th>Cooling device</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leyte</td>
<td>Philippines</td>
<td>61</td>
<td>wet</td>
</tr>
<tr>
<td>Mak-Ban</td>
<td>Philippines</td>
<td>15,7</td>
<td>wet/dry</td>
</tr>
<tr>
<td>Miravalles 5</td>
<td>Costa Rica</td>
<td>18</td>
<td>wet</td>
</tr>
<tr>
<td>Mokai</td>
<td>New Zealand</td>
<td>18</td>
<td>dry</td>
</tr>
<tr>
<td>Puna</td>
<td>Hawaii, USA</td>
<td>30</td>
<td>dry</td>
</tr>
<tr>
<td>Wairakei</td>
<td>New Zealand</td>
<td>15</td>
<td>dry</td>
</tr>
</tbody>
</table>
2.2 DIRECT UTILIZATIONS OF GEOTHERMAL HEAT

Since the beginning of the geothermal energy use the direct utilization of the heat has been the most immediate purpose [56]. Since the power production from the geothermal heat started about one hundred and eight years ago, the direct uses have a longer history, even though they are reaching now a growing interest from the industry and research.

The scheme of Fig. 23 is a sketch of the uses of geothermal heat, with the great distinction which is considered in this work, between systems with or without fluid extraction.

The distinction between systems with or without extraction of the fluid is useful not only for a technological reason, but also for analyzing different impacts on the sustainability and durability of the resource.

It is clear that a systems in which the fluid is not reinjected again into the aquifer will surely affect the durability of the resource, respect to a system in which the heat is extracted through a secondary fluid, not affecting the hydrological balance of the aquifer.

Conventional systems, ATES (Aquifer Thermal Energy Storage) and DHE are treated from a general point of view in this section and situated into the bigger context of the sustainable use of medium-low temperature geothermal resources. Geothermal Convector (GTC) and Heat Pipe Turbine HPT systems are also discussed and described in section 2.4, in which the concept of Single Borehole Extraction System (SBES) is also introduced.

Although HPT systems have been studied and designed for power purposes (respect to direct uses of geothermal heat), they have been situated in this chapter

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8 The first experiment of geothermal energy conversion into electricity took place on the 4th of July of the year 1904, by Piero Ginori Conti in Larderello (near Pisa).
because the sustainability issues are very similar to the traditional direct uses systems.

The famous Lindal diagram for the geothermal energy utilization is well known (e.g. it is reported in Lund, 1997 [57]). It is very useful also to list and classify the several uses which deal with very different industrial and commercial fields, even though it has to be stated that a continuous evolution is occurring.

In the worldwide review from Lund et al. (2010) [58] a value of the installed capacity can be found, it is about 50,6 GW with an estimated global capacity factor of 0,27. The same data for Italy is 867 MW, with capacity factor of 0,36. It is important to see in Table 6 (from Lund et al. 2010 [58]) which is the distribution of the uses by categories. Percent on the totals of installed capacity and annual energy utilization are also shown. The capacity factor (Table 6) is defined as the ratio between the number of full load operating hours and the number of the hours in a year.

Table 6.: Summary by categories of the direct uses of geothermal heat referred to the year 2010 (from Lund et al. 2010 [58]).

<table>
<thead>
<tr>
<th>Category</th>
<th>Installed capacity MW</th>
<th>Annual utilization TJ/year (%)</th>
<th>Capacity factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geothermal heat pumps</td>
<td>35236</td>
<td>214782</td>
<td>0,19</td>
</tr>
<tr>
<td>Space heating</td>
<td>5391</td>
<td>62984</td>
<td>0,37</td>
</tr>
<tr>
<td>Greenhouse heating</td>
<td>1544</td>
<td>23264</td>
<td>0,48</td>
</tr>
<tr>
<td>Aquaculture pond heating</td>
<td>653</td>
<td>11521</td>
<td>0,56</td>
</tr>
<tr>
<td>Agricultural drying</td>
<td>127</td>
<td>1662</td>
<td>0,42</td>
</tr>
<tr>
<td>Industrial uses</td>
<td>533</td>
<td>11746</td>
<td>0,7</td>
</tr>
<tr>
<td>Bathing and Swimming</td>
<td>6689</td>
<td>109032</td>
<td>0,52</td>
</tr>
<tr>
<td>Cooling / Snow Melting</td>
<td>368</td>
<td>2126</td>
<td>0,18</td>
</tr>
<tr>
<td>Others</td>
<td>41</td>
<td>956</td>
<td>0,73</td>
</tr>
<tr>
<td>Total</td>
<td>50582</td>
<td>438073</td>
<td>0,27</td>
</tr>
</tbody>
</table>

Geothermal Heat Pumps (GHP) are clearly the most important sector in terms of power capacity and energy utilization (almost 70 % of the total installed power and 49 % of the energy used, Table 6). This aspect has to be linked to the growing weight on the energy markets and balances of the air cooling consumptions.

These applications are based on the utilization of heat pump machineries with the ground or aquifers as external heat sources. If the temperature of the ground or aquifer bodies is considered to be variable in a very small interval, they can be used as almost constant heat sources. In this work an accurate description of such systems for air conditioning and heating/cooling applications is not reported. This technology is sufficiently well known in the field of Energy systems and Renewable energies.

A classical distinction between systems with fluid extraction (from groundwater aquifers, surface water bodies) and systems without fluid extraction (DHE, GCHP) is presented.
Depending on the type of heat source, the Ground Heat Exchanger (GHE) can be subdivided in:

- “Closed loop” or “closed circuit” systems: a fluid (water or water and antifreeze, usually Ethylene glycol) is sent in a piping line which is put to direct thermal contact with the ground at different depths (through a probe or a DHE).

- Systems in which groundwater is used, in an “open loop” through shallow or also deeper wells (extraction/reinjection). The groundwater is kept in direct contact with the parts of the system. Reinjection is not always practiced, leading also to free discharge of the water extracted, with critical consequences on the hydrological balance of the basin considered.

- Systems which use the surface water of rivers, lakes or small water body as heat source, but in “open loop” or “closed loop” configuration.

Both GCHP and GWHP are reaching a growing market if one looks at the numbers worldwide. In Lund et al. 2010 [58] a comparison of the utilization categories with the previous data of the years 1995-2010 is available (see also Table 6, p. 39).

Machinery and installation of GHP could appear to be very simple, if referred only to the thermodynamic and practical implementation side. Their optimization (both thermodynamic and environmental) and integration into the so called “plant-building” system are not trivial.

2.2.1 Systems without fluid extraction

The systems without fluid extraction exchanging heat with the ground are traditionally coupled with GHP, in the particular configuration named Ground Coupled Heat Pumps (GCHP). In Fig. 24 three typical layouts are shown.

GHE (or probes) for direct heat exchange with the ground have different features. The most common are represented in Fig. 25. In the single “U” shaped GHE the pipe is put in a drilled hole and filled with grout. A mixture of water and antifreeze (usually Ethylene glycol) flows down into the pipe and raises having exchanged heat. $T_{\text{out}}$ can be higher or lower than $T_{\text{in}}$ depending on the seasonal cycle of the GHP coupled. In the double “U” GHE two shaped pipes are put into the hole filled with grout. The heat exchanged is usually higher than the previous layout, because of the double mass rate flowing. In a different configuration the flow occurs into the internal channel of a coaxial double pipe or into the external annulus.

Also in the DHE (Downhole Heat Exchanger) systems fluid extraction is not practiced. A deeper analysis about the DHE exchanging with aquifers is reported in section 2.4.

2.2.2 Systems with fluid extraction

Systems with fluid extraction can be coupled with geothermal aquifers, but also to groundwater or surface water bodies (e.g. rivers, lakes, pond). In Fig. 26 two simple layouts are shown. In case the aquifer is shallow they are usually named Groundwater Heat Pumps (GWHP).
An evolution of such systems are the so called ATES (Aquifer Thermal Energy Storage) systems. They work on the principle of the heat storage according to seasonal variations of thermal load.

It can be seen as a way to use thermal energy underground storage where either low enthalpy resources are not available. In these systems cyclic (seasonal) storage of heat in the aquifer are used. As both rock and fluid are involved in the process of heat storage, a good characterization of the soil or aquifer is needed. The basic principle is the possibility of exploiting the slow advance of the heat transport into the aquifer or ground, re-using it in the following season. Winter/summer cycles of accumulation/utilization of the underground heat are possible. Doublet systems of two wells, also linked by the same aquifer are used. Two ways of using the thermal storage are possible: a recirculation in the aquifer can be pursued or two single wells operating differently as “hot” well and “cold” well.

As ATES could need huge mass flow rates from the aquifers, hydrological studies about the evolution of the aquifer are needed. Some of the softwares described in the chapter 3 can be also used for this purpose.
Figure 25: Common GHE (Ground Heat Exchanger) shapes and fluid circulation layout.

Figure 26: Layouts and different configurations of GWHP systems with fluid extraction.
2.3 TECHNOLOGICAL AND ENVIRONMENTAL PROBLEMS OF THE MAIN TECHNOLOGIES

Both binary power plants and direct uses technologies have common problems mainly due to the necessity of pursuing a durability and sustainability oriented energy utilization. Some of these problems are discussed in this section for both applications. In the following sections and chapters solutions and design approaches are proposed, in order to consider these issues in the optimization of the whole “geothermal system”.

2.3.1 Scaling and chemical aggressiveness of geothermal fluids

Reinjection is a key point for the design of geothermal binary power plants. $T_{\text{rein}}$ can be considered as a lower limit for the $\Delta T$ that can be used into the Recovery Heat Exchanger of the power plant. A limitation of the useful $\Delta T$ affects the amount of thermal power rate entering into the plant and the efficiency (see Eq. 10, 13 and 14).

This temperature is strictly connected and dependent on the scaling and deposition phenomena, causing consequently fouling and damaging of the exchangers, pipings and reinjection wells [59]. These chemical deposition can be huge when the temperature decreases. For this reason it is not possible to cool the geothermal fluid at lower temperatures than usually $50 \div 70 \, ^\circ C$ (see Fig. 16 and Table 4), depending on the type of ions and chemicals in the fluid [60].

Over certain thresholds of deposition rate, scaling effects can seriously decrease the pipes diameters, reducing the heat transfer rate and increasing the pressure losses in the heat exchangers section and leading to corrosion. Some significant pictures of damages and depositions (calcite scaling) in plants pipelines and wellbore are shown in Fig. 27, both pictures are referred to the Kizildere geothermal field (from [75, 76]).

The early study of the “reservoir (rock/fluid) - drilling utilities - power plants” behaviour is fundamental, in order to avoid the worst consequences of fouling and corrosion of the parts of the plant, of the pipings, and the “tapping” of the wells.

A wide literature on this issues is available. Research works of authors from different fields deal with scaling and deposition: Geothermal energy, Chemistry, Geochemistry. What is still missing is a deep consideration of this problem as a part of the engineering optimization of the plant, under a perspective of long plant lifetime and resource durability. Several papers draw attention to the damages and failure risks of scaling and deposition for the power plants (also taking into account interesting case studies) and report studies about the conditions at which silica scaling or other depositions occur [59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69].

In Gunnarsson and Arnósson (2000) [64] a review about amorphous silica solubility in the range of $0 \, ^\circ C$ to $350 \, ^\circ C$ (which is interesting for the geothermal plants) and experimental results are given.

Studies and researches with laboratory equipments have been pursued by Brown and Dunstall [70, 71], Gallup et al. [72] and Angcoy (2006) [73]. Hydrodynamic conditions and reaction kinetics strongly depends on the operative conditions of
the plant, but these studies go in the direction of prevent and control scaling with respect to the plant efficiency.

A fundamental work in literature, being also a review of issues, technical solutions and practical case studies also in Italy, is the paper by Corsi (1986) [74].

From a general point of view chemical deposition and scaling depend mainly on

- pH
- temperature
- pressure

Generally scaling increases when pressure and temperature decrease. High pH let the deposition increase too. The boiling point of the mixture changes also with the concentration of diluted gases (CO$_2$ in particular, which is the most present gaseous component in the geofluids of several geothermal fields). For a correct design of the equipment for the production test of the wells and of the pipings linking the wellheads to the plant, these issues have to be considered, to keep the pressure over the critical values calculated by Aksoy [52]. For a better comprehension of the chemical-physical aspects which govern solid formation a brief classification and review is needed.

![Figure 27: Pictures of damages by scaling deposition: a) calcite scaling in the wellbore (from [75]), b) calcite scaling in KD14 well (Kizildere geothermal field) (from [76]).](image)

2.3.1.1 Classification and mechanisms of scaling formation in geothermal plants

The major classes of scaling can be listed as follows [74, 77]:

- silica and silicates
- carbonate
- sulphate and sulphide

To point out and better understand the phenomena, let us see the main environments in which scale formation and deposition occur:

1. single phase fluid (reinjection pipelines)
2. flashing fluids (wells, separators, etc)
3. steam carry-over (separators, steam pipelines, turbines in case of direct expansion or flash power plants)

As in this work only medium-low temperature reservoir are considered, the attention is focused on deposition from single-phase fluid. Anyway for the equilibria description, flashing and steam discharge from the mixture causing scaling are considered too. First of all the kinetics is affected by the degree of supersaturation of the mixture, temperature, substrata, catalytic or inhibitory effects.

In the following part the chemical activities (or concentrations) are represented in round brackets.

The two main typologies of scaling mechanisms are here briefly discussed.

Silica scaling

Silica scaling could occur particularly in the reinjection lines, separators and sometimes in the wells. The two most important forms of silica to be considered are: (a) quartz and (b) amorphous silica. In Fig. 28 the solubility of quartz and silica are shown in a diagram in which the horizontal axis is the temperature (from [74]).

Quartz solubility increases with temperature and decreases with salinity, it can be considered independent of pH in the range pH < 8. Kinetic of quartz deposition is very low and silica deposition at lower temperatures is controlled by the equilibrium of amorphous silica.

Amorphous silica solubility increases with temperature, decreases with salinity and increases sharply with pH. Its kinetics is complex and depends on the degree of supersaturation and temperature. As it discussed in the section 2.3.1.3, acidification of the geofluid slows the rate of precipitation of silica.

Carbonate (CaCO$_3$) scaling

In almost all the geothermal fields worldwide CO$_2$ is present as a dissolved gas. In the Larderello geothermal area it is about the 5% in mass percent of the steam extracted. The concentration usually consider also the presence of H$_2$CO$_3$ (carbonic acid). The following equilibrium for the CO$_3{\text{(liq)}}$ shifts to the right when production starts and consequently pressure decreases:

$$2\text{HCO}_3{\text{(aq)}} \rightarrow \text{H}_2\text{O}_{\text{gas}} + \text{CO}_2{\text{(gas)}} + \text{CO}_3{\text{(liq)}}$$  \hspace{1cm} (37)

An increase of CO$_3{\text{(liq)}}$ can cause CaCO$_3$ precipitation, depending on the constant

$$K_p^{\text{CaCO}_3} = (\text{Ca}^{++}) \cdot (\text{CO}_3{\text{}})$$ \hspace{1cm} (38)

CaCO$_3$ deposition also begins when flashing starts, depending on the part of the plant it can cause different types of damages [74]:

- in-hole scaling: flashing starts in the production well
- formation plugging: flashing starts in the rock formation
- surface equipment encrustation: flashing occurs in the surface equipment
Considering also all the other equilibria, one can predict calcium carbonate scaling measuring (Ca++) and CO₂ content, although downhole sampling is not easy or strongly reliable.

### 2.3.1.2 Corrosion due to chemical aggressiveness of geothermal fluids

Many chemical species mainly present in water dominated geothermal fields have a significative role in corrosion of metallic parts are described in [74, 77]. They can be summarized as follows:

- oxygen (dissolved oxygen, or increase of aeration in the geofluid pipelines can cause an increase of corrosive rate of carbon steel)
- hydrogen ion (controlling pH)
- chloride ion (chloride ions can concentrate to near saturation in crevices)
- hydrogen sulphide (attack to copper and nickel alloys)
- carbon dioxide species (effects on carbon and low alloys steel, low pH due to carbon dioxide in the condensate steam leads to corrosion of steam lines)
- other species: ammonia, sulphate ion

Just a brief list of possible damages due to different mechanisms of corrosion and chemical aggressiveness of geothermal fluids is here described:

- Uniform (or general) corrosion: chloride ammonia, hydrogen ions
- Pitting: breakdown of a passivation film or surface scale
- Stress Corrosion Cracking (SCC): stress and presence of chloride ion
- Sulphide Stress Cracking (SSC): presence of H$_2$S in aqueous phase
- Hydrogen blistering
- Intergranular corrosion
- Galvanic coupling
- Corrosion fatigue: cyclic stress imposed to a material in a corrosive environment
- Erosion corrosion
- Cavitation

2.3.1.3 Methods for inhibition, prevention and scaling removal

An early assumption about this topic is necessary. The literature about prevention and inhibition methods for scaling is not so wide as for the other aspects of geothermal energy. In the following section 2.3.1.4 this is deeply discussed. Companies and manufacturers have always tried to keep confidential or reserved the technological solution against damages by scaling. This is the same treatment addressed to the most strategical data and solutions, being them key success factor. Also in case of State Companies or Agencies often the diffusion of data to the scientific literature has not been large as for other geothermal plants aspects.

Anyway, as for other issues, lots of papers deal with case studies [78, 79]. But also general view works can be found, like the one by Gallup (2002) [80].

As for the previous section, a good technological report is presented in Corsi (1986) [74]. The most used methods can be here summarized, in the following they are referred to the single scale formation:

a) alteration of the pH of the geofluid
b) use of chemical additives (scale inhibitors)
c) increase of the pressure of the geofluid pipeline
d) alteration of the partial CO$_2$ pressure

Analyzing the (a) option, one can observe that pH can be kept at low values in order to avoid CaCO$_3$ formation. HCl can be used, but this has to be also evaluated from an environmental and economic point of view. Particularly in case of “traditional” geothermal power plants (dry steam, single or double flash) the cost of the acidification can be huge (because of the flow rate values to be treated) when compared to the electricity produced. The acid solution is usually introduced in the parts of the plant in which the scale could take place. In case of binary power plants the most critical sections are the reinjection pipelines, the heat exchanger (RHE) and the reinjection well (formation plugging). From a long term environmental point of view, the consequences of such practice in geothermal systems are not clear or
sufficiently studied. One can observe that the deep hydrothermal systems traditionally object of exploitation for dry-steam or flash plants are far from the drinkable water aquifers. Moreover the well casing are prescribed to be realized in order to avoid mixing of geofluid and shallow water aquifers. Anyway it is here appropriate to focus the attention on this issue, considering the new growing interest, also in Italy, for the medium temperature geothermal fields, which are not so deep as the traditional ones (e.g. Tuscany and Latium).

The (b) point of the previous list is similar to the acidification, but different additives are used. Chemical additives have been used in oil and gas industry, but the extension to geothermal energy is subordinated by the high temperatures and salinities of the fluids. In the industrial practice a lot of patents exist from companies, about the mixture of additives and the devices making the additive able to react efficiently in a specific part of the plant or well. The chemical working principle of action is different from the pH manipulation described above. Additives often act in the sense that they avoid the nucleation of ions and precipitate. The Italian experience by ENEL in the use of chemical inhibitors (also organic) until 1986 is presented in the paper by Corsi (1986) [74]. Some interesting reports about testing and experiments have been presented by Vetter and Campbell (1979) [81] and Crane (1981) [82].

The problem of chemical inhibition is treated by Ungemach (1997,2004) in some important papers [84, 83]. In particular the study of inhibitors well injection and inhibitors mixtures are developed in these papers. Remedial strategies based on material testing (removable fiberglass lining of metal casing) and downhole technologies and procedures are discussed also under an economic perspective. The necessity of an Auxiliary Injection Tubing (AIT) and its implementation are described and the different layouts and disposal (depending on depth, temperature and inhibitor) are illustrated [84, 83]. The methods illustrated are also discussed with reference to practical applications and case studies monitoring [84, 83]. Economic and project sustainability issues are also underlined.

The (c) option is clearly due, first of all, to the necessity of avoiding flash of vapour phase. The flash or phase separation creates the conditions for immediate nucleation and solid scale formation. In certain ranges pressure is a governing factor for scaling. One important point to be considered, in case of binary power plants, is that the geofluid has always to be kept liquid into the pipelines and the RHE. This technological aspect is an advantage when trying to avoid flashing, because it has in any case to be prevented. Increase of fluid pressure more than the natural in-hole pressure can be obtained by using Downhole Pump (DHP). Anyway DHP have limitations due to depth and temperature of the fluid (they work in harsh conditions that can compromise their useful lifetime, see section 2.1.3.3).

The CO$_2$ partial pressure control (d) is used when carbonate scaling has to be avoided. It can also be realized by pumping part of the CO$_2$ possibly separated in the plant again into the production well.

An other solution that has been covered in literature [74] is to allow precipitation onto a “dedicated” surface of a specific equipment (prepared with seeds for the scale formation). Vetter and Kandarpa (1982) [85] described a flash-crystallizer tank, in case of scaling located at the flash conditions. Anyway a system like this cannot prevent scale into the reinjection pipelines. Water clarification is another process
that has been proposed in literature to eliminate silica scale particles from the reinjection pipelines [74]. It is a series of processes for solid-liquid separation. It can be very economically inefficient, because of the purification plant needed. Anyway the problem of clarification of the water is strongly site-dependent, as the chemical composition of the geofluid.

The silica scaling inhibition by acidification or chemical additives can be also studied in laboratories and by numerical simulation, but fields conditions can rapidly change respect to the laboratory parameters. It is still a tough issue, particularly if considering the poor diffusion in literature about industrial tests and practice.

Scaling removal is the last choice when the problem has already occurred. In the case of heat exchangers, a wide technical literature considers the possibility of mechanical or chemical (or both combined) removal. High pressure washing with strongly acid solution can be done, to remove the scale layer from the metallic alloys. Boring machines can also be used in case of pipes operation. For the wellbores also boring operation have been practiced, until the worst possibility (the well or formation plugging or tapping) has taken place.

2.3.1.4 Some systematic outlines and critical observations about scaling and geothermal power plants

A complete public literature about industrial practice for prevention and inhibition of such problems is neither wide nor available. Industrial tests or common internal practices are often not public, with negative effects on the study and research by Universities. For example, geothermal energy industry in Italy has been dealt and operated by few players. Different laws and regulations are present worldwide, this aspect has been very constraining for the public opinion towards to specific issues and optimization proposals.

Scaling problems have been well known by industry, but a systematic approach has never been pursued for different reasons. First of all the significant difference between geothermal fields worldwide, but also for the lacking of external diffusion of important data and results (when considered strategic) the industrial practice.

Today there not exist a regulation about the acidification and chemical inhibition activities. The consequences of reinjection of HCl or other additives in the long term are not totally known. Some companies do not consider the utilization of these techniques during the early stages of a geothermal exploration project, so that the environmental impact studies often do not consider the discharge of additives. The influence of chemicals on the drinkable water aquifers has to be studied, particularly in case of medium-low temperature reservoirs, which are more diffuse worldwide (see Fig. 1) and usually not deep as the high temperature ones.

Moreover the scaling issues should be considered in the design optimization of a project, because they can affect the efficiency and the feasibility itself of the project, if not adequately taken into account. Inhibition and prevention have costs that must be considered into the economic balance and also into a thermoeconomic analysis of the plants (see chapter 5).

For the applied study of scaling for plants design, two ways can be followed. One should know and characterize the equilibrium of the complex geofluid mixture. Each geothermal field and well has its own composition, with solid - liquid - gas equilibria, maybe already known from literature. A first kind of problem is
the knowledge of the static equilibrium, when thermophysical parameters change (temperature, pressure, pH, dissolved gases).

A second kind of problem to be identified is the knowledge of the reaction kinetic for these complex or non-characterized mixtures. The kinetic can depend by the turbulence development of the flow, according to the part of the plant (pipelines, heat exchanger, wells). On this second kind of problem particular attention and strong experimental efforts should be done.

2.3.2 Reinjection strategy

Only if reinjection is practiced one can say that geothermal energy is being used as a renewable energy source.

The practice of reinjection of geofluid avoids temperature and pressure decline in geothermal field. For the binary power plants it is a basic approach to the resource management and it appears to be compulsory (see Fig. 4). In the history of geothermal energy it has been the result of such a gradual acquisition of knowledge about reservoir dynamic and behaviour. It is well known that in the most famous geothermal fields like Larderello or Yellowstone, a decline in reservoir productivity has been partially compensated when reinjection started [16].

A general methodology is not available, but the optimal strategy is site-dependant (as for the potential assessment, see section 1.1). Each site has its own optimum reinjection strategy, in relation to the type of plant to be coupled with.

Interesting discussions on this particular topic are reported by Sigurðsson et al. (1995) [86], Stefánsson (1997) [89], Bodvarsson and Stefánsson (1987) [87]. Kaya et al. [88] recently proposed a worldwide review about the reinjection, fields are subdivided by type of resource and utilization, then a lot of informations about mass flow rates reinjected (also about free discharge to surface) are reported.

For a correct reinjection strategy, the circulation model of the fluid in the regional area considered have to be taken into account. The task is in fact the optimization and enhancement of the durability of the resource [89].

An incorrect value of $T_{\text{rein}}$ can cause scaling phenomena both in the heat exchangers and in the reinjection wells (see section 2.3.1). The mutual siting of production and reinjection well is another issue of the strategy. To give a trivial example: if they are too far, the recharge could occur in a too long time interval (longer than the plant lifetime). If they are too close a cold fluid short-circuiting could occur. The design of an injection strategy for a geothermal system is a complex problem and several parameters need to be considered [89, 88], for example:

- disposal of waste fluid
- cost (of wells and disposal devices)
- selection of wells siting
- reservoir temperature and pressure
- thermal breakthrough
- production decline
- temperature of injected fluid
- silica scaling
- chemistry changes in reservoir
- subsidence

In the following Table the main advantages and disadvantages of reinjection are listed (modified from Kaya et al. (2011) [88]). An appropriate configuration should be arranged, according to the potential of the reservoir and the type of plant. The system to be considered and optimized is the aforementioned “geothermal system” (composed by the plant, the reservoir, the environment and the links between them in terms of mass/energy transfer), see Fig. 2.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages or criticalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>recharge of the reservoir (and reservoir pressure support)</td>
<td>difficulty and cost related to the siting of suitable reinjection wells</td>
</tr>
<tr>
<td>environmentally friendly method for the disposal of separated geothermal brine and steam condensate (avoiding thermal and chemical problems of pollution of shallow ground water and water bodies)</td>
<td>cooling of the production zones and quenching of steam wells</td>
</tr>
<tr>
<td>help in reducing and managing subsidence that can arise from large scale fluid withdrawal</td>
<td>induced seismic (or micro-seismic) activity</td>
</tr>
<tr>
<td>reinjection of a low-gas concentration fluid can help the plant efficiency in case of dry-steam or flash plants</td>
<td>great pressures are needed for reinjection</td>
</tr>
<tr>
<td></td>
<td>risk of groundwater contamination (or surface leakage) and ground inflation</td>
</tr>
<tr>
<td></td>
<td>change of chemistry in production wells (e.g. a change in pH will change the solubility of solids, causing corrosion or scaling)</td>
</tr>
</tbody>
</table>

Informations from various electric power producing geothermal fields show that: a reinjection plan should be developed as early as possible (during exploration and first design) and it should be flexible in order to be adapted to possible changes in the reservoir conditions with time. The optimum reinjection strategy appears to be a quite complex task and it strongly depends on the type of geothermal system [88].

The objectives that this practice has to achieve are essentially the efficient restitution of the geofluid to the reservoir in order to optimize the recharge in terms of enthalpy and fluid production, choosing the correct siting of the wells to guarantee a sustainable use of the resource. A correct reinjection strategy has to take into account the scaling phenomena. So that $T_{\text{rein}}$ is a natural lower limit to the
heat power entering the power plant. Injection of inhibitors can help to keep clean and efficient the piping and the reservoir. It is known that in a few meters radius region near the bottom-hole the chemical deposition can cause also the so-called “tapping” (or plugging) of the reservoir (complete clogging, or huge decreasing of the production/injection).

2.3.3 Reliability and uncertainty level of exploration techniques for the estimation of the main parameters of the resource

When talking about geothermal projects, a typical workflow can be considered. Exploration is a fundamental part, it is the beginning of the project (see Huenges, 2010 [17]). Exploration deals with different backgrounds and scientific/technical aspects:

- Geology (Hydrogeology, cartography, data interpretation)
- Volcanology (formation dating, depth of magmatic chamber, volcanic risk)
- Geochemistry (natural manifestation, geothermometers, isotope analysis)
- Geophysics (thermal / gravimetric / geoelectric / magnetometric prospectings, seismic study)

Exploration wells drilling and analysis is the next step after the previous exploration. One have to consider which part of the data collected during the exploration will directly give informations for the design and sizing of the plant. As the opportunity of an interdisciplinary approach is stressed in this work, even more so it is true for the exploration. Merging the different backgrounds involved in a geothermal project (Thermodynamics, Energy Engineering, Earth Sciences, Reservoir Engineering) one should build a subset of data directly useful for sizing and numerical simulation of the reservoir and the “geothermal system” itself.

A powerful campaign of exploration could lead to not significative interpretation of the data. The following steps of design and numerical simulation directly depend on the interpretation and database building, more than on the exploration itself.

A general list of the evaluation to be developed in an exploration strategy is the following, from Huenges, 2010 [17]

- assessment of the geologic and geodynamic setting
- geochemistry including fluid and rock isotope chemistry
- structural analysis of faults, fractures and folds
- determination of the regional stress field
- potential methods, mainly gravity and magnetic surveys
- electrical and electromagnetic methods (EMs)
- seismic methods, both active and passive
An exchange and co-working during the early stages could be useful, also to fix some of the fundamental design variables and determine the domain to be simulated (and the boundary and initial conditions).

All these efforts and studies have also to be referred to newly exploration fields or hidden geothermal resources (such as EGS systems). It is evident that in case of totally new exploration all the process is more difficult and onerous.

The reliability level of exploration database is a crucial point. It affects interpretation and following steps too. Interpretation and reliability are particularly important when studying the boundary conditions and internal composition of the numerical model of the reservoir (see chapter 3.1). The conceptual model (together with the numerical model) is the synthetic black-box that can be used as an interface between the different backgrounds and it has to be built gradually from exploration to final stages.
2.4 TECHNOLOGICAL PROPOSAL: SBES (SINGLE BOREHOLE EXTRACTION SYSTEM)

In regions characterized by geothermal anomalies the ground heat can be directly exploited. The heat transfer would take place without fluid extraction from the geothermal resource and with no alteration of the natural hydrogeologic balance of the basin. The direct uses of geothermal or ground heat are presented in the section 2.2 (see also Fig. 23).

An interesting solution both for thermal energy and power production could be the application of the heat pipe principle [90]. The principle of heat pipe has been proposed in applications to renewable energy sources (geothermal heat, underground water, hot-spring water and solar heat), city waste heat (waste heat from subway, river, drainage, building, etc.), and utilization of deep underground heat sources.

In shallow geothermal reservoirs with temperature below $100^\circ C$, the heat pipe mechanism and in particular the two phase closed loop thermosyphon (CLPT) can transfer heat very efficiently. In this application the most important task is the enhancement of the heat transfer mechanism to the heat exchanger in the well.

The use of DHE has been discussed in literature in the last 40 years [93, 94]. A review of particular applications connected to the geothermal heat pipe applications is here proposed, then an analysis of the main technical elements regarding the geothermal aquifer exploitation and with the CLPT system is given.

The conventional utilization plants for medium-low temperature ($60 \div 150^\circ C$) geothermal reservoirs based on fluid extraction have some considerable inconveniences:

- The extraction from the aquifer can alter the natural balance of the basin, while over-exploitation causes temperature and pressure decline during the lifetime of the plant [91].
- The flow of very corrosive or chemically aggressive geothermal fluids into the pumps and pipings leads to high installation and operation costs and short machinery useful life.
- A second well is generally necessary for the reinjection, due to technological and environmental request.

In the exploitation of great geothermal reservoirs, in particular for power purposes, other important problems can occur, like for example micro-seismicity, waste water treatment and scaling, or chemical deposition phenomena and corrosion.

These problems can be avoided when only the ground heat is transferred from the aquifer or reservoir, basing on the concept of the Single Borehole Extraction System (SBES) [92]. For this application a secondary fluid (e.g. water or a low boiling point organic fluid) is used in a Downhole Heat Exchanger (DHE) [93]. The secondary fluid is circulated by natural convection (thus eliminating the problem of disposal of geothermal fluid, since only heat is taken from the well).

Several types of downhole heat exchangers, like thermosyphon type heat pipe, concentric tube thermosyphon, Downhole Coaxial Heat Exchanger (DCHE), U-tube
downhole heat exchanger, as well as others, have been proposed in order to extract heat directly from shallow geothermal aquifers or ground. Several concepts or designs of DHE have been successfully tested. In Klamath Falls (USA) over 500 DHE installations are present [95]. Applications include space heating and snow melting, mainly in USA, Turkey and New Zealand, Iceland, Hungary, Russia, Italy, Greece, Japan [94].

The main disadvantages of DHE systems respect to fluid extraction systems deal with the absence of heat flow induced into the aquifer by fluid extraction.

An alternative and more advantageous pathway with respect to DHE is the application of the heat pipe concept both in the basic version and (in particular) as in the Closed Loop Two Phase Thermosyphon (CLTPT) version [96]. CLTPT is generally a simple pipe, that constitutes the external shell for the heat exchanger and extends itself for a certain length of the well. In geothermal applications, CLTPT works with a downhole evaporator and a condenser at the ground level.

![Diagram](image)

**Figure 29.** Scheme of a DHE for the heat extraction from a geothermal aquifer.

As before mentioned the utilization of the thermosyphon concept in the DHE avoids the use of Downhole Pump (DHP). Compared with the conventional systems based on the extraction of water, CLTPT permits to exchange heat at a constant temperature and it has other advantages:

- it can be used even in dry geothermal areas (or characterized by very low fluid circulation);
- a loop type heat pipe can control the heat transfer rate by controlling the flow rate of the returning working liquid.

Notwithstanding the scientific interest of the concept, commercial systems are not available today even if a meaningful research work has been carried out.
The scheme of Fig. 29 is based on the presence of an aquifer in which different level and thermal conditions can be identified. The heat extraction from the aquifer is due to an auxiliary fluid that in general operating between two temperatures \(T_{\text{in}}\) and \(T_{\text{out}}\), with \(T_{\text{in}} < T_{\text{out}}\). In case of a two phase system the two temperatures can be the same, but the quality of the fluid is different. The heat exchanger in the aquifer becomes then an evaporator.

It is clear that an induced circulation of fluid takes place due to the heat transfer in the surroundings of the DHE. Once the evaporator section is extracting heat and a convection cell is established, a portion of the convecting water (surrounding the heat pipe) will be fresh water entering the well from the aquifer. The same amount of cooled water leaves the well and gets back to the aquifer.

2.4.1 Geothermal heat extraction using the heat pipe and CLTPT principles

In this work the issue of resource exploitation by a CLTPT geothermal system is considered. The heat pipe technology and optimization is treated in a wide literature, and this solution is nowadays applied in a lot of contexts.

In a conventional heat pipe consisting of a single tube, thermal performance is restricted by entrainment and flooding phenomena. Several variants of heat pipes for utilization of geothermal energy and underground rock heat have been studied. Vasiliev (1990, [97]) proposed a first interesting analysis of the problem. Several factors, like operating temperature range, vapor pressure, thermal conductivity, compatibility with the wick and case materials, stability and toxicity, affect the selection of the working fluid. The heat transfer “quality” of working fluids can be expressed by a Merit Number \(M\), defined as (Peterson et al, 1994, [98]):

\[
M = \frac{\rho \sigma_{\text{st}} h_{\text{fg}}}{\mu}
\]

where \(\sigma_{\text{st}}\) is the surface tension of the working fluid, \(h_{\text{fg}}\) is the latent heat of vaporization, and \(\mu\) is the viscosity.

2.4.2 Aquifer circulation model

The heat transfer between aquifer and well and between geothermal fluid and the external surface of DHE has been object of wide analysis and optimization in the literature [93, 99, 100, 101, 102]. The formation of strong temperature gradients along the well axis imposes limits on the heat power rate (generally less than 100 kW).

In order to improve the thermal performances (mainly for a large scale heat pipe), loop type and gravity assisted heat pipe (where vapour and liquid flow passages are separated) represent a better option. The interaction between the fluid flow in the well and to the aquifer, and the interaction with the rocks surrounding the well is the real keypoint of the problem. It is discussed in this section in relation with the geothermal resource characterization.
In case of DHE exchanging heat with an aquifer system, the heat flow extracted from the reservoir is regulated by the law

\[
\dot{Q} = n\pi h D_e U \Delta T_{lm}
\]

in which \(\dot{Q}\) is the heat rate exchanged per time unit, \(n\pi h D_e\) represents the heat exchange area (being \(n\) the number of the pipes, \(D_e\) the external pipe diameter and \(h\) the total length of the evaporator), \(U\) is the global heat transfer coefficient, \(\Delta T_{lm}\) is the mean temperature difference between aquifer and the working fluid in the extraction device. The heat extraction cause temperature gradients in the aquifer so that the definition of the above mentioned mean temperature difference appears to be a quite difficult task without resorting to an experimental analysis (see Fig. 29).

Also for CLTPT the heat flow rate that can be extracted from the well is tied only to the natural heat transfer occurring in the aquifer-wells-system. For this reason, to improve the mass transfer between aquifer and well, the use of a “natural circulation promoter” is necessary (Fig. 30).

![Figure 30.: Sketch of a geothermal well with convection promoter for heat extraction.](image)

The real complex element in the sizing of a geothermal systems without water extraction is the preliminary estimation of the heat flow rate. This depends mainly on the thermal and hydrogeologic characteristics of the geothermal system (ground and aquifer) and on the well-casing system. In any case, a too high heat extraction may cause a decay in the thermal characteristics of the aquifer and this seems to be dependent only on the geothermal system. On the other hand a too low value of the heat extracted is negative too due to the quite high perforation costs.
The heat extraction is proportional to the natural mass flow rate in the aquifer. In a groundwater system like an aquifer, the volumetric flow rate $\dot{m}_{\text{vol}}$ can be evaluated according to the Darcy Law [105, 106]

$$\dot{m}_{\text{vol}} = KA \frac{\Delta h}{L}$$

(see Fig. 31) where $\Delta h/L$ is an indicator of the slope and geometric dimensions of the aquifer (being $\Delta h = h_1 - h_2$), while $K$ is the hydraulic conductivity defined as a function of the thermophysical properties of the aquifer: permeability $k$, density $\rho$, viscosity $\mu$, acceleration of gravity $g$)

$$K = k \frac{\rho g}{\mu}$$

Another important characteristic of the aquifer or porous/fractured media is the transmissivity $\tau$

$$\tau = Ke$$

where $e$ is the aquifer thickness.

![Figure 31. Conceptual scheme about Darcy's Law.](image)

The maximum of the heat extraction from the well depends on the capability of the fluid circulating in the well to return. In a general case the heat that can be extracted from an aquifer depends on some specific characteristics of the geothermal systems, according to the law

$$\dot{Q} = KA \rho \frac{\Delta h}{L} c_p (T_\infty - T_{wo})$$

(44)

where $A$ is the section of the aquifer, $T_\infty$ is the temperature of the unperturbed aquifer, and $T_{wo}$ is the well output temperature (namely it is the minimum temperature of the fluid in the well). But the real maximum heat rate available can be referred to a well inlet temperature $T_{wi}$, which is $T_{wi} < T_\infty$, so the Eq. 44 will change

$$\dot{Q} = KA \rho \frac{\Delta h}{L} c_p (T_{wi} - T_{wo})$$

(45)
This model is valid for a general fluid circulation in an aquifer. Anyway, in aquifers or groundwater bodies characterized by geothermal anomalies this model could not be complete. When temperature differences between higher and lower parts of the well or aquifer thickness exist, buoyancy phenomena start to be important. The temperature field is modified when an exchanger (like a DHE or a GTC) is used, so that these difference of temperature (and of density) have to be considered.

To treat the heat extraction from a particular aquifer and discuss the application of a CLTPT based power device a lumped parameters model is here considered.

2.4.3 Lumped parameters model for heat extraction

The advantages of a device for the heat exchange with an aquifer that works with a single well is evident. This avoids the necessity of a closed loop or circuit with the whole aquifer. Relatively medium-low heat rates can be extracted, mainly due to thermofluidodynamic limitations, than quantitative limits. The temperature \( T_{wi} \) can be defined using a lumped capacity model based on the combination of mass balance, short circuiting factor and adiabatic mixing \([99]–[104]\). Let us introduce this factors according to the following equations. According to the scheme of Fig. 32 a fluid rate balance in the well-aquifer region is given by:

\[
\dot{m}_a = \dot{m}_{a1} + \dot{m}_{a2}
\]  \hspace{1cm} (46)

where \( \dot{m}_a \) is the aquifer renewed mass flow-rate, \( \dot{m}_{a1} \) is the short-circuited part of \( \dot{m}_a \) while \( \dot{m}_{a2} \) is the totally fresh renewed water part of \( \dot{m}_a \) from the aquifer. \( \dot{m}_f \) is the mass fluid rate in the well. In this model the concept of short-circuiting is important. Part of the water which exits from the well (lower part, see Fig. 32) which flows not far from the well has a lower temperature respect to the aquifer bulk temperature. It can be also shown that the short-circuiting part of water flowing is higher when the geothermal fluid circulation increases.

A circulation ratio \( \delta \) is defined as \([99]–[104]\)

\[
\delta = \frac{\dot{m}_a}{\dot{m}_f}
\]  \hspace{1cm} (47)

It can be also referred to the mixing ratio \( r_m \) introduced by Culver and Lund \([93]\)

\[
r_m = 1 - \frac{\dot{m}_a}{\dot{m}_f} = 1 - \delta
\]  \hspace{1cm} (48)

The mixing ratio \( r_m \) values observed range is 0,5 ÷ 0,95 \([93, 100, 105]\), so that \( \delta \) can range from 0,05 to 0,5.

Let us now consider the energy balance in the aquifer-well system, it is

\[
\dot{m}_a c_p T_{wi} = \dot{m}_{a2} c_p T_\infty + \dot{m}_{a1} c_p T_{wo}
\]  \hspace{1cm} (49)
The short circuiting ratio $\sigma$ is defined according to the literature in terms of the temperatures used in the previous equations [99]–[104]

$$\sigma = \frac{T_\infty - T_{wi}}{T_\infty - T_{wo}}$$

but a more intuitive form for $\sigma$ can be written if considering the Eq. 46

$$\sigma = \frac{\dot{m}_{a1}}{\dot{m}_a}$$

being truly the ratio between the water rate which is not renewed and the aquifer water rate entering into the well.

