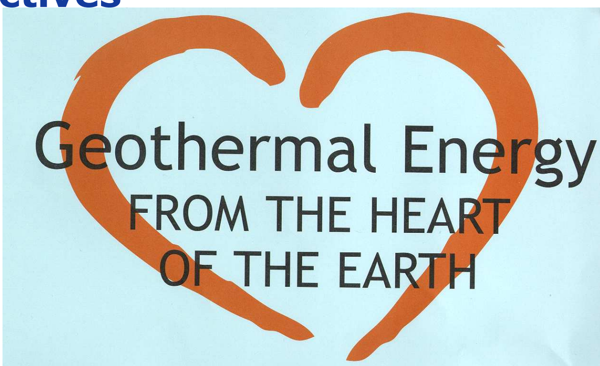
Geothermal Energy: technological and economical perspectives

Trieste, November 2011



Uso: inserire classificazione

Summary

- What Is Geothermal Energy?
- Geothermal System
- Geothermal Power Plant
- Electricity: present and future
- Green Field Evaluation
- Conclusion

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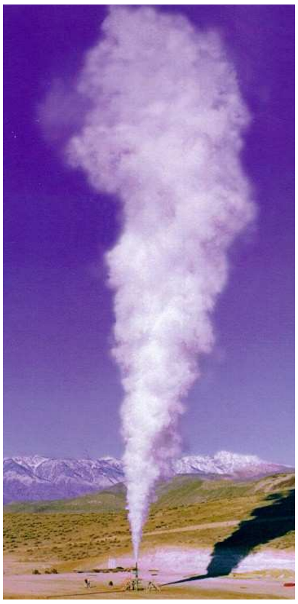
What is Geothermal Energy?



"Geothermal Energy"
From Greek ***gêo*** (earth) e ***thermòs*** (heat)

Heat inside the Earth.

"Geothermal resource"
That part of heat that can be utilized.

"Geothermal energy" is often used to indicate that part of the Earth's heat that can be recovered and exploited by man.

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What is Geothermal Energy?

In some region of the Earth the heat flux is enhanced and up to ten times more than the average value. In such area there are volcanic phenomena and seismic activities.

200 million years ago all the continents were merged in a single unit: *Pangea.*

The drift of the continents above the mantle formed the present dynamic situation of the Earth surface, with the presence of tectonic plates.

The plates boundaries are the "hot area of the Earth's surface".

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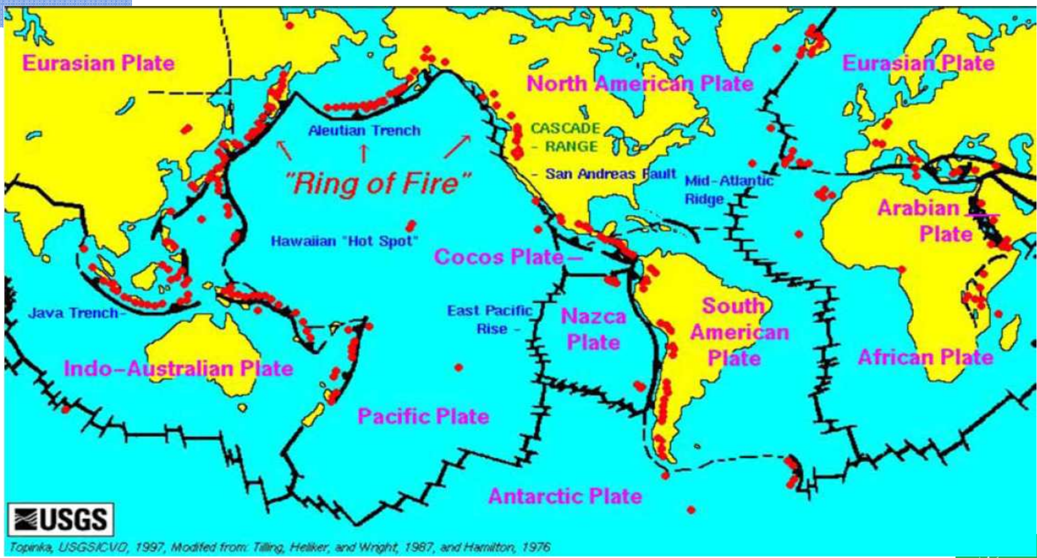
What is Geothermal Energy?



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What is Geothermal Energy?

Present electricity utilization **700x10^{12} MJ**

Even limiting to the first 3 km under the continental platforms in accessible latitudinous, the amount of geothermal heat will be **40x10^{18} MJ**

About 60,000 times the present consumption

but available at a low average temperature

The thermal energy of the Earth is therefore immense, but only a fraction can be utilized by man.

The average heat flux under the Crust of the continent in the order of **65 mW/m^2**

Total thermal capacity generating from geothermal processes **10 TW = 300 EJ/year**

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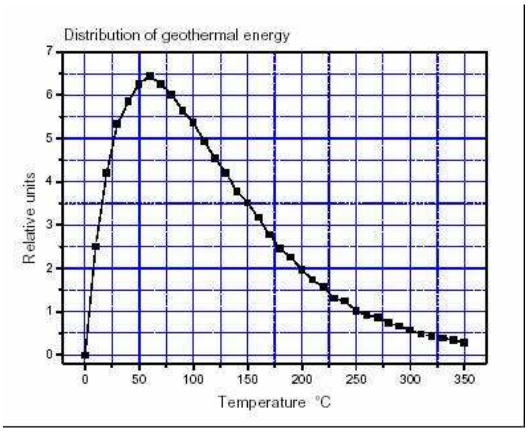
What is Geothermal Energy?

The thermal energy of the Earth is therefore immense,
but only a fraction can be utilized by man, because
this heat is available at a low average temperature

So far our utilization of this energy has been limited to areas in which geological conditions permit a carrier (water in the liquid phase or steam) to "transfer" the heat from deep hot zones to or near the surface, thus giving rise to geothermal resources.



Geothermal Energy

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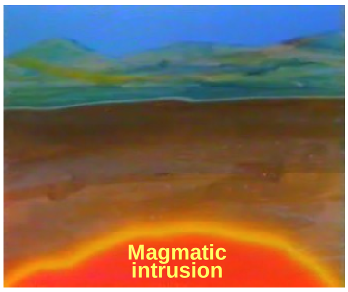
What is Geothermal Energy?

When magma reached the surface, it can originates volcanic eruptions.

..or it can create magmatic intrusion, which are the sources of the geothermal heat at depth of few kilometers.



The presence of the heat source alone is not enough for creating a "geothermal resource".

Geothermal Energy

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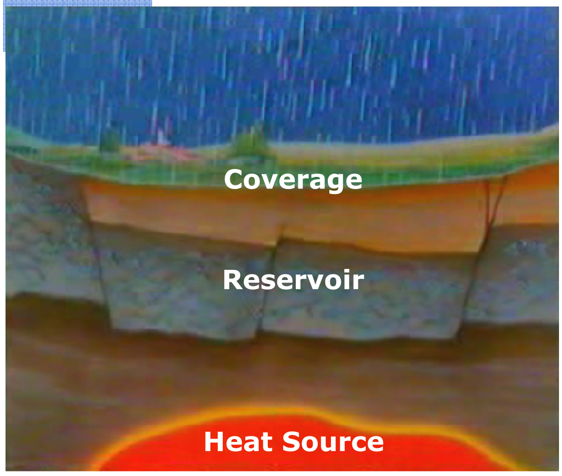
What is Geothermal Energy?



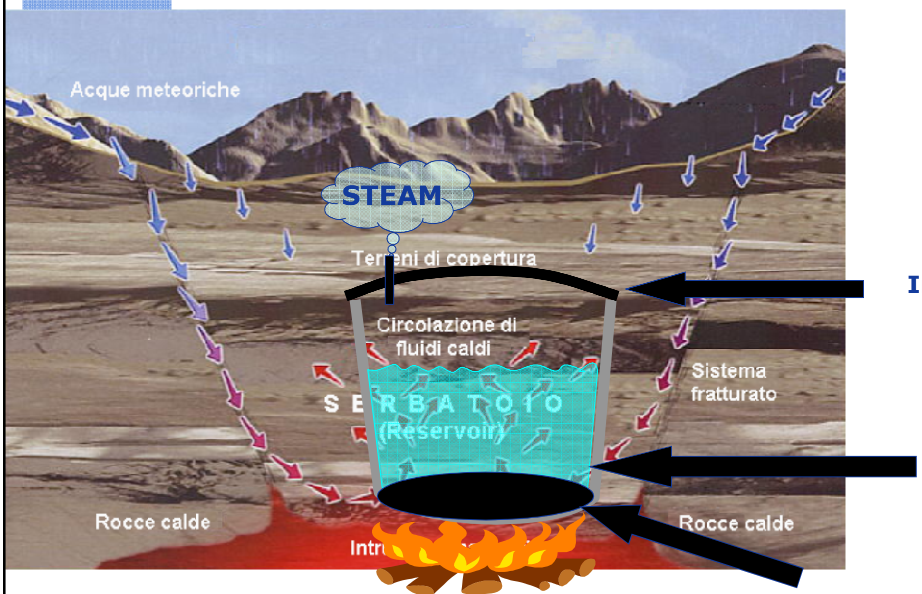
It is necessary the presence of an **heat source** nearby the surface.

It is necessary to have a **reservoir**, i.e. a **porous and fractured rock system**, where there are **fluids** (water or steam), which can be used as carrier of the heat

It is necessary to have an **impermeable coverage**, for keeping the fluid and the heat in a confined space.

In a geothermal system the meteoric waters are trapped in the reservoir, are heated and it is activated a natural convective circulation, driving the heat up to the surface.

Geothermal System



Impermeable coverage

Reservoir: fluid inside a porous and permeable rock

Heat source

Impermeable basement

Geothermal System

Geyser - Iceland

Boiling spring - USA

Geothermal System

El Tatio- Chile

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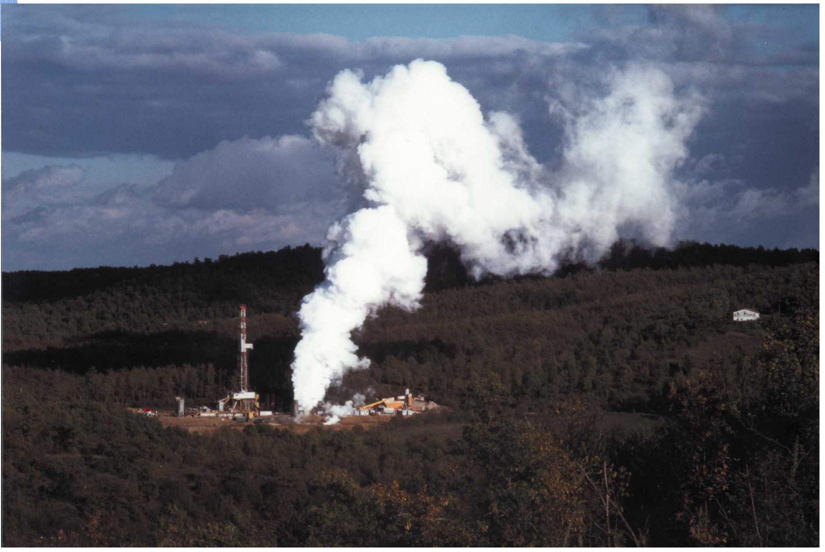
Geothermal System



Montieri 1 well: 200t/h of dry steam ➔ 20 MW, Italian Record

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Geothermal System

What is a *geothermal system* and what happens in such a system? It can be described schematically as "**convecting water in the upper crust of the Earth, which, in a confined space, transfers heat from a heat source to a heat sink, usually the free surface**".

three main elements:

a ***heat source***

a ***reservoir***

a ***fluid*** , which is the carrier that transfers the heat.