Rearranging Eq. 45 and Eq. 50 let us now write the equation of $\dot{Q}$ as a function of $\sigma$ and the temperatures of the aquifer-well system. From Eq. 50 for the difference $T_{wi} - T_{wo}$ it is

$$T_{wi} - T_{wo} = (1 - \sigma) (T_\infty - T_{wo})$$

Considering Eq. 45 one can see that $KA (\Delta h/L) = \dot{m}_{vol}$, and being $\dot{m}_{vol} \rho = \dot{m}_a$ one can write

$$\dot{Q} = \dot{m}_a c_p (T_{wi} - T_{wo})$$

Substituting Eq. 52 into the Eq. 53 it is

$$\dot{Q} = \dot{m}_a c_p (1 - \sigma) (T_\infty - T_{wo})$$
Carotenuto et al. [99] derived an analytical expression to define the heat flow rate that can be transferred in the evaporator zone. This correlates heat rate to mass flow rate in the aquifer $\dot{m}_a$ and to temperature difference between unperturbed aquifer and well output temperature $(T_\infty - T_{wo})$

$$\dot{Q} = \dot{m}_a c_p \exp \left[ -a (\dot{m}_a c_p)^b \right] (T_\infty - T_{wo}) \quad (55)$$

where $a$ and $b$ are coefficients that depend on the permeability and on the hydraulic conductivity, on the temperature difference and on the dimensionless length of the convection promoter. In the Eq. 54 the short circuiting ratio $\sigma$ (according to [99]) can be given by

$$\sigma = 1 - \exp \left[ -a (\dot{m}_a c_p)^b \right] \quad (56)$$

A maximum rate value can be identified. The theoretical maximum steady state amount of heat transferred from the aquifer would take place when the short circuiting ratio $\sigma$ is equal to zero. Since values of $\sigma$ lower than 0.5 have never been observed some common values are usually in the range from 0.5 to 0.95 [93, 90].

It is useful to introduce to efficiency parameters for the heat exchange with the aquifer [103, 104]. An efficiency parameters of the whole system made up by the aquifer, the well and the heat exchanger is $\eta$

$$\eta = \frac{T_\infty - T_{wo}}{T_\infty - T_{out}} \quad (57)$$

being $T_{out}$ the temperature of the working fluid in the exchanger (see Fig. 29). To evaluate the plant, another parameter can be introduced, the utilization factor $\theta$

$$\theta = \frac{T_\infty - T_{out}}{T_\infty - T_0} \quad (58)$$

considering that the plant works between the temperature of the aquifer and the environment temperature $T_0$.

The Eq. 54 can be then written taking into account these two efficiency parameters.

$$\dot{Q} = \dot{m}_a c_p \eta \theta (1 - \sigma) (T_\infty - T_0) \quad (59)$$

Carotenuto et al. [99] in their experimental analysis indicate some values of the typical properties for the analyzed case, which is the Island of Ischia (Italy), in an area where the temperature of the aquifer was about $70^\circ$C, using a 0.35 m well diameter; mass flow rate range between 0 and 3000 kg/h (0.83 kg/s), temperature difference between 0 $^\circ$C and 30 $^\circ$C. For an aquifer at $70 \div 80^\circ$C it is possible to observe how it is quite difficult to extract more than 50 kW from a single borehole. On the other hand, the availability of temperature values higher than 100 $^\circ$C at a depth of less than 150 m is rather limited.

With respect to Eq. 54 a sensitivity analysis for different values of the mass flow rate in the aquifer $\dot{m}_a$ ranging from 0.2 kg/s to 1.5 kg/s (for two particular values of short circuit ratio $\sigma$) and varying the $\Delta T$ is here proposed (Fig. 36 and Fig. 37).
This analysis provides an indication about which could be the heat extraction rates magnitudes according to the available literature and to practical parameters regarding aquifers and areas characterized by geothermal anomalies.

It is evident that the mass flow rate circulation into the aquifer and well (\(\dot{m}_a\) as well as \(\dot{m}_f\)) cannot be controlled totally from the surface. For this reason it is important to distinguish between:

a) forced circulation systems, for which the flow rate is controlled by the pump

b) natural circulation systems, for which the flow rate is a function of the operative temperature difference

In the first case (a) the power rate extracted is given by Eq. 59 and the operative parameters can be dependent on the thermal load (see Figs. 33–34).

In the second case (b) buoyancy force due to density and temperature difference between well and aquifer have to be considered.

The water rate effectively transferring heat to the exchanger is different if a convection promoter is present. It is a pipe larger than the exchanger which promotes the natural convection flow near the exchanging device (see Fig. 35). The possibility of application of this device depends on the aquifer characteristics. The systems without promoter are usually indicated for very thick aquifers (some tens of m), while the systems with promoter can be used in case of thin aquifers (some meters) [103].

**Figure 33.**: Scheme of a DHE for the heat extraction from a geothermal aquifer.
Figure 34.: Single well geothermal system for heat exchange, forced circulation (after [103]).

(a) without promoter, simple circulation
(b) with convection promoter, double circulation

Figure 35.: Single well geothermal system for heat exchange, natural circulation (after [103]).
Figure 36: Sensitivity analysis about heat power rate extracted with a SBES system for different values of mass flow rate in the aquifer (ranging from 0.2 to 1.5 kg/s), and for four values of $\sigma$.

Figure 37: 3D plot of the parametric variation (sensitivity analysis) of heat extraction rate at different values of short-circuiting ratio $\sigma$. 
2.4.4 Brief review of applications and proposals of DHE and CLTPT for geothermal heat extraction

The CLTPT is a device operating in a gravity field able to transfer high heat flow rate in a simple way. In the bottom part the operating fluid evaporates, the vapour rises to the top where it condenses, then the liquid returns by gravity to the evaporator section (Fig. 38).

A particular case of Closed Loop Thermosyphon, named Geothermal Convect- tor (GTC) has been proposed and tested by Carotenuto et al. [100] (see Fig. 39 a) for the heat extraction from geothermal aquifers. Interest to the utilization of two phase thermosyphon is demonstrated in connection with development of Enhanced Geothermal System (EGS) for power production by Ziapour et al. [96] and Wang et al. [107]. Recently the use of Thermosyphon Loops has been proposed for heat extraction from the ground and for heating of railway points [108].

In the central geothermal regions (Tuscany and Latium) of Italy there are very interesting areas since several thermal springs and hydrothermal systems exist, at temperatures higher than 60 °C [109, 110, 111]. Some of these springs have been known for their therapeutic properties since Roman times. These thermal waters are used primarily to supply thermal spas and public pools but a specific interest to energetic use is also possible [112].

Anyway to address the future groundwater management about these complex systems, it is important to examine the local response of the aquifers to energy and fluid withdrawals. In any case the sustainability analysis (durability of the resource during plant lifetime, technological feasibility) of the geothermal project becomes more important when the enthalpy of the source considered is relatively low.

---

**Figure 38.:** Sketch of a geothermal CLTPT system.
A large scale loop type heat pipe for extraction of geothermal energy was developed at Fujikura [113] (see Fig. 39 b). The heat pipe of 150 mm outer diameter and 150 m length was manufactured and installed in a geothermal well at 100 ÷ 150 °C, located at Kyushu Island in Japan. In the trial tests, the heat pipe was able to continuously extract 90 kW heat power rate at the working temperature of 80 °C. Heat flux at the evaporator was of the order of 3000 W/m² [114].

Recently Jeong and Lee [115] tested a two-phase thermosyphon system using CO₂ as working fluid. The total length of the thermosyphon was 1 m with inner diameter 9,9 mm and outer 12,7 mm.

Storch et al. (2012) [116] recently proposed the use of heat pipe (operating with propane or carbon dioxide) for geothermal heat extraction.

2.4.5 Applications of the heat pipe technology (CLTPT configuration) for power production (HPT)

The use of heat pipe technology has also been proposed also for geothermal power production since the early 1990s [117, 118, 119, 120].

The concept for power production here described has been proposed with different configurations in literature: Heat Pipe Turbine (HPT), Thermosyphon Rankine Engine (TSR) [118], Thermosyphon Rankine Cycle (TRC) [96] or Geothermal Energy Extraction System Organic Rankine (GEESOR) [92].

The basis of the cycle is the modification of a heat pipe to incorporate a turbine or expander. This system overcomes the necessity of a reinjection well as depicted in Fig. 40 (horizontal sizes are exaggerated respect to the vertical ones).
This system could represent an interesting alternative to the classical binary plant, in particular for small size power units (50 ÷ 100 kW). HPT have been studied and analyzed in the literature [107, 117, 118, 121] even if no real technological development has been observed and only some design schemes or prototypes are available, briefly reviewed in Table 7. Kusaba et al. [119], Akbarzadeh et al. [120] proposed HPT for power generation using geothermal temperature resources in the range 80 ÷ 150 °C, referred to specific geothermal sites.

In these applications a relatively high heat power rate (about 100 kW) was extracted, but with low conversion efficiencies. The authors also calculated the extraction rate for different heat pipe lengths and temperatures of the geothermal source.

In Fig. 40 the details of an heat pipe turbine system are shown. The configuration involves a closed, vertical cylinder working as an evaporator (in the lower part), then an insulated section and a condenser (in the higher part). The turbine is placed near the upper end between the insulated section and a condenser section; a plate is installed to separate the higher pressure region from the lower pressure region. The conversion of the fluid enthalpy to kinetic energy is achieved through a nozzle. The mechanical energy developed by the turbine can be converted to electrical energy by direct coupling to an electrical generator. It is important to notice that the expected performances of the systems described in Table 7 are very low (below 1 %). This is because a single pipe is used and the power extraction is mainly related to the kinetic effect.

Figure 40: A scheme of the operating principle of the HPT.
Table 7.: Review of different Heat Pipe Turbine systems proposed in literature.

<table>
<thead>
<tr>
<th>Authors</th>
<th>$T_{geo}$ ($^\circ$C)</th>
<th>Power (W)</th>
<th>Fluid</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lockett, 1986 [92]</td>
<td>&gt; 80</td>
<td>5.5</td>
<td>water</td>
<td>0.1 $\div$ 0.21</td>
</tr>
<tr>
<td>McGuinness et al., 1993 [117]</td>
<td>(only concept)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nguyen et al., 1995 [118]</td>
<td>&gt; 80</td>
<td>100</td>
<td>water</td>
<td>0.1 $\div$ 0.21</td>
</tr>
<tr>
<td>Nguyen et al., 1999 [121]</td>
<td>120 $\div$ 150</td>
<td>7800</td>
<td>R123</td>
<td></td>
</tr>
<tr>
<td>Kusaba et al., 2000 [119]</td>
<td>80 $\div$ 120</td>
<td>3000</td>
<td>R114</td>
<td></td>
</tr>
<tr>
<td>Yamamoto et al., 2001 [120]</td>
<td>R123</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wang et al., 2009 [107]</td>
<td>ground</td>
<td>isopentane</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ziapour, 2009 [96]</td>
<td>(only concept)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In a conventional thermosyphon consisting of a single tube, thermal performance is restricted by entrainment and flooding phenomena and it is difficult to maintain a uniform liquid film, which causes a decrease of the heat transfer performances. In order to improve the performance of a TRC system, Ziapour [96] has developed a loop type system where vapour and liquid flow passages are separated by installing liquid feeding tube with showering nozzle. The working fluid used was water and the operating temperature range between 25 and 75$^\circ$C.

2.4.5.1 The use of a CLTPT system for power production (Single Borehole Binary Cycle Power Plant)

For what discussed above the use of the concept of CLTPT would be more efficient for power production applications if compared with the HPT systems. In Fig. 41 the system is sketched and some typical dimensions from literature application are indicated. This configuration would involve a pump to increase the pressure of the fluid and an expander working on the enthalpy difference between the two parts of the loop system (Single well binary cycle). Let us refer to this configuration as an “advanced HPT”, as this concept represents a further evolution of the idea already proposed by Ziapour [96]. The fundamental difference is represented by the presence of a condensation system and of a pump permitting to define the two pressure levels and to obtain a meaningful pressure drop. Moreover, due to opportunity of working with this pressure drop, it is possible to resort to a conventional turbine system or two-phase expanders.

In this case the enthalpy drop in the turbine can be referred to the operating pressure in the loop thermosyphon. The operating conditions of heat pipe and CLTPT have been tested by Franco and Filippeschi [122, 123] with special attention to small dimensions systems.

In CLTPT, several key parameters influences the heat transport together with the heat flow (at the evaporator section, from the source), such as:

- diameter of riser and downcomer tube (d);
- distance between evaporator and condenser (H);
• length of the heat input zone (h);
• thermophysical properties of working fluid;
• operating pressure, $\Delta p$ and pressure drops;
• volumetric filling ratio or driving head;
• thermal resistances.

![Diagram](image)

**Figure 41:** The operating principle (conceptual scheme) of an advanced HPT.

2.4.5.2 *Thermodynamic analysis of a SBES shaped binary cycle system with different working fluids*

Let us now analyse the technical feasibility of power production using a CLTPT system to exchange heat with a geothermal aquifer. A Rankine cycle layout has been considered for the analysis. The calculations of this section have been referred to the data of the natural resource considered by Carotenuto et al. [100]: the temperature of the geothermal source is $70^\circ C$ at 15 m depth and the maximum heat flow rate to maintain the temperature is assumed to be 15 kW. Considering a Rankine cycle, operating between the temperatures of $30^\circ C$ and $60^\circ C$ and considering an isentropic expansion efficiency of 0.85 it is possible to foresee the performances of a power production of 1 kW unit. Table 8 provides an estimation of gross power, mass flow rate $\dot{m}_{wf}$ and efficiency $\eta_I$ in a Single Borehole Organic Rankine Cycle calculated using different working fluids.
Table 8.: Rankine cycle results with different working fluids (resource characteristics: 70 °C at 15 m depth, maximum heat flow rate 15 kW).

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Δp (bar)</th>
<th>Power (kW)</th>
<th>( \dot{m}_{\text{w-f}} ) (kg/s)</th>
<th>( \eta_1 ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R134a</td>
<td>9,112</td>
<td>1,064</td>
<td>0,08</td>
<td>7,1</td>
</tr>
<tr>
<td>R152a</td>
<td>8,175</td>
<td>1,076</td>
<td>0,05</td>
<td>7,2</td>
</tr>
<tr>
<td>R123</td>
<td>1,774</td>
<td>1,064</td>
<td>0,08</td>
<td>7,1</td>
</tr>
<tr>
<td>R21</td>
<td>3,07</td>
<td>1,078</td>
<td>0,06</td>
<td>7,2</td>
</tr>
<tr>
<td>R600</td>
<td>3,499</td>
<td>1,060</td>
<td>0,04</td>
<td>7,1</td>
</tr>
<tr>
<td>R600a</td>
<td>4,714</td>
<td>1,060</td>
<td>0,04</td>
<td>7,1</td>
</tr>
</tbody>
</table>

\( T_{\text{sat}} = 70 ^\circ \text{C} ; p_{\text{sat}} = 8,87 \text{ bar} \)
\( T_{\text{sat}} = 20 ^\circ \text{C} ; p_{\text{sat}} = 5,72 \text{ bar} \)

Figure 42.: A power cycle (Rankine) in the T-s diagram of R134a fluid (suitable values for sizing).

2.4.5.3 Discussion about technological issues and design of a CLTPT system for geothermal heat extraction (SBES)

Despite the thermodynamic analysis of the previous paragraph some technological issues and critical elements have to be treated about this systems. As one can see the efficiencies of such systems appear to be quite low (\( \eta_1 \)), see Table 8. If the real aquifer behaviour is analysed maybe that the efficiencies would further decline. For this reason a strong effort has to be done in evaluating all the factors that would contribute to very low performances.

From a technological point view a two pressure CLTPT, with confined regions into it has never been tested successfully. The power production system concept here proposed would open a technical feasibility issue. In this case the introduction of such a pump before the evaporator in systems traditionally characterized by natural
circulation is proposed. Depending to the mass flow rate and heat extraction rate this element can be critical for the First Law efficiency of the global system.

Differently from heat pipe or CLTPT heat extraction systems, in this case a considerable sub-cooling of the fluid has to be realized, facing heat exchange and phase mixing problems. On a theoretical point of view the subcooling cause a strong reduction of mass flow rate circulation for a given heat flow rate. Fig. 43 is referred to a CLTPT of 10 mm inner tube diameter in which it is clearly shown how the subcooling at different $\Delta T$ is sufficient to reduce the mass flow rate (from [124]).

For this reason, depending on the “aquifer-DHE” system circulation, the heat extracted can rapidly vary with time, with quality increasing at the expander.

![Figure 43: The effect of subcooling on the mass transfer (working fluid: water) in a CLTPT.](image)

Two-phase expanders could be considered in the design of this systems, to prevent low turbine performance and lifetime decline in case of reduction of heat extraction. Talking about the heat extraction let us refer to the “geothermal system” constituted by the resource, the heat extraction system and energy conversion system, the environment and all the links between them, in terms of mass and energy exchanges. The use of systems based on CLTPT shows remarkable differences with respect to the traditional geothermal utilizations. These differences are in positive as for example

- the use of single well systems instead of a multiwell systems (no reinjection);
- the use of a gravity head two-phase thermosyphon in place of downhole pumps;
- the possibility of using a secondary working fluid that permits the utilization of sources at temperatures below $100 \degree C$.

Moreover the thermosyphon can be beneficial in providing a more advantageous energy cycle. But some problems must be solved for the engineering development of these systems, such as:

- estimation of heat flow rate in the aquifer $\dot{Q}$;
- optimization of the CLPT system to maximize the mass flow rate;
- technological aspects linked to this application (in terms of components).

It is difficult to define and individuate the heat transfer equilibrium value between the aquifer and the evaporator of the thermosyphon. Let us summarize some fundamental outlines about this:

- without the benefit of aquifer fracture circulation the system capacity would be limited and heat extraction would quickly decline;
- convection promoters are devices proposed to increase the fluid (and heat) transport between aquifer, well and DHE, they can be used in the case of the particular application here discussed;
- heat flow rate is a function of the mass circulation rates and it reaches a maximum;
- near to this maximum, the values show a small difference from the maximum for a large range of mass circulation rates.

It is important to underline that the device operates in the way such that the maximum of the heat flow is obtained. The determination of an heat transfer equilibrium point between well-evaporator and well-aquifer and mass transfer in the thermosyphon requires further research activity, mainly if the development of a power purpose systems is considered.
3 NUMERICAL SIMULATION OF GEOTHERMAL RESERVOIRS

3.1 GENERAL ASPECTS

The optimization of the global system “reservoir-power plant” is here proposed as one of the task of a geothermal project. The problems of incorrect characterization of geothermal source and of an appropriate reinjection strategy are analyzed as main causes of geothermal plant failure.

Numerical simulation could be a fundamental and strongly interacting instrument for plant design. Different approaches to the numerical simulation of geothermal reservoirs operation are considered with reference to several case studies of geothermal fields which are reviewed and discussed. The perspectives of numerical simulation of geothermal reservoirs as support to the design and sizing of geothermal plants are outlined. Some general aspects, limitations and remarks are reported in this section, leaving more detailed aspects to the other sections of this chapter.

Some fundamental requirements of the numerical simulation that have to be remarked, in relation with the design strategy are:

- building of a database of physical and geological data for the geothermal potential assessment;

- set of thermophysical parameters for the design and optimization of the power plant or the thermal energy utilization plant (to elaborate exploitation scenarios).

Numerical simulation of geothermal reservoirs allows to understand the hydrogeological behaviour and heat transport (or also chemicals) into the reservoir. As it is described in section 3.2, the simulation process substantially deals with the numerical resolution of mass, momentum and energy conservation equations in porous and fractured media.

3.1.1 Main aims of numerical simulation of geothermal reservoirs

Two main goals or aims can be individuated from a literature review [14]:

**HISTORY MATCHING** The history matching is usually done to check the reliability of a model and evaluate the sustainability level in retrospect. It is the analysis of an exploitation strategy according to his history data log until present time or during a particular time interval. This is done to evaluate how a resource has been used during the history of its exploration and exploitation. This allows also to check the numerical model in a “feedback loop” and calibrate or adapt
it to what is reported in the history data (in order to improve future scenarios forecast). This is practically done assigning temperature and mass flow rate of both the geofluid extracted and reinjected, and anything else which has been recorded during time and can be translated into thermophysical parameters or boundary/initial conditions. Some phenomena which affect the history of a field utilization could not be put into a simulation in a proper way, without knowing them from the history (natural recharge, natural change of the pathways of circulation into the rock formations, losses of pressure for different reasons than the extraction, etc.).

**Forecast of future scenarios** Use of the numerical models to foresee the response of the geothermal system to different utilization scenarios. If a model can be considered to be reliable, it can be used to study how the durability of the resource changes depending on different extraction rates, reinjection temperatures, wells sitings, fractures (also induced) field. An actual previsional strategy can be based on the results of a model simulation. This is true for both power plants and thermal energy direct uses.

The hydrogeological problem (the complete knowledge of the geological structures and of the circulation system) has to be connected with the engineering tasks of the design and optimization of the energy conversion system. Using the numerical simulation one can study the whole system of a geothermal reservoir by solving the balance equations of mass, momentum and energy in the particular volume estimated to be interested by hydrothermal circulation of fluid. Softwares are evolving very quickly, but a key factor is the quality and reliability of the data and thermophysical parameters processed. For example it is difficult to have precise values of effective porosity of the rocks or permeability. Numerical simulation is an optimal tool for predictions about geothermal resource evolution and then exploitation strategy elaboration, but it is sensible to unrealistic data input. We can learn a lot from the “history matchings” of geothermal reservoirs exploitation experiences around the world [14].

Numerical model of the geothermal reservoir is important both during the initial steps, to define the thermophysical characteristics of the reservoir and the circulation model and during the life cycle of the plant. The simulation can be very important in order to modify the management strategy of the geothermal field. The model must be enriched including the database of historical data collected during exploration. The construction of the numerical model must be supported by a detailed knowledge of the spatial distribution of the properties of the reservoir: the accuracy in the definition of the dataset is fundamental for the construction of the model. The results obtained depend a lot from the accuracy level of the input data, as much details are known about the geological properties of the rocks (effective porosity, density, specific heat, permeability, thermal conductivity), thermophysical properties of the fluid (specific heat, density, thermal conductivity), fractures in the system, natural recharge of fluid, geothermal boundary conditions, as much accurate the model will be. In the next paragraphs the steps for the construction of the model will be explained.
3.1.2 Block-structure and conceptual model

The conceptual scheme for the realization and simulation of a model of a geothermal reservoir is represented in Fig. 44 (modified from [127]).

If a numerical model is realized in a multidisciplinary team or environment it happens that who is in charge of building up the model with a dedicated software or simulation code is not totally aware of the conceptual model of the field. It is necessarily a work of a team in which different geothermal backgrounds and experiences are shared. An important step of “interpretation” and appropriate data collection has to be pursued, as a previous step for the elaboration of the conceptual model (Huenges, 2010 [17]). This is to be considered as the physical and geological basic scheme to evaluate the results of the simulation. The development of the numerical model itself has to follow two main directions:

1. the unperturbed (or undisturbed) natural state
2. the utilization scenarios (during the exploitation)

Different phases in the development of the model can be individuated. A first “block-structure” has to be built together with the dataset of the parameters which best fit what it is expected by the conceptual model. This first step model should reproduce:

- geological structure of the reservoir
- geometrical features of wells and fracturactions
- Hydraulic, Thermal, Mechanic and Chemical conditions (HTMC)

![Figure 44. Conceptual scheme for the realization and simulation of a model of a geothermal reservoir (modified from [127]).](image)

The model should then pass a further step of calibration and refinement. It is an iterative process, in which the parameters and boundary conditions should be adjusted according to the conceptual and physical model previously elaborated and
to the uncertainty level of part of the database used. Some thermophysical properties change with siting, depth, hydrothermal alteration. Their value (permeability, thermal conductivity, porosity, specific heat capacity) can be adjusted and the mesh can be refined during this step.

A first model of the unperturbed state is the result of the attempts here described. It should be run for a long simulation time interval, in order to verify the model stability and convergence. In case of strong uncertainty about both the heat transport phenomena and geophysical data, simple 2D models (or lumped parameters models) could be firstly run.

Exploitation and energy utilization scenarios can be then run starting from the unperturbed state simulation as initial conditions. The renewability assessment and durability of the resource have to be results of the scenarios simulation. In particular temperature and pressure should be kept stable into the reservoir as much as possible. If chemical properties and saturation curve of the specific geofluid mixture are known, scaling and chemical deposition phenomena can be also introduced in the calculations, in a multiphysics simulation environment\textsuperscript{1}. Models can couple different transport equations, referring to mass, heat and chemicals.

It is important to remark that in the results of the simulation some effectively useful data for the plant design have to be extracted. It is evident that some of the geophysical and general result are not directly necessary or relevant for who is in charge to design the plant. A close interaction between who elaborates the numerical model and who designs the resource utilization plant would be needed (according also to the considerations and remarks about multidisciplinary work discussed in the previous chapters).

Some of the technological and environmental issues discussed until now are going to be treated under the perspective of the numerical models. They are summarized in the sketch of Fig. 45.

Three different levels are identified in the perspective of an optimum design of the whole system. It is obvious that a design of the plant that is not interacting with the underground levels is not successful. In this integrated approach, numerical simulation is considered as a fundamental instrument for the prediction of reservoir response, in particular for medium to low temperature fields.

3.1.3 Conceptual model and numerical model

The step which follows the data collection and interpretation is the definition of a conceptual model of the reservoir (see Fig. 44). Each geothermal field in the world is different for reasons of structure, stratigraphy, temperature, pathways of circulation of fluids, number of reservoirs, chemical properties of fluid and rocks, origin of the thermal anomaly, hydrothermal alteration involved.

Theoretical and experimental basis about main structures and features of the field, and main circulation pathways are fundamental for the definition of the numerical model domain (grid) in terms of extension and refinement. The domain size, orientation and shape are defined in order to include all the rock formations involved in the circulation system. The model should not be too big or dispersive to waste computa-

\textsuperscript{1} This could complicate in a sensible way the model, it is possible only when the awareness about the specific geothermal field is high and if the numerical stability of the model would be not affected.
Figure 45.: Conceptual scheme of the approach proposed, different operational steps are collocated at different “depths” in the model of the “geothermal system”.

tional power, or too small to be not reliable and neglect important inflows/outflows or sources. The numerical model has to be consistent at least with the hypothesis collected in the conceptual scheme.

3.1.4 Simulation strategies

After the construction of the model domain, the first goal of the simulation is to reproduce the unperturbed natural state, that means the situation at which the system goes to the stationary state without any artificial withdrawal or recharge. Long simulation time could be needed, usually between $10^4$ years and $10^6$ years, as order of magnitude.

A calibration process of the model is based on the data available for the field (geophysics exploration, geological maps, natural manifestations, wells temperature profile) to fix the parameters and to achieve an acceptable reliability level. Then a simulation of the various scenarios of utilization (production and reinjection) can be performed.

Techniques and strategies to conceive and correctly simulate a numerical model have been studied, and widely proposed (among others) by Ungemach et al. [125, 127].

The results of the simulation should show in particular the migration of the cold front to the production zone during time and the depletion of the resource with respect to the exploitation level. The results of a good simulation model allow to
design and correctly size the power plants, taking into account the sustainability of the whole system.

3.1.5 Limitations and criticalities

Anyway it has to be clear from the beginning that numerical simulation has some important limits (which are treated and discussed in this work):

- it strongly depends on the reliability and accuracy of the data;
- numerically stable models can be physically not consistent.

The first limit can be also expressed by the principle “trash in - trash out”. It must be clear which is the physical-numerical problem to recourse numerical simulation for. One should evaluate if the numerical simulation is the more appropriate instrument to face a specific problem. Usually a problem can be simplified in a proper way to be solved according to calculus or numerical analysis without using dedicated softwares. Reservoir model simulation has to be pursued only if it is the most suitable and appropriate way to elaborate a design strategy.

“Lumped parameters” models can be very useful for some medium-low temperature fields, having not too much thick lithological layers. Sometimes, for particularly linear and simple problems they can be satisfactory, in spite of more sophisticated elaborations.

One possible risk is to start “asking too much” or “asking too bad informations” to the numerical models, being them “too much” or “too less powerful”. For example, starting from the same geological features of a field, a model can give different results depending on the resolution of the spatial distribution of the data.

Some typical problems due to incorrect initial characterization of the resource can also be faced with an appropriate model simulation, they can deal with:

- oversizing of the plant (leading to excessive extraction)
- scaling (causing corrosion, productivity drop, diameter reduction)
- wrong reinjection strategy (losses of fluid or cooling of the reservoir)

3.2 MATHEMATICAL - PHYSICAL BACKGROUND

The basic calculations executed by the softwares for numerical simulation substantially deal with the resolution of the flow into porous and fractured media. Equations of conservation of the following properties are solved:

- mass
- momentum
- energy
- concentration of pollutant or chemicals dissolved
Let us focus briefly on the equation system. In this chapter $q$ is used instead of $\dot{m}_{vol}$ for the volumetric flow rate of geofluid. According to the most important constitutive equation (Darcy Law) the volumetric flow rate $q$ is proportional to the slope $i = \Delta h/L$, according to the Law 41 (see Fig. 31):

$$q = KA \frac{\Delta h}{L}$$

(60)

where hydraulic conductivity $K$ is proportional to the permeability $k$ according to the law (Eq. 42)

$$K = k \frac{\rho g}{\mu}$$

(61)

The $\Delta h$ introduced in the previous Eq. 41 is the difference of piezometric head. It is the sum between the geometric head or depth) $z$ and the dynamic head

$$h = z + \frac{p}{\gamma}$$

(62)

where $\gamma$ is the specific weight force. The variations of the kinetic head can be neglected in these cases.

If one extends the study to bidimensional or tridimensional velocity field it is possible to write

$$\vec{m}_{vol} = -k \nabla h$$

(63)

In case of anisotropy an hydraulic conductivity tensor $\vec{K}$ can be defined, being

$$\vec{K} = \begin{pmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{pmatrix}$$

(64)

and the Eq. 63 becomes

$$\vec{q} = -\vec{K} \cdot \nabla h$$

(65)

3.2.1 Mass and heat transport in porous and fractured media

From an historical point of view, the studies about transport in reservoirs or aquifers born in the field of mining engineering and applied thermodynamics. The task is to understand the response of a porous or fractured system when a hydraulic gradient is applied. Anyway the application of some experimental concepts to the geothermal fields is not a trivial task. The hypothesis and the real situation of the field should be compared very carefully.

An example is the application of average properties to rock formation in which anisotropy or local variation could be present. For example porosity changes also with pressure and depth, it is important to understand what assumption have to be done when assigning an average value of such properties to an extended rock body with an unknown field of fracturation.

Fracturations are particularly difficult to reproduce in a numerical model. In fact their accurate description is important if their spatial extension is comparable to the rock formation mass and volume, otherwise average properties can be considered.
Some fundamental differences between the flow in porous and coherent media than in fractured media have to be considered. The reasons and outlines are here reported from Garg and Kassoy, in Rybach and Muffler (1981) [136]:

a) permeability induced by fracturing (so called secondary permeability) is generally higher than average formation permeability

b) fracturing permeability is usually anisotropic (it depends on fracturing preferential direction)

c) the permeability due to fracturing is considerably more dependent on pressure and on tension field in the rock respect to rock matrix permeability

For the study of flow in porous media Darcy’s Law (Eq. 41 and Eq. 42, Fig. 31) is currently used if the hypothesis of local thermal equilibrium can be considered to be satisfied.

The main equation systems for the solution of the liquid flow into porous or fractured media are here described, from Rybach and Muffler (1981) [136]. Also the fundamental papers by Diersch et al. [138, 139, 140] are used in this section, regarding basic reservoirs equations, boundary conditions and initial conditions. For a detailed description of the approach considered by the different software used for this work see the Appendix A, p. 211, and also [138, 143, 129].

For a detailed approach and descrition of these phenomena see the volume by Rybach e Muffler, 1981 [136], in particular chapter 2 (Conective Heat and Mass Transfer in Hydrothermal Systems) and chapter 5 (Heat Extraction from Geohermal Systems).

3.2.1.1 Single phase flow

Let us now consider a single phase (liquid) flow in a geothermal system. According to Rybach and Muffler (1981) [136] the following assumptions have to be considered:

- rock matrix is homogeneous and isotropic, in particular referring to porosity, permeability and thermal conductivity (considered to be independent by temperature)

- incompressible fluid, with density and kinematic viscosity dependent by temperature according to the laws:

\[
\rho = \rho_0 \left[ 1 - \alpha (T - T_0) - \beta (T - T_0)^2 \right]
\]
\[
\nu = \nu_0 \sigma (T)
\]

being \(\rho_0, \alpha, \beta\) and \(T_0\) opportune constants, while \(\sigma(T)\) is a function of \(T\)

- pressure work and dissipations due to viscosity can be neglected, internal energy of solid matrix and liquid being

\[
E_l = c_{l,vol} (T - T_0)
\]
\[
E_r = c_{r,vol} (T - T_0)
\]
with \( c_{r,\text{vol}} \) and \( c_{l,\text{vol}} \) specific volumetric heat capacities of rock and liquid.

Under these assumptions the balance equations of mass, momentum and energy can be written according to [136]:

**Mass**

\[
\nabla \bar{q} = 0
\]

\( (70) \)

**Momentum**

\[
\left( \frac{\nabla p}{\rho_0} - \bar{g} \right) + \alpha (T - T_0) \left[ 1 + \frac{\beta}{\alpha} (T - T_0) \right] \bar{g} + \frac{\gamma_0 \sigma}{k} \bar{q} = 0
\]

\( (71) \)

**Energy**

\[
[(1 - \phi) \rho_r c_r + \phi \rho_0 c_v] \frac{\partial T}{\partial t} + \rho_0 c_v \bar{q} \cdot \nabla T = \nabla \cdot (k_m \nabla T)
\]

\( (72) \)

being \( k_m \) the thermal conductivity of the mixture solid liquid.

### 3.2.1.2 Double phase flow

A double phase system, in which also the vapour phase is considered, is described by similar equations [136]. The following assumption about porosity has to be done:

- porosity \( \phi \) only depends on local pressure of fluid
- liquid and vapour phases are in local thermal equilibrium

**Mass**

\[
\frac{\partial}{\partial t} (\phi \rho) + \nabla \cdot (\rho_l \bar{q}_l + \rho_v \bar{q}_v) = 0
\]

\( (73) \)

**Momentum**

(liquid)

\[
\bar{q}_l = - \frac{R_l \kappa}{\mu_l} \cdot (\nabla p - \rho_l \bar{g})
\]

\( (74) \)

(vapour)

\[
\bar{q}_v = - \frac{R_v \kappa}{\mu_v} \cdot (\nabla p - \rho_v \bar{g})
\]

\( (75) \)

**Energy**

(rock-liquid-vapour)

\[
\frac{\partial}{\partial t} [(1 - \phi) \rho_r E_r + \phi \rho E] + \nabla \cdot \left( \rho_l E_l \bar{q}_l + \rho_v E_v \bar{q}_v + (p \bar{q}_l + p \bar{q}_v) \right) = \nabla \cdot \left( k_m \nabla T \right) + \nabla \cdot (\rho_l \bar{q}_l + \rho_v \bar{q}_v) \cdot \bar{g}
\]

\( (76) \)

where \( E \) is the internal energy of the liquid-vapour mixture, \( \kappa \) is the permeability tensor and \( R_i \) is the relative permeability of the \( i \)-th phase \( (i = l, g \) liquid or vapour).
saturation in the mixture (geothermal fluid). Several models have been proposed in literature. The models here cited are used in TOUGH2. The diagrams about the models are shown in Fig. 47. The data for the diagrams are taken from the Petrasim guide and ThunderHead Engineering website\(^2\) [130]. The models shown are: the linear model [129, 130], the perfectly mobile gas model (Pickns, 1979) [131, 130], the Corey model (Corey, 1954) [132, 129, 130], the Grant model (Grant, 1977) [133, 130], the van Genuchten-Mualem Model (1976,1980) [134, 129], the Verma model\(^3\) (1985). In Fig. 46 the capillary pressure models adopted in TOUGH2 are shown, from [129, 130, 131, 135, 134].

![Capillary Pressure Models](image_url)

**Figure 46.:** Capillary pressure models.

---


Relative Permeability
Liquid Saturation
Linear Model
k Rel Liquid k Rel Gas

Gas Perfectly Mobile
k Rel Liquid k Rel Gas

Corey’s Curves
k Rel Liquid k Rel Gas

Grant’s Curves
k Rel Liquid k Rel Gas

van Genuchten-Mualem Model
k Rel Liquid k Rel Gas

Verma model (1985), from [129, 130]

Figure 47.: Relative permeability models.
3.2.1.3 Boundary conditions - Flow

Appropriate Boundary Conditions (BC) have to be assigned to the set of equation
described. Both for the hydrological problem and for the heat transfer. The BC kind
are similar when considering flow or heat transport (see section 3.2.1.5). Mainly four
types of BC are used:

1. First kind or Dirichlet condition - along a border or a boundary the hydraulic
   head (see Eq. 62) is assigned
2. Second kind or Neumann condition - along a border or a boundary the fluid flux
   is assigned
3. Third kind or Cauchy condition - transfer coefficients are used particularly for the
   hydraulic head
4. Fourth kind condition - single well or singular point source, typically used for
   wells conditions (extraction or reinjection, according to the sign convention),
   implementing Dirac δ function.

3.2.1.4 Heat transport - conduction

In particularly dry reservoirs, conduction is the prevalent mechanism of heat trans-
fer. In hydrothermal aquifers and traditional geothermal systems also convection
and advective flow contribute to the mass/heat transport phenomena. In this sec-
tion conductive heat flux \( \vec{q} \) is briefly described, to introduce the typical boundary
conditions considered in the numerical simulations.

From the Fourier’s postulate one can write that

\[
\vec{q} = -\lambda \nabla T
\]

being \( \lambda \) the heat conductivity of the rock formation. Typical values of \( \lambda \) of rock
formations are listed in [136] or in other similar manuals. An important reference
dealing with properties of reservoirs is the survey by Björnsson and Bodvarsson
(1990) [137]. Also in the softwares thermophysical parameters database are available.
Anyway, as stated in this work, a characterization of the parameters should by site-
dependent in order to obtain reliable and physically consistent results.

Substituting the Fourier’s postulate into the local equilibrium equation heat con-
duction equation is

\[
\rho c \frac{\partial T}{\partial t} - \nabla \cdot (\lambda \nabla T) = \varphi
\]

(being \( \varphi \) the heat production term and \( \rho c \) the specific heat capacity) which is a par-
tial derivative equation in \( T(x_i, t) \). If the following two assumptions are considered:

- \( \rho c \) and \( \lambda \) do not change with temperature
- the solid matrix is homogeneous

then Eq. 78 can be modified into the Equation of Fourier

\[
\nabla^2 T - \frac{1}{\alpha} \frac{\partial T}{\partial t} = \frac{\varphi(x_i, t)}{\lambda}
\]
where $\alpha$ is the thermal diffusivity defined as

$$\alpha = \frac{\lambda}{\rho c} \quad (80)$$

### 3.2.1.5 Thermal boundary conditions

The BC for the heat transfer to be applied to the numerical models of geothermal reservoirs are here described

1. **First kind** - Temperature distribution assigned
   
   $$T_i = T_i(\vec{r}_i, t) \quad (81)$$

2. **Second kind** - Heat flux distribution assigned
   
   $$\frac{dT}{dx} = q_i(\vec{r}_i, t) \quad (82)$$

3. **Third kind** - Convective boundary condition, the temperature $T_f$ of the fluid on the boundary is assigned together with the convective heat transfer coefficient $h_f$
   
   $$- \lambda \left( \frac{dT}{dx} \right)_{\vec{r}_i} = h_f(T - T_f) \quad (83)$$

4. **Fourth kind** - For bodies in thermal contact surface heat exchange have to be equal at the contact points (in case of perfect thermal contact also surface temperature have to be equal). 4th kind BC are also thermal “wells” conditions.

### 3.2.1.6 Initial conditions and constraints

Initial conditions represent the status of a system for which a transitory simulation has to be run.

Considering a certain domain $\Omega$ in a three-dimensional space, it is $\Gamma$ its border (or frontier). $\Gamma$ is made by disjointed portions $\Gamma_i$ adequately subdivided depending on the type of condition to be assigned [138, 139, 140]. Initial conditions can be prescribed to $\Omega$ about flow rate, heat flux and concentration of pollutants.

**Fluid mass flow rate (hydraulic head)**

$$h(x_i, 0) = h_I(x_i) \quad (84)$$

**Temperature initial condition**

$$T(x_i, 0) = T_I(x_i) \quad (85)$$

In the last two equations $h_I$ and $T_I$ are initial distributions (space dependent functions) respectively of the hydraulic head and temperature. The initial condition about the hydraulic head can be also replaced by a condition of pressure.

Also constraints to some of the main variables can be put, in order to keep the results in a known range of realistic values, forcing the calculations.
Figure 48.: Example of boundary conditions (both thermal and mass conditions) in a 3D numerical model grid of a geothermal reservoir: a) 1st kind conditions - thermal; b) 2nd kind conditions - flow.

3.2.2 Boundary and initial conditions assignment and model features

The structural-physical model has to be set with the boundary and initial conditions, and also with constraints that can be useful for the stability of the results. The user can define the maximum simulation time and the time-step extent.

The thermal boundary conditions can usually represent:

- heat flow from the bottom
- fixed temperature at bottom/top or intermediate layers
- adiabatic conditions

Concerning the conservation of mass flow rate, the boundary conditions are used to reproduce:

- natural manifestations
- natural recharge
- lateral or regional flows
- wells withdrawal/reinjection in the aquifers
• hydraulic head

Wells withdrawal/reinjection rates and the values of temperatures and enthalpy associated are important conditions for the reliability of the simulation of an exploitation scenario.

The initial conditions are usually

• the thermal gradient
• the pressure distribution
• hydraulic head levels (of rivers or aquifers)

The initial temperature distribution (in °C) can be given by a linear gradient of the type

$$T_{(t=0)} = a - b \cdot z$$

where \( z \) is the depth with respect to the ground level, \( a \) and \( b \) are appropriate parameters calculated according to the particular geothermal field and to the known thermal gradient (being \( a \) the ground temperature, usually 15 °C).

The initial pressure gradient can be expressed (in Pa) by

$$p_{(t=0)} = c - d \cdot z$$

where \( c \) is usually the atmospheric pressure (101325 Pa) and \( d \) is calculated according to the hydrostatic maximum pressure level in the domain (or differently, depending on the type of aquifer).

To hold the results range near a specific expected value, some constraints about max/min fluid rate, pressure or heat flow can be set.

Fig. 48 a collection of possible boundary conditions is given.