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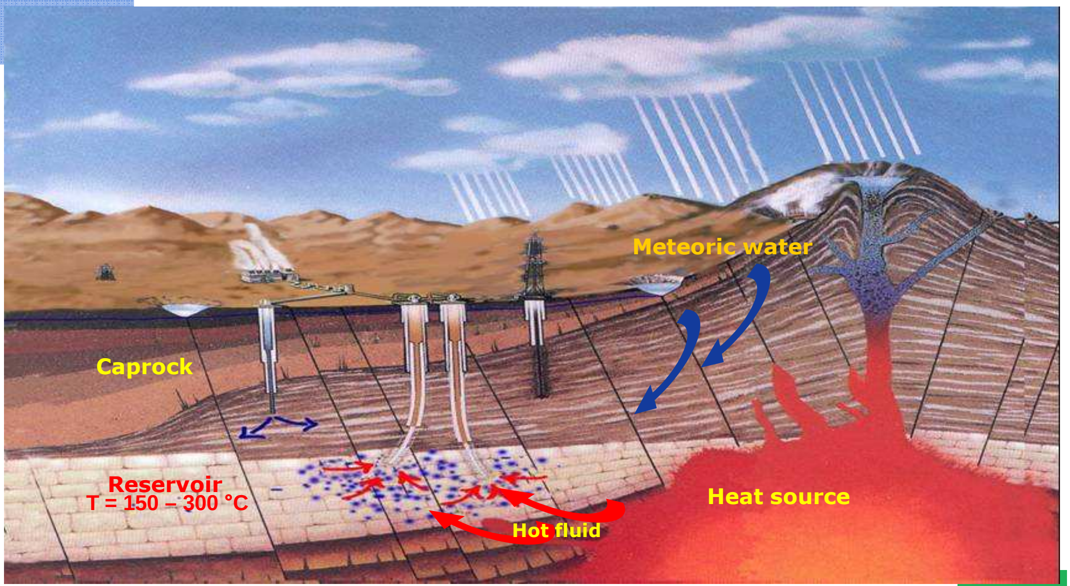
Geothermal System



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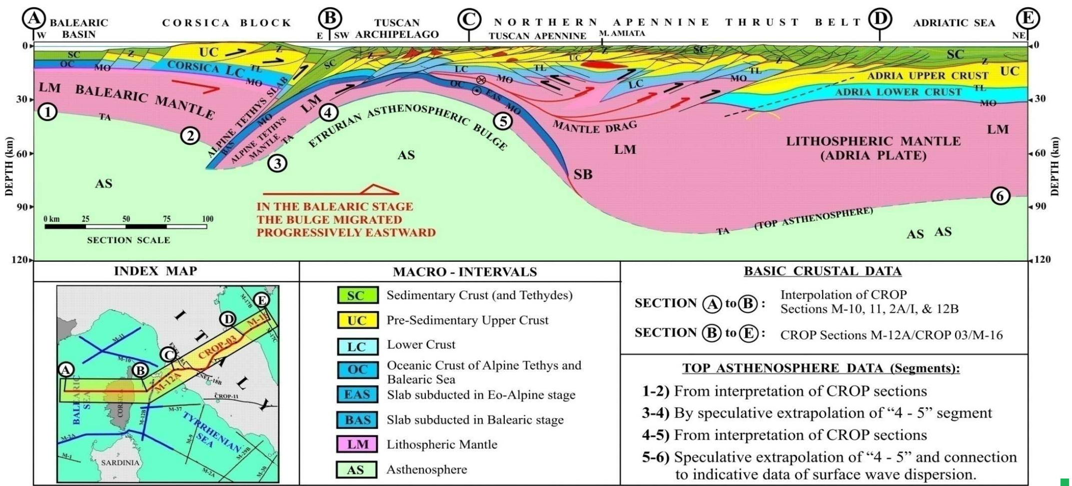
Geothermal System



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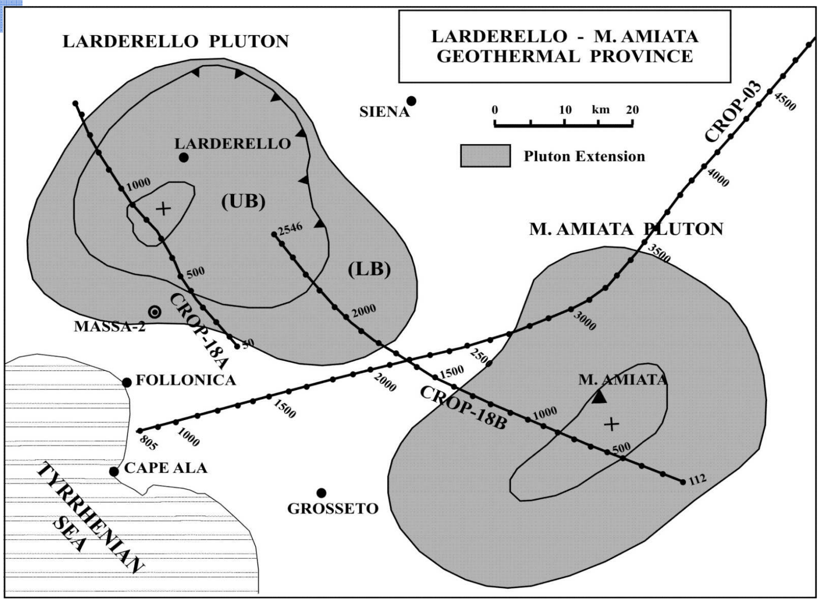
Geothermal System



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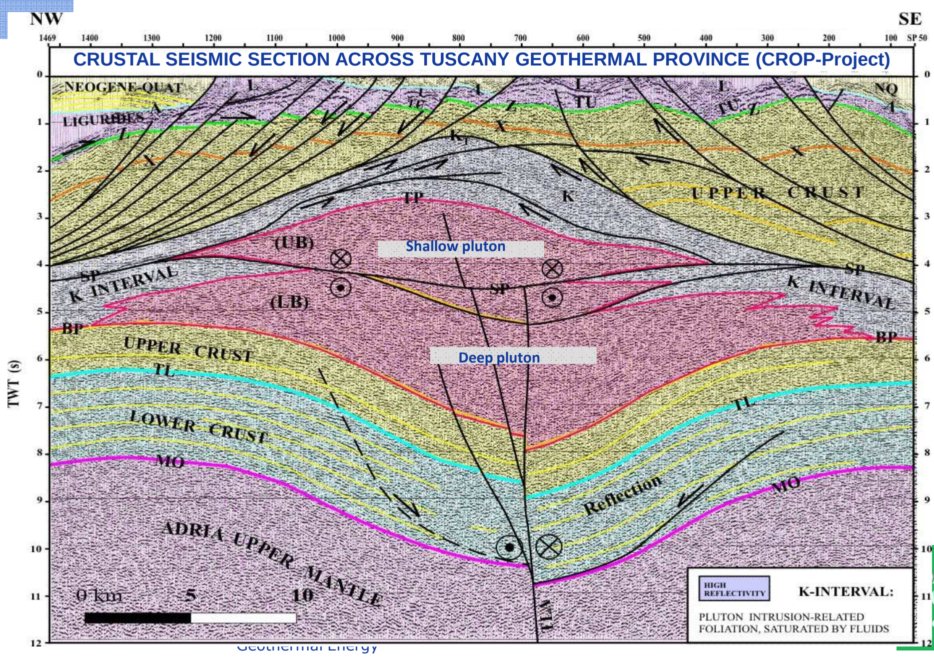
Geothermal System



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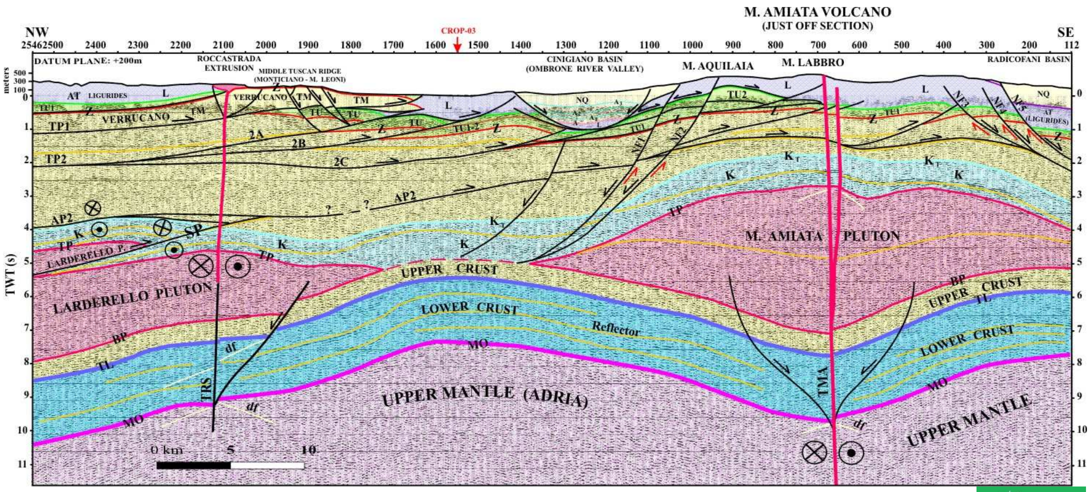
Geothermal System



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Geothermal System

Lagoncelli, putizze and old wells
San Federico c/o Lago Boracifero

“Bocca della Balena”
(Whale Mouth)
Bagni San Filippo

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Geothermal System

Geothermal manifestation
Monterotondo Marittimo

Mud Lagoncelli
Sant'Adriana

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Geothermal System

Champagne pool – New Zealand

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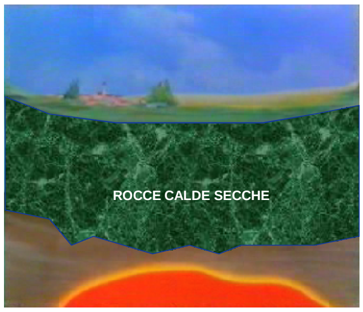
Geothermal System

Natural discharge of hot water or steam:
geothermal manifestation.

Hydrostatic pressure in the reservoir:
Water dominated systems.

In some situations, the pressure is relatively low and the temperature is regulated by the steam phase:
Steam dominated systems



In some situation there is an heat source without reservoir:
Hot Dry Rock
Enhanced Geothermal System

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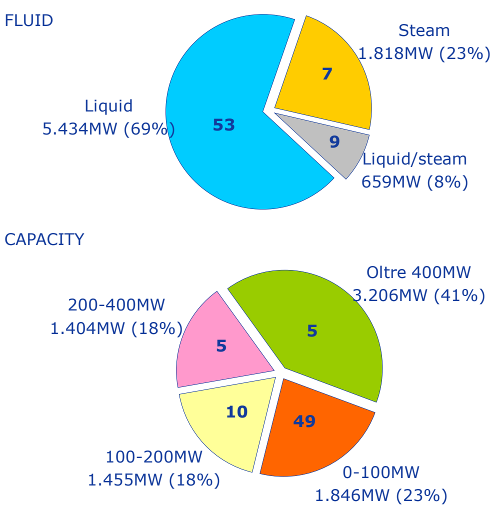
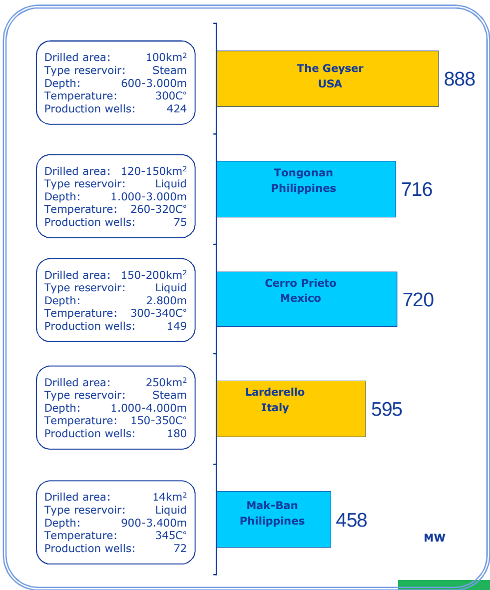
Geothermal System





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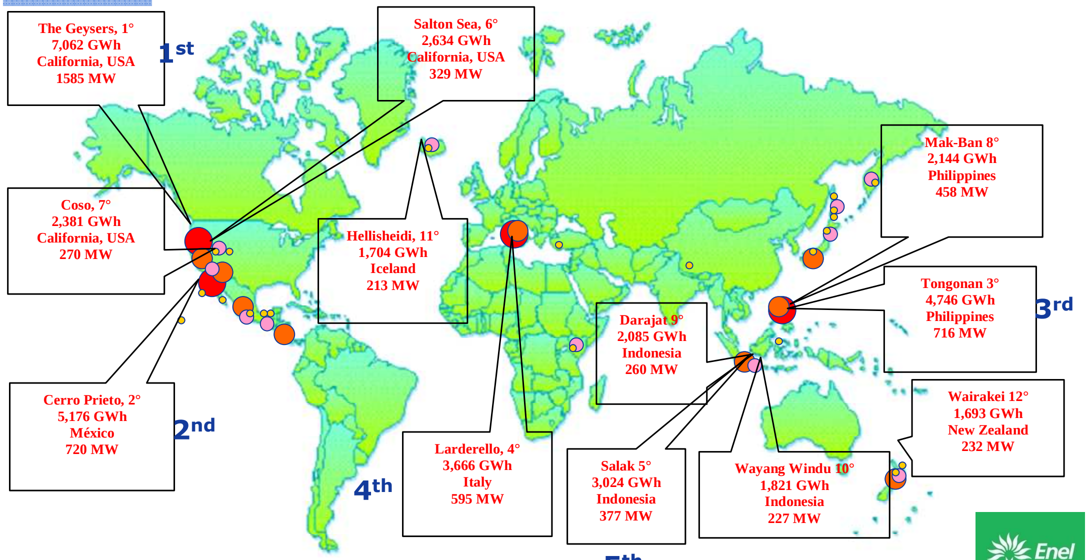
2010 Geothermal World: fields