3.2.3 Numerical discretization of the transport equations

The integration of all the interdisciplinary inputs and procedures is the most challenging and crucial part of a modelling process. An important issue of this process deals with the quality of informations and data flowing through the starting phase, the development of the model and the simulation itself. This has to be treated and used as an iterative process, continuously changing and improving, as the information flow goes both ways [126]. A good and reliable model is often object of discussion and reinterpretation.

The numerical model must be reliable in order to be used as a prediction of the real reservoir. For example the results of pressure tests and interference tests can be previously simulated in order to understand the appropriate permeability and porosity values for different parts of the reservoir (rock formations, fractures).

After a brief description of the physical equations background, in this section an example of discretization technique is given. A finite difference method is described in a general way. Numerical techniques strongly depend on the type of software used. In the following section (3.2.4, p. 91) two of the most used softwares and codes are described. They use different discretization techniques: TOUGH2 is a finite difference code, while in Feflow the finite element method is used.
The method here reported is implemented in many codes and is based on the integrated finite difference technique developed at Lawrence Berkeley Laboratory, it is similar to the TOUGH2 approach. It is described by Antics (2001) [126], also in Ungemach and Antics (2008) [127]. This approach is considered to be suitable in case of low temperature geothermal systems simulation [126]. A finite difference method is also described in Watson, 1987 [128].

Let us consider a reservoir domain portion divided into two blocks (volumes or elements) “i” and “j”, being respectively $V_i$ and $V_j$ their volumes, as shown in Fig. 49. The i-th block is connected to the j-th block by the area $a_{ij}$ (Fig. 49). Quadrangular or triangular shaped grids are the most used, but also polar coordinate grid systems can be considered for special applications.

![Figure 49: Spatial discretization (blocks or volumes), after [126] and [127].](image)

In the following $p_i^n$ and $T_i^n$ represent respectively the pressure and the temperature in the i-th block at the end of the n-th time step. The n-th time step lasts $\Delta t_n$. Pressure, temperature and production rate are calculated at the center of the block (block-centred), while fluxes are calculated at block interfaces.

The two main assumptions at the base of this method are:

a) the difference equations of mass and energy balance evaluated at the new time step $n+1$ are fully implicit,

b) interface quantities and exchanges are calculated with Upstream weighting.

The discretized balance equations are described in the following form

**Mass balance**

$$V_i(A_{mi}^{n+1} - A_{mi}^n) = \sum_j a_{ij} Q_{mi}^{n+1} \Delta t_{n+1} + q_{mi}^{n+1} \Delta t_{n+1}$$

(88)
Energy balance

\[ V_i (A_i^{n+1} - A_i^n) = \sum_j a_{ij} Q_{eij}^{n+1} \Delta t_{n+1} + q_{ei}^{n+1} \Delta t_{n+1} \]  \hspace{1cm} (89)

Darcy law

\[ Q_{mij}^{n+1} = - \left( \frac{kk_{rl}}{\nu_l} \right)_{ij}^{n+1} \left[ \frac{(p_j - p_i)^{n+1}}{d_{ij}} - \rho_{iij}^{n+1} g_{ij} \right] \]  \hspace{1cm} (90)

\[ Q_{mvij}^{n+1} = - \left( \frac{kk_{rv}}{\nu_v} \right)_{ij}^{n+1} \left[ \frac{(p_j - p_i)^{n+1}}{d_{ij}} - \rho_{vij}^{n+1} g_{ij} \right] \]  \hspace{1cm} (91)

\( Q_{mij}^{n+1} \) is the mass flux from block \( i \) to block \( j \) calculated at the end of the \((n+1)\)-th time step. \( q_{mi}^{n+1} \) is the mass production (kg/s) occurring in the block \( i \) evaluated at the end of the \((n+1)\)-th time step (positive in case of injection). \( Q_{eij}^{n+1} \) and \( q_{ei}^{n+1} \) are referred to the energy transport and they have similar meaning as for the mass equation.

Darcy law gives the production rate as a function of the \( \Delta p \). The subscripts “\( l \)” and “\( v \)” refer to the liquid and vapour phases respectively.

The terms \( A_{mi}^{n+1} \) and \( A_{ei}^{n+1} \) are defined as follows:

\[ A_{mi}^{n+1} = \phi_i (S_l \rho_l + S_v \rho_v)_{i}^{n+1} \]  \hspace{1cm} (92)

\[ A_{ei}^{n+1} = (1 - \phi_i) \rho_l C_{rl} T_i^{n+1} + \phi_i (S_l \rho_l u_l + S_v \rho_v u_v)_{i}^{n+1} \]  \hspace{1cm} (93)

Variations of porosity with pressure and temperature could be included by adding the \( n+1 \) superscript to \( \phi_i \).

In Eq. 90 and Eq. 91 the term \( g_{ij} \) is the component of gravity acting through the interface. For example, \( g_{ij} = 0 \) in case of two blocks horizontally adjacent, and \( g_{ij} = g \) for two blocks with block \( i \) vertically above block \( j \).

The interface densities in the “weight” terms (Eq. 90 and Eq. 91) are evaluated by the following equations:

\[ \rho_{lij}^{n+1} = \frac{(\rho_{li} + \rho_{lj})^{n+1}}{2} \]  \hspace{1cm} (94)

\[ \rho_{vij}^{n+1} = \frac{(\rho_{vi} + \rho_{vj})^{n+1}}{2} \]  \hspace{1cm} (95)

d_{ij} is the distance between the adjacent block centers (see Fig. 49), being the sum of d_{i} and d_{j} from the centers of the i-th and j-th block center respectively from their connecting interface.

The interface permeabilities and hydraulic conductivities are calculated using harmonic weighting and usually they can be considered to be independent of pressure.
and temperature [126]. Under this assumption they can be evaluated only once at the beginning of the simulation:

\[
\frac{1}{k_{ij}} = \frac{d_i + d_j}{d_{ij}}
\]  

(96)

Let us now consider the aspect of upstream weighting of the mobilities and enthalpies for the interface calculations. For the mobilities of the liquid phase it is:

\[
\left(\frac{k}{\nu_l}\right)_{ij}^{n+1} = \begin{cases} 
\left(\frac{k}{\nu_l}\right)_{i}^{n+1} & \text{for } G_{l}^{n+1} < 0 \\
\left(\frac{k}{\nu_l}\right)_{j}^{n+1} & \text{for } G_{l}^{n+1} > 0
\end{cases}
\]

(97)

where the term \(G_{l}^{n+1}\) is given by

\[
G_{l}^{n+1} = \frac{(p_j - p_i)^{n+1}}{d_{ij}} - \rho_{lij} g_{ij}
\]

(98)

For the mobilities of the vapour phase it is:

\[
\left(\frac{k}{\nu_v}\right)_{ij}^{n+1} = \begin{cases} 
\left(\frac{k}{\nu_v}\right)_{i}^{n+1} & \text{for } G_{v}^{n+1} < 0 \\
\left(\frac{k}{\nu_v}\right)_{j}^{n+1} & \text{for } G_{v}^{n+1} > 0
\end{cases}
\]

(99)

where the term \(G_{v}^{n+1}\) is given by

\[
G_{v}^{n+1} = \frac{(p_j - p_i)^{n+1}}{d_{ij}} - \rho_{vij} g_{ij}
\]

(100)

In a similar way for the evaluation of the enthalpies the following equations can be used

\[
(h_{l})_{ij}^{n+1} = \begin{cases} 
(h_{l})_{i}^{n+1} & \text{for } G_{l}^{n+1} < 0 \\
(h_{l})_{j}^{n+1} & \text{for } G_{l}^{n+1} > 0
\end{cases}
\]

(101)

\[
(h_{v})_{ij}^{n+1} = \begin{cases} 
(h_{v})_{i}^{n+1} & \text{for } G_{v}^{n+1} < 0 \\
(h_{v})_{j}^{n+1} & \text{for } G_{v}^{n+1} > 0
\end{cases}
\]

(102)

The total mass flow can then be calculated as

\[
Q_{mij}^{n+1} = (Q_{ml} + Q_{mv})_{ij}^{n+1}
\]

(103)
and the energy flow rate can be calculated as

\[ Q_{n+1}^{eij} = (h_1 Q_m + h_v Q_m)^{n+1} - K_{n+1}^{eij} \left( \frac{T_j - T_i}{d_{ij}} \right) \]  

(104)

In the Appendix A (section A.1, p. 211) the finite difference and finite volume approach used by the code TOUGH2 is described more in detail.

### 3.2.4 Softwares and codes used in geothermal reservoirs simulation

In literature there is a certain number of softwares (both commercial or not) dedicated to the study and simulation of geothermal reservoirs. Among the commercial softwares for the numerical simulation of geothermal reservoirs, the two following can be mentioned for diffusion:

- **TOUGH2** (Earth Sciences Division, Lawrence Berkeley National Laboratory University of California), for the purposes of this work it has been used through the graphic interface (commercial software) Petrasim (Rockware - Thunderhead Engineering)

- **Feflow**, DHI-WASY GmbH (DHI Group)

In this work these two softwares are described. Other softwares are used in literature and in industry, just to cite other examples: SHEMAT and ECLIPSE (Schlumberger). Many other softwares have been developed and used by Research Institutes or Universities. Their number has grown in the last years. A complete state of the art is difficult to realize, but very significant works are present in literature, like the one by O’Sullivan et al. (2001) [14].

In this softwares a lot of the most known resolution algorithms (from numerical analysis and calculus) are implemented.

In TOUGH2 and Petrasim a finite difference approach to the resolution of the equation systems is adopted, while FEFLOW is a finite element code (the acronym means Finite Element subsurface FLOW system). Pre and post-processors are embedded in commercial softwares, so that graphical interface and elaboration of the data can be easily carried out. These softwares allow to consider also the transport equations of chemicals and solid dissolved. When the coupling of the phenomena is simulated they can give a very useful contribution for the scaling phenomena limitation (concentration, inflow-outflow, and variation during withdrawal-reinjection must be known).

An higher accuracy level has to be achieved when a 3D model is elaborated, than in 2D simulations. The mesh refinement is a fundamental instrument that can be adopted to improve the analysis and optimize the computational tasks (concentrating for example the mesh number in the wells area or along the faults). Different techniques can be adopted for the modeling of the faults, but once more the data input accuracy (upflow/downflow, fluid rate, permeability, thermal anomaly) has to be very high to achieve reliable results.

Some of the most famous geothermal fields which have had a big industrial exploitation history have then been simulated and a lot of models are now available. In chapter 4 a review of some of this models is available.
For example the case of the Wairakei field is useful to give an idea of the possible evolution in modeling the history and evolution of a field [141, 142], see section 4.1.4. All the most used softwares are multipurpose, involving the possibility of simulating different types of diffusion phenomena. Their applications are usually:

- Geothermal reservoir engineering
- Nuclear waste disposal
- Contaminant transport
- Remediation
- Environmental assessment
- Saturated and unsaturated zone hydrology
- Mine dewatering studies
- Saltwater intrusion
- Groundwater age calculations
- Groundwater management and allocation (particularly Feflow)

In the Appendix A (p. 211) a detailed description of the physical-mathematical schemes and numerical resolution techniques is given, both for the TOUGH2 and for Feflow, as they use different numerical techniques.

3.2.5 TOUGH2 - Petrasim

TOUGH2 is an acronym for Transport Of Unsaturated Groundwater and Heat. The second version (2.0) has been used in this work [143], through the software Petrasim (as a graphical interface). It has been used in this research work for the simulation of different gothermal reservoirs through the software Petrasim[4] [129].

A synthetic description of this code and its purposes is given in the User’s Guide by Pruess et al. (1999)[5]: «TOUGH2 is a numerical simulator for nonisothermal flows of multicomponent, multiphase fluids in one, two, and three-dimensional porous and fractured media. [143]».

TOUGH2 is a multi-dimensional numerical model for simulating the coupled transport of water, vapor, non-condensible gas, and heat in porous and fractured media. It offers added capabilities and user features, allowing to use different fluid mixtures. Petrasim and the TOUGH2 “family” softwares implement different equations of state, also for water-steam, gas, salt systems. In Table 9 the Modules (and their properties and capabilities) of the Equation Of State (EOS) of TOUGH2 are listed. Petrasim also has tools for generating and managing mesh.

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4 For the utilization of this software prof. Alessandro Sbrana of the Department of Earth Science (DST - Dipartimento di Scienze della Terra) of the University of Pisa has to be acknowledged.

5 For more informations about the TOUGH2 “family” softwares:
   http://esd.lbl.gov/research/projects/tough/
Table 9.: TOUGH2 fluid property modules (EOS), from Pruess et al. [143].

<table>
<thead>
<tr>
<th>Module</th>
<th>Capabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>EOS1*</td>
<td>water, water with tracer</td>
</tr>
<tr>
<td>EOS2</td>
<td>water, CO2</td>
</tr>
<tr>
<td>EOS3*</td>
<td>water, air</td>
</tr>
<tr>
<td>EOS4</td>
<td>water, air, with vapor pressure lowering</td>
</tr>
<tr>
<td>EOS5*</td>
<td>water, hydrogen</td>
</tr>
<tr>
<td>EOS7*</td>
<td>water, brine, air</td>
</tr>
<tr>
<td>EOS7R*</td>
<td>water, brine, air, parent-daughter radionuclides</td>
</tr>
<tr>
<td>EOS8*</td>
<td>water, “dead” oil, non-condensible gas</td>
</tr>
<tr>
<td>EOS9</td>
<td>variably-saturated isothermal flow according to Richards’ equation</td>
</tr>
<tr>
<td>EWASG*</td>
<td>water, salt (NaCl), non-condensible gas (includes precipitation and dissolution, with porosity and permeability change; optional treatment of vapour pressure lowering effects)</td>
</tr>
</tbody>
</table>

* optional constant-temperature capability

TOUGH2 uses an integral finite difference method for space discretization, and first-order fully implicit time differencing. A choice of a sparse direct solver or various preconditioned conjugate gradient algorithms are available for linear equation solution. The program provides options for specifying injection or withdrawal of heat and fluids.

Although primarily designed for geothermal reservoir studies and high-level nuclear waste isolation, TOUGH2 can be applied to a wider range of problems in heat and moisture transfer, and in the drying of porous materials. The TOUGH2 simulator was developed for problems involving strongly heat-driven flow. To describe these phenomena a multi-phase approach to fluid and heat flow is used, which fully accounts for the movement of gaseous and liquid phases, their transport of latent and sensible heat, and phase transitions between liquid and vapor. TOUGH2 takes account of fluid flow in both liquid and gaseous phases occurring under pressure, viscous, and gravity forces according to Darcy’s Law.

Interference between the phases is represented by means of relative permeability functions. Heat transport occurs by means of conduction (with thermal conductivity dependent on water saturation), convection, and binary diffusion, which includes both sensible and latent heat. Also relative permeability and capillary pressure models are implemented, see section 3.2.1 and Figs. 46–47.

Petrasim is a graphical interface for the TOUGH2 family software developed by ThunderHead Engineering [129]. It helps users to rapidly develop models and view results.

3.2.6 Feflow

The acronym Feflow means Finite Element subsurface FLOW system. According to the commercial description from the website6: it «is a professional software

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6 For more informations about Feflow: [http://www.feflow.info/](http://www.feflow.info/).
package for modeling fluid flow and transport of dissolved constituents and/or heat transport processes in the subsurface\(^7\).

It is a complete software, provided with pre- and post-processing tools, with a lot of options for managing graphics and geological database implementation\(^8\). In Feflow both graphical interface and calculation engine are provided. Also user codes can be used through a public interface.

FEFLOW is developed by DHI-WASY GmbH, the German branch of the DHI group (Danish Hydraulic Institute)\(^9\). The set of codes proposed by DHI are a complete group of models for water cycle and water resources management. Hydrological models are the base of these codes. Hydrological balances, rivers and water bodies, groundwater resources and sea and marine environment (waves and coastal erosion) can be simulated. Also urban water distribution and management, and solid transport can be implemented in modular codes that can be coupled to Feflow.

One of the main differences respect to TOUGH2 (apart from the numerical methods) is the necessity of assigning (at least) an hydraulic head Boundary Condition. At least a value of the hydraulic head in the domain is needed, otherwise the model cannot be run. This clearly derives from the hydrological basis of the DHI softwares.

Feflow is not an “open” source software, although user plug-ins for the Feflow programming interface IFM can be used to extend FEFLOW’s functionality (to replace internal functionality, to couple other simulation or database software and to automate workflows). For example two interesting plug-ins\(^{10}\) allow to simulate GHP, GWHP and ATES systems (see chapter 2, section 2.2). Direct uses of geothermal heat can be then simulated in this multipurpose software. Hydrologic balance impact of “open loop” systems can be simulated coupling the utilization to the hydraulic head distribution from the simulation.

Feflow appears to be more suitable to reproduce orography and complex grids (refinement and de-refinement tools) than Petrasim. Both quadrangular and triangular elements can be used (their regularity can be always checked and a tool for cells “smoothing” can be used).

\(^7\) [http://www.feflow.info/aboutfeflow.html](http://www.feflow.info/aboutfeflow.html).

\(^8\) For the utilization of this software prof. Alessandro Sbrana of the Department of Earth Science (DST - Dipartimento di Scienze della Terra) of the University of Pisa has to be acknowledged.


\(^{10}\) BHELoop, OpenLoop, and OpenLoopQt, see [http://www.feflow.info/existing_ifm_modules.html](http://www.feflow.info/existing_ifm_modules.html).
4

NUMERICAL MODELS: REVIEW AND APPLICATIONS

4.1 A “BRIEF” REVIEW

In this part of the work some examples of numerical simulations of geothermal reservoirs are analysed and critically reviewed. As it can be observed, each simulation has its own peculiarity, concerning with dimensional scale, enthalpy of the geofluid, extraction/reinjection rate, software used and model arrangement.

The great part of the case studies reviewed are not directly correlated with the development of a binary plant but their are considered to be interesting for the methodological perspective. An attempt of summary of the meaningful data and outlines is made. In Table 11 (p. 107) a summary of the models reviewed is presented.

4.1.1 Momotombo reservoir (Nicaragua)

The first case analysed is the geothermal field of Momotombo in Nicaragua for which a meaningful set of data is available from literature. This case study has been chosen to remark how important is the characterization and the assessment of the geothermal potential to undertake a correct industrial exploitation of a reservoir. This analysis is based on the literature data available, mainly from Porras et al. [144, 145, 146]. The geographical position of the field is shown in Fig. 50. In Fig. 51 temperature profiles near some production wells are shown on a vertical cross section of the reservoir.

This model has been reproduced, analysed and discussed also in this work. The simulation results are presented in section 4.2.1, p. 108. It is also analysed under the thermoeconomic approach proposed in the chapter 5 (see section 5.3, p. 168). It is a case study that has been reproduced to understand the history of the whole “Reservoir-Plant” system. The aim of the simulation is to study different production scenarios. First of all an unperturbed state simulation has been carried out in order to define the steady state of the geothermal reservoir without fluid extraction. Secondly different production scenarios (production and reinjection rate and position of reinjection wells) can be simulated in order to prevent possible temperature, pressure and storage reduction in the reservoir and avoid short-circuiting effect from reinjection to production wells.

4.1.1.1 History of the field utilization

The problem of the correct definition of the reservoir potential is well evidenced in the history of the Momotombo power plants, in a recent paper by Porras and Björnsson [144]. The utilization of the Momotombo geothermal area in Nicaragua
Figure 50: Map of the volcanoes of the Cordillera de los Marrabios (Momotombo volcano and geothermal field location are evidenced), Nicaragua (the capital Managua is also shown), from Porras and Bjornsson, 2007 [146].

is a well-known example of excessive production (extraction rate). This geothermal field has been developed for more than twenty years since 1983 when the first unit of 35 MW was commissioned. A second unit (same power size) was installed in 1989 by increasing steam production rate. During this period the production wells showed marked changes in flow rates, fluid chemistry and specific enthalpies of geothermal fluids, see Fig. 52 and Fig. 53. These changes were mainly attributed to reservoir pressure decline because of excessive fluid production. The overestimation of the geothermal potential brought to a gradual and progressive impoverishment of the resource in terms of temperatures, pressures and wells productivity.

Since the first years of industrial interest (1983-1989) the production decreased and different problems came out (see Fig. 52).

Figure 51: Momotombo geothermal field: temperature profiles on a WE cross section, from Porras and Bjornsson (2010) [144].
Figure 52.: History of productivity at Momotombo: total electrical output (after Porras and Bjornsson, 2010 [144]); legend: a) scaling phenomena occurred, b) minimum production: 9 MW, c) production attested on 35 MW.

Figure 53.: History of productivity at Momotombo: mean electrical output per well, from Porras and Bjornsson (2010) [144].

4.1.1.2 Boundary conditions and production scenarios

A three-dimensional model of the system was developed and calibrated and it was utilized to study the response of the geothermal reservoir under different scenarios. The initial common hypotheses for the entire exploitation scenarios considered are:

- 100 % reinjection of the fluid extracted
- Reinjection conditions: 100 °C and 5 bar
- Time-constant fluid rates
A meaningful set of data is available from literature about this model. Four different scenarios of field exploitation are proposed in the literature by Porras et al. [144, 145]:

**Scenario I** represents the situation in 2004 (see Fig. 52): the total power size of the plants is 32 MW, 10 active production wells and 4 active reinjection wells.

**Scenario II** 3 more producing wells, changing in the distribution of fluid rate in the reinjection wells.

**Scenario III** 1 reinjection well is not considered, 3 more reinjection wells are added.

**Scenario IV** same reinjection scheme of the previous scenario, increase of production due to 2 new withdrawal wells.

In [144, 145, 146] the authors state that in the model a satisfactory agreement was obtained between measured and computed discharge enthalpies and flow rates for most of the shallow wells. The model also qualitatively reproduce the pressure drawdowns measured in selected wells.

4.1.2 Ngatamariki geothermal field (New Zealand)

The Ngatamariki geothermal field is located 17 km from Taupo (North Island, New Zealand). It is one of the many high enthalpy geothermal systems within the Taupo Volcanic Zone (they are more than 20). Exploration wells were first drilled in 1985-1986, and Mighty River Power then drilled further wells in 2008-09. The company has planned the installation of overall 130 MW electric power output, from a condensing unit and an ORC unit integrated in a combined cycle configuration (to be first run in 2013).

The data available about this geothermal field can be find in a group of industrial reports by Burnell and Kissling (2009), in particular the one about the reservoir model [149]. In this example, a very complete conceptual model can be found. The geothermal reservoir is composed by 3 parts:

- a shallow aquifer (50 - 100 m deep);
- an aquitard in the rock formation of Huka Falls (50 — 400 m deep), between the surface aquifer and the intermediate one;
- intermediate aquifer, between Huka Falls rock formation and the clay cap.

The grid has globally 26 horizontal layers (of different thickness), subdivided in 928 elements, reaching a total number of 24128 blocks. The surface extension of the model is 132 km². In Fig. 55 the geologic features and the model grid are shown. Thermal inversions can be identified at the wells to the North and near the centre of the field, while the thermal anomaly increase with depth at the centre. Also an “upflow” zone can be found from the shallow aquifer to the intermediate, through the Huka Falls formation. The surface area considered has an extension of 115,5 km². An inlet of fluid flow (70 kg/s) is considered, entering from the bottom of the model, at a specific enthalpy of 1450 kJ/kg, with an heat flow of 101,5 MW. From the basement a constant heat flow of 11 MW is considered. A first value for
the natural recharge of water is 350 kg/s. Appropriate values of fluid output are used to represent the natural surface springs.

As constraints, areas with known flow direction and impermeable formations are simulated using fixed state (T, p) conditions. The simulation considered has been performed by the authors [149] with the TOUGH2 simulator.

![Diagram](image)

**Figure 54.** Workflow for the elaboration of the model as identified in [149] (Ngatamariki geothermal field).

![Conceptual model](image)

![Grid map](image)

**Figure 55.** Features of the numerical model of Ngatamariki geothermal field [149].

The validation of the model is based on temperatures and pressure data measured in different wells and on the calibration of other parameters like porosities, permeabilities, upflow mass and enthalpy, hydraulic connections between the deep reservoir and the groundwater system. The calibration of the parameters is a fundamental step to improve the matching of the results with the dataset available and to characterize the geothermal resource. In [149] a scheme of the procedure for the calibration is provided, it is here represented in Fig. 54.
The model matched quite good with data, in particular in terms of pressures and fluid rate of the natural manifestations and springs. In [149] the unperturbed state simulations and also two scenarios of exploitation (ORC power plant and fluid separation plant) are presented.

4.1.3 Larderello geothermal field (Italy)

4.1.3.1 2010 model by ENEL [150, 151, 152]

Larderello field (Italy) is one of the most anciently known and studied geothermal areas of the world. This field has been widely drilled and developed, with an almost hundred-year-old history in geothermal energy utilization for power purposes.

Average fluid production in the Larderello field, after the most recent explorations and improvements is now about 3700 t/h. The exploration extended in the early 1950s to the near Travale field (10–15 km SE of Larderello), which has now increased its fluid production to an average value of 1000 t/h. For this reason, when talking about large scale model of this geothermal system, usually one can talk about Larderello-Travale geothermal field.

A numerical model about the field has been recently realized and improved, increasing the dimensions of the geological domain considered, by Romagnoli et al. 2010 [150], Barelli et al. 2010 [151], Arias et al. 2010 [152].

The model domain extent is $4900 \text{ km}^2$ (70 km each side), with a total thickness of 7.5 km (see Fig. 56). The grid is made of 10000 cells and 16 vertical layers. The geological scheme refers to five main rock formations:

- clayey-shaley caprock (0 – 500 m)
- fractured carbonate reservoir (500 – 1000 m)
- metamorphic reservoir (1000 – 5000 m)
- granitic intrusion as heat source of the system

Sixteen rock materials are considered. An impermeability condition along the boundaries is assigned. Fixed state (time invariant) conditions of temperature are considered at the top ($15 \degree \text{C}$, atmospheric pressure) and at the bottom of the producing layer ($350 – 400 \degree \text{C}$). Natural manifestations and cold inflow from the shallow aquifers are the only interactions with the external environment.

The simulation of natural state has been carried out (millions of years as temporal scale) and then also a simulation of the exploitation history of the field has been modelled. The historical data of 700 wells have been represented with 20 “virtual” wells. The conclusion of Romagnoli et al. [150] are that only few changes in the conditions of the natural system have been caused by industrial development of the area.

4.1.3.2 2008 model by Della Vedova et al. [153]

A different model of this field has been proposed by Della Vedova et al. (2008) [153]. This model deals only with the natural state of the geothermal system, without
considering the industrial exploitation. A very large temporal scale is considered (8–12 millions of years). The dimensions of the considered domain are $42 \times 26$ km$^2$, with a total thickness of 10 km. The total depth of the model is very high, to include the K-horizons and the data from fluid inclusions. K-horizons are considered to be the main reservoir bottom, corresponding to the 400 °C isotherm; collocated between 3000 m in the Larderello zone and 10000 m in the Travale zone. For this model the numerical simulator SHEMAT has been tested and validated with the geophysical data available for the upper crust.

The mesh cell size is $1 \times 1 \times 0.3$ km. The upper surface boundary conditions are 20 °C and 0.1 MPa, impermeable and adiabatic conditions are assigned at the lateral boundaries. The bottom boundary is assumed to be impermeable and at a fixed temperature of 400 ÷ 600 °C. Also a sensitivity analysis about thermal parameters is considered in [153]. The authors remark that a lot of simulation have been run to match a composite target function, due to the uncertainty about several input data (geometry, rock data).

The work considered is an example of deep field simulation, oriented to the comprehension of the deep field phenomena more then to a sustainable exploitation approach.

### 4.1.4 Wairakei geothermal field (New Zealand)

Wairakei is another well-known geothermal field located in the Taupo Volcanic zone (New Zealand). The extent of the area is almost 25 km$^2$.

A complete report about the industrial history and the evolution of the numerical models can be found in O’Sullivan et al. (2009) [142] and Bixley et al. (2009) [154]. Fifty years of activity on this field have been reached in 2008.
In the period 1958-1990 the power installed was increased up to 140 MW. After 1990 the power installed has approached 200 MW (with the plant of Poihipi, 55 MW). The specific enthalpy of the geofluid trend in the field fits the evolution during the years [154]:

- rise of pressure due to reinjection activity
- increase of temperature in the wells in the “Eastern Borefield”
- seepage of cold water in the reservoir

Several models have been proposed and tested for Wairakei reservoir [142]. The common aspects and main characteristics of the conceptual schemes are:

- big fractures and faults (NE-SW), increasing permeability
- two big upflow areas (260 °C at Wairakei, 300 °C at Tauhara)
- heat flux fixed values as BC, in the range 300 ÷ 600 MWth
- two regions at different pressures (high pressure at Te Mihi, low pressure at Southern Wairakei)
- natural recharge and rainwater infiltrations (1000 mm/year, 5 % infiltration)

Discussion about the calibration of the model is reported also in Mannington et al. (2000 and 2004) [155, 141].

The code iTOUGH2 [156], a TOUGH2 family software for inverse simulation, has been used to support the calibration process of the parameters and improve the match to the field data. Good matching results have been reached when Tauhara field (strictly connected with Wairakei) has been introduced in the domain of the model. In Table 10 a summary of the developed models is shown, from O’Sullivan et al. (2009) [142].

Table 10.: Evolution of the models of Wairakei geothermal field, from O’Sullivan et al. (2009) [142].

<table>
<thead>
<tr>
<th>Year</th>
<th>Blocks</th>
<th>Columns</th>
<th>Layers</th>
<th>Fluid type</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>1345</td>
<td>112</td>
<td>12</td>
<td>Water/steam</td>
<td></td>
</tr>
<tr>
<td>1996</td>
<td>1417</td>
<td>118</td>
<td>12</td>
<td>Water/steam</td>
<td></td>
</tr>
<tr>
<td>1997</td>
<td>1509</td>
<td>118</td>
<td>14</td>
<td>Water/steam/air</td>
<td></td>
</tr>
<tr>
<td>1998</td>
<td>1515</td>
<td>118</td>
<td>16</td>
<td>Water/steam/air</td>
<td></td>
</tr>
<tr>
<td>1999</td>
<td>3982</td>
<td>173</td>
<td>25</td>
<td>Water/steam/air</td>
<td></td>
</tr>
<tr>
<td>2000–2002</td>
<td>5418</td>
<td>216</td>
<td>32</td>
<td>Water/steam/air</td>
<td>[159]</td>
</tr>
<tr>
<td>2002–2004</td>
<td>6307</td>
<td>252</td>
<td>32</td>
<td>Water/steam/air</td>
<td>[142]</td>
</tr>
<tr>
<td>2004–2006</td>
<td>8055</td>
<td>312</td>
<td>32</td>
<td>Water/steam/air</td>
<td>[142]</td>
</tr>
<tr>
<td>2008</td>
<td>8679</td>
<td>312</td>
<td>32</td>
<td>Water/steam/air</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>27886</td>
<td>996</td>
<td>34</td>
<td>Water/steam/air</td>
<td></td>
</tr>
</tbody>
</table>
The 2006 model has been realized to enhance the knowledge about the Poihipi Road area, in which a new power station has been installed. The last model of Wairakei-Tauhara geothermal field is made by 8055 blocks. The perspective is to improve a 27886-blocks model (comprehending Wairakei – Tauhara – Rotokawa).

The models have been used to simulate different scenarios of field development. The more interesting are: scenario “A” with low infield reinjection and scenario “B” with almost total infield reinjection (with an increase of internal pressure, but with a reservoir temperature drop due to high infiltrations, 270 °C – 200 °C in the Te Mihi area).

4.1.5 Groß Schönebeck reservoir (Germany)

A case study about a simulation of an Enhanced Geothermal System (EGS) in a deep geothermal reservoir with hydraulic stimulation is discussed in Blöcher et al. (2010) [160]. The geothermal research site of Groß Schönebeck is located 40 km north of Berlin (Germany).

This case is presented as an example of well-based hydrothermal problem with a good match with the sustainable energy exploitation issue. A very good approach both to the numerical simulation and to the accuracy of the data is achieved.

The software used for the simulations is FEFLOW [138]. The simulation deals with a doublet of wells. The reservoir is located between -3815 to -4247 m below sea level, in the Lower Permian of the Northeast German Basin.

The hydraulic stimulation is a technology used to improve the productivity of a reservoir by inducing artificial fractures through high pressure fluid injection (water, gel-proppant). Six geological formations are considered, with different lithologies. Two sandstones formations (between -4000 and - 4100 m depth) are the most appropriate for geothermal power production. Natural fracture system is studied to analyse the conceptual scheme of circulation of the water, and to develop the induced fractures layout. The wells have a distance of 28 m at the surface, the injection well is vertical, while the production well is deviated to guarantee a sufficient distance of 500 m between them within the reservoir.

An interesting aspect remarked in [160] is the dependence of the hydraulic properties with temperature and pressure in the reservoir (density, permeability, porosity, thermal conductivity) to be considered as part of the model. Also the total dissolved solids and chemical composition are considered in the whole model.

The model has an extension of $4,809 \times 5,448$ km$^2$, with a depth of almost 0,6 km. The grid is made by 489591 prismatic elements and 254744 nodes, discretizing 27 spatial layers. The induced fractures are represented by 2D quadrilateral vertical elements.

The production well has a fluid rate of 75 m$^3$/h ($\approx$ 21 kg/s) at 150 °C with a concentration of solids of 265 g/l. The injection well has the same fluid rate and concentration of solids but the temperature is 70 °C. The quasi-stationary conditions are reached after almost $4 \times 10^4$ years of simulation time (hydraulic head levels are matched). A 30 years simulation of the exploitation with the above mentioned wells conditions gives a production temperature drop from 150 °C to 125,8 °C.
4.1.6 Mt. Amiata geothermal system (Italy)

In a recent paper of Barelli et al. (2010) the Tuscan geothermal system of Mount Amiata is considered [161]. The fields of Bagnore and Piancastagnaio have been explored and drilled (more than 100 wells) for about 50 years. In this field two main reservoirs are present:

- the first one is in the carbonatic formations, between 500 – 1000 m deep, at average temperature of 150 – 220 °C
- the second reservoir is in the Paleozoic metamorphic basement at depths of 2500 – 4000 m, at temperatures of 300 – 350 °C.

The Mt. Amiata Volcanic Complex has a total area of 80 km². The peculiarity of the model is not only to analyse the exploitation of the reservoir but also to verify the possibilities of interaction between a phreatic aquifer (separated from the shallow aquifer by few hundred meters of impermeable formations) and the geothermal system. Moreover another particular aspect is that the two main reservoirs are characterized by gaseous caps (gas, vapor), in structures named “traps”. This is a peculiarity of Mt. Amiata field, occurring in the definition of the pressure distribution and fluid circulation model.

The numerical model considered has been simulated with the software TOUGH2 [143]. The surface extension of the model is more than 1100 km², with a total thickness between -4 km and 1,738 km (a.s.l., Mt. Amiata top elevation). A time-constant heat flow (average 400 mW/m², with peaks of 600 – 700 mW/m²) is the bottom boundary condition. The model is globally closed, referring to inflow-outflow of water. As remarked in [161], the outputs match with the field data.

4.1.7 Dubti geothermal field (Tendaho Rift, Ethiopia)

The model of the Dubti geothermal field review is based on a paper by Battistelli et al. (2002) [162]. The Tendaho Rift was identified as a promising geothermal area since an exploration project of the late 1960s, and early 1970s. More recently (1990s) a drilling and wells-testing activity was carried out to explore and assess the geothermal resource present in the area (central part of Northern Tendaho Rift). The drilling in the area of Dubti plantation confirmed the existence of a shallow geothermal reservoir.

The temperature recorded in the drilled wells is in the interval 245 – 270 °C, while the temperature of the geofluid rising in a fault in the area is about 290 °C (natural manifestations and fumaroles are present in the whole area). Lots of production/injection tests have been carried out in the area, and the paper cited is very detailed about these data and permeability distribution [162].

The Dubti fault is considered to be ascending and upflow hypothesis is at the base of the conceptual model. Horizontal circulation (with eventually two-phase conditions), when crossing permeable layers, is also considered. For the numerical model the software TOUGH2 [143] has been used, implementing the EWASG equation-of-state module (see Table 9, p. 93) developed for water, sodium chloride and CO2 mixtures (Battistelli et al., 1997 [163]). The simple 3D model is extended about 7,5 km² with a total thickness of about 2 km.
Natural meteoric recharges are considered (coming from the Ethiopian Plateau) together with horizontal and sub-vertical flows. Natural outflow is represented by natural manifestations, fumaroles and steaming grounds. One important characteristic of this field is the near-surface boiling zone (at wells TD-2 and TD-4). The assumed initial temperature of the hot upflow is $290^\circ\text{C}$.

Model results and further drillings confirmed the presence of a hot fluid circulation zone at depths between 250 and 500 m in the Dubti area, confirming also the existence of more permeable zones along the Dubti fault. A possible development program is proposed in [162]: an extraction fluid rate of 140 kg/s from the shallow reservoir, for an expected power plant with maximum size 3 – 3,5 MW (back-pressure or ORC), serving the near region for about 50 years.

4.1.8 General remarks about the model reviewed

As shown from the previous review analysis, the numerical simulation of a geothermal reservoir is a well known field of research in the literature. In Table 11 a summary of the cases is reported. All the cases described are different for various reasons. First of all for the typology of geothermal field: from medium enthalpy water-dominant field to dry-steam dominant field.

The differences between the models deal with simulation domains (size and features), scenarios simulated (unperturbed or exploitation) and software used. The most remarkable differences surely concern the different domain size of the reservoirs that ranges from some km (2–3 km) to about 100 km.

One concept has to be emphasized from this review: the strong dependence of the results of the numerical analysis on the quality of the inputs and the difficulty that would be afforded in realizing the models (see also section 2.3.3 p. 52 and section 3.1.5 p. 78). First of all, the data and the geo-thermo-physical parameters necessary are not always available or measurable. Moreover the definition of boundary conditions and initial conditions is not a trivial task.

Initial conditions are usually:

- current thermal gradient measured
- groundwater recharge flow in the reservoir
- pressure distribution

The boundary conditions deal both with the hydro-geologic and the thermal problem, regarding essentially:

- hydraulic head
- temperature distribution at the top/bottom of the geometrical domain
- heat flow
- natural recharge of steam or water
- gases diluted in the geofluid
and all of these conditions can vary with time during the simulated interval.

The different techniques of numerical resolution of the equations in the model are not treated as a problem here. But it is clear that it is a common problem with all the fields in which numerical simulation is involved. Although the codes used for this purpose are evolving very quickly and the results can be very detailed and widely complete, these simulations presents a remarkable grade of uncertainty.

In the perspective of a more diffused industrial development of medium to low temperature geothermal fields, the numerical simulation can be a very useful instrument that must be connected with the strategies elaboration and the environmental and economic sustainability of the design of a geothermal plant.

Overall a relatively good agreement was obtained in the various cases between the measured and computed temperature profiles, more difficult appears to be the matching of pressure. Even if the definition of the model and of the boundary conditions requires particular attention and experience in order to avoid wrong results, numerical simulation could be a good strategy for an integrated design of geothermal plants and for the prediction of the geothermal reservoir response after a long time exploitation.
Table 11.: Summary about the numerical models reviewed and analysed in the section 4.1.

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Software</th>
<th>Domain size (n. blocks)</th>
<th>T&lt;sub&gt;geo&lt;/sub&gt;</th>
<th>m&lt;sub&gt;geo&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momotombo [144, 145, 146]</td>
<td>TOUGH2</td>
<td>3,1 × 2,4 km&lt;sup&gt;2&lt;/sup&gt;</td>
<td>240 °C — 340 °C</td>
<td>≈ 357 kg/s (32 MW) 13 production wells 8 reinjection wells</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 km depth (972 blocks)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ngatamariki [149]</td>
<td>TOUGH2</td>
<td>10,5 × 11 km&lt;sup&gt;2&lt;/sup&gt;</td>
<td>80 °C (scenario A)</td>
<td>≈ 695 kg/s (2 scenarios)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>≈ 5 km depth (24128 blocks)</td>
<td>120 °C (scenario B)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Larderello [150, 151, 152]</td>
<td>TOUGH2</td>
<td>70 × 70 km&lt;sup&gt;2&lt;/sup&gt;</td>
<td>200 °C — 300 °C</td>
<td>1300 kg/s (average historical data)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>≈ 7,5 km (total thickness)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(≈ 10000 blocks)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Larderello [153]</td>
<td>SHEMAT</td>
<td>42 × 26 km&lt;sup&gt;2&lt;/sup&gt;</td>
<td>200 °C — 300 °C</td>
<td>(only natural state simulation)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 km (total thickness)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wairakei [155, 141, 142, 154]</td>
<td>Non-commercial codes; TOUGH2</td>
<td>30 × 30 km&lt;sup&gt;2&lt;/sup&gt;</td>
<td>250 °C (Wairakei - Te Mihi)</td>
<td>≈ 1460 kg/s (historical average)  &gt; 200 wells (57 years) (power units: &gt; 200 MW)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3,4 km (total thickness)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8055 blocks (2006 model, [142])</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groß Schönebeck [160]</td>
<td>FEFLOW</td>
<td>≈ 4,8 × 5,5 km&lt;sup&gt;2&lt;/sup&gt;</td>
<td>150 °C (125 °C after 30 years simulation)</td>
<td>≈ 21 kg/s (doublet of wells from the same drilling area)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>≈ 0,6 km depth</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>489591 prismatic elements</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>254744 nodes</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mt. Amiata [161]</td>
<td>TOUGH2</td>
<td>1100 km&lt;sup&gt;2&lt;/sup&gt;</td>
<td>150 — 220 °C (1&lt;sup&gt;st&lt;/sup&gt; res.)</td>
<td>(natural state simulation, interaction between reservoirs)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 5,7 km (total thickness)</td>
<td>300 — 350 °C (deep res.)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dubti (Tendaho Rift) [162, 163]</td>
<td>TOUGH2, EWASG</td>
<td>≈ 2,5 × 3 km&lt;sup&gt;2&lt;/sup&gt;</td>
<td>245 — 290 °C</td>
<td>140 kg/s (future developm. [162])</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 2 km depth</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.2 NUMERICAL SIMULATIONS: CASE STUDIES

4.2.1 Momotombo Geothermal reservoir ("small model")

This case study is already presented in section 4.1.1, p. 95. As already stated, a meaningful set of data is available in literature by Porras et al. [144, 145, 146]. In this section a simulation of Momotombo case study is presented.

In this section a "small size" model is the object of the simulation, while the total domain described by Porras et al. [144, 145, 146] is taken into account and simulated in the section 4.2.2.

The aim of the simulation is to study an unperturbed state simulation and different production scenarios, in order to prevent resource or productivity decline.

The history of the field utilization is reported in the previous section 4.1.1 (p.95). In particular in Fig. 52 (p. 97) the history of productivity is given in a time diagram of the total electrical output [144]. In Fig. 53 the mean electrical output per well is reported.

![Image of the model with geometric features](image)

**Figure 57.** Geometric features of the model, in the right figure the model reveals the inside layers, with different materials. Block with different sizes are pointed.

According to the literature, the numerical model has been built and simulated with the software PetraSim\(^1\) (ThunderHead Engineering) [129], using TOUGH2 as internal simulator [143]. A. Orlandi strongly contributed to the realization of this model with his Bachelor Thesis [148] under my supervision.

Simulations of the natural steady-state (unperturbed) conditions of the field have been run and then different scenarios of exploitation are discussed. The results matched quite well with the previous literature simulation and two new scenarios have been introduced to comprehend some aspects of the industrial strategy of the early years of exploitation of the field (e.g. preferential paths for the reinjected fluid in the cool zone).

\(^1\) For the utilization of this software prof. Alessandro Sbrana of the Department of Earth Science (DST - Dipartimento di Scienze della Terra) of the University of Pisa has to be acknowledged.
4.2.1.1 Description of the model

The larger model extension is 13.8 km × 9.4 km, while the model here considered is only a portion (“small model”). Only the production/reinjection area of the model has been here modeled, its extension is 3.1 km × 2.4 km, with a vertical extension of about 4 km (in the range between 950 m and -3000 m a.s.l.). It is divided into in 9 layers.

The grid is built with 972 blocks (minimum dimensions 200 m x 200 m, maximum dimensions 600 m x 700 m). The total number of materials considered is 18. The most permeable layer has $k = 5 \cdot 10^{-11} \text{ m}^2$, the porosities vary between 0.06 % and 0.25 %, and it is situated in a depth interval between -150 m and -450 m. The spatial (blocks) distribution of the material properties (porosity, X-Y-Z permeability) in the model are shown in Fig. 60.

In the Appendix B (section B.1.1, p. 221) the thermophysical properties of the different materials and the grid details are shown.

Boundary conditions

Atmospheric conditions for T and p are assigned on the surface (15°C and 101325 Pa). Natural recharges of fluid have been taken into account (see Fig. 59):

- a source of hot fluid at the bottom layer of the domain, with a rate of 26.5 kg/s and a specific enthalpy of 1700 kJ/kg;
- a source spot of cold fluid (near to the surface) is considered with 18 kg/s rate and 63.1 kJ/kg specific enthalpy;
• also the surface natural manifestations have been considered, at a temperature of 185 °C.

*Initial conditions*

The initial temperature distribution (in °C) is the linear gradient

\[ T(t=0) = 15 - 0.112 \cdot z \]  

(105)

where \( z \) is the depth with respect to the ground level. In an analogous way the initial pressure gradient (in Pa) is given by

\[ p(t=0) = 1.013 \cdot 10^5 - 9967 \cdot z \]  

(106)

\[ \text{Cold fluid (recharge)} \]

\[ \text{Hot fluid} \]

\[ \text{Cold fluid (recharge)} \]

\[ \text{Hot fluid} \]

(a) Inflow and outflow BC

(b) Inflow and outflow BC, 3D view

*Figure 59.*: Wells layout and 2\textsuperscript{nd} kind BC on the model of Momotombo.

4.2.1.2 *Unperturbed state simulation*

The unperturbed state simulation matches quite good with the original works in literature (see Fig. 61 and Fig. 62). The simulation time for the stationary state simulation has been conventionally considered 10\textsuperscript{6} years. The pressures in the nearest surface levels increase in the South direction, while the pressures in the deepest levels increase in the North-West direction. A higher circulation can be observed in the portion of the domain characterized by the natural manifestations. In Fig. 63 the matching between the temperature profile at the natural state of the well named MT36 by Porras et al. [146] and the same result obtained for the present work is shown.
Six exploitation scenarios have been considered. The first four scenarios are taken from literature and they are described in the section 4.1.1. The simulation results match quite good the results from literature. Scenario I results, temperature isosurface and profiles, are shown in Fig. 64. In Fig. 64 (subfigure a and b) the T-isosurfaces change in 50 years of utilization are shown. In the production wells area (see Fig. 58) the advancing of the cold fluid front can be seen (from the left in Fig. 64). In the production area the isosurfaces become more concave after the utilization, increasing the volume occupied by the cold isosurface, coming from the reinjection area (on the right). In the cross sections of Fig. 64 (subfigures c and d) this temperature decline is remarked. In the pressure profile cross section (subfigure d) an increase of pressure can be seen in the reinjection area.

The reservoir cooling process and resource depletion can be referred also to preferential fluid circulation pathways. An hydraulic short-circuiting effect can be ob-
served in all the exploitation scenarios (see Fig. 67): the cold fluid reinjected goes with higher velocity to the production area, due to the presence of more permeable layers in the upper part of the reservoir together with an higher pressure gradient in the same formation.

Two other scenarios are proposed to simulate conditions of excessive exploitation of the geothermal reservoir. Two different time intervals have been considered: 15 and 50 years respectively. In particular:

**Scenario A** power plant size is two times than previous scenarios (64 MW, to approach the total 77 MW from historical data) corresponding to a higher value of the fluid rate extracted/reinjected, which is about 555 kg/s (a leveled flow rate of 55 kg/s per well is considered).

**Scenario B** the reinjection is concentrated equally in the wells located at the maximum possible distance from the production wells area (Fig. 58), to study the interference and to observe hydraulic short-circuiting.

In the Fig. 65 a comparison between the scenarios A and B is shown (it is compared with the unperturbed steady-state). The simulated temperature profiles of the production well MT4 after time simulation of 15 years and 50 years are compared with the unperturbed state. In the Fig. 66 and Fig. 67 the features of the model simulated after 15 years are shown. In Fig. 67 in the red circle a short-circuiting effect is shown, causing cold fluid to flow more rapidly to the production area, causing a $T_{geo}$ drop.

In Fig. 68 and Fig. 69 the flow rate increase (compared with Scenario I) and the reinjection data are shown (see section 4.1.1).
Figure 61.: Unperturbed state simulation (temperature and mass flow rate vectors).

Figure 62.: Different view of the unperturbed state simulation (temperature and mass flow rate vectors).
**Figure 63.** Temperature profile in the well MT36 (see Fig. 58): (a) matching of the literature data from [146], (b) temperature profile simulated by the author.

(a) Scenario I, initial conditions (unperturbed state)

(b) Scenario I, \( t = 50 \) years

(c) Scenario I, \( t = 50 \) years, \( T \) profile (slice plan, \( y = 2200 \) m)

(d) Scenario I, \( t = 50 \) years, pressure profile (slice plan, \( y = 2200 \) m)

**Figure 64.** Momotombo (small size model), Scenario I, temperature distribution.
Figure 65.: Scenarios A and B compared with the unperturbed steady-state situation: simulated temperature profiles at the well MT4 (production) after 15 years of exploitation (a) and 50 years of exploitation (b).

Figure 66.: Scenario A: exploitation after 15 years, mass flow rate 555 kg/s (production/reinjection).

Figure 67.: Scenario A: exploitation after 15 years, mass flow rate 555 kg/s (production/reinjection); in the red circle a higher velocity vector is shown, possible short-circuiting effect.
Figure 68: Mass flow rate increase in the Scenario A, production wells (compared with Scenario I).

Figure 69: Mass flow rate increase in the Scenario A, reinjection wells (compared with Scenario I).
4.2.2 Momotombo Geothermal reservoir ("large model")

The evolution and history of the Nicaraguan geothermal field of Momotombo can be used as an example to underline the fact that geothermal resources cannot be used as tanks or energy reservoirs to be exploited indefinitely. In this section the simulation of the model by Porras et al. (2005, 2007) [145, 146] is presented and discussed in its complete features, while in the previous section it has been simulated in a “small” scale (regarding only the production/reinjection wells area).

One point for the discussion deal with the possibility of forecasting and preventing resource depletion with these kind of models.

Also this model has been realized with the software Petrasim\textsuperscript{2}, [129]) (using EOS1, see Table 9, p. 93). M. Quaia strongly contributed to the realization of this model with his Master Thesis [164] under my supervision.

The model domain is shown in Fig. 70, while in Fig. 71 some details of the internal structure can be seen deactivating some frontal blocks. 20 different materials are used, according to the literature. In the Appendix B (section B.1.2) the thermophysical properties of the different materials are described (see Table 36, p. 225).

4.2.2.1 *Simulation of the unperturbed natural state*

The unperturbed state simulation matches quite good with the literature data. In Fig. 72 the hottest zone of the field can be seen (slice plans, temperature distribution). 2D vertical cross-sections are shown in Fig. 73 (crossing the production wells area) and in Fig. 74.

4.2.2.2 *Simulation of utilization scenarios*

The history of the development of the field has been considered. The report by Porras (1991) [147] is a complete survey about the field, wells development and connection with the power plants. For the following years, hypothesis of constant production for some of the wells have been done. The wells data used in the simulations are summarized in Table 12.

A single flash power plant (see Fig. 17) with the following characteristics is considered in the simulation:

- power output: 35 MW
- evaporation temperature: 175 °C
- inlet specific enthalpy: 1277 kJ/kg
- condensation temperature: 25 °C
- isoentropic turbine efficiency: 0.8

The simulation strategy adopted, in order to match the field utilization history, is to consider 200 kg/s for the first six years, then 400 kg/s for the next ten years. Also the reinjection rate (of extracted and separated fluid) has been chosen to match the field data (higher reinjection rate have been adopted after 2000).

\textsuperscript{2} For the utilization of this software prof. Alessandro Sbrana of the Department of Earth Science (DST - Dipartimento di Scienze della Terra) of the University of Pisa has to be acknowledged.
The time variation of the average value of the specific enthalpy of the geofluid is shown in the Fig. 75. Boiling conditions have been reached by the geofluid two times during the field history. The reservoir cooling from the 1993 can be seen in Fig. 75, leading to values of specific enthalpy of about 1150 kJ/kg in 1999. The first peak can be connected with the pressure decline due to the beginning of the exploitation, while the second can be connected to an excessive extraction rate. A huge productivity decline could then be measured, also considering temperatures, fluid rate, and pressures. The enthalpy at the year 1999 is about only 60 % respect to the first year after production beginning (1984). Fig. 75 can be compared with the
electricity production (power output) time variations shown in Fig. 52 and Fig. 52 (p. 97).

In Fig. 76 and Fig. 77 respectively temperature and pressure distributions at the end of the simulation time (t ≈ 16 years) are shown. The pressure decline in the Western production area lead to the cooling of the shallow Eastern part of the reservoir.

In Fig. 78 and Fig. 79 the mass flux vectors (kg/s) are shown, respectively at the unperturbed state (initial conditions) and at the end of the simulation time. Mass flux vectors are initially oriented both to East and West, while after the exploitation they are concentrated at the centre of the production area.
Figure 74: Momotombo (large model), temperature isolines, 2D vertical cross section, production wells area, unperturbed state (from [164]).

Table 12: Momotombo scenarios (large model), wells characteristics for the numerical simulation.

<table>
<thead>
<tr>
<th>Well</th>
<th>Extraction (kg/s)</th>
<th>Power unit (35 MW)</th>
<th>Year</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>MT2</td>
<td>max 25, average 1</td>
<td>1</td>
<td>1990</td>
<td>in place of MT9</td>
</tr>
<tr>
<td>MT5</td>
<td>50</td>
<td>1</td>
<td>1983</td>
<td></td>
</tr>
<tr>
<td>MT9</td>
<td>50</td>
<td>1</td>
<td>1983</td>
<td>collapsed in 1988</td>
</tr>
<tr>
<td>MT12</td>
<td>45</td>
<td>1</td>
<td>1983</td>
<td></td>
</tr>
<tr>
<td>MT17</td>
<td>20</td>
<td>2</td>
<td>1983</td>
<td></td>
</tr>
<tr>
<td>MT20</td>
<td>23 (*)</td>
<td>1</td>
<td>1983</td>
<td>(*) estimated, vapour 12 kg/s</td>
</tr>
<tr>
<td>MT22</td>
<td>27</td>
<td>2</td>
<td>1983</td>
<td></td>
</tr>
<tr>
<td>MT23</td>
<td>60</td>
<td>1</td>
<td>1987</td>
<td></td>
</tr>
<tr>
<td>MT26</td>
<td>57</td>
<td>2</td>
<td>1983</td>
<td></td>
</tr>
<tr>
<td>MT27</td>
<td>100</td>
<td>1</td>
<td>1987</td>
<td></td>
</tr>
<tr>
<td>MT35</td>
<td>57</td>
<td>2</td>
<td>1985</td>
<td>deep well</td>
</tr>
<tr>
<td>MT36</td>
<td>25</td>
<td>2</td>
<td>1985</td>
<td>vapour 17 kg/s, high gas content</td>
</tr>
</tbody>
</table>
Figure 75.: Momotombo (large model), evolution of the specific enthalpy of the extracted fluid.

Figure 76.: Momotombo (large model), $t \approx 16$ years, temperature distribution on a 2D vertical cross section (production area).

Figure 77.: Momotombo (large model), $t \approx 16$ years, pressure distribution and isosurfaces on a 2D vertical cross section (production area).
Figure 78.: Momotombo (large model), unperturbed state, mass flow rate vectors (kg/s) in the production area.

Figure 79.: Momotombo (large model), $t \approx 16$ years, mass flow rate vectors (kg/s) in the production area.
4.2.3 Sabalan Geothermal reservoir (Iran)

4.2.3.1 Numerical model from literature

A description of the Sabalan geothermal field is here given, then the numerical model available in literature about this field is presented. Finally, an original variation of the model is shown and discussed. For the study about the Sabalan geothermal reservoir M. Quaia has to be acknowledged; he studied and worked on the numerical model simulation during his Master Degree Thesis work at the University of Pisa under my supervision and of prof. Alessandro Franco (see Quaia M., 2011) [164].

The geothermal exploration in Iran started in 1975, in the North-West region of the country [165]. Four regions have been evaluated to be interesting for energy utilization: Sabalan, Damavand, Maku-Khoy and Sahand [166, 167]. Ten new areas have been then identified between 1996 and 1999. The results by Noorollahi et al., 2008 [168] identified totally 18 areas of interest, corresponding to almost the 8.8% of the national territory.

In the Sabalan area natural manifestations at temperatures between 140 and 250 °C are present. The wells drilled between 2002 and 2004 found temperatures of 240 °C at depth of 3200 m. The Sabalan regional map is shown in Fig. 80 (also the caldera boundary can be seen).

![Figure 80: Map of the Sabalan geothermal area, Iran (from [168]).](image)

The Sabalan numerical model is described by Noorollahi and Itoi (2011) [170]. The mesh grid is rectangular, the surface extension is 12 × 8 km², with 192 cells per layer. The total depth is 4.6 km and there are 16 internal layers (with varying thickness). The active blocks are totally 2595, their number would have been 2688, but some cells of the first layers (atmosphere) are not considered to avoid some unsaturated air/water areas. The mesh is refined in the internal region which is the most interesting area to simulate.

The following list summarizes the boundary conditions of the model [170].
• At the base of the model a natural recharge condition is given at 265 °C and 90 kg/s, specific enthalpy of 1159 kJ/kg (total 104,31 MW). Uniform heat flux condition: 200 mW/m² in the Central-Southern area; it is null in the North area.

• Second to last layer (near to the base): natural recharge, 8 kg/s at 130 °C.

• At the surface: heat loss from the first layers to atmosphere; natural manifestations (considered as 4 artificial wells extracting 40 — 50 kg/s).

• Lateral faces: impermeable and adiabatic.

The natural unperturbed state has been simulated, matching the real temperature and pressure data, according to the authors [170]. Then 3 exploitation scenarios have been simulated, considering a geothermal flash power plant with a Δp = 5,5 — 0,1 bar. Turbine exit temperature is taken 46 °C, with an isoentropic efficiency of 78 %; T_rein is assumed to be 155 °C.

In the first scenario the reinjection strategy and the possible areas for make-up wells are studied.

In the second scenario an output rate of 50 MW is assumed, with an extraction of 690 kg/s (13 production wells and 7 reinjection wells). 20 total wells are expected to be present at the end of the simulation time, in order to keep the power output constant (7 make-up wells). Temperature and pressure changes and their effects are also considered.

In the third scenario the task is an electrical power output of 100 MW, with an extraction rate of 1380 kg/s. There are 35 production wells together with 16 reinjec-
Figure 82.: Conceptual model considered by Noorollahi and Itoi for the numerical model [170].

50 MW is considered to be the optimal power size for this field, according to the literature. Anyway it is important to remark that Sabaln area is a widely fractured zone, with many faults, complicating a lot the numerical model set up (see Fig. 83).

A different version of the model is here presented, basing on the data available in literature and on the previous model here described.

4.2.3.2 Numerical model simulation of the Sabalan geothermal field

The model by Noorollahi and Itoi (2011) [170] has been used and then improved in order to simulate also different scenarios. The model has been reviewed with reference to the pressure and temperature profiles of the wells, also the ones drilled after the model of Noorollahi and Itoi has been published. A good reference has been the work by Bina (2009) [169].

The software Petrasim\(^3\) (ThunderHead Engineering) has been used for the simulation [129]. By the analysis of the wells, particularly the ones with higher temperature values, the position of a heat source has been evaluated (in order to modify the thermal BC). The analysis of the fault allowed to understand the circulation paths, with reference to the temperature distribution in the wells. Hypothesis about the faults linking the wells and the ones limiting the circulation have been tested in the model, matching the wells data.

The model of Noorollahi and Itoi [170] has been modified for the following reasons:

- the first and second layers were excluded by the calculations (inactive), for an average thickness of about 1400 m, and the use of a heat dispersion condition (to the atmosphere) on the surface with no value

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\(^3\) For the utilization of this software prof. Alessandro Sbrana of the Department of Earth Science (DST - Dipartimento di Scienze della Terra) of the University of Pisa has to be acknowledged.
Figure 83: Faults on the 2D horizontal grid of Sabalan model, from Noorollahi and Itoi (2011) [170].

- the assumption of North direction advancing of the hot fluid front was used, but this is in contrast with the observations about the new wells considered and faults sitting.

For the surface condition, as a known practice, fixed values of temperature and pressure (atmospheric) have been assigned. The surface conditions could have been affecting the results of Noorollahi and Itoi, also considering the profiles of the wells NWS1, NWS3 and NWS4. In Fig. 84 six wells temperature profiles are shown, they are obtained as described, assigning constant atmospheric conditions on the surface. Also the orographic profile of the surface has been better reproduced, according to the literature available, this aspect was not applied in the Noorollahi and Itoi model.

The grid shape has been not modified respect to the original model. Two “corridors” with different permeability have been arranged in the inner part of the model, to reproduce the faults behaviour. For the permeability values the injectivity tests reported by Bina (2009) [169] have been considered. A natural underground recharge of 138 kg/s, is considered at a temperature, extracted from the geothermometers, of 270 °C [171]. A new natural recharge condition has been assigned (6 kg/s, 130 °C) to reproduce the cooling of the well NWS3 (at 1000 m a.s.l).
22 different materials are used in the model. The permeability range is between $10^{-13}$ and $10^{-17}$ m$^2$, thermal conductivity varies between 2.5 and 4.30 W/(mK), while specific thermal capacity varies between 1.6 and $1.45 \times 10^3$ J/(kgK). Porosity and density are considered constant and equal respectively to 10 % and 2500 kg/m$^3$.

As already stated for the permeability values the injectivity tests reported by Bina (2009) [169] have been considered. In the Appendix B, section B.2 (p. 227) the rock material properties of the model and its geometric features are illustrated. The model features (block, materials) are shown in Fig. 86 and Fig. 87.

The boundary conditions used to reproduce the unperturbed natural state are here listed:

- Base of the model: natural recharge 138 kg/s, at 1280 kJ/kg
- Heat flux: 500 mW/m$^2$ for the upflow blocks; 200 mW/m$^2$ near the upflow; 60 mW/m$^2$ the others
- Natural recharge from one of the bottom layers: 6 kg/s at 550 kJ/kg
- Surface conditions: atmospheric (constant), 15°C and 0.075 MPa
- Lateral faces: impermeable and adiabatic

The simulation time for the natural state is $10^6$ years, but the equilibrium of the unperturbed state is obtained after $150 \times 10^5$ years.

In the Figures from 88 to 92 some graphic results of the unperturbed natural state (temperature and pressure distributions, vectors of mass flow rate) are shown. In Fig. 95 different isothermal surfaces features in the model are shown, from higher to lower values of T. It can be seen that the natural recharge flows to the northern part of the field, through the preferential NS fault, then distributing because of the other perpendicular fault.
Figure 84: Temperature profiles of 6 extraction wells (model of [170], modified with constant T and p and orographic profile on the surface), by [164].
Figure 85.: Temperature profiles of the wells according to the model here presented (after [170]), also in [164].
Figure 86: 3D model features (Sabalan).

Figure 87: 3D model features (Sabalan), some blocks are removed to show the inner details (different size blocks are evidenced).
Figure 88.: Temperature distribution (slice plans) at the natural unperturbed state (Sabalan).

Figure 89.: Vectors of mass flow rate (kg/s) (and background T slice plans) at the natural unperturbed state (Sabalan).
Figure 90.: Vectors of mass flow rate (kg/s) (T slice plans) at the natural unperturbed state (Sabalan).

Figure 91.: Temperature distribution (°C), unperturbed state, Sabalan (cross section at the middle of x axis, SN).

Figure 92.: Pressure distribution (°C), unperturbed state, Sabalan (cross section at the middle of x axis, SN).
Figure 93: Temperature distribution (°C), unperturbed state, Sabalan (cross section at the middle of y axis, EO).

Figure 94: Pressure distribution (°C), unperturbed state, Sabalan (cross section at the middle of x axis, EO).
Figure 95: Isothermal surfaces at different temperatures, unperturbed state [164], Sabalan.
4.2.3.3 Simulation of the utilization scenarios for the Sabalan geothermal field

The expected $T_{geo}$ range for the field is between $240\,^\circ C$ and $260\,^\circ C$, considering $1109,3\,kJ/kg$ as a mean value of the specific enthalpy extracted from the wells. Three types of power plant have been considered in relation to this resource (see section 2.1, p. 15):

- single flash
- double flash
- single flash with a bottoming ORC unit

The efficiencies and specific brine consumption $\beta$ have been calculated for this three configurations. Some constraints have been fixed to the power plant parameters:

a) the condensation temperature is $25\,^\circ C$

b) the isentropic efficiency of the turbine is $0,80$ for the single flash and ORC units, while $0,82$ and $0,78$ have been considered, respectively, for the high pressure and low pressure of the double flash unit

c) final steam expansion quality is assumed to be $0,80$

d) the minimum $\Delta T$ (pinch-point) in the RHE of the ORC unit has been taken equal to $5\,^\circ C$

The specific geofluid consumption values for three plant configurations are shown in Fig. 96. In Table 13 the values of $\beta$ in case of double flash plant configuration are listed, for 4 values of $1^{st}$ flash temperature and 3 values of $2^{nd}$ flash temperature.

**Table 13.** Double flash power plant, specific geofluid consumption ($\beta$, kg/MJ) for different values of the two separation (flash) temperatures, from [164].

<table>
<thead>
<tr>
<th>$1^{st}$ flash T ($^\circ C$)</th>
<th>$2^{nd}$ flash T ($^\circ C$)</th>
<th>$\beta$ (kg/MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>120</td>
<td>110</td>
</tr>
<tr>
<td>170</td>
<td>6,48</td>
<td>6,32</td>
</tr>
<tr>
<td>180</td>
<td>6,42</td>
<td>6,29</td>
</tr>
<tr>
<td>190</td>
<td>6,42</td>
<td>6,32</td>
</tr>
<tr>
<td>200</td>
<td>6,49</td>
<td>6,43</td>
</tr>
</tbody>
</table>

The minimum of the geofluid consumption ($\beta$) can be obtained with double flash plant, higher values of $\beta$ are achieved by the flash + binary plant and single flash (particularly for $T > 160\,^\circ C$). In the Fig. 97, 98, 99 the sensitivity of $\beta$ to the extraction temperature is shown for the three plant configurations considered. The extraction rate $\beta$ declines with the increasing geofluid extraction temperature. Only in case of single flash plant (condensation at $25\,^\circ C$, as stated at the beginning of this section) a remarkable increase is observed at the separation temperature of $190\,^\circ C$ (from 10
to 30 kg/MJ). For the other configurations the range of sensitivity variation is about 50%. This is mainly due to the decline of the separated steam quality expanding in the turbine. Providing a second separation of the liquid phase would allow to expand more fluid in the second turbine stage.

After a review and calculation about the plants considered, the preferable cycle configurations would then be:

1) double flash  \( T_{1\text{st-\text{flash}}} = 170 ^\circ \text{C} \)  \( \eta_I = 14,52 \% \)
2) flash + binary cycle  \( T_{\text{flash}} = 150 ^\circ \text{C} \)  \( \eta_I = 14,23 \% \)
3) single flash  \( T_{\text{flash}} = 137,5 ^\circ \text{C} \)  \( \eta_I = 11,77 \% \)

\[ \begin{array}{|c|c|c|}
\hline
\text{Configuration} & T_{1\text{st-\text{flash}}} & \eta_I \\
\hline
\text{double flash} & 170 ^\circ \text{C} & 14,52 \% \\
\text{flash + binary cycle} & 150 ^\circ \text{C} & 14,23 \% \\
\text{single flash} & 137,5 ^\circ \text{C} & 11,77 \% \\
\hline
\end{array} \]

Figure 96.: Specific brine consumption (\( \beta \)) for three plants configuration, Sabalan case study, for the binary cycle the temperature is the value at which heat exchange in the RHE starts [164].

4.2.3.4 Resource oriented approach

It would be useful to consider the utilization of this field from a more complex point of view, in order to understand the reservoir response and the numerical model potentialities. The multidisciplinary approach described in this work should be adopted. The results about the different plant efficiency have to be considered after a more accurate resource response evaluation. Also the reinjection temperature and the other boundary conditions can be considered in a sensitivity analysis of the system performance.

The exploitation strategy, in terms of \( m_{\text{geo}} \) and \( T_{\text{rein}} \), determines the durability of the resource utilization [49]. At the same time the lifetime of the system can be optimized according to the industrial strategy, only when the resource is well characterized and a numerical model (for natural state and different scenarios) is considered to be reliable. For a long term strategy an higher temperature reinjection is indicated, while for a rapid resource depletion horizon, more flexible thermody-
namic cycles (single flash) should be considered (absorbing the reservoir depletion with no sensible efficiency decline).

Two plant configurations have been implemented in the numerical model described in section 4.2.3.2: single flash and flash with bottoming binary cycle. The model response to the utilization has been studied. Three extraction/reinjection rate values, corresponding to 20 MW, 50 MW and 80 MW power output are studied on a 35 years simulation time. Three separation temperature are considered (as parameters): 80 °C, 135 °C and 160 °C. The double flash plant have proved to be very similar to the combined flash + binary cycle case, so it is not described here.

In Table 14 the main results (in terms of power, energy and plant lifetime) of these simulation scenarios are shown. $\dot{m}_{W}$ is the mass flow rate effectively expanding in turbine (for the flash cycles it is geothermal fluid).

The production wells are almost all situated near the natural recharge area [170], while an “infield” reinjection strategy is adopted. For an interesting discussion about “infield” and “outfield” reinjection strategies see also Kaya et al. (2011) [88]. The extraction wells are productive from the two main reservoirs: the one at 0–500 m a.s.l., and the one at 1400–1900 m a.s.l. Reinjection only occurs in the deeper reservoir. In the reinjection area, at the depth of the first reservoir, only impermeable formations are present.

A constraint to the utilization is assigned: a decline of more than 20 % of the nominal power output is not acceptable.

The extraction rates, in terms of mass and specific enthalpy (from the blocks simulating the wells), are then put into the energy and mass balance of the plant in order to obtain the power output and the annual energy production.

The evolution with time of the specific enthalpy of the extracted fluid is shown in Fig. 100 ($T_{\text{rein}}$ fixed at 160 °C). A decline of enthalpy with increasing $\dot{m}_{\text{geo}}$ is expected. The curves corresponding to 366,50 kg/s and 586,40 kg/s are stopped at 31 and 7 years respectively, because of the occurring of the vapour phase in the

![Figure 97: Specific brine consumption $\beta$ as a function of geofluid temperature (for different separation temperatures), single flash plant.](image)
shallow aquifer. Specific power rate decline with time (kW per kg/s extracted) is shown in Fig. 101.

Remarkable pressure decline can be seen from the simulations more than an excessive cooling of the reservoir.

In Fig 102 the temperature distribution at the initial state (for a cross section N-S direction) is shown. The production is $\dot{m}_{\text{geo}} = 366,50$ kg/s with $T_{\text{rein}} = 160\,^\circ\text{C}$ [164]. In Fig 103 the same section with temperature distribution after 30 years is shown.

In Fig 104 the pressure distribution at the initial state (for a cross section N-S direction) is shown. The production/reinjection rate is $\dot{m}_{\text{geo}} = 366,50$ kg/s with $T_{\text{rein}} = 160\,^\circ\text{C}$ [164]. In Fig 105 the same section with pressure distribution after 30 years is shown.

**Figure 98.** Specific brine consumption $\beta$ as a function of geofluid temperature (for different separation temperatures), flash + bottoming binary cycle plant.
Figure 99.: Specific brine consumption $\beta$ as a function of geofluid temperature (for different separation T values), double flash plant (Sabalan).

Figure 100.: Specific enthalpy of the extracted fluid (simulated), $T_{\text{rein}} = 160^\circ$C (Sabalan).

Figure 101.: Specific power rate decline (simulated), $T_{\text{flash}} = 160^\circ$C (Sabalan).
Table 14: Results for the plants simulated, Sabalan geothermal field, from [164].

<table>
<thead>
<tr>
<th></th>
<th>$\dot{m}_{\text{geo}}$ (kg/s)</th>
<th>$\dot{m}_{\text{geo}}$ (kg/s)</th>
<th>$\dot{m}_{\text{geo}}$ (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash cycle + ORC unit</td>
<td>146,6</td>
<td>366,5</td>
<td>506,6</td>
</tr>
<tr>
<td>$T_{\text{rein}}$(flash)</td>
<td>$150^\circ$C</td>
<td>$80^\circ$C</td>
<td></td>
</tr>
<tr>
<td>Power (MW)</td>
<td>23,15</td>
<td>57,88</td>
<td>92,61</td>
</tr>
<tr>
<td>$\dot{m}_W$ (kg/s)</td>
<td>112,7</td>
<td>281,9</td>
<td>451,1</td>
</tr>
<tr>
<td>$h_{\text{rein}}$ (kJ/kg)</td>
<td>334,9</td>
<td>334,9</td>
<td>334,9</td>
</tr>
<tr>
<td>energy (TWh)</td>
<td>7,1</td>
<td>12,5</td>
<td>5,5</td>
</tr>
<tr>
<td>expected plant life (years)</td>
<td>35</td>
<td>24,8</td>
<td>6,8</td>
</tr>
</tbody>
</table>

Flash cycle $| T_{\text{rein}} = 135^\circ$C

<table>
<thead>
<tr>
<th></th>
<th>$\dot{m}_{\text{geo}}$ (kg/s)</th>
<th>$\dot{m}_{\text{geo}}$ (kg/s)</th>
<th>$\dot{m}_{\text{geo}}$ (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (MW)</td>
<td>19,15</td>
<td>47,87</td>
<td>76,6</td>
</tr>
<tr>
<td>$\dot{m}_W$ (kg/s)</td>
<td>109,8</td>
<td>274,5</td>
<td>439,3</td>
</tr>
<tr>
<td>$h_{\text{rein}}$ (kJ/kg)</td>
<td>567,7</td>
<td>567,7</td>
<td>567,7</td>
</tr>
<tr>
<td>energy (TWh)</td>
<td>5,8</td>
<td>9,5</td>
<td>4,4</td>
</tr>
<tr>
<td>expected plant life (years)</td>
<td>35</td>
<td>22,7</td>
<td>6,5</td>
</tr>
</tbody>
</table>

Flash cycle $| T_{\text{rein}} = 160^\circ$C

<table>
<thead>
<tr>
<th></th>
<th>$\dot{m}_{\text{geo}}$ (kg/s)</th>
<th>$\dot{m}_{\text{geo}}$ (kg/s)</th>
<th>$\dot{m}_{\text{geo}}$ (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (MW)</td>
<td>18,32</td>
<td>45,8</td>
<td>73,22</td>
</tr>
<tr>
<td>$\dot{m}_W$ (kg/s)</td>
<td>116</td>
<td>290,1</td>
<td>464,3</td>
</tr>
<tr>
<td>$h_{\text{rein}}$ (kJ/kg)</td>
<td>675,5</td>
<td>675,5</td>
<td>675,5</td>
</tr>
<tr>
<td>energy (TWh)</td>
<td>5,6</td>
<td>12,1</td>
<td>4,8</td>
</tr>
<tr>
<td>expected plant life (years)</td>
<td>35</td>
<td>30,5</td>
<td>7,6</td>
</tr>
</tbody>
</table>

Production wells 5 13 20
Reinjection wells 3 7 12

Figure 102: Temperature distribution, initial state, cross section N-S (Sabalan) [164].
Figure 103.: Temperature distribution, $t = 30$ years, cross section N-S ($m_{geo} = 366,5$ kg/s, $T_{rein} = 160\, ^\circ C$) [164].

Figure 104.: Pressure distribution, initial state, cross section N-S ($m_{geo} = 366,5$ kg/s, $T_{rein} = 160\, ^\circ C$) [164].

Figure 105.: Pressure distribution, $t = 30$ years, cross section N-S ($m_{geo} = 366,5$ kg/s, $T_{rein} = 160\, ^\circ C$) [164].
4.2.4 Monterotondo Marittimo – Torrente Milia geothermal area

A numerical model of the Monterotondo Marittimo area (Tuscany, Italy) of Larderello field has been realized using the commercial software Petrasim\(^4\) (in which the TOUGH2 simulator is implemented) [129].

The conceptual model of the field is not an aim of this work, its development is still ongoing in collaboration with other researchers. It will be covered by further paper and works I am involved in. I would like to acknowledge particularly prof. Alessandro Sbrana, dr. Paolo Fulignati, dr. Alessandro De Rosa Many data and a geological description about the area are available in the Master Degree Thesis in Earth Science of Arianna Secchiari\(^5\) (2011) [172].

The model presented can be considered to be a good qualitative representation of the reservoir, and it is here used to elaborate some specific features of the sustainable design methodology of a small size ORC power plant.

More data and details will be object of future papers (also following the current development of the project). Anyway some constraints due to the regional regulations are taken into account and discussed. Sensitivity analysis and a larger domain extension are future developments of this model.

The model domain extension and the various materials used are shown in Fig. 106. In Fig. 108 another view and a zoom on the wells area is shown. In the Appendix B, section B.3 (p. 230) the details about the model layers and materials are illustrated.

![Figure 106. Main features of the numerical model grid: a) cover; b) reservoir formation; c) basement; d) hot fluid recharge.](image)

A first task is the reconstruction of the natural unperturbed state, and then the simulation of utilization scenarios for a small size ORC unit (about 500 kW). In Italy (and generally in the proximities of the main high enthalpy fields) the medium temperature reservoir are going to be exploited in the next few years by a lot of industrial players. The model presented can be considered to be a good qualitative representation of the reservoir, and it is here used to elaborate and underline some specific features of the sustainable design methodology for an ORC power plant.

A lack of geophysical data about the area to be studied has been faced with a literature review and manual calibration of the model (it has been the result of a team work). ENEL drilled the well “Monterotondo 22” in 2004 in the area of

---

\(^{4}\) For the utilization of this software prof. Alessandro Sbrana of the Department of Earth Science (DST - Dipartimento di Scienze della Terra) of the University of Pisa has to be acknowledged.

\(^{5}\) I have been one of the co-tutors of the Master Degree Thesis of A. Secchiari [172].
Macchia al Toro (near to the model area), anyway the data about this well are not enough to elaborate a complete data set of thermophysical properties for the rock formations and temperature data. For the meteoric water recharge (rain) the data used come from the Tuscany Region data\(^6\). Some of the properties have been then compared with other models of the Larderello geothermal field (Della Vedova et al. 2008, [153], see also section 4.1.3.2). The heat flow data considered in the model come from ENEL wells logs drilled near the Torrente Milia area. Further details about the conceptual model and the material properties evaluation will be object of future papers with the collaborators acknowledged at the beginning of this section.

4.2.4.1 Description of the model

The model has an extension of \(2.7 \times 1.0\) km\(^2\) and it is 0.8 km deep. A first impermeable layer simulates the cover of the reservoir (a portion of the reservoir formation is not covered, see the Eastern part in Fig. 106), it has a depth range of 50 — 200 m. An upper layer simulates the atmosphere, according to the assumption made in the model of Momotombo (see section 4.2.1 p. 108, section 4.2.2 p. 117 and Appendix B, section B.1, p. 221) The reservoir formation has a thickness of 500 m (the range is 450 — 600 m), the name of the formation is Calcare cavernoso and it is very permeable and fractured. The basement of this model, in the remaining 200 m, has a thickness range of 200 — 300 m. In Fig. 107 a map of the zone is shown. The model area is the one in the yellow rectangular line.

![Figure 107.: Geological map of the Monterotondo Marittimo - Torrente Milia area, in [172].](image)

The model has been realised with TOUGH2 (Petrasim) [129, 143], using the EOS1 equation of state (see Table 9, p. 93).

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\(^6\) Rain gauge “Monterotondo” code 2370, Servizio Idrologico Regionale - Regione Toscana http://www.sir.toscana.it/.
Figure 108.: Sketch of the main structural features of the model grid (zoom on the wells).

**Model Grid** The model is made by 3672 blocks. Each block has the following dimensions: 100 m along the x axis, 125 m along the y axis. Each layer has then 27 blocks along x axis and 8 blocks along y axis. The blocks have different thickness: 25 m for the upper layer (cover), 50 m for the reservoir formation, 100 m for the basement.

**Initial Conditions** For the simulation of the unperturbed natural state the gradients of pressure and temperature are assigned as initial conditions. The data are taken from the Carboli C bis well drilled by ENEL, the temperature data are shown in Fig. 109 (from Secchiari 2011 [172]).

The temperature and pressure gradients used in the simulation are

\[ T(z) = 15 - 0.1387 \cdot z \ (°C) \]  
(107)

\[ p(z) = 1.013 \cdot 10^5 - 9683.3 \cdot z \ (Pa) \]  
(108)

**Boundary Conditions** The scarceness of specific (local) data lead to make assumption about the structural geology of the area and the groundwater flow. The boundary conditions are a result of this interpretation, which is the result of a team work.

The atmospheric conditions are set up at the surface of the model (15, 10^5 Pa). Another 1\textsuperscript{st} kind temperature condition (see section 3.2, p. 78) has been assigned at the bottom of the model: 126 °C and 7,36 \cdot 10^6 Pa (resulting from the hydraulic vertical pressure gradient).

The natural recharge of the reservoir is represented by a 2\textsuperscript{nd} kind condition: a lateral E-W flow of about 30 kg/s (derived from hydrogeologic balance on the domain).

In some of the bottom cells (where the reservoir formation is in contact with the bottom surface of the domain) a condition of heat flux (5 kW total) has been assigned instead of the temperature condition.

An hot upflow stream has been assigned to simulate a fault at the base of the model (SN direction). A different material (more permeable than the basement) has been used to simulate this hot fluid inlet (BUR2, see Appendix B, section B.3, Table 39, p. 230). The amount of hot fluid has been estimated from natural ground...
CO$_2$ emissions measurements (Secchiari 2011, [172])$^7$ a stream of hot fluid (liquid phase) enters from the bottom of the model at a rate of 4.32 kg/s.

4.2.4.2 Unperturbed natural state

The simulation time has been taken equal to about $10^6$ years. The results have been compared with the natural conditions of the reservoir. In Fig. 110 the iso-temperature surfaces are shown. A vertical cross section (slice plane, $Y = 500$ m) in Fig. 111 shows the temperature distribution (a). In the same Figure the vectors of the fluid flow are illustrated (b). It is possible to see how the rise of temperature begins from the upflow fault (yellow arrows in Fig. 111 b), but the natural recharge (E-W direction, right-left in the Figures) “pushes” the flow in W direction.

4.2.4.3 Simulation of utilization scenarios

After the unperturbed state it has been possible to simulate the response of the reservoir to different utilization strategies. The unperturbed state simulation is in this case the initial condition for the exploitation scenarios. As this simulation is

$^7$ A constant ratio between CO$_2$ natural concentration and hot fluid upflow has been individuated from the literature, see Secchiari 2011 [172], Gianelli et al. 1997 [173], and Minissale et al. 2000 [174]. The motivation of this hypothesis is not illustrated in this work.
still object of future publications, only a part of the simulated scenarios is here illustrated.

The most sensible interaction between production and reinjection wells has been a task of these simulations. In Fig. 112 the wells siting is shown (also a double production well layout is considered), the temperature isosurfaces distribution show a spatial advancing of the cold front from the reinjection well during the exploitation. In Fig. 113 it is possible to see a zoom on the reinjection well.

Two types of scenarios are here individuated:

- 1 production well, 1 reinjection well
- 2 production wells (same extraction rate), 1 reinjection well

In both cases some constraints have been assigned to the model

a) Maximum extraction/reinjection rate is 100 kg/s

b) 30 or 50 years are considered as time simulation limits

c) The wells siting (shown in the Figures) is assumed to be the best compromise between extraction at high temperature and soil concession (see Fig. 152, p. 231, in the Appendix B)

d) The maximum drilling depth is about 400 m, depending on Regional concession for small size power utilization (this aspect involves the economic and regulatory regulation context of the project)

In Fig. 114, thanks to a reduction of the number of T-isosurface, it is possible to see the mass flux vectors pathways (from the reinjection to the production wells). The same view, but with a slice vertical plane on the background, is shown in Fig. 115. Both these two Figures are referred to a 2 production wells scenario (50 + 50 kg/s extraction/reinjection rate), after 50 years of utilization.

The scenarios sustainability level is illustrated with the diagrams of Figures 116 and 117. The value of 15 kg/s for the extraction rate corresponds to an average value for the operation of a plant size of about 200 kW. With this low value of mass
flow rate a complete sustainability of the plant is possible, because temperature reductions of $2\,^\circ\text{C}$ in 30 years and of about $4\,^\circ\text{C}$ in 50 years (Fig. 116).

An extraction rate of 50 kg/s (for a power production of about 500 kW) determines a temperature decrease of the source of about $6\,^\circ\text{C}$ in 30 years and about $10\,^\circ\text{C}$ in 50 years: this would be critical for the plant, so a sufficient life of the plant is not assured. Besides the extraction of a mass flow rate of 100 kg/s (that would permit a power output of about 1 MW) appears to be unsustainable according to the hypothesis. The diagram of temperature reduction during the lifetime of the plant is provided in Fig. 116. It is possible to observe temperature decreases of about $11\,^\circ\text{C}$ after 30 years, and $15\,^\circ\text{C}$ after 50 years. In both the last two cases it would be difficult to maintain a correct working point of the ORC plant.