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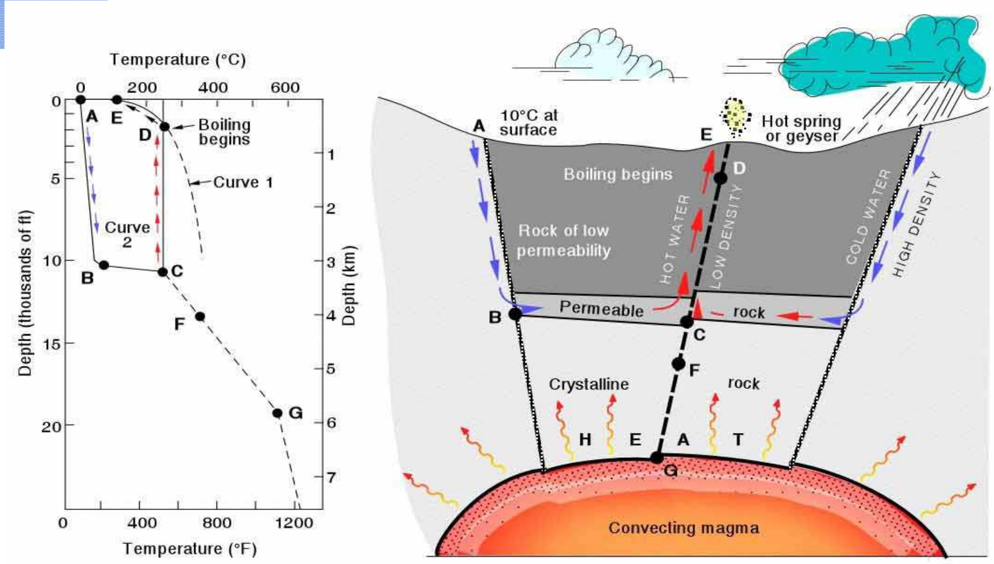
Geothermal System



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Geothermal System

Water presence (as carrier medium)

	Wet	Dry
Shallow reservoirs 5: 500 m	**Conventional hydrothermal systems or heat exchange** • **Description: Hot shallow** reservoirs are used for generation of electricity in a conventional geothermal system • **Cold shallow** reservoirs are used for heat exchange, cooling buildings in summer and heating in winter • **Uses:** Electricity generation and heat	**Heat exchange** • **Description:** Heat pumps are used to transfer heat between the surface and subterranean levels • Methods include horizontal loops, borehole heat exchanges, and energy piles • **Uses:** Heat exchange
Deep reservoirs 500: 5000 m	**Conventional Hydrothermal systems** • **Description:** Super heated ground water is released through geothermal wells and is transformed into steam to generate electricity as it travels toward the surface • **Uses:** Electricity generation	**Enhanced geothermal systems** • **Description:** Hot dry rock reservoirs are developed by injecting high pressure water into a stressed zone, causing it to fracture. Heat is transferred to the water, used for generation and re-injected into the reservoir, forming a closed-loop system • **Uses:** Electricity generation

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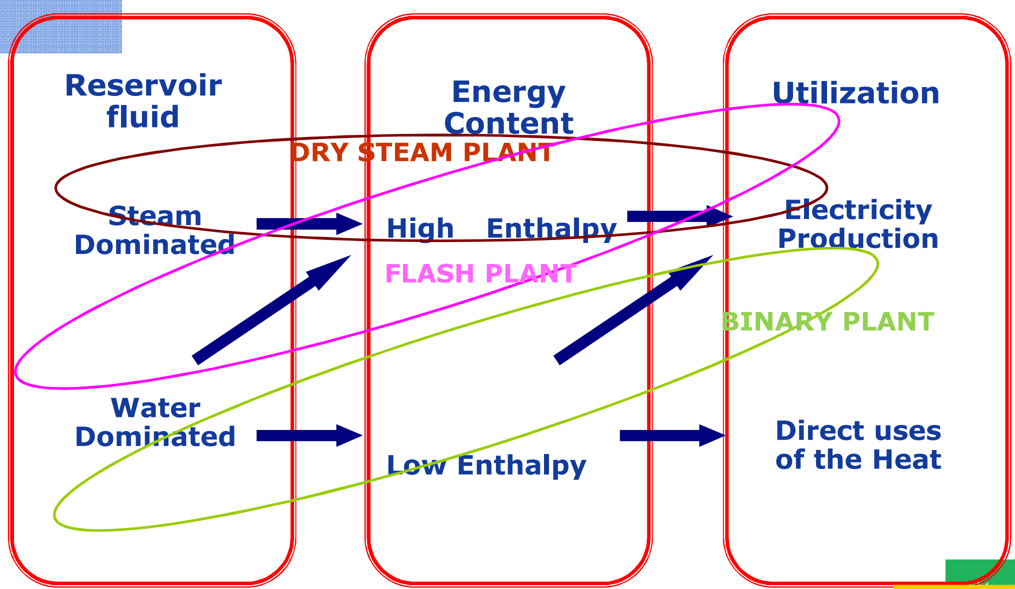
Geothermal System



2010 Geothermal World: installed>500 MW

COUNTRY	2005 MW	2005 GWh	2010 MW	2010 GWh
USA	2,564	16,840	3,093	16,603
PHILIPPINES	1,930	9,253	1,904	10,311
INDONESIA	797	6,085	1,197	9,600
MEXICO	953	6,282	958	7,047
ITALY	791	5,340	843	5,520
NEW ZEALAND	435	2,774	628	4,055
ICELAND	202	1,483	575	4,597
JAPAN	535	3,467	536	3,064

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2010 Geothermal World: increases>50 MW

COUNTRY	2010 MW	2010 GWh	NEW MW	NEW GWh
USA	3,093	16,603	530	-237
INDONESIA	1,197	9,600	400	3,515
ICELAND	575	4,597	373	3,114
NEW ZEALAND	628	4,055	193	1,281
TURKEY	82	490	62	385
EL SALVADOR	204	1,422	53	455
ITALY	843	5,520	52	180
PAPUA–NEW GUINEA	56	450	50	433

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2010 Geothermal World: increases>50 %

COUNTRY	NEW MW	NEW GWh	%MW	%GWh
GERMANY	6	49	2,774%	3,249%
PAPUA-NEW GUINEA	50	433	833%	2,547%
AUSTRALIA	1	0	633%	-5%
TURKEY	62	385	308%	368%
ICELAND	373	3,114	184%	210%
PORTUGAL	13	85	78%	94%
GUATEMALA	19	77	58%	36%
INDONESIA	400	3,515	50%	58%

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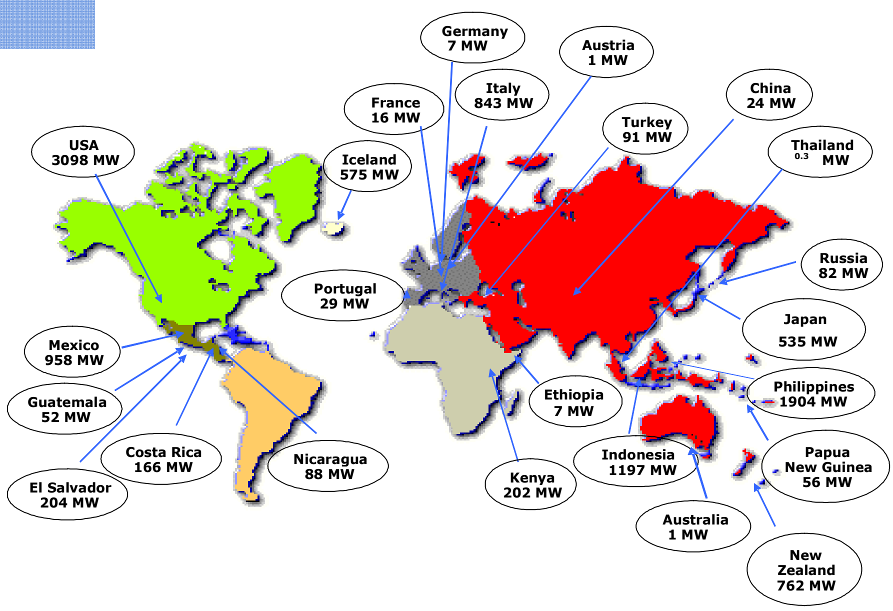
2010 Geothermal World: 10,9 GW & 67,2 TWh



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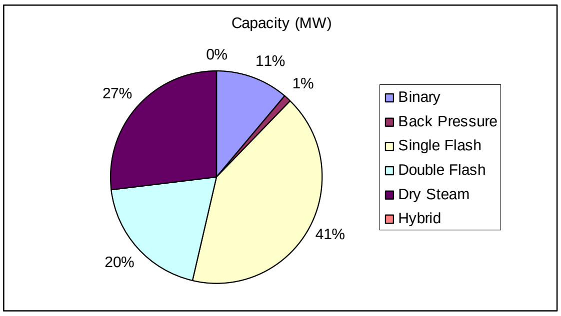
2010 Geothermal World: plants

Since WGC2005, 139 new units have been commissioned on a total of 526



TYPE	Average Energy (GWh/ unit)	Average Capacity (MW/unit)
Binary	27	5
Back Pressure	96	6
Single Flash	199	31
Double Flash	236	34
Dry Steam	260	46

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2010 Geothermal World: plants

The average geothermal capacity on the entire
526 units in operation is 20.6 MW

BIG

Only **48 units** with capacity >55 MW,
with an average of 79.5 MW.

SMALL

There are **259 units** with capacity < 10 MW,
with an average capacity of 3.2 MW.

The majority of them is binary (196 units),
22 are back pressure,
22 are single flash and 17 double flash.

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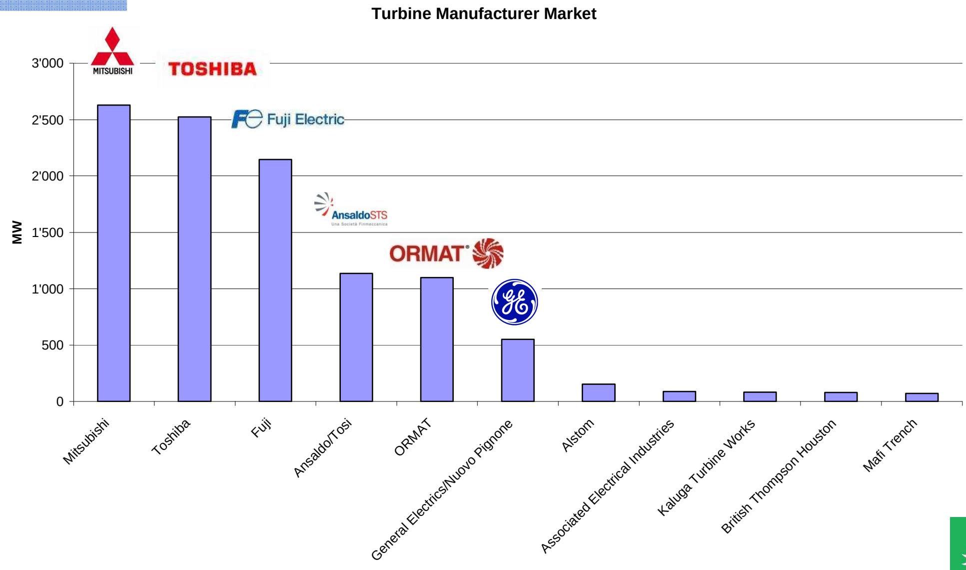
2010 Geothermal World: plants



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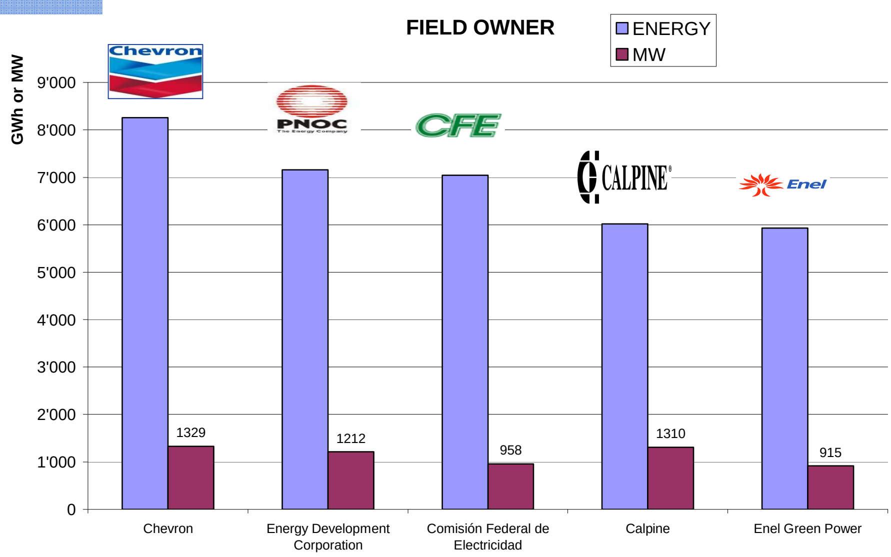
2010 Geothermal World: top five companies



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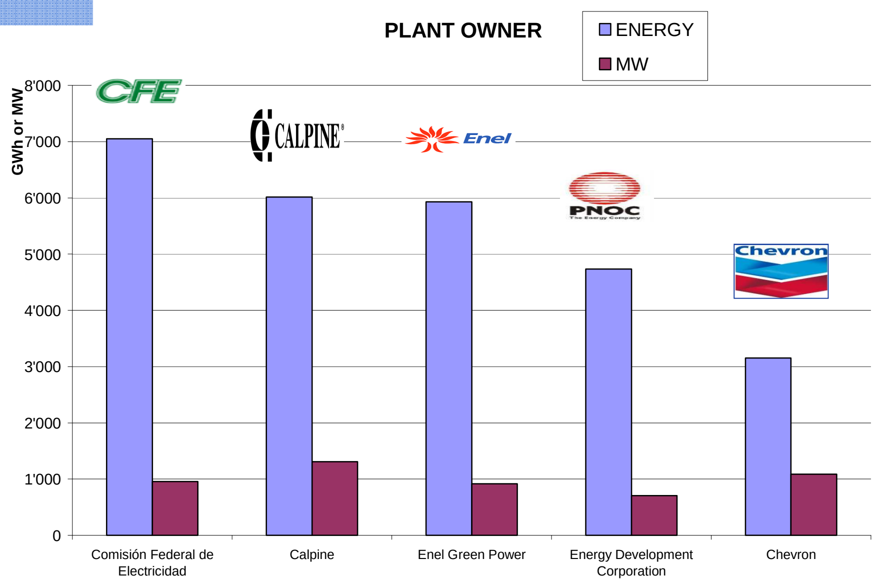
2010 Geothermal World: companies



Geothermal Energy

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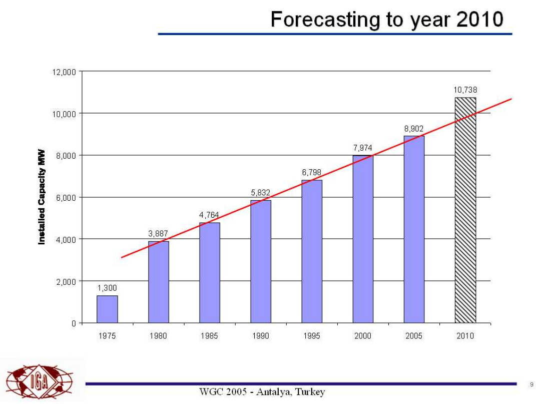
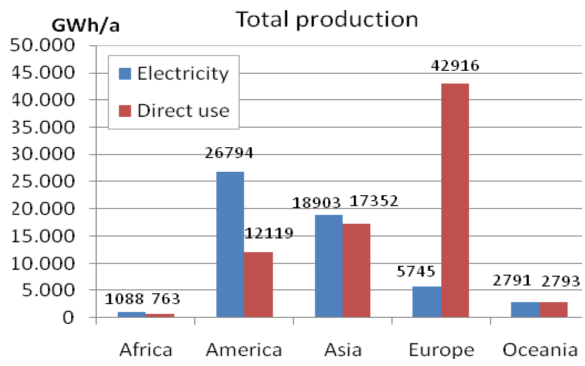
Geothermal Electricity





In the last 20 years the geothermal installed capacity in the world has been increased by about 1,000 MW every 5 years.

Geothermal Energy

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Geothermal Electricity

* = Estimated

	Installed capacity		Production per year		Capacity factor (%)
	GWe	%	TWh/yr	%	
Hydro	778	87.5	2,837	89	42
Biomass	40*	4.5	183	5.7	52*
Wind	59	6.6	106	3.3	21
Geothermal	**9**	**1.0**	**57**	**1.8**	**72**
Solar	4	0.4	5	0.2	14
Total	890	100	3,188	100	41

Geothermal energy is available day and **night every day of the year** and can thus serve as a partner with energy sources which are only available intermittently.

It is most economical for geothermal power stations to serve as **base load** throughout the year.

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Geothermal Electricity

	GWh	%
Coal	6.944.328	39,61
Gas	3.418.676	19,50
Nuclear	2.738.012	15,62
Oil	1.170.152	6,67
Other sources	2.292	0,01
Non-renewables total	**14.273.460**	**81,42**
Hydro	2.889.094	16,48
Biomass	149.811	0,85
Waste	77.471	0,44
Wind	82.259	0,47
Geothermal	55.896	0,32
Solar thermal	1.608	0,01
Solar PV	840	0,00
Tide, Wave, Ocean	551	0,00
Renewables total	**3.257.530**	**18,58**
Total world generation	**17.530.990**	**100,00**

The present geothermal installed capacity of 10 GW is expected to increase up to **18 GW in 2015.**

The overall CO_2 saving from geothermal electricity can be in the range 1000 (coal)/500 (gas) million tons per year, if the target of 140 GW will be reached

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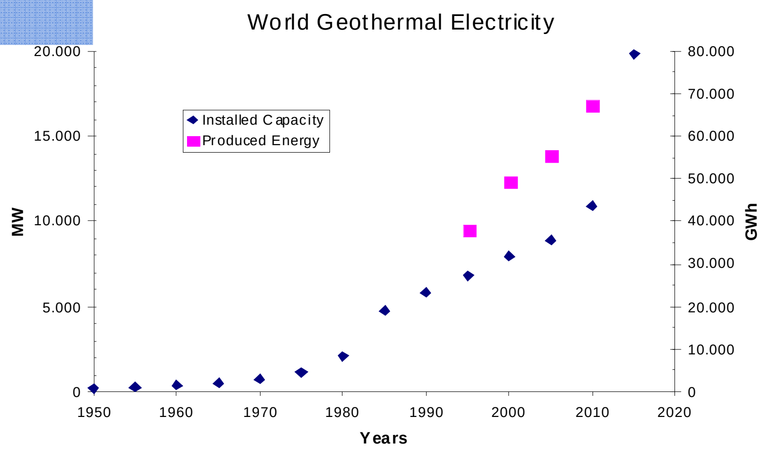
Geothermal Electricity



In the last 20 years the geothermal installed capacity in the world has been
increased by about 1000 MW every 5 years.

In the last five years, however, the total increase was 400 MW/year

Geothermal Energy 41

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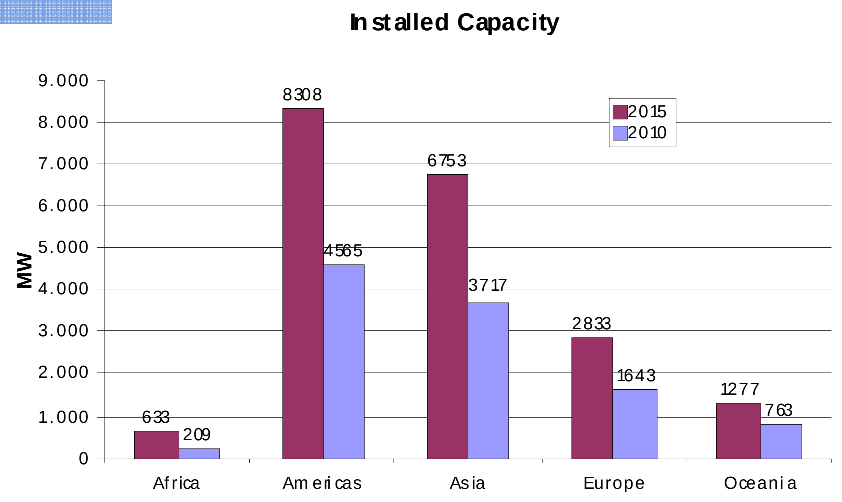
Geothermal Electricity



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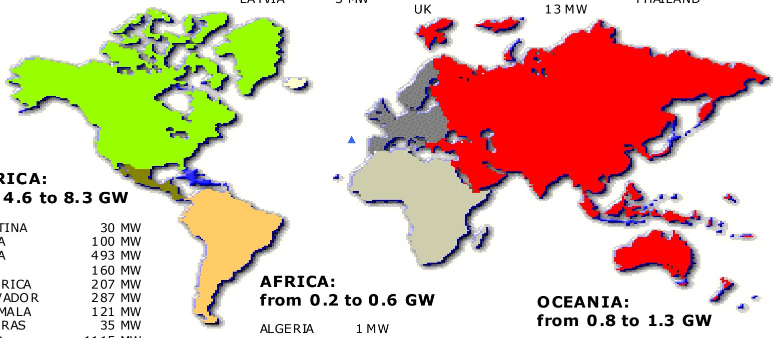
Geothermal Electricity

EUROPE: from 1.6 to 2.8 GW

AUSTRIA	6 MW
CZECH REP	5 MW
FRANCE	41 MW
GERMANY	15 MW
GREECE	18 MW
HUNGARY	5 MW
ICELAND	1285 MW
ITALY	923 MW
LATVIA	3 MW
POLAND	1 MW
PORTUGAL	60 MW
ROMANIA	5 MW
RUSSIA	194 MW
SLOVAKIA	5 MW
SPAIN	40 MW
SWITZERLAND	3 MW
THE NETHERLAND	5 MW
TURKEY	206 MW
UK	13 MW

ASIA: from 3.7 to 6.8 GW

ARMENIA	25 MW
CHINA	64 MW
INDONESIA	3451 MW
IRAN ISL.REP	50 MW
JAPAN	568 MW
PAPUA-NEW GUINEA	75 MW
PHILIPPINES	2519 MW
THAILAND	1 MW



AMERICA: from 4.6 to 8.3 GW

ARGENTINA	30 MW
BOLIVIA	100 MW
CANADA	493 MW
CHILE	160 MW
COSTA RICA	207 MW
El SALVADOR	287 MW
GUATEMALA	121 MW
HONDURAS	35 MW
MEXICO	1115 MW
NEVIS	35 MW
NICARAGUA	248 MW
PERU	40 MW
USA	5437 MW

AFRICA: from 0.2 to 0.6 GW

ALGERIA	1 MW
DJIBUTI	50 MW
ETHIOPIA	47 MW
KENYA	534 MW

OCEANIA: from 0.8 to 1.3 GW

AUSTRALIA	40 MW
NEW ZEALAND	1237 MW

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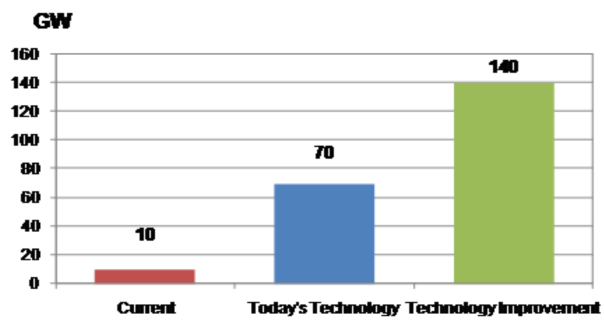
Geothermal Electricity: forecasting

It's difficult to estimate the overall world-wide potential, due to the presence of too many uncertainties. Nevertheless, it is possible to identify a range of estimations, taking into consideration also the possibility of new technologies:

permeability enhancements,
drilling improvements,
enhanced geothermal system,
low temperature production
supercritical fluid.

Standard: 70 GW
Improved: 140 GW



It is possible to produce up **8.3%** of total world electricity production, serving **17%** of world population.

39 countries (located mostly in Africa, Central/South America, Pacific) can be 100% geothermal powered.