A further layout with two production wells has been considered, the two wells are “PROD1” and “PROD2” (see Fig. 117 and Fig. 152, in Appendix B, p. 230). In the single reinjection well the sum of the extracted flow rates is reinjected. In Fig. 117 the simulated extraction temperatures evolution is shown (for a period up to 50 years). For both the production wells the extraction rate of 50 kg/s appears to be unsustainable.

Final remarks about the simulation and future developments

A moderate temperature geothermal source ($110\,^\circ\text{C}$—$120\,^\circ\text{C}$) is estimated to be available at relatively low depth (400–500 m below the ground level). The adaptability of a 200 kW plants size or discrete multiples (up to 200 kW × 5 = 1 MW) is
analyzed with the support of a numerical model of the reservoir in order to elaborate a production/reinjection strategy.

According to the qualitative model elaborated, a plant size of 200 kW could be run sustainably for a period of almost 30 years; the geofluid rate is estimated to be maximum than 20 kg/s. Higher fluid rates (for example twice the previous size) would be critical for the resource durability. The extraction of a mass flow rate of 100 kg/s, that would permit a power production of the order of magnitude of 1 MW, appears to be unsustainable.

Further developments of the model are possible, in particular regarding the calibration and better data and geometry fitting. A more specific sensitivity analysis to natural and utilization parameters and wells layout is necessary.
4.3 NUMERICAL SIMULATIONS: AN EXTENDED REVIEW

In Table 15 and Table 16 a review of several geothermal fields characteristics is reported. Numerical simulations for these fields have been carried out and they are available in literature.

The Tables of this section have been reviewed after the Master Thesis of Quaia (2011) [164]. The data have been collected and analysed during his Master Degree Thesis work.

The numerical simulations considered are referred to several geothermal fields. Different softwares are used as well as various grid shapes and configurations are adopted. The review of about 13 geothermal fields and related 16 numerical models is illustrated and discussed.

A very famous state of the art about geothermal reservoirs numerical simulations is the one by O’Sullivan et al. (2001) [14].
Figure 116.: Monterotondo M.mo - Torrente Milia, production scenarios: temperatures of the production well (varying mass flow rate values), scenario with single production well.

Figure 117.: Monterotondo M.mo - Torrente Milia, production scenarios: temperatures of the production well (varying mass flow rate values), scenario with two production well: a) “PROD1”; b) “PROD2”.
**Table 15:** Extended review: characteristics of the geothermal fields - Part I (after [164]).

<table>
<thead>
<tr>
<th>Field name and References</th>
<th>Resource</th>
<th>Production (kg/s)</th>
<th>Power plant (MW)</th>
<th>Extent (km²)</th>
<th>Heat flux (mW/m²)</th>
<th>Max. prod. depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balcova-Narlidere, Turkey [175]</td>
<td>Water dominated, 140°C</td>
<td>20,6 (a)</td>
<td>0</td>
<td>≈ 2</td>
<td>1100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(annual avg.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cerro Prieto, Mexico [176]</td>
<td>Water dominated, double phase reservoir, 350°C</td>
<td>620 (b)</td>
<td></td>
<td></td>
<td>3000</td>
<td></td>
</tr>
<tr>
<td>Heber, USA [177]</td>
<td>Water dominated, double phase reservoir, 200°C</td>
<td>120 (c)</td>
<td></td>
<td></td>
<td>1830</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(52 effective)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kizildere, Turkey [179, 180, 181]</td>
<td>Water dominated, double phase reservoir, 200°C</td>
<td>250 (10 effective)</td>
<td>20,4</td>
<td></td>
<td>1240</td>
<td></td>
</tr>
<tr>
<td>Los Azufres, Mexico [182]</td>
<td>Water dominated, double phase reservoir, 240 — 280°C, vapour dominated after exploitation</td>
<td>≈475</td>
<td>188</td>
<td>≈20</td>
<td>1500</td>
<td></td>
</tr>
<tr>
<td>Mt. Apo - Mindanao, Philippines [183, 184]</td>
<td>Water dominated, double phase reservoir, 300°C</td>
<td>104</td>
<td></td>
<td></td>
<td>2500</td>
<td></td>
</tr>
<tr>
<td>Pauzhetsky-Kamchatka, Russia [185, 186, 187]</td>
<td>Water dominated, double phase reservoir, 200°C</td>
<td>250 (38 to reinj.)</td>
<td>6,8</td>
<td>≈5</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1000</td>
<td></td>
</tr>
</tbody>
</table>

(a) The value is referred to a district heating system using the geothermal resource.
(b) In 2000 an upgrade up to 720 MW was planned, a further upgrade to 820 MW was planned for 2012.
(c) Updated at 1996 [177].
<table>
<thead>
<tr>
<th>Field name and References</th>
<th>Resource</th>
<th>Production</th>
<th>Heat flux</th>
<th>Max. Prod. depth</th>
<th>Extent</th>
<th>Power plant</th>
<th>Heat dom. double phase reservoir, 200°C</th>
<th>Water dominated double phase reservoir, 0°C</th>
<th>Water dominated double phase reservoir, 0°C</th>
<th>Water dominated double phase reservoir, 0°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ogiri, Japan [188, 189, 190]</td>
<td>1st reservoir (75°C)</td>
<td>200</td>
<td>430</td>
<td>40</td>
<td>30</td>
<td>320 (243 rein.)</td>
<td>250°C</td>
<td>(19.5 rein.)</td>
<td>(19.5 rein.)</td>
<td>(19.5 rein.)</td>
</tr>
<tr>
<td>Olkaria, Kenya [191]</td>
<td>2nd reservoir (120°C to 300°C)</td>
<td>121</td>
<td>80</td>
<td>1600</td>
<td>121</td>
<td>200°C</td>
<td>200°C</td>
<td>121</td>
<td>80</td>
<td>1600</td>
</tr>
<tr>
<td>Onokobe, Japan [192]</td>
<td>1st reservoir (-200°C to 300°C)</td>
<td>12,5</td>
<td>1</td>
<td>175</td>
<td>12,5</td>
<td>200°C</td>
<td>200°C</td>
<td>12,5</td>
<td>1</td>
<td>175</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>New Zealand [193]</th>
<th>1st reservoir (75°C)</th>
<th>200</th>
<th>430</th>
<th>40</th>
<th>30</th>
<th>320 (243 rein.)</th>
<th>250°C</th>
<th>(19.5 rein.)</th>
<th>(19.5 rein.)</th>
<th>(19.5 rein.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olkaria, Kenya [191]</td>
<td>2nd reservoir (120°C to 300°C)</td>
<td>121</td>
<td>80</td>
<td>1600</td>
<td>121</td>
<td>200°C</td>
<td>200°C</td>
<td>121</td>
<td>80</td>
<td>1600</td>
</tr>
<tr>
<td>Onokobe, Japan [192]</td>
<td>1st reservoir (-200°C to 300°C)</td>
<td>12,5</td>
<td>1</td>
<td>175</td>
<td>12,5</td>
<td>200°C</td>
<td>200°C</td>
<td>12,5</td>
<td>1</td>
<td>175</td>
</tr>
</tbody>
</table>

Table 16: Extended review: characteristics of the geothermal fields - Part II (after [164]). (continued from Table 15, p. 151)
Table 17: Extended review: numerical model simulations - Part I (after [164]).

<table>
<thead>
<tr>
<th>Field name and ref.</th>
<th>Simulation</th>
<th>Software</th>
<th>Geometry</th>
<th>Mesh</th>
<th>Conditions and parameters</th>
<th>Calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balcova-Narlidere, Turchia [175]</td>
<td>Natural state; History matching (5 y); Evolution (20 y, 3 cases)</td>
<td>TOUGH2</td>
<td>3D: 3 × 4 km² thick.: 1,53 km (30 ÷ -1500 m asl)</td>
<td>Irregular grid 13 layers 5194 blocks (a)</td>
<td>Deep nat. recharge: 40 kg/s; shallow recharge: 11 kg/s; total heat rate input: 33 MW</td>
<td>k (b) nat. recharge</td>
</tr>
<tr>
<td>Cerro Prieto, Mexico [176]</td>
<td>Natural state; History matching; Evolution (30 y, 3 cases)</td>
<td>TETRAD</td>
<td>3D: 11 × 10 km² thick.: 3,6 km</td>
<td>7 layers x 1296 cells 9072 blocks (c) range size: 0,25÷2 km</td>
<td>Top: T = 40 °C Lateral BC: T assigned to second and penultimate layers, lateral heat flux, fluid losses (347,2 kg/s) Bottom: T assigned, nat. recharge 347,2 kg/s (350 °C) (\phi) decrease with depth (range 0,176÷0,01), fractures have constant porosity. (k_{x,y}) assumed as a logarithmic function of (\phi)</td>
<td>k, (\lambda) (b) nat. recharge</td>
</tr>
<tr>
<td>Heber, USA [177]</td>
<td>Natural state</td>
<td>TOUGH2</td>
<td>3D: 14 × 13 km² thick.: 3 km</td>
<td>8 layers x 201 cells (1608 blocks) (d)</td>
<td>Top: T = 25 °C, p = 0,1 MPa Lateral BC: impermeable, adiabatic Bottom: T and p assigned, nat. recharge</td>
<td>k (b)</td>
</tr>
<tr>
<td>Hengill Area, Iceland [178]</td>
<td>Natural state (10(^{1}) y) History matching (20 y) Evolution (30 y)</td>
<td>TOUGH2</td>
<td>3D: 100 × 100 km² thick.: 2,9 km (400 ÷ -2500 m asl)</td>
<td>9 layers x 996 cells (8964 blocks) (a)</td>
<td>Top: T = 15 °C, p = 0,1 MPa (e) Penultimate layer: nat. recharge 1 kg/s (1500 kg/kg) Bottom: T and p assigned (≈265 °C), fluid flows</td>
<td>k and nat. recharge (iTOUGH2)</td>
</tr>
<tr>
<td>Kizildere, Turkey [179]</td>
<td>Natural state History matching (17 y) Evolution (12 y, 9 cases)</td>
<td>STARS</td>
<td>3D: 840 × 600 m² thick.: 1÷1,2 km (estimated)</td>
<td>5 layers (8 × 12 cells)</td>
<td></td>
<td>(\phi) k (SAPHIR)</td>
</tr>
</tbody>
</table>

(a) Mesh refinement in the production wells zone.  
(b) Manual iterative calibration.  
(c) Matrix and fracture are both simulated in the cells.  
(d) Both quadrangular and polygonal shaped blocks (the last ones are used to simulate the fracture).  
(e) Meteoric water recharge is also considered.
Table 18: Extended review: numerical model simulations - Part II (after [164]).

<table>
<thead>
<tr>
<th>Field name and ref.</th>
<th>Simulation Software</th>
<th>Geometry</th>
<th>Mesh conditions and parameters</th>
<th>Calibration</th>
<th>Conditions and parameters</th>
<th>Evolution (20 % of cases)</th>
<th>Final layer pressure on the sea level layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kizildere, Turkey</td>
<td>SUTRA (f)</td>
<td>3D: 870 × 720 m²</td>
<td>T and p constant at 29 × 24 cells</td>
<td>Double φ model</td>
<td>3D: polygonal (f)</td>
<td>History matching (66 %)</td>
<td>Russia [185]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2² 29 × 24 cells</td>
<td>Top: natural emissions, 100 °C</td>
<td>131 cells × layer</td>
<td>170 km (394)</td>
<td>A-Mesh</td>
<td>Double φ model</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2² 29 layers × (18 × 26) cells</td>
<td>Top: natural emissions 100 °C</td>
<td>22 layers × (11 × 17) cells</td>
<td>2.2 km</td>
<td>SUTRA</td>
<td>Mesh</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2² 29 layers × (18 × 26) cells</td>
<td>Top: natural emissions 100 °C</td>
<td>22 layers × (11 × 17) cells</td>
<td>2.2 km</td>
<td>SUTRA</td>
<td>Mesh</td>
</tr>
<tr>
<td>Los Azufres, Mexico</td>
<td>TETRAD (g)</td>
<td>3D: 12 × 26 km²</td>
<td>Top: 65 °C; 0.1 MPa</td>
<td>9 layers × (18 × 26) cells</td>
<td>3.2 km</td>
<td>TETRAD</td>
<td>3D: 12 × 26 km²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2² 29 layers × (18 × 26) cells</td>
<td>Top: natural emissions 100 °C</td>
<td>22 layers × (11 × 17) cells</td>
<td>2.2 km</td>
<td>SUTRA</td>
<td>Mesh</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2² 29 layers × (18 × 26) cells</td>
<td>Top: natural emissions 100 °C</td>
<td>22 layers × (11 × 17) cells</td>
<td>2.2 km</td>
<td>SUTRA</td>
<td>Mesh</td>
</tr>
<tr>
<td>Mt. Apo - Mindanao,</td>
<td>TETRAD (g)</td>
<td>3D: 12 × 26 km²</td>
<td>Top: 65 °C; 0.1 MPa</td>
<td>9 layers × (18 × 26) cells</td>
<td>3.2 km</td>
<td>TETRAD</td>
<td>3D: 12 × 26 km²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2² 29 layers × (18 × 26) cells</td>
<td>Top: natural emissions 100 °C</td>
<td>22 layers × (11 × 17) cells</td>
<td>2.2 km</td>
<td>SUTRA</td>
<td>Mesh</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2² 29 layers × (18 × 26) cells</td>
<td>Top: natural emissions 100 °C</td>
<td>22 layers × (11 × 17) cells</td>
<td>2.2 km</td>
<td>SUTRA</td>
<td>Mesh</td>
</tr>
<tr>
<td>Mt. Apo - Mindanao,</td>
<td>TETRAD (g)</td>
<td>3D: 12 × 26 km²</td>
<td>Top: 65 °C; 0.1 MPa</td>
<td>9 layers × (18 × 26) cells</td>
<td>3.2 km</td>
<td>TETRAD</td>
<td>3D: 12 × 26 km²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2² 29 layers × (18 × 26) cells</td>
<td>Top: natural emissions 100 °C</td>
<td>22 layers × (11 × 17) cells</td>
<td>2.2 km</td>
<td>SUTRA</td>
<td>Mesh</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2² 29 layers × (18 × 26) cells</td>
<td>Top: natural emissions 100 °C</td>
<td>22 layers × (11 × 17) cells</td>
<td>2.2 km</td>
<td>SUTRA</td>
<td>Mesh</td>
</tr>
<tr>
<td>Mt. Apo - Mindanao,</td>
<td>TETRAD (g)</td>
<td>3D: 12 × 26 km²</td>
<td>Top: 65 °C; 0.1 MPa</td>
<td>9 layers × (18 × 26) cells</td>
<td>3.2 km</td>
<td>TETRAD</td>
<td>3D: 12 × 26 km²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2² 29 layers × (18 × 26) cells</td>
<td>Top: natural emissions 100 °C</td>
<td>22 layers × (11 × 17) cells</td>
<td>2.2 km</td>
<td>SUTRA</td>
<td>Mesh</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2² 29 layers × (18 × 26) cells</td>
<td>Top: natural emissions 100 °C</td>
<td>22 layers × (11 × 17) cells</td>
<td>2.2 km</td>
<td>SUTRA</td>
<td>Mesh</td>
</tr>
<tr>
<td>Pauzheisky-Kamchatka</td>
<td>TETRAD (g)</td>
<td>3D: 12 × 26 km²</td>
<td>Top: 65 °C; 0.1 MPa</td>
<td>9 layers × (18 × 26) cells</td>
<td>3.2 km</td>
<td>TETRAD</td>
<td>3D: 12 × 26 km²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2² 29 layers × (18 × 26) cells</td>
<td>Top: natural emissions 100 °C</td>
<td>22 layers × (11 × 17) cells</td>
<td>2.2 km</td>
<td>SUTRA</td>
<td>Mesh</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2² 29 layers × (18 × 26) cells</td>
<td>Top: natural emissions 100 °C</td>
<td>22 layers × (11 × 17) cells</td>
<td>2.2 km</td>
<td>SUTRA</td>
<td>Mesh</td>
</tr>
</tbody>
</table>

(continued from Table 17, p. 153)

(f) SUTRA - Saturated-Unsaturated TRAnsport.
(h) Mesh refined at the sea level layers.
(i) 7 sides polygonal area: 2 × 3 × 2 × 3 × 2 × 3 × 1.5 × 1.5 km
Table 19: Extended review: numerical model simulations - Part III (after [164]).

(continued from Table 18, p. 154)

<table>
<thead>
<tr>
<th>Field name and ref.</th>
<th>Simulation</th>
<th>Software</th>
<th>Geometry</th>
<th>Mesh</th>
<th>Conditions and parameters</th>
<th>Calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pauzhetsky-Kamchatka, Russia [186]</td>
<td>Natural state</td>
<td>TOUGH2</td>
<td>3D: polygonal (i)</td>
<td>3 layers (424 blocks, only 294 active)</td>
<td>Top: atm. T, p; nat. emissions (100 °C)</td>
<td>iTOUGH2: T, p, nat. emissions, nat. recharge (T, p, k, φ)</td>
</tr>
<tr>
<td></td>
<td>Hist. match. (36 y)</td>
<td>iTOUGH2</td>
<td>thick.: 0.85 km</td>
<td>Double φ model</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A-Mesh</td>
<td>(100÷750 m asl)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lateral BC: impermeable, constant T, p</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Bottom: heat flux 63 mW/m², nat. recharge 224 kg/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Hist. match.: prod. wells (T, p), φ, k fractures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ogiri, Japan [188, 189, 190]</td>
<td>Natural state</td>
<td>TOUGH2</td>
<td>3D: 5.5 × 3.9 km²</td>
<td>7 layers × (23×11) cells (1771 blocks)</td>
<td>Top: T=75 °C, p=0.0981 MPa</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hist. match.</td>
<td>iTOUGH2</td>
<td>thick.: 2.85 km</td>
<td>(a) (l) cell size: 0.1÷3 km (l. thick.: 0.1÷1.6 km)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(250÷2600 m)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lateral BC: impermeable, adiabatic</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Bottom: heat flux 43.2 mW/m² (432 mW/m², S), total heat in 19.5 MW (260 mW/m² avg.); nat. recharge: (E) 30 kg/s (240 °C), total inflow 31.4 MW); 55 kg/s (1062.7 kJ/kg, inflow 58.4 MW), production area.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Olkaria, Kenya [191]</td>
<td>Nat. state (10⁴ y)</td>
<td>TOUGH2</td>
<td>3D: polygonal</td>
<td>5 layers × 158 cells</td>
<td>Top: atm. cond. (e), natural emissions (vapour) 366 kg/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(120 km²) (m)</td>
<td>thick.: 2.55 km</td>
<td>(790 blocks)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2000÷550 m asl)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lateral BC: E-W impermeable,</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N p=45 bar, S p=25 bar (1075 m asl)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Bottom: nat. recharge 1253 kg/s (6 blocks), 1600 kJ/kg (avg.); fluid loss 958 kg/s.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(continue)</td>
<td></td>
<td></td>
<td>k (b) nat. recharge</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(l) MINC model applied to the main fault of the geothermal system (MINC - Multiple INteracting Continua).
(m) 7 sides polygonal area: 11 × 11 × 5 × 9 × 10 × 2.5 × 6 km²
Table 20: Extended review: numerical model simulations - Part IV (after [164]).

<table>
<thead>
<tr>
<th>Field name and ref.</th>
<th>Simulation Software</th>
<th>Geometry</th>
<th>Mesh Conditions and parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onikobe, Japan</td>
<td>RANGER</td>
<td>3D: 6,5 × 8 km</td>
<td>Top: atm. cond. (T=10°C), nat. recharge</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16 layers × (9 × 10) cells</td>
<td>Bottom: heat flux 175 mW/m², nat. recharge 10 kg/s (330°C) production area</td>
</tr>
<tr>
<td></td>
<td>Hist. matching (21 y)</td>
<td>STAR</td>
<td>Evolution (50 % 1 case)</td>
</tr>
<tr>
<td></td>
<td>STAR thick.: 2,4 km (1540 blocks)</td>
<td>(a) (g) (l)</td>
<td>Lateral BC: N-E impermeable and nat. recharge</td>
</tr>
<tr>
<td></td>
<td>[192]</td>
<td></td>
<td>(o) (p) First six layers reproduce orography.</td>
</tr>
<tr>
<td>Poihipi - Wairakei,</td>
<td>TOUGH2</td>
<td>porous/homogeneous media</td>
<td>Production area and nat. recharge 10 kg/s (330°C) multiple faults/reefs (4)</td>
</tr>
<tr>
<td>New Zealand</td>
<td>iTOUGH2</td>
<td>double faults/reefs (4)</td>
<td>Bottom: heat flux 175 mW/m², nat. recharge</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AWTAS (n)</td>
<td>Evolution (10 % 1 case)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>iTOUGH2 double</td>
<td>(b) (m) fractional dimension model</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WELSIM</td>
<td>(c) (f)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TOUGH2</td>
<td>Prod. wells</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AWTAS (m)</td>
<td>Prod. wells</td>
</tr>
<tr>
<td>Sumikawa, Japan</td>
<td>STAR</td>
<td>3D: 3.3 × 5 km²</td>
<td>Top: atm. cond. (T=10°C), nat. k(b)</td>
</tr>
<tr>
<td></td>
<td>STAR</td>
<td>16 layers × (9 × 10) cells</td>
<td>Bottom: heat flux 400 mW/m² (tot 6 MW)</td>
</tr>
<tr>
<td></td>
<td>[194]</td>
<td></td>
<td>Evolution (50 % 1 case)</td>
</tr>
<tr>
<td></td>
<td>STAR</td>
<td>2,8 km (1440 blocks)</td>
<td>Vapour emissions nat. recharge (1200÷-1600 m asl)</td>
</tr>
<tr>
<td></td>
<td>[195]</td>
<td></td>
<td>Lateral BC: E-W impermeable and nat. recharge</td>
</tr>
<tr>
<td></td>
<td>STAR</td>
<td>(o) (p)</td>
<td>Lateral BC: E-W impermeable and nat. recharge</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[199]</td>
<td>Nat. state (3.179)</td>
</tr>
<tr>
<td></td>
<td>AWTAS - Automated Well-Test Analysis System.</td>
<td>(a) (g) (l)</td>
<td>Lateral BC: E-W impermeable and nat. recharge</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(b) (m)</td>
<td>fractional dimension model</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(c) (f)</td>
<td></td>
</tr>
</tbody>
</table>

(continued from Table 19, p. 155)
The sustainability of a geothermal project also deal with economic issues. Risk assessment is probably the main aspect, in terms of economic and financial involvement. In this chapter the thermoeconomic analysis of both the geothermal energy conversion systems (power plant) and the global “geothermal system” is discussed. For the analysis described in this chapter Gianmarco Tedesco has to be acknowledged, for his work on his Master Degree Thesis\(^1\) in Energy Engineering at the University of Pisa, under my supervision and of prof. Alessandro Franco.

The point is that if thermoeconomic analysis of the power plant is made in the preliminary stage, this would open different strategies about (particularly) the power output and extraction rate. The evaluation of the global feasibility of a project should then take into account not only economic, but also thermoeconomic issues, depending also on on the type of plant considered. This aspect is strictly connected with the possibility of standardization of the technology of (for example) ORC geothermal plants (see also section 2.1.4, p. 31).

Due to the large development that is expected for these resources and the sustainability issues described in the previous chapters, one should evaluate the competitiveness of geothermal energy utilization under specific conditions and through this point of view too. A comparison should be then made between geothermal energy and other renewable resources, always considering the different areas of coverage and utilization.

According to Sanyal (2004) \(^{[196]}\) the factors that affect the geothermal energy cost can be grouped as:

a) economy of scale

b) well productivity characteristics

c) development and operational options

d) macro-economic climate

The evaluation of the specific cost of the electricity produced is not a trivial task, particularly for medium-low temperature resources, due to the great number of variables and sensitivity of the efficiency to external parameters.

\(^{1}\) At the moment of the final release and printing of this work the Thesis of G. Tedesco is still in progress. The provisional title of the Thesis is “Analisi termoeconomica di impianti geotermoelettrici per l’utilizzazione di risorse geotermiche a media entalpia”, original in Italian.
5.1 GEOTHERMAL ENERGY COSTS: A BRIEF REVIEW

An evaluation of the costs of the energy produced from geothermal resources is here presented. Also the impact on the global economic feasibility, depending on the specific (natural and economic) context is treated. All the factors affecting the specific cost of geothermal energy conversion are analyzed and linked to the technical and geological-geophysical issues previously presented in this work.

The specific cost of the electricity or Levelized Energy Cost (LEC) is the sum of investment cost \( (c_Z) \), O&M (Operation and Management) cost \( (c_{O&M}) \), make-up wells cost \( (c_{MW}) \), plant cost \( (c_{pp}) \), and inhibitors cost \( (c_{inhib}) \) (see Sanyal, 2004 [196]):

\[
LEC = c_Z + c_{O&M} + c_{MW} + c_{pp} + c_{inhib}
\]

(109)

The LEC is equal to the \( C_{in} \) further described in Eqs. 136–138, being the sum of the effective costs. In section 5.2.3 it is shown that a geothermal plant is economically convenient if the \( C_{in} = LEC \) is less than the maximum cost \( C_{max} \) deriving from a thermoeconomic balance.

The evaluation of the LEC is a very difficult task, particularly for moderate temperature geothermal resource utilization. The data are not immediately evident, but a preliminary cost assessment can be seen as a part of an iterative process for decision making about the operative parameters of the plant. For example the wells productivity (deliverability) strongly affects the specific cost, and it varies with time. It can be considered constant until the time when make-up well drilling became necessary to restore productivity (namely \( t_c \)). The productivity is kept constant by the make-up wells until \( t_d \), but after a decline starts.

**Investment cost**

This cost component can be usually evaluated by an exponential law, assuming that

\[
c_Z = c_d \cdot P
\]

(110)

where \( P \) is the total power output, and the specific costs, \( c_d \) (M€/kW) indicates an exponential decline trend with power output (after [196])

\[
c_d = 3000 \cdot e^{-0.003(P-5)}
\]

(111)

so that small plants require high investment capital costs. This is conservative if referred to the general calculations presented below\(^2\).

According to Stefánsson (2002) [199] the investment costs can be divided into surface costs and underground costs. Surface costs are mainly referred to the power plant (energy conversion system), while the underground costs deal mainly with the drilling operations (see section 5.1.1). Exploration costs, in case of medium-small plant size (5–10 MW), are usually a relatively little component, if dealing with already known fields. Anyway the exploration and geothermal plants development is now focusing on unknown or not developed fields, so that the exploration costs would have more importance in the future.

\(^2\) In the original version [196] of Eq. 111 the coefficient was 2500, but it has been increased to take into account the cost time-discounting since 2004.
O&M cost

Also the \( c_{O&M} \) trend is an exponential decline [196]:

\[
c_{O&M} = 3 \cdot e^{-0.0025(P-5)}
\]  

(112)

In the original formula the coefficient was 2, but a time-discounting since 2004 has been considered. Operation and management specific cost can be divided into two components

\[
c_{O&M} = c_{of} + c_{ov}
\]  

(113)

one constant respect to power output variations (\( c_{of} \)) and one dependent on the output (\( c_{ov} \)).

Make-up wells cost

The make-up wells cost can be indicated by a complex function of the initial number of wells, the specific cost per well, the annual energy produced by the plant, and the decline rate of productivity of the other wells. In the following analysis this cost item is neglected, having adopted more conservative trends for the investment costs (and also due to a lack of data about make-up wells for the case studied).

5.1.1 Evaluation of the drilling cost

Drilling costs can represent the 50% of the global geothermal project cost [199]. In case of a low-temperature geothermal project (for direct use) the drilling cost is typically about 10% — 20% of the total development cost, while for high-temperature fields it is usually in the range 20% — 50% of the total cost (Stefánsson, 2002 [199]). In [199] an interesting review of case studies (mainly from Iceland) is presented, together with estimation of cost equations for both known fields and developing fields. In EGS (Enhanced Geothermal System) projects perforation costs would also reach 42% — 95% of the whole initial cost.

The components of the cost of geothermal wells are essentially five:

- pre-drilling (movement and transport of the drilling tools)
- casing and cementation
- “rotating” costs due to the shaft rotation and machinery use (running of the perforation)
- non-“rotation” costs (post-drilling operations, drill stopped, evaluation and check of the well)
- other costs (e.g. blocked tubings, fluid losses, structural or cementation problems)

An interesting report by MIT\(^3\) (2006) reviews a wide range of drilling technologies and costs [200]. In Table 21 the estimates of drilling costs for EGS projects wells are

---

listed, divided into shallow, mid range and deep wells, according to the report by MIT [200]. In the same report the definitions and evolutions of some drilling cost indexes are given (deriving from oil & gas industry). The *MIT Composite Drilling Cost Index* (MIT index) is only referred to the 1977 experience and gives yearly evolution of the drilling cost. The *MIT Depth Dependent* (MITDD index) is also function of the depth and it is more accurate than the MIT index [200].

An interesting synthetic study about the drilling cost calculation (deriving from oil & gas industry) in available in Shevenell, 2012 [201]. Four models are described, all of them being function of the depth. In the following equations (Eqs. 114 – 117) the depth $z$ has to be converted in feet, while the costs are in US $.

- **Mansure, 2005** [202]
  \[ \log(C_{\text{well}}) = 3.882 \cdot z^{0.0558} \]

- **Augustine, 2006** [203]
  \[ \log(C_{\text{well}}) = 4 \cdot 10^{-9} \cdot z^2 + 5 \cdot 10^{-5} \cdot z + 5.3262 \]

- **Klein, 2004** [204]
  \[ \log(C_{\text{well}}) = 4.0883 \cdot z^{0.0551} \]

- **Bradys**
  \[ \log(C_{\text{well}}) = 3.988 \cdot z^{0.0485} \]

These equations are used for the analysis of the case studies presented in the next section. In Fig. 118 their trend with depth (m) is shown.

**Table 21.** EGS well drilling cost estimates (in 2004 U.S. $) from [200].

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Casing strings (no.)</th>
<th>Cost (M$)</th>
<th>Depth (m)</th>
<th>Casing strings (no.)</th>
<th>Cost (M$)</th>
<th>Depth (m)</th>
<th>Casing strings (no.)</th>
<th>Cost (M$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>4</td>
<td>2.3</td>
<td>4000</td>
<td>4</td>
<td>5.2</td>
<td>6000</td>
<td>5</td>
<td>9.7</td>
</tr>
<tr>
<td>2500</td>
<td>4</td>
<td>3.4</td>
<td>5000</td>
<td>4</td>
<td>7.0</td>
<td>6000</td>
<td>6</td>
<td>12.3</td>
</tr>
<tr>
<td>3000</td>
<td>4</td>
<td>4.0</td>
<td>5000</td>
<td>5</td>
<td>8.3</td>
<td>7500</td>
<td>6</td>
<td>14.4</td>
</tr>
<tr>
<td>10000</td>
<td>6</td>
<td>20.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.1.2 Evaluation of the plant cost

As a part of the investment also the plant cost has to be considered. This can be estimated according to Bejan et al., 1996 [195]. The plant cost is compared to a reference plant, of known power output and cost, which has to be similar to the case studied. The reference plant considered for the following analysis is the binary plant of Magma-max (California, USA), data from DiPippo 2008 [16], chapter 18. Its
size is 11 MW, with a cost (referred to 1980) of about 15 M$ (US). This value can be actualized up to about 29,3 M€. Considering 20 years as reference time interval for the analysis, a linear distribution of 1,5 M€ can be considered (increased from the actual 1,4 M€). According to Bejan et al. the cost of the plant $C_{pp}$ is given by [195]

$$C_{pp} = C_{pp}^* \left( \frac{P}{P^*} \right)^{0.6}$$

(118)

where the annual cost of the reference plant (Magmamax) $C_{pp}^*$ is equal to 1,5 M€, while the reference power size $P^*$ is 11 MW.

Also inhibitors have to be considered in the composition of the total cost of a plant, so that an item $C_{inhib}$ should possibly be considered. In the following analysis a linear specific cost is used for some of the case studied.

Considering total costs instead of specific item costs, the effective cost balance is then given by the following equation:

$$C_{in} = C_Z + C_{O&M} + C_{pp} + C_{inhib}$$

(119)

5.2 INTRODUCTION TO THERMOECONOMIC OPTIMIZATION

The thermodynamic optimization of energy systems is a well known practice in engineering [195]. Energy systems development should take into account also economics (mainly costs and medium-long term evaluation). The thermoeconomic approach to engineering problems is an useful instrument of synthesis between thermodynamic optimization and economics. In this section a brief outline about this approach and analysis is given.
For the classic thermal and energy systems a huge literature exists (see Bejan et al. 1996 [195]). The exergy balance of geothermal energy conversion systems is here treated, and further evaluations of the performances are discussed. The classical exergy balance for an energy system can be written as:

$$\dot{E}_i + \dot{E}_q = \dot{E}_e + W + I$$

(120)

where $\dot{E}_i$ and $\dot{E}_e$ are respectively the exergy fluxes that enter and exit the system. $\dot{E}_q$ is the exergy due to heat exchange, $W_x$ is the useful power produced by the system, and $I$ is the flux of the irreversibilities. These fluxes can be written also by referring to the mass streams:

$$\dot{E}_i = \sum_{i}^{IN} (\dot{m}_i \varepsilon_i) \quad \dot{E}_e = \sum_{i}^{OUT} (\dot{m}_i \varepsilon_e)$$

(121)

Specific exergy term $\varepsilon$ is the sum of the four components: physical exergy, chemical exergy, potential exergy and kinetic exergy, according to the following equations:

$$\varepsilon = \varepsilon_{ph} + \varepsilon_0 + \varepsilon_p + \varepsilon_k$$

(122)

$$\varepsilon = (h - T_0 s) - (h_0 - T_0 s_0) + \varepsilon_0 + gz + \frac{c^2}{2}$$

(123)

The subscripts “0” indicate the reference state (environment); $h$ and $s$ are, respectively, the specific enthalpy and the specific entropy; $c$ is the velocity (taking $c_0 = 0$ as reference value) and $z$ is the altitude (referred to a reference). $Q_r$ is the thermal power exchanged, at the temperature $T_r$. The irreversibilities flux (or exergy destruction) has the form

$$I = T_0 \left( \sum_{i}^{OUT} (\dot{m}_i s) - \sum_{i}^{IN} (\dot{m}_i s) - \sum_{r} \frac{Q_r}{T_r} \right) = T_0 \dot{S}_{gen}$$

(124)

The attention is here focused only on thermoeconomic aspects, energy and exergy flux costs. Exergy efficiency can be used, for example, to evaluate somehow the economic feasibility of an energy conversion system. The integration of this aspect with the global methodology proposed in this work is one of the tasks of this chapter.

Thermoeconomic requires a further balance equation respect to the classical mass and energy transport equations: the cost balance equation.

Two main levels of analysis can be individuated:

- detailed optimization (exergonomic)
- global system optimization (thermoeconomic)

The first approach is referred to an optimization of the exergy and money fluxes of each component. A large number of informations about the several components of an energy system must be known.

According to the second approach a system can be seen under an overall point of view, considering its global energy, exergy and money fluxes and balances. This “black box” approach would be more useful for the purposes of this work, in order to
elaborate some outlines for a thermoeconomic approach to the sustainability assessment of different types of geothermal power plants. The thermoeconomic approach is here also applied to the economic feasibility of the plants under some market context hypothesis.

A brief introduction to Exergonomic and Exergoenvironemtal analysis is presented in Appendix C (p. 233).

5.2.1 Thermoeconomic approach

The thermoeconomic approach allows to consider also different thermodynamic systems and compare them (under well defined hypothesys). The task proposed here is to consider the whole system optimization (in terms of resource durability and technical-economical feasibility), instead of studying each single component of the plant. The exergonomic optimization should follow the thermoeconomic one, as a second level type of analysis.

5.2.2 Approaches to the definition of the cost balance equation

According to the type of power plant, different ways of cost balance definition can be adopted. There exist both exergonomic methods and higher system-level methods.

A valid method proposed in literature is the one named SPECO, by Lazzaretto and Tsatsaronis (2006) [198], which is based on the Specific Exergy Costing (SPECO) approach. The three basic steps of the SPECO method are: (i) identification of exergy streams; (ii) definition of “fuel” and “product”; (iii) cost equation (energy specific €/GJ, in order to obtain money fluxes €/h. With reference to the second step, a definition of “fuel” and “product” should be given. “Fuel” is every flux that enters into the k-th element and losses exergy into the component (e.g.: an hot fluid flux into an heat exchanger). “Product” is every stream that exits from the system increasing its exergy content.

In Fig. 119 a scheme of the generic k-th element with different input and output is shown. The difference between fuel and product is indicated by an increase or decrease of the exergy content of the stream. In Fig. 119 the streams 1 and 2 are clearly, respectively, a “fuel” and a “product”, because they clearly enter or exit into/from the system. Stream 3 is a “fuel” because its exergy content decreases from the inlet to the exit of the k-th element. Stream 4 is a “product” because its exergy content (as difference $\dot{E}_{4e} - \dot{E}_{4i}$) increases.

Exergy costing balances are formulated for each component separately. For the k-th component, the sum of cost rates associated with all exiting exergy streams equals the sum of cost rates of all entering exergy streams plus the appropriate charges (cost rate) due to capital investment and operation and maintenance expenses. The sum of the last two terms is denoted by $\dot{Z}$. According to this approach, in case of a k-th component receiving a heat input and generating power this can be expressed as

$$
\sum_{e}^{\text{OUT}} (c_{e} \dot{E}_{e})_{k} + (c_{W} \dot{W})_{k} = (c_{q} \dot{E}_{q})_{k} + \sum_{i}^{\text{IN}} (c_{i} \dot{E}_{i})_{k} + \dot{Z}_{k}
$$

Equation (125)
For a $k$-th element with $N_e$ exergy fluxes there is only one balance cost equation, $N_e - 1$ more auxiliary equations have to be defined [198]. *Principle “F”* and *principle “P”*, as defined in literature, help in finding this further equations.

**Figure 119.** “Fuel” and “product” streams referred to the generic $k$-th element.

5.2.2.1 *Principles “F” and “P”*

*“F” principle*  The specific cost of the fuel (cost per exergy unit) is constant from the entry to the exit of the $k$-th component. There is a number of equations equal to the number of fluxes degrading exergy.

*“P” principle*  The specific cost of the products is defined by the ratio between the difference of the cost fluxes from entry to exit of the $k$-th element, and the difference between the exergy from entry to exit of the $k$-th element (see Eq. 129).

These principles take their name from the “fuel” and “product”, as described above [198]. Let us refer to Fig. 119 to obtain the cost balance equation of the $k$-th element and its exergy fluxes. The exergy associated to the fuel ($\dot{E}_F$) and product ($\dot{E}_P$) fluxes is given by

$$\dot{E}_F = \dot{E}_1 + (\dot{E}_{4i} - \dot{E}_{4e})$$  \hspace{1cm} (126)  

$$\dot{E}_P = \dot{E}_3 + (\dot{E}_{3e} - \dot{E}_{3i})$$  \hspace{1cm} (127)  

The “$F$” principle gives that

$$c_{4i} = c_{4e}$$  \hspace{1cm} (128)  

while according to the “$P$” principle one can write

$$c_{3i} = c_{3e} = \frac{\dot{C}_{3e} - \dot{C}_{3i}}{\dot{E}_{3e} - \dot{E}_{3i}}$$  \hspace{1cm} (129)  

The cost balance equation referred to the scheme of Fig. 119, according to Eq. 125, is then

$$\dot{C}_2 + \dot{C}_{3e} + \dot{C}_{4e} = \dot{C}_1 + \dot{C}_{3i} + \dot{C}_{4i} + \dot{Z}$$  \hspace{1cm} (130)  

The cost fluxes of the products (exit streams) can then be evaluated by the balance (from Eq. 127 and Eq. 130)

$$c_P \dot{E}_P = \dot{C}_1 + (\dot{C}_{4i} - \dot{C}_{4e}) + \dot{Z}$$  \hspace{1cm} (131)
5.2.3 Thermoeconomic assessment of energy systems

Referring to a k-th element of a plant (identified also by its fuel and product fluxes as defined above), the concepts and cost balance described can be then applied.

To write the exergy balance referred to the k-th element let us define the concept of destroyed exergy $\dot{E}_D$ and lost exergy $\dot{E}_L$. $\dot{E}_D$ is the exergy dissipated inside the component, it corresponds to the irreversibility term $\dot{I}$ of Eq. 120 and Eq. 124, while $\dot{E}_L$ is the flux due to discharge to the environment. According to this aspect the exergy balance for the k-th element can then be written as (see Fig. 120)

$$\dot{E}_{F,k} - \dot{E}_{P,k} = \dot{E}_{D,k} + \dot{E}_{L,k}$$ (132)

The exergetic efficiency $\xi_k$ can be then defined as

$$\xi_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}}$$ (133)

![Figure 120: Exergy streams referred to the generic k-th element.](image)

Let us consider again the example balance of Eq. 131, referred to Fig. 119. The specific cost of the products ($c_P$) can be obtained by dividing the Eq. 131 by the quantity $\dot{E}_P$. It can be seen as the sum of two terms: one related to the fuel $c^F_P$, and one due to the investment cost $c^Z_P$

$$c_P = \frac{\dot{C}_1 + (\dot{C}_{4i} - \dot{C}_{4e})}{\dot{E}_P} + \frac{\dot{Z}}{\dot{E}_P} = c^F_P + c^Z_P$$ (134)

The component $c^F_P$ of k-th component can be linked to the exergy efficiency $\xi_k$ defined in Eq. 133

$$c^F_P = c^F_P \frac{\dot{E}_F}{\dot{E}_P} = \frac{c^F_P}{\xi_k}$$ (135)

where $c^F_P$ is an average value between the specific cost of stream “1” and specific cost of stream “3” (which is equal from entry to exit because of the F principle). From Eq. 135 and keeping $c_P$ constant (Eq. 134) one can see that if $\xi_k$ increases, then $c^F_P$ diminishes, leading to an increase of the investment specific costs $c^Z_P$. This is clearer
if considering the fact that a very efficient component requires high investment costs, at the contrary of a scarcely efficient component.

The cost of irreversibilities has to be mentioned in the balance cost equations. In Fig. 121 the two balance schemes are shown. Irreversibility cost is indicated between the inputs to the cost balance, while it is an output in the exergy balance. The lost income is then calculated as a cost. In the Fig. 121 let us call $C_I$ the cost of the irreversibilities, and $\dot{E}_{in} = \dot{m}_{in} \varepsilon_{in}$ the exergy stream entering into the system. The final balance cost equation of the system is then

$$c_{fuel} E_{in} + C_{in} + c_I I = p_{en} E_{out}$$

(136)

![Energy conversion system](image)

(a) Exergy fluxes

![Energy conversion system](image)

(b) Thermoeconomic fluxes

**Figure 121.**: Exergy and thermoeconomic balance for an energy system.

When considering a renewable energy system, in which one can put $C_{fuel} = 0$, the system is considered suitable from a thermoeconomic point of view only if

$$C_{in} < C_{max} = p_{en} E_{out} - c_I I$$

(137)

where $C_{max}$ is the maximum sustainable (or affordable) cost. If time specific quantities are considered (being $t$ the reference time interval), the Eq. 137 becomes

$$C_{in} < C_{max} = (p_{en} \dot{W} - c_I \dot{I}) t$$

(138)

and $C_{in}$ can be considered as the maximum sustainable cost referred to the time interval $t$.

Considering the energy price, the primary energy source cost and the plant cost, a "gain factor" $f_g$ can be defined [197]

$$f_g = p_{en} \dot{W} - c_{fuel} \frac{E}{\eta} - \sum C_{comp}$$

(139)
\(p_{en}\) and \(c_{fuel}\) indicate respectively the minimum energy price and the specific cost of the “fuel” (both terms are cent\(\mathbf{€}/\text{kWh}\)). \(W\) is the output of the plant, while \(C_{\text{comp}}\) is the cost of the plant components (\(\mathbf{€}\)).

Considering renewable energy systems one can assign a null cost to the primary energy source (specific cost of the “fuel”). The gain factor \(f_g\) would then be always higher in these cases. Anyway geothermal energy is different form other renewable resources (for example sun or wind): its renewability is dependent on several factors, also technological and due to the exploitation strategy (see chapter 1, p. 1 and chapter 2, p. 15). This assumption of null energy source cost (in case of geothermal energy) can also be reviewed, in order to better comprehend technical-economic feasibility and sustainability assessment.

It appears to be important how the specific price is assigned to an energy output according to the National or Regional energy price policies and regulations. This issue is valid also in case of thermal power output (e.g. district heating). National/Local energy policies, electric grid and market planning are important external factors that have to be considered when evaluating the feasibility of a geothermal plant.

A brief introduction to Exergonomic and Exergoenvironmental analysis is presented in Appendix C (p. 233).

5.2.4 “Modified” power and extraction rate

Let us now introduce the concepts of “modified” power \(W^*\) and “modified” extraction rate \(\dot{m}_{geo}^*\). They indicate the values of power output and extraction flow rate necessary to balance the effective costs \(C_{in}\). In the following case studies the \(C_{in}\) is always higher than the maximum sustainable cost \(C_{\text{max}}\) (except the case of Miravalles). \(W^*\) is then the power output corresponding to the \(C_{in}\) value, while \(\dot{m}_{geo}^*\) is then the extraction mass flow rate associated to the \(W^*\) value. In other words \(W^*\) and \(\dot{m}_{geo}^*\) give an idea of the production/extraction rate according to the effective costs sustained. They can be calculated keeping \(C_{in} = C_{\text{max}}\) in the Eqs. 137,138. In general \(W^*\) and \(\dot{m}_{geo}^*\) are higher than the real values in case \(C_{in} > C_{\text{max}}\). But in the case of Miravalles (see section 5.4) the \(C_{\text{max}}\) is considered for the calculation of the “modified” power and extraction rate.

In Eq. 138, let us assume, for the hypothesis here described, that

\[
C_{in} = C_{\text{max}} = (p_{en} W^* - c_I \dot{I}) t \tag{140}
\]

The entering exergy rate is equal to the sum of the modified output and the wasted exergy stream

\[
\dot{E}_{in} = W^* + \dot{I}^* \tag{141}
\]

and \(\eta_{III}\) can be written as

\[
\eta_{III} = \frac{W^*}{\dot{E}_{in}} = \frac{W^*}{\dot{m}_{geo}^* \varepsilon_{in}} \tag{142}
\]
Substituting the expression of $\dot{I}^*$ from Eq. 141 into Eq. 140 then a relation for $\dot{W}^*$ can be derived

$$\dot{W}^* = \frac{C_{in} + c_I t E_{in}}{t (p_{en} + c_I)}$$  \hspace{1cm} (143)

The modified extraction rate can be then calculated as

$$\dot{m}_{geo}^* = \frac{\dot{W}^*}{\eta_{II} \varepsilon_{in}} = \frac{C_{in}}{t \varepsilon_{in} [p_{en} \eta_{II} - (1 - \eta_{II}) c_I]}$$  \hspace{1cm} (144)

As it is shown in the case study presented in this section, the $C_{in}$ can be smaller or higher respect to $C_{max}$ according to the thermoeconomic sustainability level of the energy system. The “modified” power and extraction rate must be referred to the larger cost trend (see Miravalles case study). Then a further condition on the relation of Eq. 144 can be given

$$\dot{m}_{geo}^* = \begin{cases} 
\frac{C_{in}}{t \varepsilon_{in} [p_{en} \eta_{II} - (1 - \eta_{II}) c_I]} & \text{if } C_{in} > C_{max} \\
\frac{C_{max}}{t \varepsilon_{in} [p_{en} \eta_{II} - (1 - \eta_{II}) c_I]} & \text{if } C_{max} > C_{in}
\end{cases}$$  \hspace{1cm} (145)

It is evident that the Eq. 144 has no meaning in case the denominator is negative, so a condition like the following has to be assigned:

$$\eta_{II} > \frac{c_I}{c_I + p_{en}}$$  \hspace{1cm} (146)

This brief introduction to the geothermal energy costs is used in the following analysis. In the next section the thermoeconomic approach is introduced for the plants in order to be integrated with the sustainability assessment.

5.3 MOMOTOMBO CASE STUDY: A THERMEOECONOMIC APPROACH

Another approach for the analysis of the case study of the utilization of Momotombo geothermal field is here proposed. Production history data here used are derived from Porras and Bjornsson, 2010 [144]. For the the time evolution of the field in terms of power output and drilled wells see Fig. 52 and Fig. 53 (p. 97) (from [144]).

Different plants have been used to exploit the Momotombo resource, a single flash unit (35 MW) from 1984 to 1988, two flash units (total 70 MW) from 1989 to 2001, then a binary cycle unit (7.5 MW until 2008) [144]. In 1999 a stronger reinjection rate is adopted (in 1999 Ormat Technologies, Inc. took over the plants). Since 2008 a total reinjection strategy has been adopted. In Fig. 122 the evolution of extraction and reinjection rates during years are shown.

In this section an estimation of the maximum sustainable (or affordable) cost and of the effective costs is given. The missing energy production (respect to the nominal power size) is here considered as a missing income, and a “cost” of 0.1 c€/kWh
is assigned to this gaps (it is the same value as for the selling energy price here hypothesized). The operative costs are then higher when the production is far from the nominal level (of the year considered).

5.3 Thermoeconomic assessment

From the entering exergy stream and the missing production it is possible to evaluate the maximum sustainable cost, according to Eqs. 137–138. In the missing power production (compared to the entering stream) also the irreversibilities are involved. A “cost” of 0,05 €/kWh is associated to the missing production (irreversibilities or missing output for different unknown reasons). The price of energy is also here assumed 0,1 €/kWh, considering 8000 working hours per year.

In Table 22 the data about nominal power, missing production, and annual energy are shown, the last column is the maximum cost, to be then compared with the effective cost evaluated in the following.

To calculate the $C_{in}$ the sum of the items discussed in section 5.1 is considered: investment costs $C_Z$ (20 years is the interval considered to distribute the investment over), O&M costs $C_{O&M}$, plant costs $C_{pp}$ (estimated according to Bejan et al., 1996 [195], see section 5.5.2), inhibitors costs $C_{inhib}$ (equal to 0,175 c€/kWh). The estimated effective costs per year are given in Table 23.

Comparing the effective cost and the maximum affordable cost it can be seen that the effective costs follow the theoretical power, in terms of investments and plant cost, although if the plant is not running. This is the reason because of the $C_{in}$ trend in Fig. 123, compared with $C_{max}$.

Let us now consider a more severe point of view, affected by a more severe approach. If the assumption about the missing production respect to the nominal power installed is now considered, it is possible to consider also the “cost” due to...
Table 22.: Thermoeconomic analysis, Momotombo: power (nominal, missing) and energy production, $C_{\text{max}}$ estimation.

<table>
<thead>
<tr>
<th>Year</th>
<th>Nominal $\dot{W}$ (MW)</th>
<th>Effective $\dot{W}$ (MW)</th>
<th>Missing production (MW)</th>
<th>Annual energy (GWh)</th>
<th>$C_{\text{max}}$ (M€)</th>
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</thead>
<tbody>
<tr>
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<td>35</td>
<td>35</td>
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<td>280</td>
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<td>10</td>
<td>480</td>
<td>44</td>
</tr>
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<td>77,5</td>
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<td>42,5</td>
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<td>35</td>
<td>42,5</td>
<td>280</td>
<td>11</td>
</tr>
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</table>

the gap between nominal and effective power output. A “cost” equal to the selling price is associated to this lack of productivity (0,1 c€/kWh). A comparison with the $C_{\text{max}}$ is given in Fig. 124.

5.3.1.1 “Modified” power and extraction rate

Let us now consider the same analysis of section 5.2.4, about the “modified” power and extraction rate. In the case of Momotombo the modified power estimation gives very tough response about the performances of this power plants group. $\dot{W}^*$ reaches more than 140 MW. This element has to be linked also to periods of low productivity ($\approx$10 MW), without reinjection and with a nominal power installed of 70 MW. This trend lead to $C_{\text{max}}$ reduction and a growth of $C_{\text{in}}$. Resource depletion lead certainly to a lack of productivity (decline of energy production, growth of costs), also for a scarce characterization of the field and reservoir behaviour.
Figure 123.: Comparison between $C_{\text{max}}$ and $C_{\text{in}}$ trends with time (Momotombo).

Table 23.: Thermoeconomic analysis, Momotombo: effective costs estimation.

<table>
<thead>
<tr>
<th>Year</th>
<th>$C_Z$ (M€)</th>
<th>$C_{O&amp;M}$ (M€)</th>
<th>$C_{pp}$ (M€)</th>
<th>$C_{\text{inh}}$ (M€)</th>
<th>$C_{\text{in}}$ (M€)</th>
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</table>
Figure 124.: Comparison between $C_{\text{max}}$ and $C_{\text{in}}$ referred to the missing production respect to the nominal power (Momotombo).

Figure 125.: Comparison between nominal, effective and modified power trends with time (Momotombo).
5.4 **MIRAVALLES CASE STUDY (COSTA RICA): THERMOECONOMIC ASSESSMENT**

The Miravalles geothermal power plant (Costa Rica) is here introduced to evidence a case study in which thermoeconomic sustainability is achieved, through the approach described in this chapter ($C_{in}$ is always less than $C_{max}$).

The Miravalles plant is situated in the Guanacaste province, in the North-Western part of Costa Rica [16, 42]. A 55 MW unit was first run in 1994, since then 53 wells have been drilled, with depths in the range between 900 m and 3000 m (production, reinjection and exploration wells) [205]. The reservoir is water dominated, with an average geofluid temperature 240°C.

**Table 24:** Miravalles case study: power units (from [207]).

<table>
<thead>
<tr>
<th>Unit</th>
<th>Power size (MW)</th>
<th>First run (Year)</th>
<th>Stop production (Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNIT 1</td>
<td>55</td>
<td>3/1994</td>
<td></td>
</tr>
<tr>
<td>WHU 1</td>
<td>5</td>
<td>1/1995</td>
<td></td>
</tr>
<tr>
<td>WHU 2</td>
<td>5</td>
<td>9/1996</td>
<td>4/1999</td>
</tr>
<tr>
<td>UNIT 2</td>
<td>55</td>
<td>8/1998</td>
<td></td>
</tr>
<tr>
<td>UNIT 3</td>
<td>29</td>
<td>3/2000</td>
<td></td>
</tr>
<tr>
<td>UNIT 5</td>
<td>19</td>
<td>1/2004</td>
<td></td>
</tr>
</tbody>
</table>

The data about the evolution of the power units from 1994 to 2006 are here illustrated, from Sánchez-Rivera et al., 2010 [206, 207]. Details about the power units are given in Table 24, where the the power size values do not take into account the auxiliary systems consumptions (gross power rate). In Table 25 the net power output, together with annual energy and efficiencies ($\eta_I$ and $\eta_{II}$) are given for years 1994 to 2006. In Fig. 126 the annual net power value is compared with the lost exergy rate (irreversibilities).

5.4.1 **Evaluation of the thermoeconomic sustainability**

In the case of Momotombo geothermal utilization the gap between nominal power and effective productivity was known. In the Miravalles case study the nominal power is assumed to be equal to the annual value of the net power listed in Table 25. The maximum sustainable can be then calculated, starting from the values of $\dot{I}$ in Table 25, being the difference between the $\dot{E}_I$ and the net power.

Once the exergy streams are estimated the cost balance equation for the Miravalles plants can be built, in order to estimate the maximum sustainable cost. It is possible to calculate the $C_{max}$ as described in Eqs. 137–138, see Table

An interesting review and discussion of the data about the inhibition and scaling removal is available in literature for the Miravalles geothermal reservoir utilization [207, 208, 209]. According to Moya and Nietzen (2010) [207], both a inhibition systems and acid neutralization systems are used. A very interesting evaluation (both
Table 25.: Miravalles case study: annual power and energy output, extraction rate and efficiencies.

<table>
<thead>
<tr>
<th>Year</th>
<th>Net power (MW)</th>
<th>hours/year (h)</th>
<th>Annual energy GWh</th>
<th>(\dot{m}_{geo}(\text{kg/s}))</th>
<th>(\dot{I}(\text{MW}))</th>
<th>(\eta_I(%))</th>
<th>(\eta_{II}(%))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>52</td>
<td>6648</td>
<td>345,7</td>
<td>760</td>
<td>47,6</td>
<td>7,2</td>
<td>27,7</td>
</tr>
<tr>
<td>1995</td>
<td>57</td>
<td>8211</td>
<td>468</td>
<td>780,1</td>
<td>45,3</td>
<td>7,7</td>
<td>29,6</td>
</tr>
<tr>
<td>1996</td>
<td>62</td>
<td>8219</td>
<td>509,6</td>
<td>800,3</td>
<td>42,9</td>
<td>8,1</td>
<td>31,4</td>
</tr>
<tr>
<td>1997</td>
<td>67</td>
<td>8124</td>
<td>544,3</td>
<td>820,4</td>
<td>40,5</td>
<td>8,6</td>
<td>33,1</td>
</tr>
<tr>
<td>1998</td>
<td>119</td>
<td>4973</td>
<td>591,8</td>
<td>1526,3</td>
<td>81,1</td>
<td>8,2</td>
<td>31,6</td>
</tr>
<tr>
<td>1999</td>
<td>114</td>
<td>7051</td>
<td>803,8</td>
<td>1506,1</td>
<td>83,4</td>
<td>8</td>
<td>30,7</td>
</tr>
<tr>
<td>2000</td>
<td>136,5</td>
<td>7164</td>
<td>977,9</td>
<td>1906,1</td>
<td>113,4</td>
<td>7,5</td>
<td>29</td>
</tr>
<tr>
<td>2001</td>
<td>136,5</td>
<td>7229</td>
<td>986,7</td>
<td>1906,1</td>
<td>113,4</td>
<td>7,5</td>
<td>29</td>
</tr>
<tr>
<td>2002</td>
<td>136,5</td>
<td>8210</td>
<td>1120,7</td>
<td>1906,1</td>
<td>113,4</td>
<td>7,5</td>
<td>29</td>
</tr>
<tr>
<td>2003</td>
<td>136,5</td>
<td>8380</td>
<td>1143,9</td>
<td>1906,1</td>
<td>113,4</td>
<td>7,5</td>
<td>29</td>
</tr>
<tr>
<td>2004</td>
<td>152</td>
<td>7930</td>
<td>1205,3</td>
<td>1906,1</td>
<td>131,7</td>
<td>8,4</td>
<td>32,3</td>
</tr>
<tr>
<td>2005</td>
<td>152</td>
<td>7559</td>
<td>1149</td>
<td>1906,1</td>
<td>131,7</td>
<td>8,4</td>
<td>32,3</td>
</tr>
<tr>
<td>2006</td>
<td>152</td>
<td>7566</td>
<td>1150</td>
<td>1906,1</td>
<td>131,7</td>
<td>8,4</td>
<td>32,3</td>
</tr>
</tbody>
</table>

In terms of delivered energy and costs) has been made by the authors, to individuate the advantage of having an inhibition system. The lack of inhibition system would lead to an undelivered annual energy of about 12,8 GWh (61,3 GWh would be the annual production using inhibition). The inhibition system total cost has been estimated to be about 1,53 M$ (in 2010), with an annual cost of about 0,2 M$ (2010) per year [207].

Table 26.: Miravalles case study: maximum sustainable cost evaluation.

<table>
<thead>
<tr>
<th>Year</th>
<th>(p_{en}W) · t (M€)</th>
<th>(c_{I}l) · t (M€)</th>
<th>(C_{max}(M€))</th>
<th>(C_{Z}(M€))</th>
<th>(C_{pp}(M€))</th>
<th>(C_{O&amp;M}(M€))</th>
<th>(C_{in}(M€))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>34,57</td>
<td>15,83</td>
<td>18,74</td>
<td>6,11</td>
<td>3,81</td>
<td>7,15</td>
<td>18,02</td>
</tr>
<tr>
<td>1995</td>
<td>46,8</td>
<td>18,58</td>
<td>28,22</td>
<td>6,8</td>
<td>4,03</td>
<td>9,55</td>
<td>21,33</td>
</tr>
<tr>
<td>1996</td>
<td>50,96</td>
<td>17,63</td>
<td>33,33</td>
<td>7,52</td>
<td>4,23</td>
<td>10,27</td>
<td>22,98</td>
</tr>
<tr>
<td>1997</td>
<td>54,43</td>
<td>16,47</td>
<td>37,96</td>
<td>8,3</td>
<td>4,44</td>
<td>10,84</td>
<td>24,52</td>
</tr>
<tr>
<td>1998</td>
<td>59,18</td>
<td>20,16</td>
<td>39,02</td>
<td>16,16</td>
<td>6,26</td>
<td>10,35</td>
<td>33,72</td>
</tr>
<tr>
<td>1999</td>
<td>80,38</td>
<td>29,41</td>
<td>50,97</td>
<td>16,16</td>
<td>6,1</td>
<td>14,23</td>
<td>37,44</td>
</tr>
<tr>
<td>2000</td>
<td>97,79</td>
<td>40,61</td>
<td>57,18</td>
<td>21,39</td>
<td>6,8</td>
<td>16,37</td>
<td>45,5</td>
</tr>
<tr>
<td>2001</td>
<td>98,67</td>
<td>40,97</td>
<td>57,7</td>
<td>21,39</td>
<td>6,8</td>
<td>18,76</td>
<td>47,89</td>
</tr>
<tr>
<td>2002</td>
<td>112,07</td>
<td>46,54</td>
<td>65,53</td>
<td>21,39</td>
<td>6,8</td>
<td>18,76</td>
<td>47,89</td>
</tr>
<tr>
<td>2003</td>
<td>114,39</td>
<td>47,5</td>
<td>66,89</td>
<td>21,39</td>
<td>6,8</td>
<td>19,14</td>
<td>48,28</td>
</tr>
<tr>
<td>2004</td>
<td>120,53</td>
<td>52,23</td>
<td>68,3</td>
<td>26,68</td>
<td>7,25</td>
<td>19,41</td>
<td>54,29</td>
</tr>
<tr>
<td>2005</td>
<td>114,9</td>
<td>49,79</td>
<td>65,11</td>
<td>26,68</td>
<td>7,25</td>
<td>18,5</td>
<td>53,38</td>
</tr>
<tr>
<td>2006</td>
<td>115</td>
<td>49,83</td>
<td>65,17</td>
<td>26,68</td>
<td>7,25</td>
<td>18,51</td>
<td>53,4</td>
</tr>
</tbody>
</table>

In order to evaluate the effective costs of the plants at Miravalles (according to the literature available) the inhibition and acid neutralization systems costs \(C_{neutr}\) are assumed to be, respectively, 0,57 M€ and 0,38 M€. The effective costs assessment
(from 1994 to 2006) is reported in Table 26, in which the values of $C_{in}$ includes also the inhibition and neutralization systems costs.

It is evident from Fig. 127 (in which the annual trends of $C_{in}$ and $C_{max}$ are shown) that the Miravalles geothermal production is sustainable according to the thermoeconomic approach here considered, as $C_{in}$ is kept always smaller than $C_{max}$. One of the reason is surely linked to the inhibition systems (used since the beginning of the production), which help to reach a higher productivity rate respect to a scenario without any inhibition aor acid neutralization [207, 208, 209].

As for the case study of Momotombo (section 5.3) also for the Miravalles geothermal production the “modified” power can be evaluated. In this case the effective costs are always less than the maximum sustainable (or affordable) costs, then it
would be possible to have a “modified” smaller than the effective one. This is obvious but more important is to evaluate the possibility of producing at higher extraction rates. This could be done implementing a numerical model to understand the reservoir behaviour under a more severe extraction rate. The point is to determine how far from the current equilibrium point the production can be brought without disturbing too much the geothermal system. In other words simulation of this reservoir could give informations about the enhancement of the productivity of the power units.

![Graph showing annual trend of maximum sustainable costs and effective costs](image)

**Figure 128.:** Miravalles case study: annual trend of maximum sustainable costs and effective costs.

5.4.2 Numerical model of Miravalles geothermal field

The author is involved in a study in this direction, developing and enhancing existing models from literature about this field. In Haukwa et al. (1992) [210] the study of the reservoir through a numerical model is shown. Other useful data about this field are available in Parini et al. (1996) [211], and in Vallejos-Ruiz (2010) [212].

As this study is still ongoing here only some outlines about the model and the strategy are illustrated.

The task is to compare the current exploitation scenario (from literature data about the plants operative data) with a different one (more severe) respect to the one described. The sustainability level could be evaluated through a model of the reservoir in which the extraction rate is increased in order to study the resource response.

The material data are still object of calibration, respect to the original model (from literature). The data about the model such as rock properties or boundary conditions are not complete, so that a calibration and integration phase has been done. Only

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6 Gianmarco Tedesco has to be acknowledged, for his work on his Master Degree Thesis in Energy Engineering at the University of Pisa, under my supervision and of prof. Alessandro Franco. At the moment of the final release and printing this work the thesis of G. Tedesco is still in progress, the provisional title is “Analisi termoeconomica di impianti geotermoelettrici per l’utilizzazione di risorse geotermiche a media entalpia”, original in Italian.
few details about the model are here presented, as this topic will object of a future publication in which the author is involved in.

The unperturbed state has been simulated, comparing the temperature distribution obtained with the literature data (simulation end time of $10^6$ years). Then a scenario reproducing the production of the year 2006 has been simulated. The total output is then assumed to be 152 MW, corresponding to an extraction of 1906 kg/s of geothermal fluid (see Table 25).

The second scenario simulated has been elaborated in order to verify the resource sustainability when the extraction is the one given by a condition of equivalence between $C_{in}$ and $C_{max}$.

![Figure 129](image1.png)

(a) Polygonal mesh  
(b) Quadrangular mesh

**Figure 129.** Miravalles case study: numerical model domain.

![Figure 130](image2.png)

(a) Polygonal mesh  
(b) Quadrangular mesh

**Figure 130.** Miravalles case study: Temperature distribution at -200 m b.s.l. with different meshes.
The model is realised with TOUGH2 simulator \[143\], using Petrasim \[129\] (see section 3.2.5).

As the models of the Miravalles geothermal field from literature have a polygonal mesh, in this study both a polygonal and a regular (quadrangular) type of mesh are adopted. The model domain has an extension of \(6 \times 8 \text{ km}^2\), with a thickness of 1,6 km (from 100 m a.s.l. to -1500 m b.s.l.).

The calibration in this phase takes into account the 2D horizontal temperature distribution at -200 m b.s.l. available in Haukwa et al. (1992) \[210\]. In Fig. 130 the temperature distribution at this depth with different meshes are shown.

A more realistic result in term of thermal gradient distribution is achieved with the quadrangular mesh. In Fig. 131 the wells temperature evolution obtained with this mesh are shown.

Figure 131.: Miravalles case study: wells temperature, unperturbed state (quadrangular mesh model).

Figure 132.: Miravalles case study: Scenario I, changes in the temperature profiles near the wells \((t = 50 \text{ years})\), vertical sections at different \(X,Y\) values.
5.4.2.1 Scenario I: numerical simulation for thermoeconomic assessment

The extraction rate in this scenario is the 1900 kg/s mentioned above. The extracted fluid is separated, the vapour phase is expanded in a turbine. The liquid phase feeds the evaporator of a binary cycle unit. Then only the 83% of the fluid is reinjected. Reinjection occurs into “hot” wells at temperatures of 136°C–165°C (specific enthalpy 636,5 kJ/kg) and “cold” reinjection wells at temperatures of 98°C–100°C 98-100 °C (specific enthalpy 414 kJ/kg) [16].

It can be seen from this study which is the resource decline rate due to the current exploitation scenario (I). The temperature decline into the wells is shown in Fig. 133.

![Figure 133: Miravalles case study: Scenario I, production wells temperature.](image)

In 50 years the temperature decline undergoes variations of 14% – 24% for the more productive wells, while a decline of 3% – 8% can be observed in the less productive wells.

5.4.2.2 Scenario II: increased extraction rate

The task of this scenario is to evaluate how an increase of the extraction and production rate would affect the resource behaviour. The Miravalles geothermal production is the only one resulting sustainable from a thermoeconomic point of view considered in this work (Cin < Cmax, see Fig. 127), so the possibility of increase the productivity can be investigated.

To evaluate the increase of extraction the concept of “modified” power and extraction rate can be used. If at the numerator of the Eqs. 143–144 the Cmax is considered, then the resulting \( \dot{W}^* \) and \( \dot{m}^*_{geo} \) values would be referred to the maximum sustainable (or affordable) cost level:

\[
\dot{m}^*_{geo} = \frac{C_{max}}{\epsilon_{in} [p_{en} \eta_{II} - (1 - \eta_{II}) \epsilon_{I}]} \quad \eta_{II} = \frac{\dot{W}^*}{\dot{m}^*_{geo} \epsilon_{in}}
\] (147)

This extraction rate represents then the exploitation level of the reservoir can be considered to be the maximum to be faced by the “geothermal system”. The mass fluid rate extracted in the Scenario II keeps still the plant to be thermoeconomically sustainable, but it is not the one necessary to cover the effective costs.
The maximum power output to be achieved by a plant, according to this assumption is then 172.3 MW (more than the 152 MW of the Scenario I), still being thermo-economically sustainable. Thanks to a numerical model simulation the reservoir response can be studied, in order to verify the environmental sustainability too. A higher extraction rate causes the decline of productivity of the wells (temperature, extraction). Respect to the Scenario I the production is increased in some of the wells (PGM1, PGM5, and PGM10).

The temperature decline is used as criterion to evaluate the resource impoverishment. In Fig. 134 the temperature evolution of the wells resulting from the simulation is shown. A temperature reduction of 39 % can be observed at the well PGM1 in 50 years of simulation time. Temperature reduction at wells PGM5 and PGM10 is, respectively, 31 % and 10 %, while for wells PGM3 and PGM43 the reduction is, respectively, of 5 % and 11 %. In Fig. 135 the temperature decline for wells PGM1 and PGM5 in the two scenarios is shown, a higher exploitation in the second scenario can be observed. This resource decline can cause a lack of productivity of the plants and a deliverability and heat extraction capacity.

Scenario II is not appropriate for a sustainable exploitation strategy, though its extraction rate is at the limit of the thermoeconomic acceptability. It is better to have a working point which keeps a reliability margin (respect to the natural or unavoidable resource decline due to the utilization).

As it is evident the numerical model elaboration for Miravalles is still ongoing. The model will be object of future development and future publications. The results here briefly described are referred to the current state of development and these preliminary hypothesis.

Anyway the case study of Miravalles is significant being the only one here presented to be sustainable under the thermoeconomic assumptions here considered. It is also presented here in order to study how the productivity of a field can be enhanced taking into account both cost items and reservoir behaviour.
Figure 135.: Miravalles case study: temperature drop in Scenario I and Scenario II (wells PGM1 and PGM5).
5.5 CASE STUDIES: APPLICATION OF THERMOECONOMIC APPROACH

5.5.1 Context description

In this section mainly four Turkish power plant case studies are considered, due to the amount of data from literature. Geothermal exploration in Turkey started in the 1960s, firstly focusing on high enthalpy reservoirs [213]. In 1968 the Kizildere field has been explored. Then also the moderate temperature fields of Balcova and Seferihisar have been discovered. In the 1980s the high enthalpy field of Germencik and the medium enthalpy field of Salavatli have been explored. The energy utilization at Kizildere started in 1984, while in 1987 the first district heating grid was launched, using the resource at Gönen field. Some basic data about the Turkish power plants considered in this analysis are listed in Table 27.

The Valle Secolo geothermal power plant (near Larderello, Pisa, Italy) is considered in this section as a comparison. It is an efficient, high enthalpy power plant, with very low cost (mainly O&M) if compared with the others. It is obvious that it is a greater size plant, working with high reliability, with higher number of annual hours working respect to other similar Italian (and also worldwide) plants by a technological point of view. It would not be compared to flash, or combined, or binary plants. But here a matching is given to have an idea of the different order of magnitudes of power/energy production and costs, and to remark quantitatively the difference between the geothermal utilizations.

Also a binary cycle power plant is considered to be compared with the Turkish case studies, having a smaller power size. Bad Blumau (Austria) ORC plant is also described by the Table 3 (p. 36) and Table 4 (p. 36).

The plants used in the analysis here proposed are briefly described in the following sections.

Table 27.: Main data about the case study power plants.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Power (MW)</th>
<th>$\eta_I$ (%)</th>
<th>$\eta_{II}$ (%)</th>
<th>$E_i$ (MW)</th>
<th>Hours per year (h)</th>
<th>Energy (GWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuzla</td>
<td>5,2</td>
<td>14,06</td>
<td>57,7</td>
<td>8,96</td>
<td>8541</td>
<td>1,21</td>
</tr>
<tr>
<td>Dora 1</td>
<td>6,5</td>
<td>12,2</td>
<td>45,9</td>
<td>14,17</td>
<td>8462</td>
<td>55,0</td>
</tr>
<tr>
<td>Dora 2</td>
<td>9,8</td>
<td>9,3</td>
<td>35,8</td>
<td>27,35</td>
<td>7143</td>
<td>70,0</td>
</tr>
<tr>
<td>Kizildere</td>
<td>15,6</td>
<td>12,8</td>
<td>59</td>
<td>26,4</td>
<td>5751</td>
<td>89,6</td>
</tr>
</tbody>
</table>

5.5.1.1 Tuzla geothermal plant

Tuzla power plant is located in an area located in Northwestern Anatolia (Turkey) [214]. The first well was drilled in 1982, at a depth of 333–553 m, reaching fluid at 174 °C. The second drilled well reached 1020 m depth. Two shallow wells have minimum depth of 81 m and 128 m, with temperatures, respectively, of 146 °C and 165 °C [214].
The pH of the geofluid extracted is in the range 5.7—6.5. Scale inhibitors are used, with a flow injection rate of 7 kg/s and having a specific cost of 2.32 €/kg.

A schematic view of the plant is shown in Fig. 136 (after [214]). The geothermal fluid (extracted from wells T9 and T16) is separated into two phases, then it feeds the evaporator, the working fluid is isopentane, which is then expanded in a turbine. The geofluid exits the evaporator and is used to preheat isopentane (before it is sent to the evaporator). The reinjected geofluid stream goes to the wells T10 and T15. Another internal preheater is used, to exchange the residual heat of the expanded isopentane to the condensed stream.

Some main data about the Turkish power plants considered in this analysis are listed in Table 27, while the main wells data are listed in Table 30. The net power produced is 5,165 MW, while the inlet exergy stream (\(\dot{E}_{\text{in}}\)) is 8,96 MW. \(\eta_{\text{II}}\) is equal to 57.7 %, and the irreversibilities (calculated as the difference between the entering exergy stream minus the produced power) are equal to 3.79 MW. For the following analysis the environment temperature is considered \(T_0 = 10^\circ\text{C}\).

Figure 136: scheme of the Tuzla power plant, after [214].

5.5.1.2 Dora 1 - Dora 2

Dora 1 and Dora 2 power plants are associated to the Aydin Salavatli geothermal field, in Turkey. Their net power output is, respectively, 6.5 MW and 9.8 MW (see Table 27).

DORA 1 The plant is situated 22 km far from the city of Aydin, near the cities of Aydin Sultanhisar and Kosk. The average gross power is 7.3 MW, while the total energy output in a year is 55000 GWh [216] (Table 30).

The plant layout is similar to the one of Tuzla (see Fig. 136): binary plant with preheating made with the liquid phase of the separated geofluid. The entering exergy stream is equal to 14.17 MW, \(\eta_1\) is equal to 45.9 %. Irreversibilities (calculated as the difference between the entering exergy stream minus the produced power) are equal to 7.67 MW. \(T_0\) is assumed to be 18°C.
Dora 2  Dora 2 power plant is situated 20 km far from the city of Aydin. First wells were drilled in 1987–1988, at a depth in the range of 962—1510 m [217]. The highest temperature is about 171 °C. The plant is running since 2009, and it has a gross power of 11,2 MW, with an annual energy output of 70000 GWh, having an efficiency (\(\eta_I\)) of 35,8 %. The wells data are available in Table 30. There are two extraction wells (AS3 and AS4) and two reinjection wells (ASR4 and ASR5) [216, 217]. The entering exergy stream is equal to 27,35 MW. Irreversibilities (calculated as the difference between the entering exergy stream minus the produced power) are equal to 17,53 MW. \(T_0\) is assumed to be 18 °C.

5.5.1.3 Kizildere

The plant is situated in the South-Western region of Denizli. A pilot power plant of 0,5 MW was launched in 1984. Nowadays the plant produces 15,58 MW (combined plant, flash with bottoming binary unit) [218, 219]. The average geofluid temperature \(T_{geo}\) is 200 °C. The geofluid undergoes a flash separation and then the vapour phase is expanded in a turbine. The fluid is then sent to an evaporator of a binary cycle. Seventeen wells have been drilled between 1968 and 1986, with depths in the range 370 m – 1241 m (average \(T_{geo}\) in the range 198 °C – 212 °C). Extraction rate \(\dot{m}_{geo}\) is equal to 28,5 kg/s. The extraction wells characteristics are listed in Table 30.

5.5.1.4 Bad Blumau (Austria)

The Turkish power plant are compared with another binary cycle small size power plant, the Bad Blumau (Austria), which produces 250 kW, from the wells having the characteristics listed in Table 28 [220]. \(T_0\) is equal to 8 °C. Other parameters are listed in Table 29.

<table>
<thead>
<tr>
<th>Well</th>
<th>(\dot{m}_{geo}) (kg/s)</th>
<th>(T_{geo}) (°C)</th>
<th>Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraction</td>
<td>BLUMAU 2</td>
<td>30</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td>BLUMAU 3</td>
<td>1,5</td>
<td>47</td>
</tr>
<tr>
<td>Reinjection</td>
<td>30</td>
<td>89</td>
<td>3000</td>
</tr>
</tbody>
</table>

Table 29.: Main data about power plants of Bad Blumau (Austria) and Valle Secolo (Italy).

<table>
<thead>
<tr>
<th>Plant</th>
<th>Power (MW)</th>
<th>(\eta_I) (%)</th>
<th>(\eta_{II}) (%)</th>
<th>(\dot{E}_i) (MW)</th>
<th>Hours per year (h)</th>
<th>Energy (GWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bad Blumau</td>
<td>0,18</td>
<td>1,4</td>
<td>73,5</td>
<td>0,25</td>
<td>6717</td>
<td>1,21</td>
</tr>
<tr>
<td>Valle Secolo</td>
<td>103,6</td>
<td>17</td>
<td>62</td>
<td>170,6</td>
<td>(\approx8000)</td>
<td>828,8</td>
</tr>
</tbody>
</table>
Table 30.: Turkish case studies: data of the wells linked to the power plants.

<table>
<thead>
<tr>
<th>Well</th>
<th>$m_{\text{geo}}$ (kg/s)</th>
<th>$T_{\text{geo}}$ (°C)</th>
<th>Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuzla</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extraction</td>
<td>T9</td>
<td>79,11</td>
<td>156,8</td>
</tr>
<tr>
<td></td>
<td>T16</td>
<td>23,42</td>
<td>164,2</td>
</tr>
<tr>
<td>Reinjection</td>
<td>T10</td>
<td>51,27</td>
<td>90,6</td>
</tr>
<tr>
<td></td>
<td>T15</td>
<td>51,27</td>
<td>90,6</td>
</tr>
<tr>
<td>Dora I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extraction</td>
<td>AS1</td>
<td>75,6</td>
<td>165</td>
</tr>
<tr>
<td></td>
<td>ASR2</td>
<td>72,9</td>
<td>165</td>
</tr>
<tr>
<td>Reinjection</td>
<td>AS2</td>
<td>146</td>
<td>81,7</td>
</tr>
<tr>
<td>Dora II</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extraction</td>
<td>AS3</td>
<td>117,96</td>
<td>176</td>
</tr>
<tr>
<td></td>
<td>AS4</td>
<td>112,54</td>
<td>174</td>
</tr>
<tr>
<td>Reinjection</td>
<td>ASR4</td>
<td>113,85</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>ASR5</td>
<td>113,85</td>
<td>68</td>
</tr>
<tr>
<td>Kizildere</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extraction</td>
<td>KD6</td>
<td>104,2</td>
<td>201</td>
</tr>
<tr>
<td></td>
<td>KD7</td>
<td>70</td>
<td>208</td>
</tr>
<tr>
<td></td>
<td>KD13</td>
<td>115,8</td>
<td>201</td>
</tr>
<tr>
<td></td>
<td>KD14</td>
<td>80,6</td>
<td>210</td>
</tr>
<tr>
<td></td>
<td>KD15</td>
<td>120,8</td>
<td>209</td>
</tr>
<tr>
<td></td>
<td>KD16</td>
<td>117,2</td>
<td>212</td>
</tr>
<tr>
<td></td>
<td>KD20</td>
<td>97,2</td>
<td>204</td>
</tr>
<tr>
<td></td>
<td>KD21</td>
<td>83,3</td>
<td>205</td>
</tr>
<tr>
<td></td>
<td>KD22</td>
<td>97,2</td>
<td>205</td>
</tr>
</tbody>
</table>

5.5.1.5 Valle Secolo (Larderello, Italy)

Valle Secolo power plant is totally different if compared with the plants described in this section. It is associated to the well known field of Larderello-Travale (province of Pisa, Italy). Valle Secolo is a direct expansion power plant, equipped with $H_2S$ and Hg abatement devices (AMIS)\(^7\) [221]. The extracted steam is at about 200 °C. The power output is 103,6 MW, while the wasted exergy is estimated to be 67 MW. Mass flow rates of the extraction and reinjection wells linked to this plant are not available. $T_0$ is equal to 25 °C [222]. Other parameters are listed in Table 29.

Valle Secolo is known to be a very reliable power plant, with a great number of working hours per year. For this reason this is used in the next analysis as a comparison between the medium-low temperature technologies of the aforementioned plants, and a “traditional” geothermal power plant. In the following Tables Valle Secolo is presented as last, divided by a thicker line, as its remarkable differences in terms of efficiency and performance evaluation.

\(^7\) AMIS, acronym from the Italian “Abbattimento Mercurio e Idrogeno Solforato”, which means Hg and $H_2S$ abatement.
5.5.2 Thermoeconomic analysis of geothermal power plants

Knowing the energy and exergy streams in/out from these energy systems, an estimation of the maximum sustainable cost \( C_{\text{max}} \) is carried out (see Eq. 137 and Eq. 138). This cost is then compared to the effective cost \( C_{\text{in}} \) (estimated through the relations of section 5.1, see Eq. 119), being the sum of the three components of Eq. 109: investment cost, O&M cost, plant cost \( C_{pp} \), and inhibitors cost \( C_{\text{inhib}} \). For the investment cost the Eqs. 110–111 are used. The inflation and interest rate are here neglected. The well productivity is considered constant for all the time interval considered in this analysis (20 years). Operation and maintenance (O&M) cost are given by Eq. 112, which is an energy specific cost.

5.5.2.1 Maximum sustainable cost and effective cost

Let us now calculate and compare \( C_{\text{max}} \) with \( C_{\text{in}} \). The specific price of energy \( p_{\text{en}} \) is here assumed to be 0,1 €/kWh. This estimation can be considered surely conservative, respect to the national market policies about renewable energy resources incentive. For the irreversibilities the hypothesized specific cost is

\[
c_I = 0,1 \cdot 0,65 \, \text{€/kWh} = 0,065 \, \text{€/kWh}
\]

being 65 % a weight referred to the exergy destruction. Having the Dora 2 power plant a very low \( \eta_{II} \) a \( c_I \) equal to 0,05 €/kWh is considered, otherwise a negative value of \( C_{\text{max}} \) would result (if \( c_I \) is kept equal to 0,065 €/kWh). Anyway a certain economic unsustainability of this plant would be evident. The results about the calculation of \( C_{\text{max}} \) are shown in Table 31.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Power (MW)</th>
<th>Income ( p_{\text{en}} W ) (M€)</th>
<th>Irreversibilities cost ( c_I ) (M€)</th>
<th>Max. cost ( C_{\text{max}} ) (M€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuzla</td>
<td>5,2</td>
<td>4,41</td>
<td>2,1</td>
<td>2,31</td>
</tr>
<tr>
<td>Dora 1</td>
<td>6,5</td>
<td>5,5</td>
<td>4,22</td>
<td>1,28</td>
</tr>
<tr>
<td>Dora 2</td>
<td>9,8</td>
<td>7</td>
<td>6,26</td>
<td>0,74</td>
</tr>
<tr>
<td>Kizildere</td>
<td>15,6</td>
<td>8,96</td>
<td>4,04</td>
<td>4,92</td>
</tr>
<tr>
<td>Bad Blumau</td>
<td>0,18</td>
<td>0,12</td>
<td>0,03</td>
<td>0,09</td>
</tr>
<tr>
<td>Valle Secolo</td>
<td>103,6</td>
<td>82,88</td>
<td>34,84</td>
<td>48,04</td>
</tr>
</tbody>
</table>

This analysis can be used to focus on the fact that small size plants can not easily defined to be more sustainable respect to greater size plants. Obviously in this analysis environmental benefits are not considered. For this purpose an exergonomic or exergoenvironmental analysis should be done (see Appendix C, p. 233).