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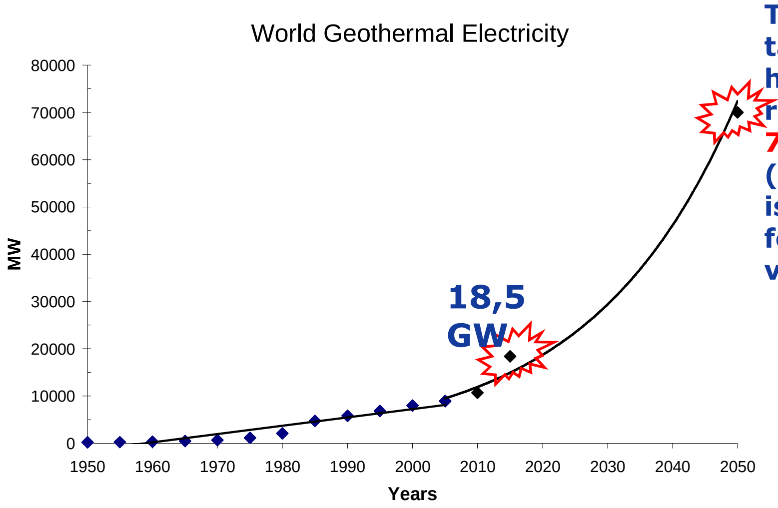
2050 Geothermal World: forecasting



The expected target from hydrothermal resources of 70 GW (EGS contribution is not considered) for year 2050 is very ambitious

Geothermal Energy

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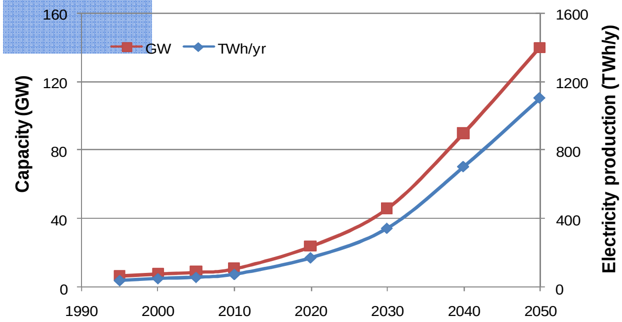
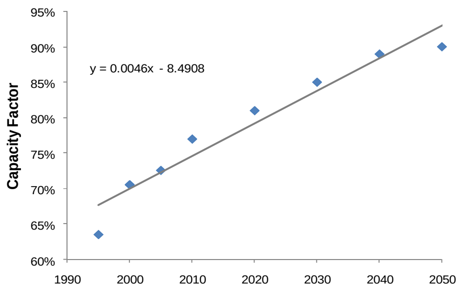
Geothermal Electricity: forecasting



It is expected that the next generation will see the implementation of Enhanced Geothermal System (EGS) and an intensive increase in low-to-medium temperature applications through binary cycles and cascade utilisations. Geothermal energy is not so considerable, but its base-load capability is a very important factor for its success. The utilisation of binary plants and the possibility of production from enhanced geothermal systems (to be considered as possible future developments) can expand its availability on a worldwide basis

Long-Term Forecasting of

Electricity Production
Installed Capacity
Capacity factor



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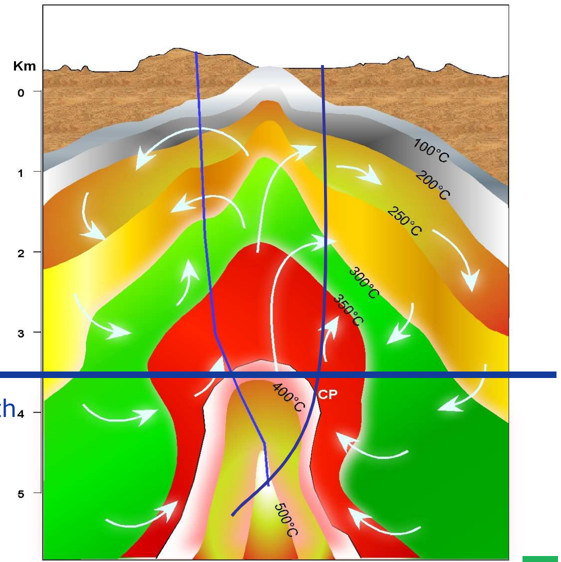
Geothermal Electricity: new technology

Conceptual model
of a geothermal
reservoir at
supercritical
Condition:
Icelandic Deep Drilling project



3,5 km
Casing depth

4 - 5 km
Target depth

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Geothermal Electricity: new technology

The current plan is to drill and test at least three 3.5-5 km deep boreholes in Iceland within the next few years (one in each of the Krafla, Hengill, and Reykjanes high-temperature geothermal systems). Beneath these three developed drill fields temperatures should exceed 550-650°C, and the occurrence of frequent seismic activity below 5 km, indicates that the rocks are brittle and therefore likely to be permeable. Modelling indicates that if the wellhead enthalpy is to exceed that of conventionally produced geothermal steam, the reservoir temperature must be higher than 450°C.

A deep well producing 2500 m^3/h of steam from a reservoir with a temperature significantly above 450°C could yield enough high-enthalpy steam to generate **40-50 MW** of electric power.
This exceeds by an order of magnitude the power typically obtained from conventional geothermal wells. This would mean that much more energy could be obtained from presently exploited high-temperature geothermal fields from a smaller number of wells.

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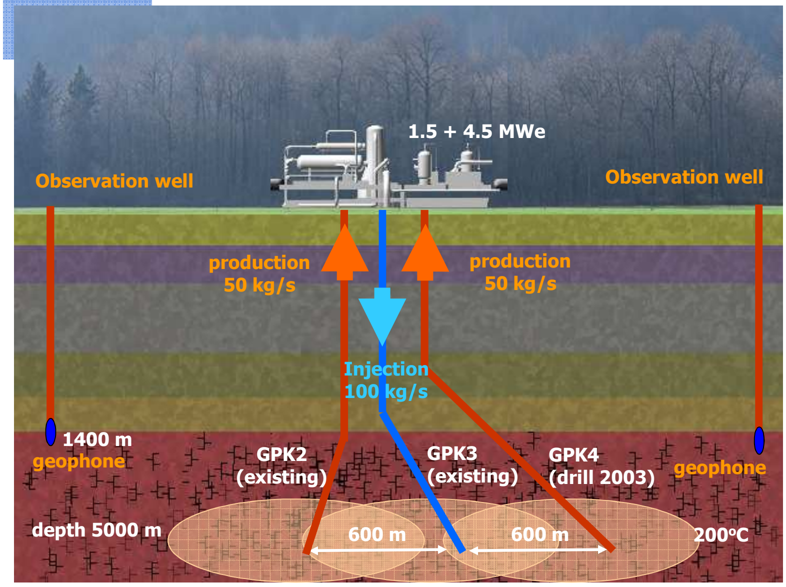
Uso: inserire classificazione

Geothermal Electricity: new technology



Enhanced Geothermal System:
European Soultz project

Geothermal Energy 49

Enel Green Power

Uso: inserire classificazione

Geothermal Electricity: new technology

First EGS Power Plant

(J.V. Turboden- Cryostar - start up in 2008)

- Heat source: Geothermal fluid at 175°C (return at 70°C)
- Cooling: air
- Total electric power: 1.5 MW

The EU project "**EGS Pilot Plant**" in Soultz-sous-Forêts/France, active since 1985

Geothermal Energy 50

Enel Green Power

Geothermal Electricity: new technology

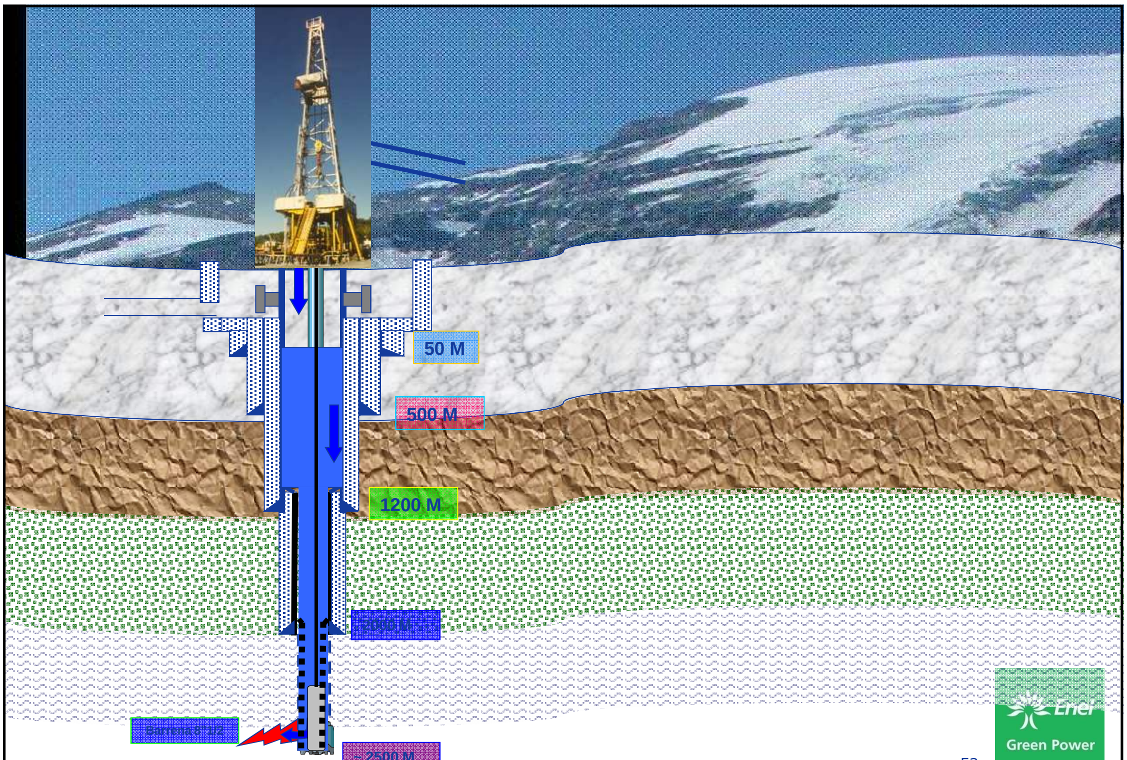
For the "**zero-emission** in geothermal program", an important investment plan has been approved by Enel, in order to mitigate the H_2S and Hg effluent to the environment with a specific treatment, using a technology fully designed and developed by Enel: **AMIS** plant, reaching a very high efficiency in H_2S and Hg removal, lower capital and O&M costs in comparison with commercial process, no solid sulphur by-products (liquid streams reinjected in the reservoir) and unattended operation (remote control).

Approximately **80% of the effluents** are currently treated by AMIS systems.

51

Geothermal Electricity: new technology

Drilling technology: both evolutionary improvements on conventional approaches to drilling such as more robust drill bits, innovative casing methods, better cementing techniques for high temperature, improved sensors, electronic capable of operating at higher temperature in downhole tools, revolutionary improvements utilizing new methods of rock penetration. It will result in reducing the drilling cost and it will allow to access deeper and hottest regions.



Geothermal Electricity: new technology

- **Power conversion technology**: improving heat-transfer performance for low temperature fluid, developing plant design with high efficiency and low parasitic losses. It will increase the available resource basis to the huge low-temperature regions, not bounded to the plate boundary.

- **Reservoir technology**: increasing production flow rate by targeting specific zones for stimulation and improving downhole lift systems for higher temperature, improving heat-removal efficiency in fractured rock system. It will lead to an immediate cost reduction increasing the output per well and extending reservoir operating life.

Uso: inserire classificazione

Geothermal Electricity Plant

Geothermal sheep – New Zealand

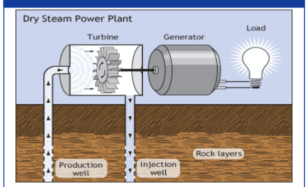
Larderello – Italy

Green Power

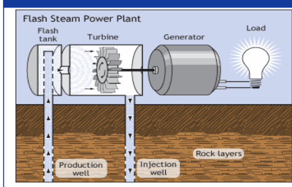
Uso: inserire classificazione

Geothermal Electricity Plant

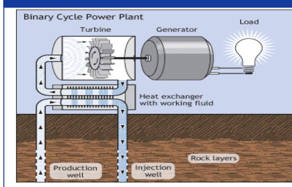
•Dry steam power plants	•Flash steam power plants	•Binary cycle power plants



Dry steam plants use hydrothermal fluids that are primarily steam. The steam goes directly to a turbine, which drives a generator that produces electricity.



•**Flash steam power plants** tap into reservoirs of water with temperatures greater than **182ºC**. As it flows, the fluid pressure decreases and some of the hot water boils or "flashes" into steam. The steam is then separated at the surface and is used to power a turbine/generator unit



•**Binary cycle power plants** operate on water at lower temperatures of about **107-182ºC**. These plants use the geothermal heat from the geothermal water to boil a working fluid, usually an organic compound with a low boiling point.

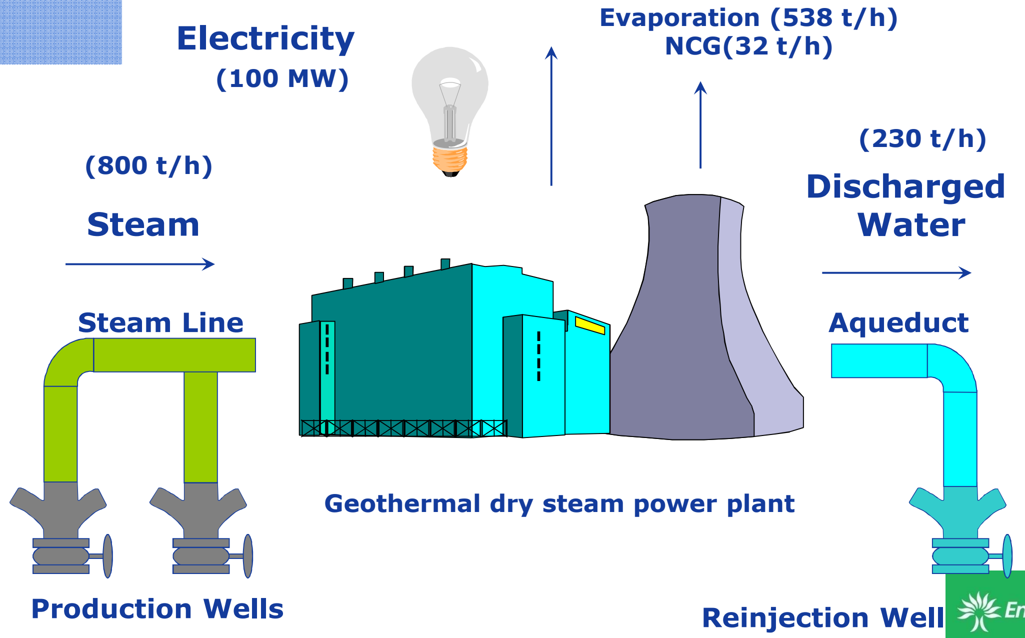
Global Installed capacity 2007	Dry steam	Flash steam	Binary cycle
Units	58	195	237
Capacity (GW)	2.6	5.6	0.8

- Highly cost competitive but geographically limited
- Most dominant in terms of global capacity
- Useful alongside geothermal heating, hot springs, etc

Green Power

Uso: inserire classificazione

Geothermal Electricity Plant: dry steam



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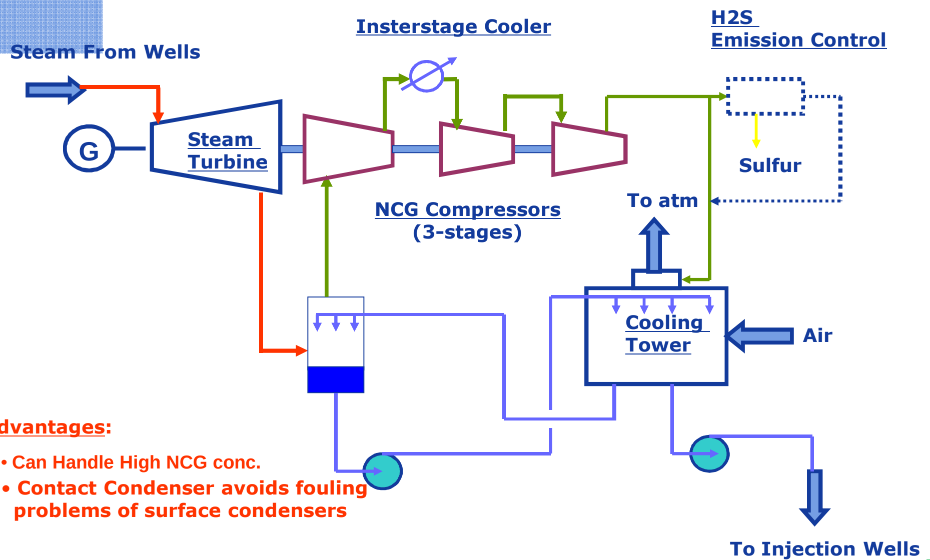
Uso: inserire classificazione

Geothermal Electricity Plant: dry steam



Advantages:

- Can Handle High NCG conc.
- Contact Condenser avoids fouling problems of surface condensers

Typical Enel "Dry Steam" Geothermal Power Plant

Enel Green Power

Uso: inserire classificazione

Geothermal Electricity Plant: dry steam

Technology Advantages

- Resembles a typical Steam Cycle Power Plant
- Most equipment can be obtained from a variety of suppliers
- Condensing Steam Turbines have a high power conversion efficiency (+75%)

Technology Disadvantages

- Since 2/3 of the steam is lost in the cooling tower, geothermal fields get depleted with time
- Use of Steam Ejectors more suitable for low NCG concentrations – high steam usage
- Gas Compressors have high parasitic load and high maintenance

Main Equipment Suppliers

Steam Turbine: GE; Mitsubishi; Sumitomo; Ansaldo

Generator: GE; Alstom; Siemens

Cooling Tower: Marley; Niagara

Economics

Power Plant Construction Cost: $1,000 – $1,500 / kW

O&M Cost: $10 - $20 / MWh

Typical "Dry Steam" Geothermal Power Plant

Enel Green Power

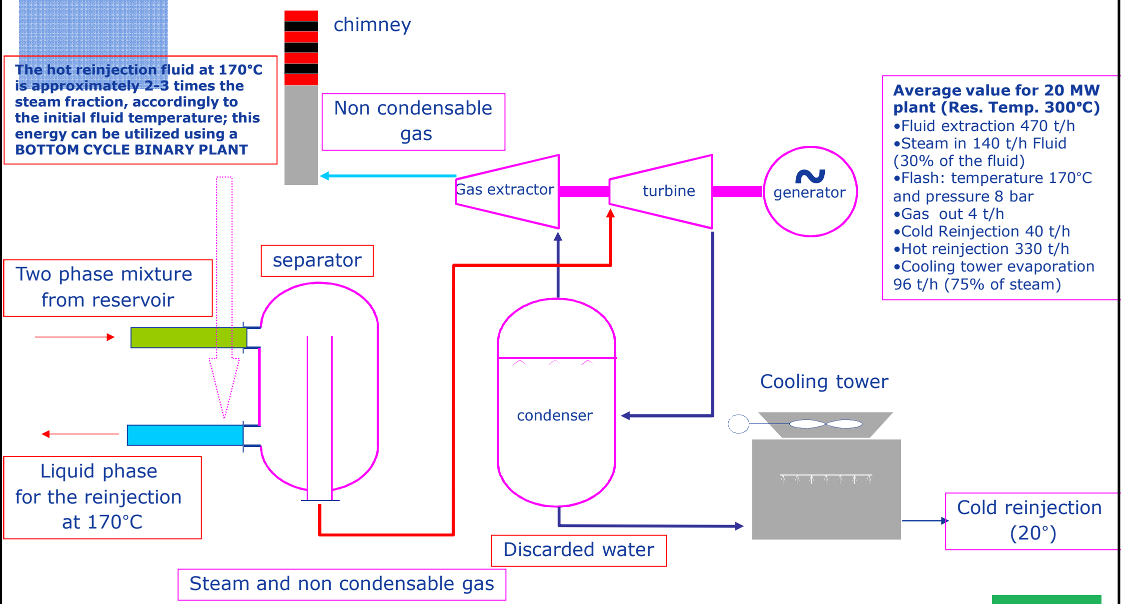
Uso: inserire classificazione

Geothermal Electricity Plant: dry steam

Larderello – Italy

Enel Green Power

Geothermal Electricity Plant: flash



Typical condensing plant from high enthalpy Liquid Reservoir

Enel Green Power

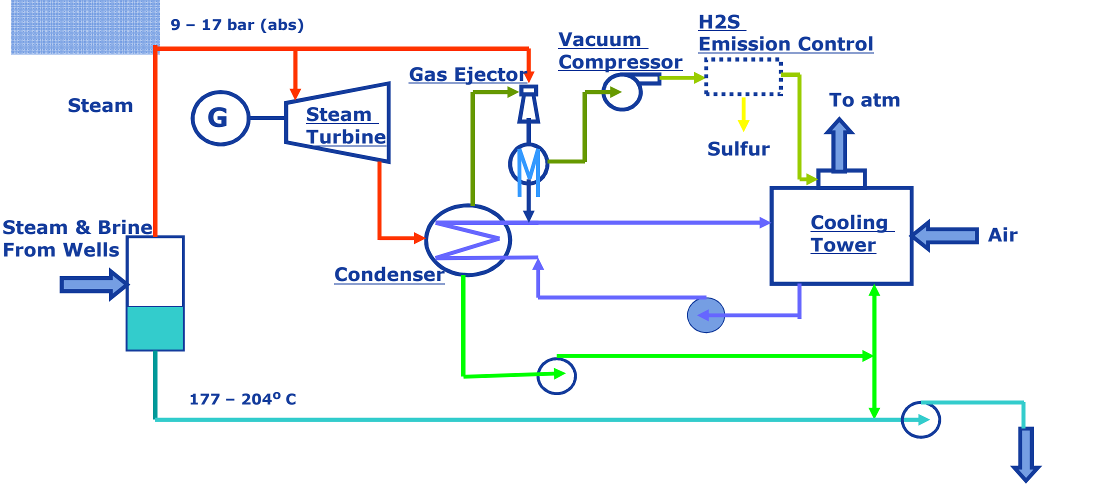
Geothermal Electricity Plant: flash

Berlin 44 MW– El Salvador

Enel Green Power

Uso: inserire classificazione

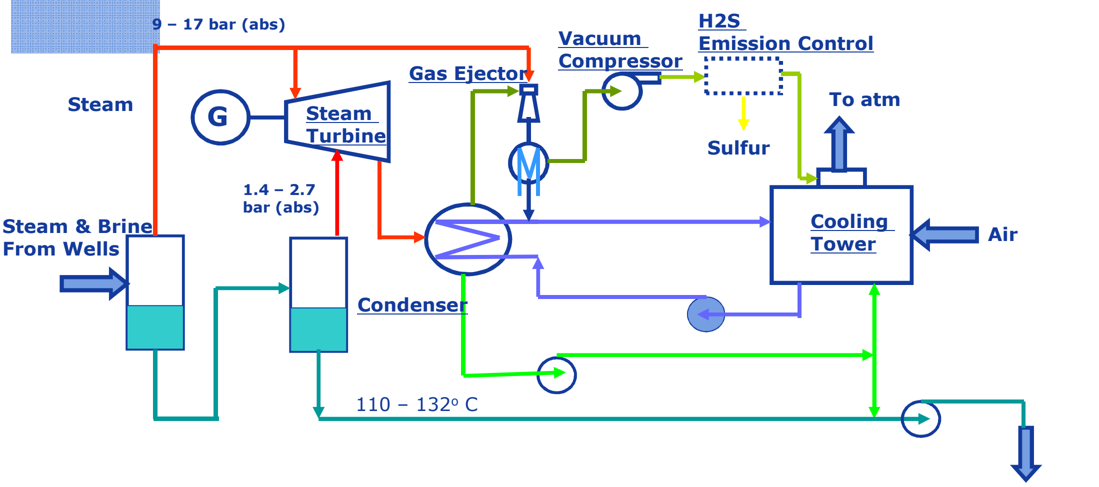
Geothermal Electricity Plant: flash



Typical "Single- Flash" Geothermal Power Plant

Uso: inserire classificazione

Geothermal Electricity Plant: flash



Typical "Double - Flash" Geothermal Power Plant

Uso: inserire classificazione

Geothermal Electricity Plant: flash

Technology Advantages

- Most equipment can be obtained from a variety of suppliers
- Most of the water drawn from the reservoir is return. Source generally have a higher useful life

Technology Disadvantages

- Use of Steam Ejectors more suitable for low NCG concentrations
- Brines may have high concentrations of silica and/or Calcium salts which can cause troublesome scaling requiring frequent clean-ups of separators and wells.
- Single Flash preferred when high solids concentration are found in the brine

Main Equipment Suppliers

Steam Turbine: GE; Mitsubishi; Sumitomo; Ansaldo

Generator: GE; Alstom; Siemens

Cooling Tower: Marley; Niagara;

Economics

Power Plant Construction Cost: $1,500 – $2,000 / kW

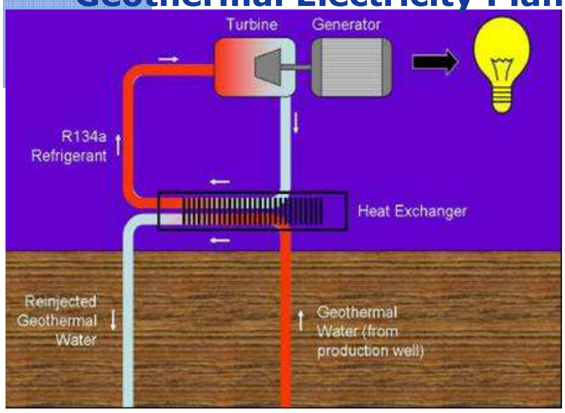
O&M Cost (direct): $15 - 20 / MWh

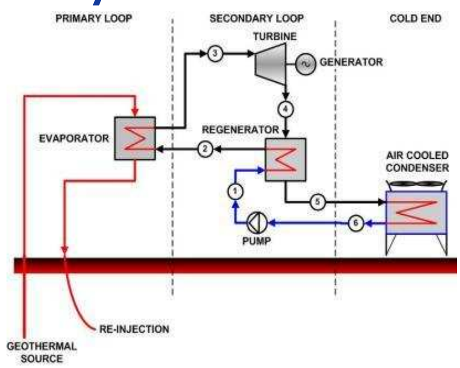
"Flash" Geothermal Power Plant

Enel Green Power

Uso: inserire classificazione

Geothermal Electricity Plant: binary



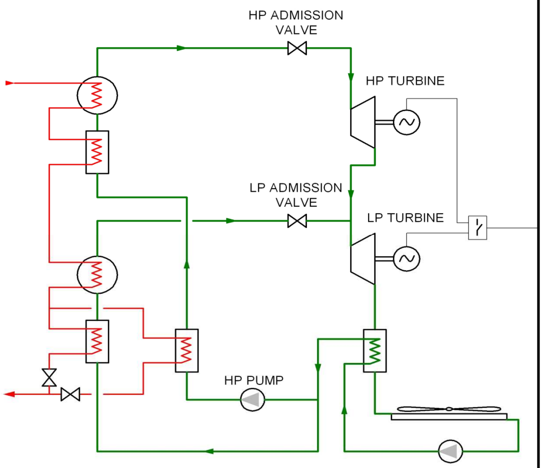


Geothermal binary power plant

Enel Green Power

Uso: inserire classificazione

Geothermal Electricity Plant: binary



5 MW Geothermal binary power plant

Enel Green Power

Uso: inserire classificazione

Geothermal Electricity Plant: binary

There is a
"pot of gold "
at the
end of the
rainbow
-
USA

Green Power

Uso: inserire classificazione

Geothermal Electricity Plant: binary

- Geothermal Electricity Production reached the value of **9,700 MW in 24 countries**;
- The economics of electricity production is influenced by the drilling costs and resource development;
- The productivity of electricity per well is a function of reservoir fluid thermodynamic characteristics (phase and temperature);
- The higher the energy content of the reservoir fluid, the lesser is the number of required wells and as a consequence the reservoir CAPEX quota is reduced:

•Utilization of low temperature resource can be achieved only with binary plant.