The strong difference with the case of Valle Secolo power plant is here evident. Although the power size is higher, \( \eta_{II} \) is also higher and the plant is relatively more simple (no need for secondary circuit).
In this calculations the drilling costs are already considered in the investment costs, they are underground costs, according to Stefánsson (2002) [199]. Drilling costs are listed in Table 32 and also shown in Fig. 137. A graphic comparison between the maximum sustainable (or affordable) cost and the effective cost is shown in Fig. 138.

Table 32.: Thermoeconomic analysis, case studies: effective costs.

<table>
<thead>
<tr>
<th>Plant</th>
<th>C_{Z} (M€)</th>
<th>C_{O&amp;M} (M€)</th>
<th>C_{pp} (M€)</th>
<th>C_{inhib} (M€)</th>
<th>C_{in} (M€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuzla</td>
<td>0,6</td>
<td>1,03</td>
<td>0,95</td>
<td>0,14</td>
<td>2,72</td>
</tr>
<tr>
<td>Dora 1</td>
<td>0,75</td>
<td>1,27</td>
<td>1,09</td>
<td></td>
<td>3,11</td>
</tr>
<tr>
<td>Dora 2</td>
<td>1,12</td>
<td>1,61</td>
<td>1,4</td>
<td></td>
<td>4,13</td>
</tr>
<tr>
<td>Kizildere</td>
<td>1,75</td>
<td>2,03</td>
<td>1,85</td>
<td>0,2</td>
<td>5,83</td>
</tr>
<tr>
<td>Bad Blumau</td>
<td>0,02</td>
<td>0,03</td>
<td>0,13</td>
<td></td>
<td>0,18</td>
</tr>
<tr>
<td>Valle Secolo</td>
<td>8,96</td>
<td>15,06</td>
<td>5,76</td>
<td></td>
<td>29,78</td>
</tr>
</tbody>
</table>

Figure 137.: Costs distribution for the plants considered.

In case of small size power plants the plant cost itself tends to prevail. For the greater size plants investment costs and O&M cost are greater (this is also true and stressed in the case “off-size” of Valle Secolo).

Also through this approach it is evident how the technical and economic sustainability of a geothermal plant strictly depends on the type of resource and power output.

The power specific cost is also higher for small size plants (see Fig. 139), anyway the environmental benefits or incentives are not considered in this conservative analysis.

Cases like the one of Valle Secolo are usually associated to reservoirs with great extension, which allow a huge extraction rate (at a higher enthalpy content of the
fluid). In case of moderate temperature fields\footnote{Particularly in case of new exploration fields, like the one which are now considered interesting by the market and policy institutions (see section 5.6).} huge extraction rates can lead to unsustainability and fast resource depletion.

5.5.2.2 Evaluation of the drilling costs

It has been assumed that the drilling costs are a part of the investment cost (underground costs \cite{199}). The specific investment costs are divided by the number of years of the interval considered (20 years), so also the drilling costs here considered are distributed in this way. Let us now compare the investment cost with the drilling cost as calculated from the equations described in section 5.1.1 (Eqs. 114–116). The Fig. 140 shows the drilling costs calculated according to these relations and compared with investment costs. The Klein relation tends to penalize more the fields in which a lot of perforation activity has been pursued. In these evaluations, also the exploration wells are counted (not only production/reinjection wells).

To better evaluate the weight of drilling on the global cost of the geothermal projects, let us analyze the power specific well cost and the depth specific well cost. The first one refers the cost to the power output of the plant, while the second is related to the depth, see Fig. 141. It is clear that it the drilling of a well linked to a small size plant is more onerous. The real drilling costs trend is not linear (as it could appear from this evaluation). Mansure equation (Eq. 114) is used in Fig. 141, being a compromise between the one by Klein (Eq. 116) and the one by Augustine (Eq. 115) \cite{201}.

5.5.3 “Modified” power and extraction rate

The values of $W^*$ and $\dot{m}_{geo}^*$ (see section 5.2.4, p. 167) calculated for the studied power plant are shown in Table 33. The inlet exergy stream and the working hours are the same used above (see Table 27). The bad performances of the Dora 2 power plant, already observed from the previous Tables, are here evident. About 5.5 times the actual extraction rate and power size would be necessary to make this plant sustainable, according to the conservative hypothesis about market and economic context here considered. The mass flow rate to be extracted according to this analysis is surely unsustainable from an environmental point of view (resource durability oriented approach). The complexity of the geothermal exploitation is stressed also by economic and thermoeconomic observations.

A point to be here underlined, is that an exclusively economic way of decision making about the plant parameters (power size, extraction rate, thermodynamic cycle) is not good if the whole “geothermal system” and its implications are considered. A more advanced approach which takes into account also resource depletion, technical feasibility, and environmental impact should be pursued. Some of the possible decision making tools are described in this work.
Table 33.: Thermoeconomic analysis, case studies: “modified” power and “modified” extraction rate.

<table>
<thead>
<tr>
<th>Plant</th>
<th>$C_{in} = C_{max}$ (M€)</th>
<th>$\dot{m}_{geo}^*$ (kg/s)</th>
<th>$\dot{m}_{geo}$ (kg/s)</th>
<th>$W^*$ (MW)</th>
<th>$W$ (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuzla</td>
<td>2,72</td>
<td>122,2</td>
<td>103,7</td>
<td>6,1</td>
<td>5,2</td>
</tr>
<tr>
<td>Dora 1</td>
<td>3,11</td>
<td>399,4</td>
<td>149,1</td>
<td>17,4</td>
<td>6,5</td>
</tr>
<tr>
<td>Dora 2</td>
<td>4,13</td>
<td>1304,4</td>
<td>244,2</td>
<td>55,3</td>
<td>9,8</td>
</tr>
<tr>
<td>Kizildere</td>
<td>5,83</td>
<td>325,3</td>
<td>274,1</td>
<td>18,5</td>
<td>15,6</td>
</tr>
</tbody>
</table>

Figure 138.: Costs estimation for the plants considered.

Figure 139.: Power specific costs comparison.
Figure 140.: Drilling costs (M€) according to different methods (see section 5.1.1), compared with investment costs.

Figure 141.: Power specific well cost (left axis, €/kW) and depth specific well cost (right axis, €/m).
5.6 REMARKS ABOUT THE CURRENT DEVELOPMENT OF GEOTHERMAL INDUSTRY IN ITALY

The development of geothermal binary cycle power plants appears to be one the aims of different countries worldwide. New players are now interested in the development of this technology. The engineering and service companies are active (as primary players or new entry) in the market of ORCs, also because of the interest in binary plants applications to biomass and waste heat.

In Italy the geothermal resource utilization for electricity has a long history [56]. Anyway the market of geothermal power plants has been controlled since tens of years from one single player (ENEL). The liberalization of the energy market started in 1999\(^9\). Only recently the market of geothermal power production has also been liberalized\(^10\) (2010).

In Italy, at the present time, about 43 applications for geothermal exploration are active according to the Ministry for Economic Development website\(^11\) (Fig. 142), almost all in Latium (25), Tuscany (7), Sardinia (7), Sicily (4), Umbria (4), and Lombardy (1). 43 geothermal exploration concessions have been granted\(^12\), mainly in Tuscany (33), Latium (9), Sicily (1), and Lombardy (1). 10 “experimental plants”\(^13\) instances of permission [54] are in progress, and 13 are the received applications by the Ministry of Economic Development\(^14\).

This could determine a meaningful expansion of geothermal power plants market in Italy, which is historically one of the most important countries for geothermal energy exploitation and tradition. Anyway, by outside the industry, it could appear that both players and legislation are not up-to-date about technology and sustainability assessment of medium-low temperature geothermal projects.

In this work it is shown that, particularly for small size ORC plants, technical-economic and environmental sustainability are not ensured only thanks to the small plant size. The characterization of the resource together with an exploitation strategy based on a numerical simulation of the system (plant-reservoir) can be seen as key factors of this assessment. A high quality environmental impact analysis should be carried out in order to take into account all the possible consequences. Evaluation tools like exergoenvironmental analysis are not implemented in market or institutional backgrounds yet.

The historical presence of a single player\(^15\) has not stimulated any private initiative in the sector. At the same time ENEL has been the main know-how owner in the country, in particular from a technological point of view. Its explorations are a great part of the knowledge of the Italian geothermal resources inventory. On the

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9 Decreto legislativo 16 marzo 1999, n. 79, known as “decreto Bersani” ([http://www.parlamento.it/parlam/leggi/deleghe/99079d1.htm](http://www.parlamento.it/parlam/leggi/deleghe/99079d1.htm)).
13 “Impianti pilota” in Italian.
14 [http://unmig.sviluppoeconomico.gov.it/unmig/info/impianti_pilota.asp](http://unmig.sviluppoeconomico.gov.it/unmig/info/impianti_pilota.asp), some applications are counted twice because they are referred to more than one Region.
other hand a part of this important background is now a company property and
privilege\(^{16}\), so that from an academic point of view there is a lack in terms of diffu-
sion of exploration data. Scaling inhibition and wells management, for example, are
some of the critical knowledge-sharing point (see section 2.3.1.4, p. 49).

In the last three years also foreign investors entered in this “new” market of bi-
nary cycle plants, considering the great number of medium temperature resources
distributed along the Tyrrhenian Italian Regions (mainly Tuscany, Latium, Cam-
pinia, Sicily).

Enel Green Power appears not to be investing so much on the Italian territory
(that means in a massive way, if compared with other competitors or respect to in-
vestments in foreign countries). Anyway the first Italian geothermal binary cycle
power plant will probably be run by ENEL Green Power. It is the Bagnore (Mount
Amiata, Tuscany) binary power plant (1 MW), which future opening has been an-
nounced by Enel Green Power and Exergy (the company which has designed and
manufactured the plant)\(^{17}\).

In this work (in particular in this chapter) a focus on the economic sustainability,
in relation with all the possible technical and management issues, is presented. The
know-how about technical problems (scaling, wrong reinjection strategy) also dur-
ing the initial exploration step, could avoid some wrong investments. It is clear that
an adequate exploration is more economic (also in terms of internal scientific results

\(^{16}\) Enel Green Power was born in December 2008, it is the Enel Group company dedicated to developing
and managing energy generation from renewable sources (http://www.enelgreenpower.com/en-GB/).


Figure 142.: Distribution of the exploration permissions in Italy (the applications are in round
brackets, the “experimental plants” permissions are in italic).
and external communication) than periodic restoration of the plant due to damages or reduction of the output due to resource decline. A purely economic approach to the industry and market evolution of these systems is not successful. A wider perspective approach is needed, to consider the evolution of the plant-reservoir system behaviour and economic sustainability. Typically an economic self-sustainability is not considered in the profitability evaluation of the plant. In particular national or regional policies provide incentives for renewable energy plants. This aspect affects a lot the economic and financial evaluations of profitability and investments. Anyway the trend of scale cost with size, in relation to the drilling cost item must be seriously evaluated both by companies and by Institutions, during the related legislation development.
In this chapter some recapitulatory and synthetic outlines to summarize what discussed in this work are presented. The goal is to elaborate a methodological approach which takes into account the observations and the significant case studies results. Some outlines are then proposed and related to the market evolution, also considering some elements from the Italian energy market.

### 6.1 Sustainability of Geothermal Projects

#### 6.1.1 Technological-Environmental-Economic sustainability

As discussed in the previous chapters, the evaluation of the sustainability of a geothermal project for power purposes is a complex goal. It involves the geothermal potential assessment, the economic (or thermoeconomic) study of the context and cost items, and environmental issues. As it is shown above a multidisciplinary approach is needed (see Fig. 3, p. 12). The study of different case studies in this work, under various perspectives, shows that geothermal assessment is strongly dependent on the single context, both natural (environmental and geological), social and economic.

An upper limit to resource exploitation by binary plants has been individuated and discussed in section 2.1.3 (p. 27). The sustainability level of a “geothermal system” has to be evaluated looking at the expected durability with time of the resource itself, under given extraction/reinjection rates. For this reason a strategy scenario (involving also reinjection feedbacks and cold fluid front evolution) has to be prepared, simulated and somehow previously tested.

Environmental sustainability depends on several issues and compliances, which are here briefly listed.

- **Hazardous substances releases from the geofluid pipelines:**
  in case of binary power plants the total insulation of the geofluid from the atmosphere is needed, often the geofluid is kept at high pressure to avoid flashing and possible vapour phase release

- **Shallow aquifers pollution due to drilling or production stages:**
  appropriate casing and well design avoid this kind of problem

- **Subsidence:**
  usually due to reinjection, strong pressure gradient and fluid movement change the tension field in the rock formations
- **Micro-seismic activity:**
  related also to the reinjection and extraction activity and structural changes in the rock

- **Resource impoverishment:**
  in case the reinjection strategy is not efficient or the circulation model has not been properly interpreted

- **Soil occupation:**
  this problem mainly regards the cooling devices (like air-condensers, because of the high amount of heat to be dissipated) and the drilling operations

- **Dilution of inhibitors or acidificators in the reinjected geofluid:**
  often the companies are not constrained to declare details about this activity, which can be also part of industrial confidential strategy

If some of the above mentioned problems are not considered also the costs of the project and its time scheduling will be affected.

Social acceptance has to be considered in the global methodology outlines. It is known that in typically exploited geothermal areas the population is receptive when discussing about environmental or landscape impact\(^1\). It is undeniable that steam and geofluid pipelines have an impact in rural context or landscape known areas. So a lot of attention has to be focused on a reduction of the visual impact.

Also electric grid connection is not always guaranteed in such geothermal areas which can be far from the main high-medium voltage lines. This is another fact to consider in the cost and financial planning of the project, together with the road accessibility for the drilling and power plant facilities (this cost must be integrated in the estimation of the investment and plant costs).

A key concept that is here underlined deals with optimal sustainability level. The optimization of the project from only one of the proposed approach reveals to be incomplete or counter-productive. The adequate perspective has to involve all the backgrounds presented. For example, an optimization of the plant sizing which is simply economic is improper, because it does not consider the behaviour of the reservoir during time. Moreover a simple cost minimization based on purely financial and economic balances would lead to a size which too small or too great for an appropriate earning level, which depends on the productivity, which a complex function (constrained) of the resource and environment parameters.

### 6.2 Outlines for a methodological “Reservoir – Plant” approach

A typical way of looking at these kind of projects (particularly in the industrial and financial fields) is sketched in Fig. 144. This scheme is representative of how different backgrounds encounter and face geothermal projects. Thanks to the very

\(^{1}\) For example in the Mount Amiata, Tuscany (Italy) complex discussions are ongoing about new power plants installation.
productive interdisciplinary framework in which I worked in the last three years\textsuperscript{2} I could directly taste the different work planning and project ideas, and also merge them.

As a final task it is appropriate to reorganise the ideas and concepts illustrated in this work. Some useful outlines are proposed for the decision making processes in a geothermal project (particularly for medium-low temperature resources utilization). In this section some of the most important elements of the methodological approach are listed and briefly discussed.

**CASE STUDY ANALYSIS** In this work it is remarked how important is to understand errors, problems and solutions from past projects. It is known that geothermal plants have different response depending on the geographic area and resource type. Anyway similar issues and workflow have to be studied and can be adopted or enhanced. The study and comparison with literature case studies improves the elaboration of the conceptual model, and the use of simulation softwares (e.g. preparation of the boundary conditions, constraints, geometry fitting).

The study of the production histories from different fields has been one the bases of geothermal energy knowledge, since its beginning. It would be more important today to recuperate this trend in a strongly developing phase of the renewable energy source field. In this perspective it would be even more important to share research results and informations. From an academic and also personal point of view the present technological context of geothermal energy is too much affected by confidentiality.

\textsuperscript{2} I have had the possibility of working together with geologists and geochemist, at the Department of Earth Sciences (Dipartimento di Scienze della terra, DST) of the University of Pisa. Particularly with prof. Alessandro Sbrana and dr. Paolo Fulignati.
It is here shown how important can be the context in affecting the plant efficiency and the economic sustainability. Technical and resource management backgrounds are here considered. The technological offer can change according to the market orientation, but it has to be coupled with a reliable knowledge and running capability. A marked competitiveness is typical of these projects. In particular regarding the exploration step, geographical areas of interest for several companies (for example due to the constrictive distribution of geothermal resources in Italy) are usually object of competition procedures.

It has been shown how important is to consider the economic and financial scenario. The energy price is a triggering factor for a lot of players (particularly small players). So it is typical to observe lobbying activities on the political system in order to subsidize and incentivize the sector by energy fares.

ORC technology is considered to be mature. But a lot of work is still to do in order to elaborate optimization strategies which integrates the resource evolution with the durability of the whole system. While the thermodynamic optimization is at a good point of development (being ORC a derivation of traditional Rankine cycles), stronger efforts should be done in order to elaborate “standardised” market proposals (size, cooling device, etc.). For a larger diffusion of these systems adequate provisional instruments must be developed. For plant sizing two elements are of primary importance: the definition of the geothermal potential assessment and of the reinjection strategy.

As illustrated in section 3.1.2 (p. 75) and shown in Fig. 44 (p. 75) the data collection is fundamental, particularly for the conceptual and numerical model setting up. It has been here remarked how important is to build a database considering also the plant design parameters in the previous stages. The interpretation of the exploration data can be seen as the first very interdisciplinary step. It should be more focused on the design parameters, than on the wide geological context.

A lot of observations about this point are reported in the Chapter 1 of this work. It is the fundamental result of the geothermal exploration. The exploitation strategy and plant sizing start from here. Numerical simulation of the field can be a very useful tool in this case. The assessment has to be “resource utilization”-oriented: the specific utilization (ORC, district heating) affects the potential assessment. Since the early literature works this step has been not underlined, but the utilization context (and then its optimization) contribute to the definition of the upper limit to the exploitation.

All the project steps deal with environmental impact issues: from the drilling to the first running of the plant and then during the plant lifetime. In this chapter an overview of the possible impacts is given. Social acceptance is always a not well categorised variable, that can often affect very much the time scheduling of a project. Companies and new player should consider from the beginning all the possible impacts, to avoid pollution and plant failure or power plant stops.
Companies often declassify this argument with local communities. It is evident how important is the social participation and awareness about local resources, and avoid collision. When talking about a technology of recent diffusion, to not specialised audience, a particular carefulness and total honesty must be adopted, in order to make comprehensible for everybody which are the advantages and which are the problems. Social acceptance is not only an issue related to the type of technology, but also to the level of self-awareness of the communities and particularly to their previous experiences.

Incentive and subsidies are a great help to the diffusion of the small size geothermal plant. But this has to be analysed and reconsidered after looking how the thermoeconomic balance of the project (and its economical sustainability) change on the medium-long term. When elaborating large scale strategies, local resource durability is often neglected, leading to oversizing and wrong financial plans. Policies and strategic decisions could also change the market horizon, in favour of different renewable sources and create critical competitiveness between them if the national/regional energy plan is not reliable.

It is the most important tool individuated after the review presented in this work. It allows to make outstanding decisions and simulate future scenarios of exploitation. Its reliability depends on the accuracy level of interpretation of the exploration data. In substance for the numerical simulation of the geothermal reservoirs is valid the principle “trash in - trash out”. Through numerical simulation is possible to evaluate the production history of a field and try to understand which have been the wrong steps of the previous strategy. Some key concepts about this important tool are here listed:

- It is a strategic instrument, as it allows synthesis of the data and elaboration of scenarios.

- It is a way to integrate the different backgrounds involved, as it is necessary to individuate common inputs and outputs for the assessment of the resource and the “geothermal system” evolution.

- A numerical model is always the result of a collective work, in which all the different disciplines and contributes are fundamental (see section 4.2.4). It allows to merge ideas in a very formative framework.

- It can give a perspective of systematic development of the branch.

- An extended background is nowadays available (see the reviews in section 4), but a lack in terms of disclosure has to be underlined.

An interdisciplinary approach to the “geothermal system” analysis

Since the first chapter of this work the necessity for an interdisciplinary approach to geothermal energy study and utilization is remarked. In light of the discussion faced in the previous chapters, a new version of Fig. 3 is here given in Fig. 145.
In light of what discussed in chapter 5 the economic context and the thermoeconomic analysis can be considered as a part of the strategical and interdisciplinary approach to the geothermal energy utilization.

The technical-economic feasibility is affected by a great number of variables. The global sustainability of the “geothermal system” must be evaluated, since not only the plant thermodynamic optimization has to be considered.

Thermoeconomic approach and its modifications (for the environmental impact analysis, taking into account LCA and LCIA) can be integration tools, and they can contribute to the development of more suitable regulations.

Figure 145.: Multidisciplinary approach, after the methodological outlines.

A possible workflow for the sizing and sustainability assessment of a geothermal power plant is shown in Fig. 146. This sketch is valid only in case of medium-low temperature geothermal resources. High enthalpy fluid utilization have different problems, and in general their productivity is more robust respect to external parameters variations. On important element of this sketch is that the power output of the plant (and consequently the extraction/reinjection rate $\dot{m}_{geo}$) is not an independent variable, but it derives from an iterative process. In Fig. 146 the $W^{(1)}$ represents a first attempt value of the power output. A first level analysis is based on the sustainability by thermoeconomic balances like the one used in this work (chapter 5). Then the main parameters of the “geothermal system” are analysed. Numerical simulation of the reservoir has a key-role. At the end of the simulation of different scenarios the inputs to the technical sizing and optimization of the plant unit are calculated.

6.2.2 Limits and comparison with the geothermal industry and market

National/Local organizations and regulation organisms are often not aware about medium-low temperature resources utilization. For example in Italy a long tradition
Figure 146.: Sketch of a possible workflow proposed in the integrated approach.

about high enthalpy power plants exists, but not all of that background is useful in case of small size power plants.

The awareness of some of the market players and companies can be lacking, if compared to a new entry item in the investment portfolio (of energy companies).

In a more productive way the integration of all the disciplinary “views” can already give a great help in the context of the diffusion of these utilizations. The outlines and remarks of this chapter have to be seen as a drive to more aware programs and proposals.

This work has been elaborated in a multidisciplinary context, but a wider perspective is needed. A particular focus has been done on integration, but more work and specific attention is needed for problems and issues that here are only sketched.
6.3 OPEN ISSUES

Scaling and chemical aggressiveness of geothermal fluids

In section 2.3.1 (p. 43) the scaling problem into the geothermal power plants are illustrated and the methods for inhibition and removal are treated (section 2.3.1.3, p. 47). A discussion about how to study and face this phenomena is presented in section 2.3.1.4 (p. 49).

A complete public literature about industrial practice for prevention and inhibition of such problems is neither wide nor available. Industrial practices are often not public, with negative effects on the study and research by Universities. Scaling problems have been well known by industry, but a systematic approach has never been pursued for different reasons: first of all the significant difference between geothermal fields worldwide, but also for the industrial practice of lacking external diffusion of important data and results (when considered strategic). Today there not exist a study or a regulation about the acidification and chemical inhibition activities. The consequences of acid reinjection are not totally known. Some companies do not consider the utilization of these techniques during the early stages of a geothermal exploration project, so that the environmental impact studies often do not consider the discharge of additives. Inhibition and prevention have costs that have to be considered into the economic balance and also into a thermoeconomic analysis of the plants.

While the equilibria which rule the precipitation rate of specific mixtures are known, often the kinetic of these reactions are not studied for the particular flow conditions of, for example, the heat exchanger (RHE) or the reinjection pipelines. On this second kind of problem particular attention and strong efforts should be done.

The negative effects of the temperature (reservoir and environmental) on the ORC efficiencies have been here illustrated. The change of heat transfer coefficient and diameter reduction in the pipelines due to the scaling can have also worse effects.

Geothermal ORC: technology standardization

For other renewable energy sources the machinery standardization has been a triggering factor for the development of the market, thanks to a mature technology able to promote investments and easier sizing (e.g. wing energy). Also for geothermal energy (in particular for the medium-low temperature resources) this could fundamental for a stronger diffusion (see section 2.1.4, p. 31). Anyway all the issues treated in this work should be taken into account when facing standards development. It is a tough problem, mainly because of the differences between the worldwide context in which geothermal is available (reservoirs structure and fluid geochemistry, electric grid accessibility, environmental temperature, market regulation, financial and economic context).

The technological problem of binary plants design and optimization involves a lot of different variables: selection of working fluids, heat recovery system definition and heat transfer surfaces sizing, definition of thermodynamic cycle, auxiliary systems consumption. ORC plants have a great variability of thermodynamic solutions, but a critical point to be seriously faced is the strong dependence of $\beta, \eta_1$ and $\eta_{11}$
on external parameters (reservoir and environment) [2]. Some manufacturers have started to design and propose standardized machineries (see section 2.1.4, p. 31).

The geothermal resource assessment and the definition of a correct reinjection strategy are fundamental for the optimized design. These two goals can be pursued only under a multidisciplinary integrated approach. This argument is crucial for the future development of small geothermal plants, mainly in Europe, where a wide expansion of this industrial market is being pursued.

*Geothermal heat utilization: direct uses and innovative methods*

The utilization of the numerical simulation also to small scale models (urban, residential or private housing contexts) is now a developing sector. Many local authorities are now interested in an integrated management of hydraulic resource and also geothermal shallow aquifers utilization. The sizing of the GHP (Geothermal Heat Pumps) and GCHP (Ground Coupled Heat Pumps) systems is much more reliable when based on the understanding of the local resource study. The response of ground systems (low temperature) coupled to heat pump systems for air conditioning can be easily studied when the ground is characterised with standard tests (TRT, Thermal Response Test, GRT, Ground Response Test). But the installers and technician approach is today far from a resource-oriented approach. In case of ground exchange systems this could lead to wrong sizing, causing high energy consumption or need of excessive fossil fuels integration. In case of aquifer exchange systems a resource depletion or hydraulic balance disturbance.

In this work an innovative way of geothermal heat extraction for power purposes is illustrated and its potentialities are discussed. Anyway this will more efforts, a technology study and experimental tests should be carried out. The HPT concept has been considered a low efficiency system, but the concept of the CLTPT principle application for power production has to be faced by its technological and practical aspects.

The application of numerical simulation to the analytical method (lumped parameter) briefly described in section 2.4.3 (p. 59), distinguishing the case of highly porous aquifer or fractured media is a future development perspective.

The study of the possibility of enhancing housing and residential buildings with Geothermal Piles is surely an evolving research topic. At the moment only in particular cases these structures show efficient exchange and storage performances in relation to the buildings requirements (thermal comfort conditions).

*Regulation limits*

By now the impression about the regulations and norms development by technical and national/local authorities is that the complexity of the geothermal resource utilization is not considered.

In this work the limits of the development of the binary cycle concessions in the Italian market and regulatory context are discussed in section 5.6 (p. 191). recently the necessity of a numerical model interpretation and exploitation scenario simulation has been reached by the authorities and market players. Anyway an integrated approach to the resource study and utilization is not current yet.
Also talking about GHP and GCHP systems the regulations are not able to consider the utilizations from the necessary points of view (Geological and Energy engineering) in order to fix common standards.
The main themes of this work of Thesis are: geothermal binary power plants, medium-low temperature geothermal resources sustainable utilization, numerical simulation of geothermal reservoirs (oriented to the exploitation), and the evaluation of the technical-economic feasibility of these plants. In this chapter the main conclusions and remarks are summarized.

A methodological proposal for the design and sustainability assessment of geothermal projects has been elaborated, keeping into account the experiences and case studies available in literature or directly simulated (Chapter 6). The necessity of an “integrated” approach to the study of geothermal reservoirs utilization is shown in this work. The fields involved are Thermodynamics and Energy Engineering (plant optimization, sizing); Geophysics and Geochemistry (exploration, geofluid composition, model of groundwater flow) and Reservoir engineering (drilling technology, reinjection strategy, reservoir monitoring). Anyway it is evident that in a market framework also economic aspects have to be considered. Renewable energy sources are attractive for the investors, but in case of geothermal energy the sustainability level, and consequently the resource durability and renewability are function of the utilization strategy.

The study of different case studies in this work, under various perspectives, shows that geothermal assessment is strongly dependent on the single context, both natural (environmental and geological), social and economic. It is known that the characteristics of geothermal resources change during the exploitation period, so that a compromise has to be found. One way indicated in this work is to merge the data and the systems connections through the numerical simulation of the “geothermal system”: as external parameters affect the plant efficiency, the system to be studied is composed by the plant, the reservoir, the environment and all the links between them.

ORC is a mature technology but efforts should be done in order to enhance machinery standardisation (to increase diffusion) and to match the resource characteristics (optimized performances). A correct potential assessment is at the base of this approach, so an interdisciplinary method is even more important. Exploration and data interpretation have to be carried out looking at the specific type of utilization (and its criticalities). External elements to the design like regulations, social acceptance and economic framework can be merged into the design process through a thermoeconomic approach (or also exergoeconomic and exergoenvironomics, as future developments).

A great part of this work deals with numerical simulation of geothermal resources oriented to the study of the response during the utilization.
The review of important case studies is here presented. In Table 11 (p. 107) and in Tables from 15 (p. 151) to 20 (p. 156), the main characteristics of about 24 numerical models available in literature are illustrated, and the main features of 21 geothermal fields are briefly described. Some constant elements can be individuated, but a wide set of strategy can be evidenced. Some common points are, for example: the simulation of the unperturbed natural state, before starting with the simulation of the utilization; the use of numerical simulation for history data matching, model calibration, and forecast of future scenarios. In almost all the reviewed cases the permeability appears to be the thermophysical parameter which is always object of calibration (it is difficult to measure, but it is basic for the models used). The most used softwares use finite difference (or finite volume) or finite elements space discretization, while often fully implicit methods are adopted for time discretization. The most used software appears to be the code TOUGH2 [143].

A certain level of homogeneity about the assignment of the boundary conditions can be observed. These are mainly referred to natural recharge (both shallow or deep), meteoric water inflow, natural manifestations, natural heat flow, temperature (1st kind condition) assignment at the surface or at the bottom of the domain, lateral impermeable/adiabatic condition, extraction/reinjection wells.

A general discussion about the level of evolution and diffusion of the models is carried out. The limitations and potentiality of simulation have to be clear when starting with a modelling process. The reliability of the simulation of such extended domains strongly depends on the quality of the input data. The results can be affected by personal contributes more based on experience that on real data. The availability of parameters and initial data depends on the exploration. Generally is not easy to find in literature data that can be fitted from different geographical areas, as geothermal reservoirs have dissimilar origins.

Talking about the integrated approach methodology, numerical simulation of the reservoirs has a key role. It is a strategic instrument, as it allows synthesis of the data and elaboration of scenarios. It permits the integration between the different backgrounds involved, promoting the individuation of common inputs and outputs for the assessment of the resource and its evolution. A numerical model is always the result of a collective work, as it allows to merge ideas in a very formative framework. An extended background is now available, but a lack in terms of disclosure has to be underlined.

Two existing models from the literature (Momotombo and Sabalan) and one completely new model (Monterotondo Marittimo, Torrente Milia) have been simulated, a description of method and results is given in the chapter 4. In the following chart some remarks about these model are given.

**MOMOTOMBO (NICARAGUA)** "Small size" model – A first model simulated is limited to the production/reinjection wells area. Four scenarios (from [146]) have been reproduced and 2 additional (more severe) scenarios have been elaborated and simulated to study the response of the reservoir (and wells mutual interference).

"Large size" model – Original extension model [145, 146] simulated to study the history matching (wells productivity).
A data matching respect to the natural present situation has been carried out, basing on literature data [170, 169]. An attempt of enhancing of the model has been implemented, according to a great number of literature data (see section 4.2.3). Utilization scenarios for power production have been tested, study the system response though the numerical model. Three scenarios are compared: single flash, double flash, and flash with bottoming binary cycle.

The conceptual and numerical model have been built in a very interdisciplinary framework, after the interpretation of literature and exploration data. An iterative assessment of the model reliability has been carried out, together with the manual calibration of the main parameters (mainly permeability), to obtain a qualitative model of the area. Natural unperturbed state, and also midterm power production scenarios with ORC units have been simulated. A parametric study about power size and extraction rate to maximize durability and sustainability level is illustrated.

The main problems about the models development and their reliability when compared with engineering sizing of the plant are discussed in chapter 3 and chapter 4.

The binary cycle technological issues have been here treated too. The efficiencies ($\eta_I$, $\eta_{II}$) and specific geofluid consumption ($\beta$) have been linked to the variation of the external parameters, depending on the resource evolution and environmental temperature variations. The possible technological enhancements respect to the traditional cycle layouts are described, for example the regenerative Rankine cycle.

The perspectives of a machinery standardization is discussed, with respect to other renewable energy diffusion on the market.

For the optimization of the power plants and the maximization of the resource durability the integrated approach here proposed is fundamental, because of the great number of external variables. The resource characterization (potential assessment) is then fundamental, in order to guarantee the maximization of the plant productivity and a sustainable level of utilization of the resource.

An upper limit to the utilization by ORC plants is individuated. It is then dependent on the technology and the resource. ORC units have low efficiencies when they work in off-design conditions. For example a $T_{geo}$ decline due to resource depletion, can cause $\eta_I$ decline, but to keep maintained the energy balance at the exchanger the extraction mass flow rate $m_{geo}$ has to be increased (and nominal output and working is approached). Anyway, as it is shown here, a maximum level of extraction from the reservoir has to be assigned, in order to avoid resource depletion, in terms of cooling. Once a term on a temporal scale is fixed then the resource has to be used in order to guarantee sustainability and renewability on this interval. Then the potential, or the maximum rate level appears to be clearly a function of the whole "geothermal system" and time: being $m_{geo, max} = \Pi(\text{geothermal system}, t)$

1 This model has been realised in collaboration with prof. Alessandro Sbrana (Department of Earth Sciences, DST - Dipartimento di Scienze della Terra, of the University of Pisa) and his collaborators, mainly dr. Paolo Fulignati (that I would like to acknowledge). The model is the result of a collective and multidisciplinary work. The geological features and conceptual model are object of future publications.
The scaling and chemical deposition phenomena are illustrated and their negative effects on pipelines and machinery are illustrated. Inhibition (mechanical and chemical) and removal methods are described. The influence of these phenomena on the performance of the plants is discussed. In terms of geothermal heat utilization the reinjection temperature should be as minimum as possible, in order to maximize $\Delta T$. But the scaling phenomena could increase when temperature declines, so that $T_{\text{rein}}$ is usually a compromise value.

Scaling is mainly controlled by temperature, pressure and pH, so that the main methods of inhibition deal with variations of these parameters.

An innovative heat extraction system is described in chapter 2, section 2.4. A particular application of the heat pipe principle to a DHE system has been studied in literature [99]–[102]. From those results and applying the lumped parameter model there proposed, the possibility of applying the CLTPT concept for power production from shallow aquifers is illustrated. HPT (Heat Pipe Turbine) systems from literature are reviewed, and an enhancement based on the closed loop heat pipe principle is proposed. A preliminary analysis of the possible thermodynamic efficiencies is presented, in a single borehole extraction system (SBES), as the technological design issues are a future development of this part of the Thesis.

As a part of the integrated approach, also a thermoeconomic analysis of some case studies is carried out (chapter 5). A review of the cost items of geothermal power plant is presented, according to the current literature assessments. The economic sustainability of medium-small size geothermal plants is studied considering a review of all the cost items. The balance cost equation is used in order to evaluate the maximum sustainable cost ($C_{\text{max}}$), which considers also the irreversibilities cost (missed income). When the effective costs value is equal or less respect to this maximum sustainable (or affordable) cost then the utilization can be considered to be thermoeconomically sustainable.

The Momotombo case study is again used as a literature reference case. Also four Turkish power plants are studied and the thermoeconomic approach is applied to them. Assuming some very conservative hypothesis about the market energy price, almost all the plants result to be unsustainable. A comparison, unrealistic, but interesting to understand how this approach works, is made with the well known (using high enthalpy geofluid) power plant of Valle Secolo (Larderello geothermal field, Italy).

**FUTURE DEVELOPMENTS**

Thermoeconomic analysis

Different efficiency parameters can be individuated. Considering the strong interdisciplinary framework, more resource-utilization oriented indexes could be indicated, respect to the purely thermodynamic efficiency.

A way to include the mining risk and more realistic drilling cost for small depth perforation projects (small size ORC utilization) should be studied.
Exergonomic and exergoenvironmental analysis could be successfully applied after the review of the issues presented in this work. The environmental impact could then be evaluated in a more objective way (LCIA, LCA).

Innovative heat extraction methodologies

The experimental and technological development of sytems like the one presented here (SBES), considering the application of the CLTPT concept to a single borehole system for power purposes.

Another innovation deals with the development of systems and design strategy for ground heat exchange (for GHP or GCHP) in densely inhabited areas or old town centers (with landscaping and historical significance) like in many Italian cities.

Approaches effective integration

The integration between the different backgrounds, here described, should be effectively applied and pursued. Also the regulations should keep into account that the complexity of the geothermal resource utilization can be faced merging the different backgrounds and methodologies.
In this Appendix the basic mass, momentum and energy balance equations as implemented in the TOUGH2 code are described. Petrasim is a very useful graphic interface (for pre- and post-processing) and uses TOUGH2 as internal calculation code, so the same concepts are valid also for this software.

The following description is taken from the TOUGH2 User’s Guide, by Pruess et al., 1999 (revised 2012) [143], and from the Petrasim 5 User Manual [129].

A.1.1 Balance equations

The general balance equation (mass or energy conservation) in TOUGH2 can be written in this form:

\[
\frac{d}{dt} \int_{V_n} M^\kappa dV_n = \int_{\Gamma_n} F^\kappa \cdot n d\Gamma_n + \int_{V_n} q^\kappa dV_n
\]

(149)

The subdomain \( V_n \) is an arbitrary volume of the flowing system, bounded by the closed surface \( \Gamma_n \).

In the left hand side, in the accumulation term, the quantity \( M \) represents mass or energy per volume, being \( \kappa \)

\[
\kappa = 1, \ldots, NK
\]

(150)

labeling the mass (water, air, H2, solutes, ...), and being

\[
\kappa = NK + 1
\]

(151)

the heat “component”.

\( F \) is the mass or heat flux (see below), and \( q \) is the sink/source term.

\( n \) is a normal vector on surface element \( d\Gamma_n \), pointing inward into \( V_n \).

The general form of the mass accumulation term is

\[
M^\kappa = \phi \sum_\beta S_\beta \rho_\beta X^\kappa_\beta
\]

(152)

\( \beta \) is here the fluid phase (liquid, gas). The total mass of component \( \kappa \) is obtained by summing over the fluid phases \( \beta \).

\( \phi \) is the porosity, \( S_\beta \) is the saturation of phase \( \beta \) (e.g., the fraction of pore volume occupied by phase \( \beta \)), \( \rho_\beta \) is the density of phase \( \beta \), and \( X^\kappa_\beta \) is the mass fraction of
component \( \kappa \) present in phase \( \beta \). A more general form of the mass accumulation term that includes equilibrium sorption on the solid grains (adsorption of radionuclides on the solid grains) is given [143]

\[
M^\kappa = \phi \sum_\beta S_\beta \rho_\beta X_\kappa^\beta + (1 - \phi) \rho_R \rho_{aq} X^\kappa_{aq} K_d
\]

being \( K_d \) the aqueous phase distribution coefficient\(^1\). Radionuclides partition between aqueous and gaseous phases according to Henry’s law. The thermophysical properties of the aqueous phase are assumed independent of radionuclide concentrations. Implicit in this approximation is the assumption that aqueous radionuclide concentrations are small.

Similarly, the **heat accumulation term** in a multiphase system is

\[
M^{NK+1} = (1 - \phi) \rho_R C_R T + \phi \sum_\beta S_\beta \rho_\beta u_\beta
\]

where \( \rho_R \) and \( C_R \) are, respectively, grain density and specific heat of the rock, \( T \) is the temperature, and \( u_\beta \) is specific internal energy in phase \( \beta \).

The advective mass flux is given by the sum over phases

\[
(F^\kappa)_{adv} = \sum_\beta X_\kappa^\beta F_\beta
\]

while individual (mass) phase fluxes are given by a **multiphase version of Darcy’s law**:

\[
F_\beta = \rho_\beta u_\beta = -k_{r\beta} \frac{\rho_\beta \mu_\beta}{\mu_\beta} (\nabla p_\beta - \rho_\beta g)
\]

Here \( u_\beta \) is the Darcy velocity (volume flux) in phase \( \beta \), \( k \) is absolute permeability, \( k_{r\beta} \) is relative permeability to phase \( \beta \) (see section 3.2.1, Fig. 47, p. 83), \( \mu_\beta \) is viscosity. \( g \) is the vector of gravity acceleration.

The fluid pressure in phase \( \beta \)

\[
p_\beta = p + p_{c\beta}
\]

is the sum of a reference pressure \( p \) and of the capillary pressure \( p_{c\beta} \).

For the capillary pressure see the section 3.2.1, Fig. 46, p. 82. In [143] a further model is described. Vapor pressure lowering due to capillary and phase adsorption effects is modeled by Kelvin’s equation\(^2\)

\[
p_v(T, S_L) f_{VPL}(T, S_L) \cdot p_{sat}(T)
\]

---


where $p_{sat}$ is the saturated vapor pressure of bulk aqueous phase, and $f_{VPL}$ is the vapor pressure lowering factor

$$f_{VPL} = \exp \left[ \frac{M_w p_{cl}(S_t)}{\rho_l R(T + 273, 15)} \right] \tag{159}$$

$p_{cl}$ is the difference between aqueous and gas phase pressures, $M_w$ is the molecular weight of water, and $R$ is the universal gas constant.

The heat flux is the sum of the conductive and convective components

$$F_{NK+1}^{N} = -\lambda \nabla T + \sum_{\beta} h_\beta F_\beta \tag{160}$$

being $h_\beta$ the enthalpy of the phase $\beta$.

In TOUGH2 also mass transport occurring by diffusion and hydrodynamic dispersion (in addition to Darcy flow) and molecular diffusion mass flux can be considered [143].

### A.1.2 Space and time discretization

To discretize Eq. 149 the integral finite difference method is used (IFD)$^3$. Appropriate volume averages of the quantity are applied

$$\int_{V_n} M dV = V_n M_n \tag{161}$$

where $M$ is a volume-normalized extensive quantity, and $M_n$ is the average value of $M$ over $V_n$.

Surface integrals are approximated as a discrete sum of averages over surface segments $A_{n,m}$:

$$\int_{\Gamma_n} F^{k} d\Gamma = \sum_{m} A_{n,m} F_{n,m} \tag{162}$$

$F_{n,m}$ is the average value of the (inward) normal component of $F$ over the surface segment $A_{n,m}$ between volume elements $V_n$ and $V_m$. The discretization approach and the definition of the geometric parameters are illustrated in Fig. 147.

The discretized flux is expressed in terms of averages over parameters for elements $V_n$ and $V_m$.