•Binary plant can be an efficient way for recovering the energy content of the reservoir fluid after its primary utilization in standard flash plant, achieving a better energy efficiency of the overall system.

Enel Green Power

Geothermal Energy 69

Uso: inserire classificazione

Geothermal Electricity Plant: binary

OPTIMIZATION

•Bottoming cycle technique is widely used worldwide, as shown in the attached table;

•This electricity is produced using the waste water from the separated brine: it can be considered as an un-expensive and rich of value by-product of the primary flash power plant;

The total installed capacity of such binary plants is about 160 MW worldwide.

• BINARY PLANTS FOR OPTIMIZATION

Country	Plant	Capacity (MW)
Iceland	Svartsenegi	8
El Salvador	Berlin	9
Mexico	Los Azufres	3
New Zealand	Kawerau	6
New Zealand	Mokai	27
New Zealand	Rotokawa	13
New Zealand	Wairakei	14
Nicaragua	Momotombo	7
Philippines	Mak-Ban	16
Philippines	Tongonang	19
Philippines	Mahandong	19
Philippines	Mahiaio	5
Philippines	Malitbog	12
TOTAL		**160**

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Geothermal Energy 70

Uso: inserire classificazione

Geothermal Electricity Plant: binary

LOW TEMPERATURE

•For temperature below 150°C, the conventional flash is not able to reach satisfactory efficiency: at this temperature, only **10%** of steam can be produced at about 1 bar of separation pressure; the steam will have a very low efficiency, due to its low pressure and temperature: for producing **20 MW** it is necessary to mine up to **3,000 t/h** of fluid; on the other hand, with a binary process, **only 1,800 t/h** are necessary (from 300°C liquid reservoir for flash plant only **500** t/h).

•The unique way to exploit the geothermal energy for producing electricity is the use of a binary plant on the pressurized fluid, which will be handled through a closed loop from production and reinjection;
it is a zero emission cycle.

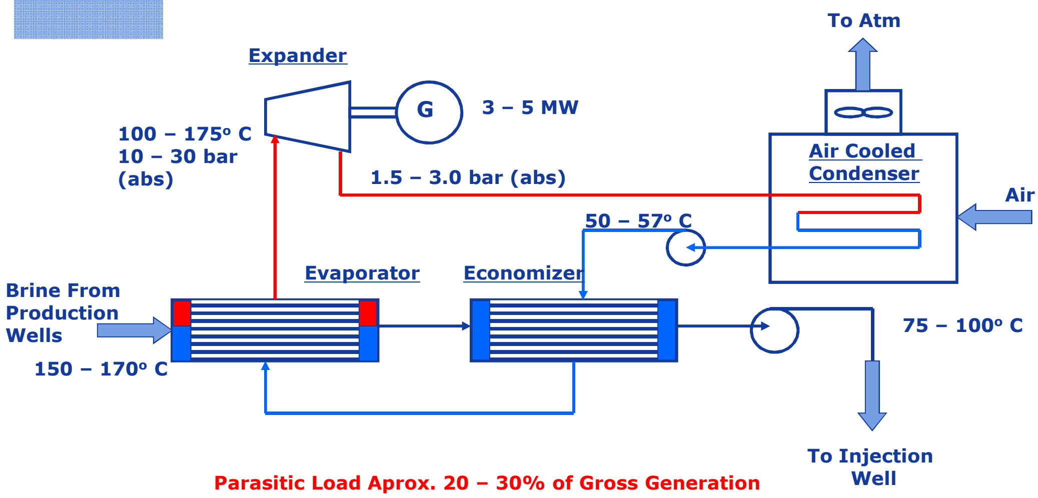
The total installed capacity of such binary plants is about 600 MW worldwide.

Enel Green Power

Geothermal Energy 71

Uso: inserire classificazione

Geothermal Electricity Plant: binary



Typical Simple "Binary Cycle" Geothermal Power Plant

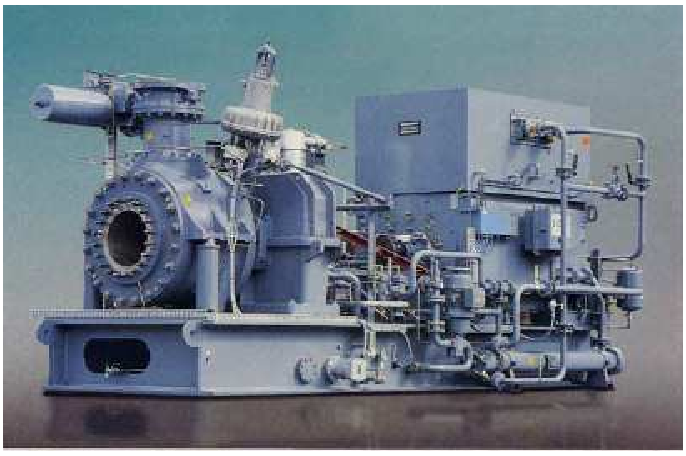
Enel Green Power

Geothermal Energy 72

Uso: inserire classificazione

Geothermal Electricity Plant: binary

Typical Industrial Expander on a Skid with Gearbox and Generator



Expander Suppliers:

Rotoflow (Div of GE)
Elliott Turbines
Texas Turbines
Mafi-Trench
Air Products
Ormat
Turboden

Enel Green Power

Uso: inserire classificazione

Geothermal Electricity Plant: binary

Typical Ormat Binary Power Plant Arrangement

Ormat SIGC Binary Plant (SIGC) with Water Cooled Condensers

Ormat SIGC Binary Plant (Soda Lake II) with Air Cooled Condensers

Green Power

Uso: inserire classificazione

Geothermal Electricity Plant: binary

Views of Ormat Binary Cycle Generation Units

Enel Green Power

Uso: inserire classificazione

Geothermal Electricity Plant: binary

Technology Advantages

- Can exploit low temperature heat sources
- Most equipment can be obtained from a variety of suppliers
- Plant can be constructed in shops on skid mounted modules for easy shipping and field assembly
- Negligible emissions from NCGs
- All of the water drawn from the reservoir is return. Source generally have a higher useful life.

Technology Disadvantages

- Lower energy conversion rate than steam turbine plants
- More process equipment thus requiring more maintenance effort and expense
- Brines may have high concentrations of silica and/or Calcium salts which can cause troublesome scaling requiring frequent clean-ups of heat exchangers and wells.

Main Equipment Suppliers

Turbine/Expanders: Rotoflow; Elliott Turbines
Texas Turbines; Mafi-Trench
Air Products; Ormat, Turboden

Generators: GE; Alstom; Siemens, Kato

Condensers: Marley; Aerofin; BAltimore Coil

Economics

Power Plant Construction Cost:
$2,000 – $3,000 / kW

O&M Cost (direct): $15 - $20 /MWh

Typical "Binary Cycle" Geothermal Power Plant

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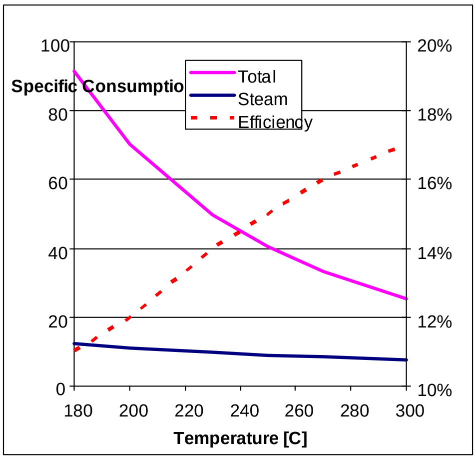
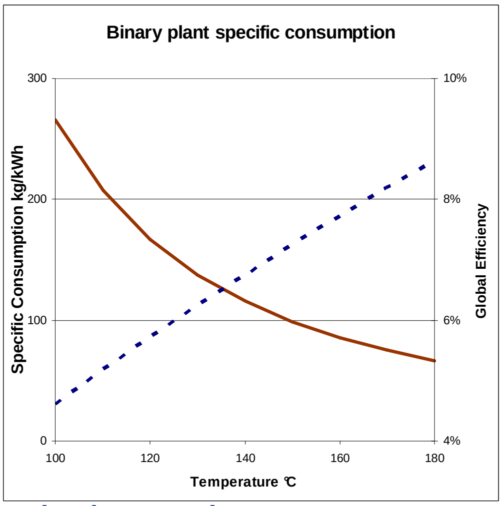
Uso: inserire classificazione

Geothermal Electricity Plant: binary





- **Provide Opportunities for new project developments in numerous low temperature geothermal areas throughout the world.**
- **Provide Opportunities for recovering power generation from matured projects where the temperature of the source has decreased substantially.**

Enel Green Power

Uso: inserire classificazione

Geothermal Electricity Plant: binary

At the common temperature of 180°C, the two technologies have the following figures:

PARAMETER	BINARY	FLASH
Efficiency	7,5%	11%
Specific Consumption kg/kWh	76	92
Steam Specific Consumption kg/kWh		12
Steam Fraction		14%

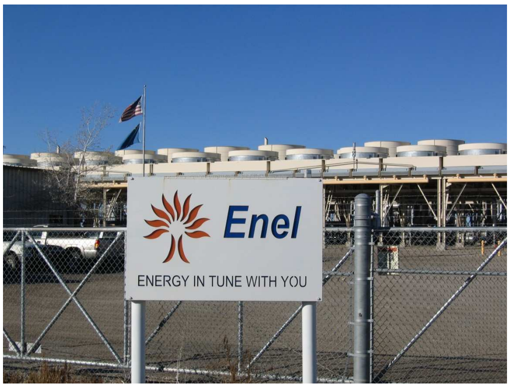
Flash technology has better efficiency but a worst specific consumption on the total fluid.
A better energy recovery is from the utilization of a bottoming binary cycle on the stream of the hot reinjected water

Enel Green Power

Uso: inserire classificazione

Geothermal Electricity Plant: Salt Wells

Enel Development of Binary Cycle Technology



Labeling the activity…

Enel Green Power

Uso: inserire classificazione

Geothermal Electricity Plant: Salt Wells

Enel Development of Binary Cycle Technology

Air cooler: each 10 MW unit has 3x21 fans

Enel Green Power

Uso: inserire classificazione

Geothermal Electricity Plant: Salt Wells

Enel Development of Binary Cycle Technology

Feed pumps and regenerator

Enel Green Power

Uso: inserire classificazione

Geothermal Electricity Plant: Salt Wells

Enel Development of Binary Cycle Technology

Geothermal fluid and evaporator

Enel Green Power

Uso: inserire classificazione

Geothermal Electricity Plant: Salt Wells

Enel Development of Binary Cycle Technology

Expander and view of the geothermal field

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Uso: inserire classificazione

Geothermal Electricity Plant: Innovative Design

Optimization of low enthalpy geothermal resources exploitation

The project aims to develop innovative electric generation systems to upgrade the exploitation low enthalpy geothermal resources.