The discretization of the basic Darcy flux term, Eq. 156, gives

$$F_{\beta,n,m} = -k_{n,m} \left( \frac{k_{r\beta} \rho_\beta}{\mu_\beta} \right)_{n,m} \left( \frac{p_{\beta,n} - p_{\beta,m}}{D_{n,m}} \right) - \rho_{\beta,n,m} g_{n,m} \tag{163}$$

where the subscripts $n,m$ indicate denote a suitable averaging at the interface between grid blocks $n$ and $m$ (interpolation, harmonic weighting, upstream weighting). $D_{n,m} = D_n + D_m$ is the distance between the nodal points $n$ and $m$, while $g_{n,m}$ is the component of gravitational acceleration in the direction from $m$ to $n$.

---

Substituting Eq. 161 and Eq. 162 into Eq. 149 a set of first-order ordinary differential equations in time is obtained

\[
\frac{dM^\kappa}{dt} = \frac{1}{V_n} \sum_m A_{nm} F^{\kappa}_{nm} + q_n^\kappa
\]  

(164)

Time is discretized as a first-order finite difference, and the flux and sink and source terms on the right-hand side of Eq. 164 are evaluated at the new time level, \( t^{k+1} = t^k + \Delta t \), to obtain the numerical stability needed for an efficient calculation of multiphase flow. This process is known as “fully implicit”, because the fluxes are expressed in terms of the unknown thermodynamic parameters at time level \( t^{k+1} \), so that these unknowns are only implicitly defined in the resulting equations\(^4\).

The time discretization results in the following set of coupled non-linear, algebraic equations. For the residuals it is

\[
R^\kappa_{n,k+1} = M^\kappa_{n,k+1} - M^\kappa_n = \frac{\Delta t}{V_n} \left( \sum_m A_{nm} F^{\kappa}_{nm,k+1} + V_n q^\kappa_n,k+1 \right) = 0
\]  

(165)

For each volume element (grid block) \( V_n \), there are \( \text{NEQ} \) equations\(^5\), being

\[ \kappa = 1, 2, ..., \text{NEQ} \]  

(166)

---


\(^5\) \( \text{NEQ} = \) Number of equations
usually $\text{NEQ} = \text{NK} + 1$. For a flow system with $\text{NEL}^6$ grid blocks, Eq. 165 represents a total of $\text{NEL} \times \text{NEQ}$ coupled non-linear equations. The unknowns are the $\text{NEL} \times \text{NEQ}$ independent primary variables

$$x_{i}^k; \quad i = 1, \ldots, \text{NEL} \times \text{NEQ} \quad (167)$$

which completely define the state of the flow system at time step $t^{k+1}$. These equations are solved by Newton/Raphson iteration, which implementation is described in Pruess et al. 1999 (rev. 2012) [143] (Appendix B).

“It is appropriate to add some comments about our space discretization technique [143]. The entire geometric information of the space discretization in Eq. 165 is provided in the form of a list of grid block volumes $V_n$, interface areas $A_{nm}$, nodal distances $D_{nm}$ and components $g_{nm}$ of gravitational acceleration along nodal lines. There is no reference whatsoever to a global system of coordinates, or to the dimensionality of a particular flow problem. The discretized equations are in fact valid for arbitrary irregular discretizations in one, two or three dimensions, and for porous as well as for fractured media. This flexibility should be used with caution, however, because the accuracy of solutions depends upon the accuracy with which the various interface parameters in equations such as Eq. 163 can be expressed in terms of average conditions in grid blocks. A general requirement is that there exists approximate thermodynamic equilibrium in (almost) all grid blocks at (almost) all times (Pruess and Narasimhan, 1985)$^7$. For systems of regular grid blocks referenced to global coordinates (such as $r - z$, $x - y - z$), Eq. 165 is identical to a conventional finite difference formulation (e.g., Peaceman$^8$, 1977; Moridis and Pruess$^9$, 1992)”. [143]

---

6 NEL = Number of elements
A.2 FEFLOW

A.2.1 Balance equations

The equations of balance as followed by the software Feflow are basically linked to the equations (already discussed in this work) for the flow in porous media transport. Conservation equations for the mass, momentum, concentration of pollutant and energy have to be taken into account.

The balance equations, expressed in macroscopic form, and following Diersch [138], referred to a single phase $\alpha$:

**Mass**

$$\frac{\partial}{\partial t} (\epsilon_\alpha \rho_\alpha) + \frac{\partial}{\partial x_i} (\epsilon_\alpha \rho_\alpha v_i^\alpha) = \epsilon_\alpha \rho_\alpha Q_\rho^\alpha$$  \hspace{1cm} (168)

**Momentum**

$$v_i^\alpha + \frac{\kappa_{ij}^\alpha}{\epsilon_\alpha \mu_\alpha} \left( \frac{\partial p^\alpha}{\partial x_j} - \rho^\alpha g_j \right) = 0$$  \hspace{1cm} (169)

**Energy**

$$\frac{\partial}{\partial t} (\epsilon_\alpha \rho_\alpha E^\alpha) + \frac{\partial}{\partial x_i} (\epsilon_\alpha \rho_\alpha v_i^\alpha E^\alpha) + \frac{\partial}{\partial x_i} (j_{i,T}^\alpha) = \epsilon_\alpha \rho_\alpha Q_T^\alpha$$  \hspace{1cm} (170)

**Concentration of pollutant or dissolved chemicals**

$$\frac{\partial}{\partial t} (\epsilon_\alpha C_k^\alpha) + \frac{\partial}{\partial x_i} (\epsilon_\alpha v_i^\alpha C_k^\alpha) \frac{\partial}{\partial x_i} (j_{i,k}^\alpha) = \epsilon_\alpha R_k$$  \hspace{1cm} (171)

where [138]

- $\epsilon_\alpha$: volume fraction for phase $\alpha$, being $0 \leq \epsilon_\alpha \leq 1$ and $\sum_\alpha \epsilon_\alpha = 1$
- $\rho_\alpha$: density of phase $\alpha$
- $v_i^\alpha$: velocity $i$-direction of phase $\alpha$
- $C_k^\alpha$: chemical concentration of $k$ component in the phase $\alpha$
- $j_{i,k}^\alpha$: vector of the diffusive (fickian) flux of phase $\alpha$
- $j_{i,T}^\alpha$: vector of the diffusive thermal (Fourier) flux of phase $\alpha$
- $\kappa_{ij}^\alpha$: permeability tensor of phase $\alpha$
- $p^\alpha$: relative pressure of phase $\alpha$
- $\mu_\alpha$: dynamic viscosity of phase $\alpha$
- $E^\alpha$: internal energy of phase $\alpha$
- $Q_\rho^\alpha$, $Q_T^\alpha$: source terms (or sink) for mass and heat (referred to phase $\alpha$)
- $T^\alpha$: temperature of phase $\alpha$
A.2.2 Boundary conditions

The boundary $\Gamma$ of the domain $\Omega$ is defined by appropriate separate portions $\Gamma_i$ (see section 3.2.1.6):

$$\Gamma = \bigcup_i \Gamma_i \quad (172)$$

**Hydraulic Flow**

1. First kind (Dirichlet)

$$h(x_i, t) = h^R_i(t) \quad (173)$$

2. Second kind (Neumann)

3D and vertical 2D

$$q_{nh}(x_i, t) = q^R_{h_i}(t) = -K_{ij} f_{\mu} \left( \frac{\partial h}{\partial x_j} + \frac{\rho^f - \rho^f_0}{\rho^f_0} e_j \right) n_i \quad (174)$$

horizontal 2D, not confined aquifer

$$q_{nh}(x_i, t) = q^R_{h}(t) = -K_{ij} \frac{\partial h}{\partial x_j} n_i \quad (175)$$

horizontal 2D confined

$$q_{nh}(x_i, t) = q^R_{h}(t) = -\tau_{ij} \frac{\partial h}{\partial x_j} n_i \quad (176)$$

3. Third kind (Cauchy)

3D and vertical 2D, not confined aquifer

$$q_{nh}(x_i, t) = -\Phi_h (h^R_2 - h) \quad (177)$$

horizontal 2D, confined aquifer

$$q_{nh}(x_i, t) = -\Phi_h (h^R_2 - h) \quad (178)$$

where $\Phi_h$ and $\Phi_h$ are transfer coefficients, they are inflow or outflow according to the following cases

$$\Phi_h = \begin{cases} 
\Phi^i_h & h^R_2 > h \\
\Phi^o_h & h^R_2 \leq h 
\end{cases} \quad (179)$$

$$\Phi_h = \begin{cases} 
\Phi^i_h & h^R_2 > h \\
\Phi^o_h & h^R_2 \leq h 
\end{cases} \quad (180)$$
in the case in which it is $\Phi_h = \Phi_{h}^{in} = \Phi_{h}^{out}$ or $\Phi_h = \Phi_{h}^{in} = \Phi_{h}^{out}$ is referable to a case of flow independent by direction and indifferently from or to the domain.

4. Fourth kind (singular point source)

$$Q_{\rho}^{w}(x_i, t) = \sum_{m} Q_{m}^{w} \prod_{i} \left[ \delta(x_i - x_{m}^{i}) \right], \quad \forall(x_i, x_{m}^{i}) \in \Omega \quad (181)$$

For this kind of condition the following conditions of free surface have to be satisfied

$$\Phi_h = \begin{cases} 
-q_{n_{h}} = n_{l} \left( P_{0} - \phi_{e} \frac{\partial h}{\partial t} \right) \\
h = x_{l} 
\end{cases} \quad (182)$$

The symbols used in the last equations are here listed (from [138])

- $h_{1}, h_{2}$: hydraulic head $h$ on the boundary
- $q_{n_{h}}$: specific volumetric flow rate or Darcy velocity
- $q_{n_{h}}$: specific volumetric flow rate, vertical average
- $q_{R}$, $\bar{q}_{R}$: specific flow rate on the boundary respectively, for 3D and horizontal 2D
- $\Phi_{h}$, $\Phi_{h}$: transfer coefficients, loss parameters, respectively, for 3D and horizontal 2D
- $\Phi_{h}^{in}$, $\Phi_{h}^{out}$: direction coefficients for inflow/outflow, horizontal 2D
- $f_{\mu}$: viscosity relation function, $f_{\mu} = \frac{\mu_{0}^{f}}{\mu^{f}(C, T)}$, where $\mu_{0}^{f} = \mu_{C_{0}, T_{0}}^{f}$, is the viscosity at $T_{0}$ and for the reference concentration $C_{0}$
- $\delta$: delta Dirac function
- $K_{ij}$: hydraulic conductivity tensor, $K_{ij} = \frac{k_{ij} \rho_{0}^{f} g}{\mu_{0}^{f}}$
  - where $k_{ij}$ is the permeability tensor
- $n_{i}$: normal surface unit vector
- $P_{0}$: seepage flow rate, surface water recharge
- $Q_{w}^{w}$: well extraction (well function)
- $Q_{m}^{w}$: withdrawal/reinjection rate of a single well
- $\phi_{e}$: effective porosity
- $\tau_{ij}$: transmissivity tensor
- $x_{l}^{m}$: single well coordinate $(m)$
- $x_{l}$: elevation

**Boundary Conditions on Phreatic Surfaces**

Different type of 2nd and 3rd kind conditions exist for free or phreatic surfaces. They are usually integral conditions.
• **Integral** Second kind condition - 3D (referred to the initial stratigraphic condition):

\[ q_{n_h}(x_i, t) = q^R_h(t) \]  
(183)

horizontal 2D - not confined, deep integrated flux:

\[ q_{n_h}(x_i, t) = \bar{q}^R_h(t) \]  
(184)

• **Integral** Third kind condition - 3D (referred to the initial stratigraphic condition):

\[ q_{n_h}(x_i, t) = -\Phi_h(h^R_2 - h) \]  
(185)

horizontal 2D - not confined, deep integrated flux:

\[ q_{n_h}(x_i, t) = -\bar{\Phi}_h(h^R_2 - h) \]  
(186)

The use of these conditions guarantees that, given a value of the boundary flux this is independent by the thickness of the aquifer and the free surface head. This allows to avoid problems on the mass balance, being then independent by the siting of the free surface.

**Energy Transport**

1. First kind (Dirichlet)

\[ T(x_i, t) = T^R_1(t) \]  
(187)

2. Second kind (Neumann)

3D and vertical 2D axisymmetric

\[ q_{n_T}(x_i, t) = q^R_1(t) = -\lambda_{ij} \frac{\partial T}{\partial x_j} n_i \]  
(188)

\[ q_{n_h}(x_i, t) = q^R_{h}(t) = \rho f c f T^R_2 q_{n_h} - \lambda_{ij} \frac{\partial T}{\partial x_j} n_i \]  
(189)

horizontal 2D, confined / not confined

\[ \bar{q}_{n_T}(x_i, t) = \bar{q}^R_1(t) = -\bar{\lambda}_{ij} \frac{\partial T}{\partial x_j} n_i \]  
(190)

\[ \bar{q}_{n_h}(x_i, t) = \bar{q}^R_{h}(t) = \rho f c f T^R_2 \bar{q}_{n_h} - \bar{\lambda}_{ij} \frac{\partial T}{\partial x_j} n_i \]  
(191)

3. Third kind (Cauchy)

3D and vertical 2D, not confined aquifer

\[ q_{n_T}(x_i, t) = -\Phi_T(T^R_3 - T) \]  
(192)

horizontal 2D, confined aquifer

\[ \bar{q}_{n_T}(x_i, t) = -\bar{\Phi}_T(T^R_3 - T) \]  
(193)
where the transfer coefficients $\Phi_T$ e $\bar{\Phi}_T$ are defined as

$$\Phi_h = \begin{cases} 
\Phi^\text{in}_T & T_3^R > T \\
\Phi^\text{out}_T & T_3^R \leq T 
\end{cases} \quad (194)$$

$$\bar{\Phi}_h = \begin{cases} 
\bar{\Phi}^\text{in}_T & T_3^R > T \\
\bar{\Phi}^\text{out}_T & T_3^R \leq T 
\end{cases} \quad (195)$$

it is important to distinguish when the heat is entering the domain $q_{nT} < 0$ or it is going outside the domain $q_{nT} > 0$

4. Fourth kind (singular point source)

$$Q^w_T(x_i, t) = \rho f^c \sum_m T^w_m Q^w_m \prod_i [\delta(x_i - x^m_i)] , \quad \forall (x_i, x^m_i) \in \Omega \quad (196)$$

The symbols used in the last equations are here listed (from [138])

$T_1^R, T_2^R, T_3^R$ assigned T on boundary

$q_{nT}$ thermal flux (normal)

$q_{nT}$ thermal flux vertical average

$q^R_T, q^R_{\bar{T}}$ assigned thermal flux on boundary

$\Phi_T, \bar{\Phi}_T$ heat transfer coefficient

$Q^w_T$ heat flux well function

$T^w_m$ single well m temperature

$Q^w_m$ thermal flux during extraction/reinjection of the single well (m)

$\lambda_{ij}$ hydrodynamic thermal dispersion coefficient

$x^m_i$ single well m coordinate

$\delta$ delta Dirac function

Also for energy transport it is possible to use integral boundary conditions of 2nd and 3rd kind, for free surface problems.

In this work the BC for the transport of dissolved chemicals and pollutants have been not used.
P R O P E R T I E S A N D G R I D D E T A I L S 
O F T H E N U M E R I C A L M O D E L S 
S I M U L AT E D

B.1 MOMOTOMBO GEOTHERMAL RESERVOIR

B.1.1 “Small size” model

The layers of the model presented in section 4.2.1 (p. 108) are here described. The characteristics of the model are the same of the literature (Porras et al. [144, 145, 146]).

In this section the “small size” model is described, while the details about the “large size” model of section 4.2.2 (p. 117) are available in the next section (B.1.2).

In Table 34 the layers depth and thickness are listed, while in Fig 148 the layers are shown together with the location of the wells (from [145]).

In Table 35 the thermophysical parameters used in the simulation of the “small size” model of Momotombo geothermal reservoir are shown, from [144, 145, 146].

The ATM material would represent the atmosphere, but it can be observed that the values of such properties are not realistic for this layer. Anyway this aspect has been confirmed by other literature matching and comparison for this procedure. Anyway this could be appropriate in order to keep homogeneous the contact between the materials (dealing with strongly different orders of magnitude).

Table 34.: Layers of the Momotombo numerical model (the depth is in m below the sea level), from [144, 145, 146].

<table>
<thead>
<tr>
<th>Layer</th>
<th>Depth (m b.s.l.)</th>
<th>Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA</td>
<td>-950 – 0</td>
<td>950</td>
</tr>
<tr>
<td>BB</td>
<td>0 – 150</td>
<td>150</td>
</tr>
<tr>
<td>CC</td>
<td>150 – 300</td>
<td>150</td>
</tr>
<tr>
<td>DD</td>
<td>300 – 450</td>
<td>150</td>
</tr>
<tr>
<td>EE</td>
<td>450 – 700</td>
<td>250</td>
</tr>
<tr>
<td>FF</td>
<td>700 – 1000</td>
<td>300</td>
</tr>
<tr>
<td>GG</td>
<td>1000 – 1500</td>
<td>500</td>
</tr>
<tr>
<td>HH</td>
<td>1500 – 2000</td>
<td>500</td>
</tr>
<tr>
<td>II</td>
<td>2000 – 3000</td>
<td>1000</td>
</tr>
</tbody>
</table>
Figure 148: Layers of the Momotombo numerical model (details in Table 34) and location of the wells, from [145].

8.1.2 “Large size” model

The material properties used in the simulation of the unperturbed state and utilization scenario (history matching) of the Momotombo “large size” numerical model are listed in Table 36.
<table>
<thead>
<tr>
<th>Rock type</th>
<th>Density (kg/m³)</th>
<th>Porosity</th>
<th>Permeability</th>
<th>Thermal conductivity (W/mK)</th>
<th>Specific heat capacity (J/kgK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOW</td>
<td>2500</td>
<td>0,08</td>
<td>5,5·10⁻¹⁵</td>
<td>2,5·10⁻¹⁶</td>
<td>2,3</td>
</tr>
<tr>
<td>VLOW</td>
<td>2500</td>
<td>0,06</td>
<td>3,0·10⁻¹⁶</td>
<td>6,3·10⁻¹⁷</td>
<td>3</td>
</tr>
<tr>
<td>MED3</td>
<td>2500</td>
<td>0,06</td>
<td>5,0·10⁻¹⁴</td>
<td>6,2·10⁻¹⁵</td>
<td>2,3</td>
</tr>
<tr>
<td>MED2</td>
<td>2500</td>
<td>0,2</td>
<td>4,0·10⁻¹⁵</td>
<td>1,0·10⁻¹⁵</td>
<td>2,3</td>
</tr>
<tr>
<td>UPFLO</td>
<td>2500</td>
<td>0,2</td>
<td>1,6·10⁻¹³</td>
<td>4,2·10⁻¹⁴</td>
<td>2,3</td>
</tr>
<tr>
<td>MED1</td>
<td>2500</td>
<td>0,2</td>
<td>7,8·10⁻¹³</td>
<td>3,6·10⁻¹³</td>
<td>2,3</td>
</tr>
<tr>
<td>HIGH2</td>
<td>2500</td>
<td>0,2</td>
<td>5,0·10⁻¹⁴</td>
<td>5,0·10⁻¹⁵</td>
<td>2,3</td>
</tr>
<tr>
<td>HIGH1</td>
<td>2500</td>
<td>0,2</td>
<td>2,6·10⁻¹³</td>
<td>1,0·10⁻¹¹</td>
<td>2,3</td>
</tr>
<tr>
<td>ATM</td>
<td>2500</td>
<td>0,25</td>
<td>1,0·10⁻¹³</td>
<td>1,0·10⁻¹³</td>
<td>5,5</td>
</tr>
<tr>
<td>POR11</td>
<td>2500</td>
<td>0,2</td>
<td>6,0·10⁻¹³</td>
<td>6,0·10⁻¹²</td>
<td>2,3</td>
</tr>
<tr>
<td>POR12</td>
<td>2500</td>
<td>0,2</td>
<td>2,6·10⁻¹³</td>
<td>1,0·10⁻¹¹</td>
<td>2,3</td>
</tr>
<tr>
<td>BOUND</td>
<td>2500</td>
<td>0,2</td>
<td>5,0·10⁻¹⁵</td>
<td>5,0·10⁻¹⁵</td>
<td>2,3</td>
</tr>
<tr>
<td>STEAD</td>
<td>2500</td>
<td>0,2</td>
<td>5,0·10⁻¹⁵</td>
<td>5,0·10⁻¹⁵</td>
<td>2,3</td>
</tr>
<tr>
<td>CAPRKL</td>
<td>2500</td>
<td>0,2</td>
<td>1,0·10⁻²⁰</td>
<td>5,8·10⁻¹⁶</td>
<td>4,3</td>
</tr>
<tr>
<td>CIRCL</td>
<td>2500</td>
<td>0,08</td>
<td>4,0·10⁻¹⁴</td>
<td>4,2·10⁻¹⁶</td>
<td>2,3</td>
</tr>
<tr>
<td>DEEPRL</td>
<td>2500</td>
<td>0,1</td>
<td>4,0·10⁻¹⁶</td>
<td>4,0·10⁻¹⁶</td>
<td>2,3</td>
</tr>
<tr>
<td>EASTR</td>
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<td>0,1</td>
<td>7,5·10⁻¹⁴</td>
<td>7,5·10⁻¹⁴</td>
<td>2,3</td>
</tr>
<tr>
<td>CUPFL</td>
<td>2500</td>
<td>0,1</td>
<td>7,0·10⁻¹⁴</td>
<td>5,0·10⁻¹⁶</td>
<td>2,5</td>
</tr>
</tbody>
</table>

Table 35: Rock properties used in the “small size” model, from [148] after [144, 145, 146].
Figure 149.: Horizontal layers and materials used in the Momotombo numerical “small size” model, from [145, 148].
Table 36.: Rock properties used in the “large size” model, from [164] after [144, 145, 146].

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Density $\rho$ (kg/m$^3$)</th>
<th>Porosity $\phi$</th>
<th>Permeability $k_x$ (m$^2$)</th>
<th>Permeability $k_y$ (m$^2$)</th>
<th>Permeability $k_z$ (m$^2$)</th>
<th>Thermal conductivity $\lambda$ (W/mK)</th>
<th>Specific heat capacity $c_r$ (J/kgK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOW</td>
<td>2500</td>
<td>0,08</td>
<td>$5,5 \cdot 10^{-15}$</td>
<td>$5,5 \cdot 10^{-15}$</td>
<td>$2,4 \cdot 10^{-16}$</td>
<td>2,3</td>
<td>900</td>
</tr>
<tr>
<td>VLOW</td>
<td>2500</td>
<td>0,06</td>
<td>$3,0 \cdot 10^{-16}$</td>
<td>$3,0 \cdot 10^{-16}$</td>
<td>$6,5 \cdot 10^{-17}$</td>
<td>3</td>
<td>900</td>
</tr>
<tr>
<td>MED3</td>
<td>2500</td>
<td>0,06</td>
<td>$4,5 \cdot 10^{-15}$</td>
<td>$4,5 \cdot 10^{-15}$</td>
<td>$6,5 \cdot 10^{-15}$</td>
<td>2,3</td>
<td>900</td>
</tr>
<tr>
<td>MED2</td>
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<td>0,2</td>
<td>$3,6 \cdot 10^{-15}$</td>
<td>$3,6 \cdot 10^{-16}$</td>
<td>$1,0 \cdot 10^{-16}$</td>
<td>2,3</td>
<td>900</td>
</tr>
<tr>
<td>UPFLO</td>
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<td>0,2</td>
<td>$1,6 \cdot 10^{-14}$</td>
<td>$1,6 \cdot 10^{-14}$</td>
<td>$4,2 \cdot 10^{-14}$</td>
<td>2,3</td>
<td>900</td>
</tr>
<tr>
<td>MED1</td>
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<td>$7,8 \cdot 10^{-13}$</td>
<td>$7,8 \cdot 10^{-13}$</td>
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<tr>
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<td>$5,0 \cdot 10^{-14}$</td>
<td>$5,0 \cdot 10^{-15}$</td>
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<td>900</td>
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<tr>
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<td>2,3</td>
<td>900</td>
</tr>
<tr>
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<td>$1,0 \cdot 10^{-13}$</td>
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<td>$7,0 \cdot 10^{-14}$</td>
<td>$5,0 \cdot 10^{-16}$</td>
<td>2,5</td>
<td>1000</td>
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<td>$6,0 \cdot 10^{-13}$</td>
<td>$6,0 \cdot 10^{-12}$</td>
<td>2,3</td>
<td>900</td>
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<tr>
<td>POR12</td>
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<td>$2,6 \cdot 10^{-13}$</td>
<td>$1,0 \cdot 10^{-11}$</td>
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<td>900</td>
</tr>
<tr>
<td>BOUND</td>
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<td>$5,0 \cdot 10^{-15}$</td>
<td>$5,0 \cdot 10^{-15}$</td>
<td>$5,0 \cdot 10^{-15}$</td>
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<td>$10^5$</td>
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<td>$5,0 \cdot 10^{-15}$</td>
<td>$5,0 \cdot 10^{-15}$</td>
<td>2,3</td>
<td>900</td>
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<td>$1,0 \cdot 10^{-20}$</td>
<td>$5,8 \cdot 10^{-16}$</td>
<td>4,3</td>
<td>900</td>
</tr>
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<td>CIRCL</td>
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<td>$4,0 \cdot 10^{-14}$</td>
<td>$4,0 \cdot 10^{-14}$</td>
<td>$4,2 \cdot 10^{-16}$</td>
<td>2,3</td>
<td>900</td>
</tr>
<tr>
<td>DEEPR</td>
<td>2500</td>
<td>0,1</td>
<td>$4,0 \cdot 10^{-16}$</td>
<td>$4,0 \cdot 10^{-16}$</td>
<td>$4,0 \cdot 10^{-16}$</td>
<td>2,3</td>
<td>900</td>
</tr>
<tr>
<td>EASTR</td>
<td>2500</td>
<td>0,1</td>
<td>$7,5 \cdot 10^{-14}$</td>
<td>$7,5 \cdot 10^{-14}$</td>
<td>$7,5 \cdot 10^{-14}$</td>
<td>2,3</td>
<td>900</td>
</tr>
<tr>
<td>CUPFL</td>
<td>2500</td>
<td>0,1</td>
<td>$7,0 \cdot 10^{-14}$</td>
<td>$7,0 \cdot 10^{-14}$</td>
<td>$5,0 \cdot 10^{-16}$</td>
<td>2,5</td>
<td>1000</td>
</tr>
<tr>
<td>LOWIN</td>
<td>2500</td>
<td>0,08</td>
<td>$5,5 \cdot 10^{-15}$</td>
<td>$5,5 \cdot 10^{-15}$</td>
<td>$2,4 \cdot 10^{-16}$</td>
<td>2,3</td>
<td>900</td>
</tr>
</tbody>
</table>
Figure 150.: Horizontal layers and materials used in the Momotombo numerical “large size” model, from [164] after [145].
B.2 SABALAN GEOTHERMAL RESERVOIR

In the following Table the properties of the 22 rock formations used in the Sabalan numerical model are listed (from Noorollahi and Itoi, 2011) [170].

Note that differently from the Table 36 and 36 about the materials used in the Motomombo simulations (section B.1 of this Appendix), for this model two parameters are considered uniform and constant:

- porosity, $\phi = 0.1$
- rock density, $\rho = 2500 \text{ kg/m}^3$

Table 37.: Layers of the Sabalan (Iran) numerical model (the depth is in m below the sea level), from [144, 145, 146].

<table>
<thead>
<tr>
<th>Layer</th>
<th>Elevation (m a.s.l.)</th>
<th>Thickness (m)</th>
<th>Block center elevation (m a.s.l.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA</td>
<td>3600–2400</td>
<td>200–1000</td>
<td>Vary</td>
</tr>
<tr>
<td>BB</td>
<td>2400–2200</td>
<td>200</td>
<td>2300</td>
</tr>
<tr>
<td>CC</td>
<td>2200–2100</td>
<td>100</td>
<td>2150</td>
</tr>
<tr>
<td>DD</td>
<td>2100–2000</td>
<td>100</td>
<td>2050</td>
</tr>
<tr>
<td>EE</td>
<td>2000–1900</td>
<td>100</td>
<td>1950</td>
</tr>
<tr>
<td>FF</td>
<td>1900–1800</td>
<td>100</td>
<td>1850</td>
</tr>
<tr>
<td>GG</td>
<td>1800–1650</td>
<td>150</td>
<td>1725</td>
</tr>
<tr>
<td>HH</td>
<td>1650–1550</td>
<td>100</td>
<td>1600</td>
</tr>
<tr>
<td>II</td>
<td>1550–1400</td>
<td>150</td>
<td>1475</td>
</tr>
<tr>
<td>JJ</td>
<td>1400–1300</td>
<td>100</td>
<td>1350</td>
</tr>
<tr>
<td>KK</td>
<td>1300–1000</td>
<td>300</td>
<td>1150</td>
</tr>
<tr>
<td>LL</td>
<td>1000–500</td>
<td>500</td>
<td>750</td>
</tr>
<tr>
<td>MM</td>
<td>500–0</td>
<td>500</td>
<td>250</td>
</tr>
<tr>
<td>PP</td>
<td>0–1000</td>
<td>1000</td>
<td>500</td>
</tr>
</tbody>
</table>
Table 38.: Rock properties used in the Sabalan model, from [164] after [170].

<table>
<thead>
<tr>
<th>Rock type</th>
<th>$k_x$ (m$^2$)</th>
<th>$k_y$ (m$^2$)</th>
<th>$k_z$ (m$^2$)</th>
<th>$\lambda$ (W/mK)</th>
<th>$c_r$ (J/kgK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UPFLO</td>
<td>$3.0 \times 10^{-13}$</td>
<td>$3.0 \times 10^{-13}$</td>
<td>$3.0 \times 10^{-13}$</td>
<td>2.5</td>
<td>1000</td>
</tr>
<tr>
<td>BASE1</td>
<td>$2.0 \times 10^{-13}$</td>
<td>$2.0 \times 10^{-13}$</td>
<td>$6.0 \times 10^{-13}$</td>
<td>2.5</td>
<td>1000</td>
</tr>
<tr>
<td>BASE2</td>
<td>$6.0 \times 10^{-16}$</td>
<td>$6.0 \times 10^{-16}$</td>
<td>$2.0 \times 10^{-16}$</td>
<td>2.5</td>
<td>1000</td>
</tr>
<tr>
<td>BASE3</td>
<td>$1.0 \times 10^{-17}$</td>
<td>$1.0 \times 10^{-17}$</td>
<td>$5.0 \times 10^{-17}$</td>
<td>2.5</td>
<td>1000</td>
</tr>
<tr>
<td>BASE4</td>
<td>$9.0 \times 10^{-13}$</td>
<td>$9.0 \times 10^{-13}$</td>
<td>$9.0 \times 10^{-13}$</td>
<td>2.5</td>
<td>1000</td>
</tr>
<tr>
<td>BASE5</td>
<td>$6.0 \times 10^{-15}$</td>
<td>$6.0 \times 10^{-15}$</td>
<td>$4.0 \times 10^{-15}$</td>
<td>2.5</td>
<td>1000</td>
</tr>
<tr>
<td>LOW01</td>
<td>$2.0 \times 10^{-16}$</td>
<td>$2.0 \times 10^{-16}$</td>
<td>$2.0 \times 10^{-16}$</td>
<td>2.5</td>
<td>1000</td>
</tr>
<tr>
<td>LOW02</td>
<td>$2.0 \times 10^{-15}$</td>
<td>$4.0 \times 10^{-15}$</td>
<td>$2.0 \times 10^{-15}$</td>
<td>2.5</td>
<td>1000</td>
</tr>
<tr>
<td>MATRIX</td>
<td>$5.0 \times 10^{-15}$</td>
<td>$5.0 \times 10^{-15}$</td>
<td>$1.0 \times 10^{-15}$</td>
<td>2.5</td>
<td>1000</td>
</tr>
<tr>
<td>BOND1</td>
<td>$9.5 \times 10^{-16}$</td>
<td>$9.5 \times 10^{-16}$</td>
<td>$6.6 \times 10^{-16}$</td>
<td>2.5</td>
<td>1000</td>
</tr>
<tr>
<td>FAU3</td>
<td>$2.0 \times 10^{-16}$</td>
<td>$2.0 \times 10^{-13}$</td>
<td>$2.0 \times 10^{-15}$</td>
<td>2.5</td>
<td>1000</td>
</tr>
<tr>
<td>MAKH3</td>
<td>$4.0 \times 10^{-15}$</td>
<td>$4.0 \times 10^{-15}$</td>
<td>$8.0 \times 10^{-16}$</td>
<td>2.5</td>
<td>1000</td>
</tr>
<tr>
<td>FAULT</td>
<td>$1.0 \times 10^{-13}$</td>
<td>$1.0 \times 10^{-17}$</td>
<td>$6.0 \times 10^{-14}$</td>
<td>2.5</td>
<td>1000</td>
</tr>
<tr>
<td>LOW03</td>
<td>$3.0 \times 10^{-17}$</td>
<td>$9.0 \times 10^{-16}$</td>
<td>$2.0 \times 10^{-16}$</td>
<td>2.5</td>
<td>1000</td>
</tr>
<tr>
<td>MAKH2</td>
<td>$3.0 \times 10^{-14}$</td>
<td>$3.0 \times 10^{-14}$</td>
<td>$6.0 \times 10^{-15}$</td>
<td>3.28</td>
<td>1450</td>
</tr>
<tr>
<td>TOP02</td>
<td>$2.0 \times 10^{-17}$</td>
<td>$2.0 \times 10^{-17}$</td>
<td>$2.0 \times 10^{-16}$</td>
<td>2.5</td>
<td>1000</td>
</tr>
<tr>
<td>TOP03</td>
<td>$2.0 \times 10^{-17}$</td>
<td>$2.0 \times 10^{-17}$</td>
<td>$2.0 \times 10^{-17}$</td>
<td>2.5</td>
<td>1000</td>
</tr>
<tr>
<td>MAKH1</td>
<td>$8.0 \times 10^{-14}$</td>
<td>$8.0 \times 10^{-14}$</td>
<td>$5.0 \times 10^{-15}$</td>
<td>4.3</td>
<td>1600</td>
</tr>
<tr>
<td>TOP05</td>
<td>$1.0 \times 10^{-15}$</td>
<td>$1.0 \times 10^{-15}$</td>
<td>$8.0 \times 10^{-14}$</td>
<td>2.5</td>
<td>1000</td>
</tr>
<tr>
<td>CAP01</td>
<td>$2.0 \times 10^{-16}$</td>
<td>$2.0 \times 10^{-16}$</td>
<td>$7.0 \times 10^{-17}$</td>
<td>2.5</td>
<td>1000</td>
</tr>
<tr>
<td>TOP01</td>
<td>$5.5 \times 10^{-16}$</td>
<td>$5.5 \times 10^{-16}$</td>
<td>$1.1 \times 10^{-16}$</td>
<td>2.5</td>
<td>1000</td>
</tr>
</tbody>
</table>
Figure 151.: Horizontal layers and materials used in the Sabalan numerical, from [164] after [170].
B.3 MONTEROTONDO MARITTIMO – TORRENTE MILIA

In this section the properties of the rock materials used in the Monterotondo Marittimo - Torrente Milia numerical model (see section 4.2.4, p. 142) are illustrated.

In Fig. 152 the layers of the model are shown, while in Table 39 the thermophysical parameters used in the simulation are listed. Note that in Fig. 152, in the subfigure representing the layers GG-HH-II-JJ-KK (which are all the same), the siting of the wells is also illustrated, just because this is the only layer with only one colour.

Table 39: Rock properties used in the Monterotondo - Torente Milia numerical model.

<table>
<thead>
<tr>
<th>Rock type</th>
<th>ρ (kg/m³)</th>
<th>φ</th>
<th>k (m²)</th>
<th>λ (W/mK)</th>
<th>cₜ (J/kgK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAP</td>
<td>2350</td>
<td>0,0055</td>
<td>1,02·10⁻¹⁷</td>
<td>2,1</td>
<td>916,6</td>
</tr>
<tr>
<td>CAV</td>
<td>2500</td>
<td>0,04</td>
<td>1,02·10⁻¹³</td>
<td>2,5</td>
<td>836</td>
</tr>
<tr>
<td>BUR</td>
<td>2800</td>
<td>0,008</td>
<td>1,02·10⁻¹⁵</td>
<td>5</td>
<td>877,8</td>
</tr>
<tr>
<td>BUR2</td>
<td>2800</td>
<td>0,008</td>
<td>1,02·10⁻¹³</td>
<td>5</td>
<td>877,8</td>
</tr>
</tbody>
</table>
Figure 152.: Horizontal layers and materials used in the Monterotondo - Torrente Milia numerical model.
C

BRIEF INTRODUCTION TO EXERGONOMIC AND EXERGOENVIRONMENTAL APPROACHES

C.1 INTRODUCTION TO EXERGONOMIC APPROACH

The exergonomic approach allows to evaluate the effects of the exergy/money costs of a single component on the whole plant performances.

As it is evident, one should know the detailed structure of the plant, and the exergy balance of each component. This is necessary in order to assess the exergy destruction of each process.

The economic sustainability of a geothermal project (as well as of any energy conversion system), or of a component can be evaluated with more elaborated approaches respect to the thermoeconomic one briefly illustrated above and used in this chapter.

The economic impact due to the exergy desctruction on the investment costs can be evaluated with an “exergonomic factor” $f_k$:

$$f_k = \frac{\dot{Z}_{k}^{CI}}{\dot{Z}_{k}^{CI} + \hat{C}_{D,k}}$$

(197)

in which $\hat{C}_{D,k}$ is the cost associated to the exergy dissipation, defined as:

$$\hat{C}_{D,k} = c_{F,k} \dot{E}_{D,k}$$

(198)

$\dot{Z}_{k}^{CI}$ comes from the sum of investment ($\dot{Z}_{k}^{CI}$) and O&M costs ($\dot{Z}_{k}^{O&M}$), according to the equation

$$\dot{Z}_{k} = \dot{Z}_{k}^{CI} + \dot{Z}_{k}^{O&M} = \frac{CCs + O&M}{PEC_{tot} \tau} PEC_k$$

(199)

CCs are the annual cost of teh transports, and O&M are the annual costs for operation and management. $PEC_{tot}$ and $PEC_k$ are respectively the costs of equipments, respectively for the whole plant and for the k-th component, $\tau$ are the annual working hours.

C.2 INTRODUCTION TO EXERGOENVIRONMENTAL ANALYSIS

The environmental impact of energy systems can be evaluated by different techniques. In the past a thermo-ecologic approach has been proposed, to evaluate the
consumption of non-renewable exergy [223]. Only with a thermodynamic optimization the intermediate processes from the matters and energy to the plant operation would not be considered. Moreover a wrong approach has been used, to not assign environmental significance to the entropy generation due to renewable resources utilization systems. Enviro-nomic approaches have been elaborated to take into account processes like these. Economic evaluation of the environmental impacts of energy system has been considered by Frangopoulos (1997) [224]. One key concept deals with the environmental impact costs assignment: they can be considered internal and due to the process itself, or external to it. A complete plant lifetime analysis should consider them into the assessment.

Considering also mass and exergy fluxes into the environmental impact assessment leads to the definition of coefficients of specific environmental impact, which take part of environmental impact fluxes. Life Cycle Assessment (LCA) of each component of the plant has to be carried out, according to this approach [225]. The mass and energy/exergy fluxes for each component have then to be evaluated (Life Cycle Inventory, LCI).

The environmental impact is then evaluated from input and output fluxes through indicators (see Morosuk et al., 20012 [226]): for example Eco-Indicator 99 (ECO-99, the most used), Eco-Indicator 95 (ECO-95), and Cumulative Exergy Consumption (CExC). These are used to elaborate the Life Cycle Impact Assessment (LCIA).

According to the LCIA analysis the specific coefficients are used to evaluate the environmental impact ˙\(B\) of the j-th flux, in terms of pts/GJ (where pts are Indicator points)

\[
\dot{B}_j = b_j \dot{E}_j
\]

In an analogous way as for the exergy analysis, there are different components of the environmental impact: chemical, physical, kinetic and gravitational. To write a balance equation let us consider the term indicating the environmental impact of the k-th component ˙\(Y\)k:

\[
\dot{Y}_k = \dot{Y}^\text{CO}_k + \dot{Y}^\text{OM}_k + \dot{Y}^\text{DI}_k
\]

being \(\dot{Y}^\text{CO}_k\) the impact due to the building of the k-th element, \(\dot{Y}^\text{OM}_k\) the impact due to the O&M operations (including pollutant formation and primary resource consumption), \(\dot{Y}^\text{DI}_k\) the impact of the decommissioning operations. This values are evaluated with a LCA analysis. A summary of the inputs and outputs to be considered is shown if Fig. 153.

The balance equation for the k-th component is then

\[
\sum_{j=1}^{n} \dot{B}_{j,k,\text{in}} + \dot{Y}_k = \sum_{j=1}^{n} \dot{B}_{j,k,\text{out}}
\]

One can also consider the contribute of the pollutant formation (\(\dot{B}^\text{PF}_k\)) to be separate from the fuel stream (\(\dot{B}^\text{F}_k\)) [227]

\[
\dot{B}^\text{F}_k + \dot{Y}_k + \dot{B}^\text{PF}_k = \dot{B}^\text{P}_k
\]

being \(\dot{B}^\text{PF}_k\) equal to zero if no chemical reaction occur in the k-th element (e.g. heat exchangers).
As for the exergonomic analysis, also in the exergoenvironomic approach auxiliary equations are needed, if there is more than one flux in the balance. These equations can be defined considering again the F and P principles. Similarly to the exergonomic analysis, the terms expressing the exergy destruction has to be considered ($\dot{B}_{D,k} = \dot{b}_{F,k} \dot{E}_{D,k}$). The exergoenvironomic factor ($f_{b,k}$) can be then defined as

$$f_{b,k} = \frac{\dot{Y}^\text{CO}_k}{\dot{Y}^\text{CO}_k + \dot{B}_{D,k}}$$

\(204\)

**Figure 153.** environmental impact fluxes referred to the k-th element.

In this section the exergonomic and exergoenvironmental approaches are only briefly illustrated. Their application to the geothermal power plants sustainability evaluation is here considered as a future development. In particular the LCIA evaluation of these projects would be very interesting, particularly in a widely developing market context, not only in Europe and Italy, but also in other countries (Center and South America, Far East, and Africa).

Exergoenvironmental balance would help a lot in the evaluation of the projects and also to take into account the economic and financial aspects of a project. It has been shown in this work how a purely economic approach would lead to bad sizing and scarcely sustainable power plants.


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— Elio e le storie tese, “First Me, Second Me”

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Pisa, February 2013

Maurizio Vaccaro
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