ENHANCED PERFORMANCES

- to upgrade geothermal resources exploitation thus making the electric generation more profitable

GREATER FLEXIBILITY

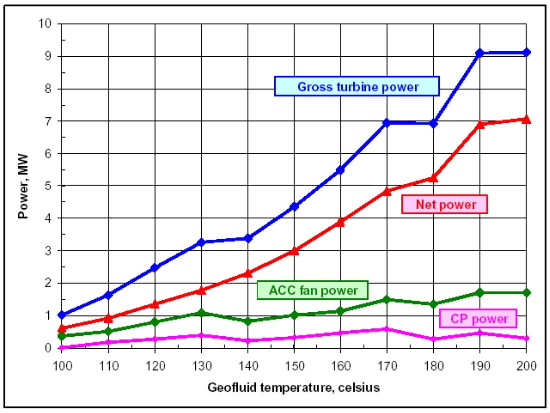
- to better match the intrinsic characteristics of geothermal reservoirs
- to avoid performance decline because of the natural resources depletion and temperature drop

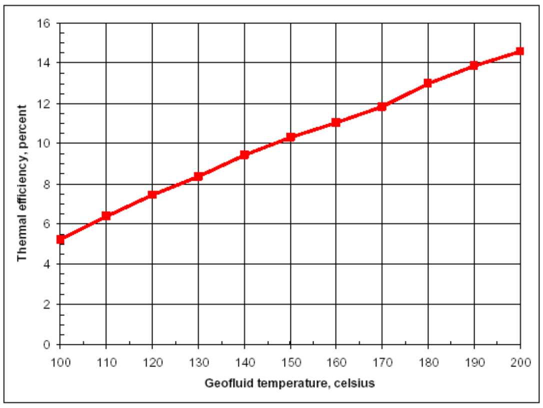
INNOVATION

Enel Green Power

Uso: inserire classificazione

Geothermal Electricity Plant: Innovative Design



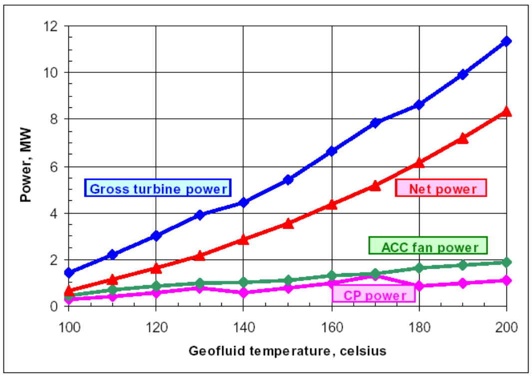


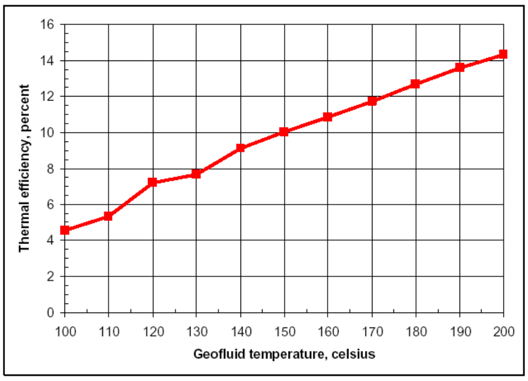
Subcritical basic binary with optimization of working fluid

Enel Green Power

Uso: inserire classificazione

Geothermal Electricity Plant: Innovative Design





Supercritical basic binary with optimization of working fluid

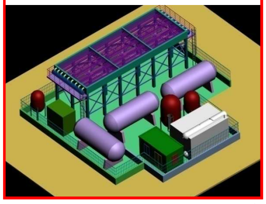
Enel Green Power

Geothermal Electricity Plant: Innovative Design

Main activities

CONVENTIONAL BINARY CYCLE POWER PLANT → INNOVATIVE BINARY CYCLE POWER PLANT

- Suitable working fluid screening → Working fluid selection
- Suitable operative cycle screening → operative cycle selection
- Operative cycle optimization (thermodynamic simulations)
- Testing theoretical data (prototypal sized pilot innovative binary plant realization)



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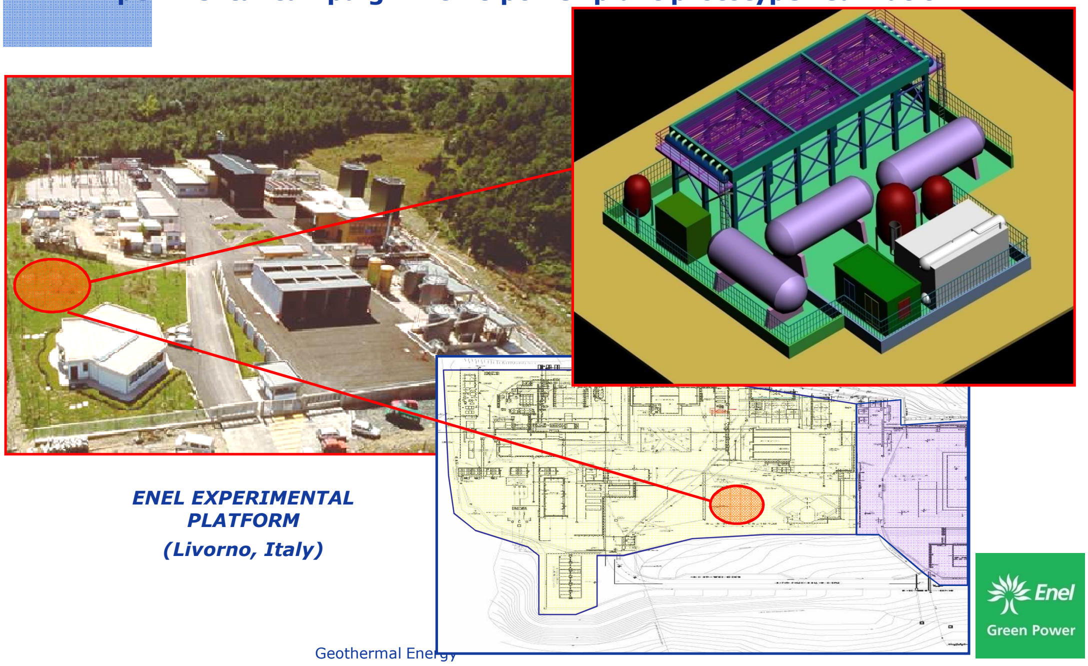
Geothermal Electricity Plant: Innovative Design

Experimental campaign – ORC power plant prototype realization



ENEL EXPERIMENTAL PLATFORM

(Livorno, Italy)

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Uso: inserire classificazione

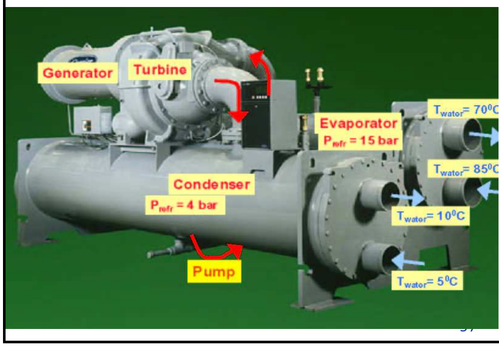
Geothermal Electricity Plant: binary

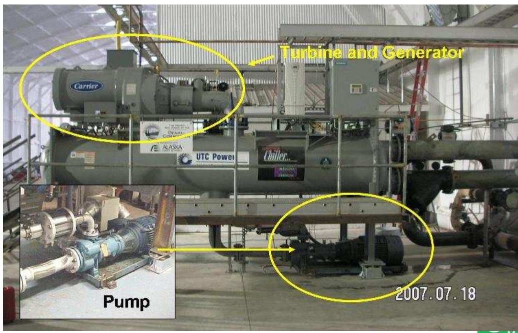
A low temperature power plant provides power for the isolated resort of **Chena Hot Springs**. The **200 kW** plant, a binary unit, is the first geothermal power plant in Alaska, and uses the **lowest temperature geothermal resource in the world** **5,4 Kg/s at 74°C for power generation**.

•Previously it was diesel-powered, around **30 cents/kWh,** daily average $1,000.

•The new power plant will provide electricity at **7 cents/kWh**. The total unit cost around $1,300 per installed kW.

•With the installation of a second unit, the capacity has been doubled; there are plan to reach shortly **1 MW.**





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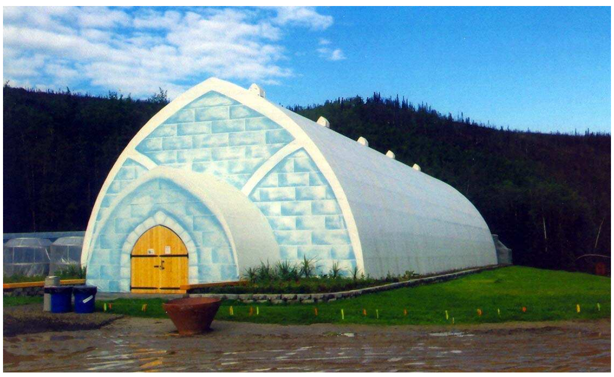
Uso: inserire classificazione

Geothermal Electricity Plant: binary

Aurora Ice Museum

Chena Hot Springs

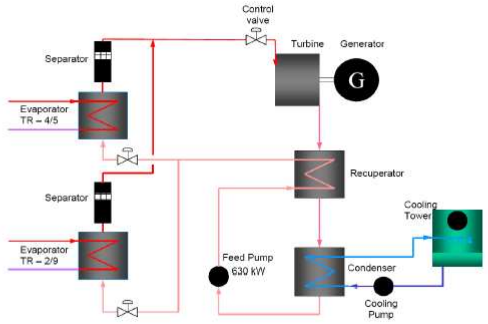


Uso: inserire classificazione

Geothermal Electricity Plant: binary

In El Salvador, LaGeo installed a new bottom cycle binary plant at the existing old power station of Berlin (2x28 MW, completed in 1999), using the separated water from four wells; it is utilized in two heat exchanger for boiling an organic fluid (Isopentane), which has a low temperature boiling point; the isopentane steam expands into a 9,5 Gross MW turbine, **generating 7,8 MW net of electricity, without any additional expenditure from the reservoir development, and achieving a better utilization of the overall energy content of the geothermal fluid.**

The cost for this unit is 16,5 MUSD, with a very positive return of the investment (IRR 18% in the base case analysis)



Total utilized geothermal fluid 1,000 t/h at 180°C; isopentane flow rate 700 t/h, working between 160°C and 44°CC; wet cooling tower;.

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Geothermal Energy

91

Uso: inserire classificazione

Geothermal Electricity Plant: binary

Aerial view of Berlin power plant in eastern El Salvador.

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Geothermal Energy

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Geothermal Green Field Evaluation

"Geothermal resource assessment for green fields" is the evaluation of the expected potential of supplied geothermal electricity that might become available for exploitation of a given reservoir.

The standard technique ("stored heat method") is taking into account only the heat reserves of the inferred geothermal field, without any consideration of the number of wells and economical feasibility: the permeability of the system is simply not used.

This approach could be considered as "step zero", for obtaining a first, rough approximation of what it is possible to install on a given field, when the available information are very poor and speculative.

Geothermal Green Field Evaluation

The basic idea in the method is the evaluation of the total available thermal energy in a given volume of rock hosting the geothermal reservoir, as result of its cooling from the resource temperature down to a "reference temperature".

This thermal energy is transformed in electricity, using the appropriate plant and thermodynamical efficiency for the conversion from the resource temperature to the ambient one.

In the proposed method the system is considered as closed, without any heat flux from its boundary, but with infinite availability of water: the limiting factor will be the **temperature of the resource**.

Geothermal Green Field Evaluation

The number of wells and their flow-rate (resource permeability) in not considered in the evaluation, but it can be assumed as infinite (high enough for extracting the required fluid).
Usually, the "reference temperature" is assumed equal to the ambient one: the total thermal energy is evaluated as if the reservoir would be cooled down to the ambient temperature value. This assumption will overestimate the electricity generation potential, for two main reasons:

- The reservoir should be abandoned much before its complete cooling;
- The specific consumption will increase dramatically at low temperature, producing much less electricity with the same thermal energy exploited.

Geothermal Green Field Evaluation

Eth=Surf*Thick*Cv*(Tres-Tab)
Where
Surf=Reservoir Surface, m^2
Thick=Reservoir Thickness, m
Tres=Reservoir (initial) Temperature, °C
Tab=Abandon Temperature, °C:
it is the temperature below which the exploitation of the reservoir should be stopped
Cv=Volumetric Specific Heat, J/m^3

Usually, only a fraction of the stored heat can be extracted from the water flow in the bulk of the reservoir porous system, connected through a network of fractures. This fraction is called "Recovery Factor" (Rf).

Uso: inserire classificazione

Geothermal Green Field Evaluation

It should be noticed that the fundamental hypothesis for the calculation of the "stored heat method" is that "we will utilize the thermal energy from the reservoir initial temperature down to the abandon value".

During the cooling the relevant parameter of the system will be strongly affected by the reduction of the thermodynamical performances, i.e. the specific consumption and the steam flash quota.

The value of reservoir capacity as obtained following the aforesaid calculations, should be considered as a "maximum indicator", calculated for all the life of the reservoir from its initial temperature down to the abandon one with the relevant parameters as calculated at its initial temperature value.

Enel Green Power

Uso: inserire classificazione

Geothermal Green Field Evaluation

An iterative approach to the calculation, performing all the calculation in step of 1°C of cooling, from the initial value to the abandon one, and calculating a "cooling correction factor", approximating it with a linear function of the temperature.

For the green field reservoir evaluation using the stored heat method, it is commonly used the Montecarlo technique, where the controlling parameter are stochastically modified using a given distribution for each one, and the random distribution of the expected capacity and reservoir life is presented. We use only Gaussian distributions for reservoir surface and thickness, porosity, recovery factor, plant efficiency and –the most important element- the expected resource temperature. The calculated capacity is subsequently reduced by the cooling correction factor.

Enel Green Power

Uso: inserire classificazione

Geothermal Green Field Evaluation

PARAMETER	VALUE	UNIT
Reservoir area (300 °C isotherm) corrected for the hot deep recharge	$9\ 10^6$ $12\ 10^6$	m^2
Reservoir thickness	$2\ 10^3$	m
Reservoir temperature (now)	300	°C
Abandon temperature	180	°C
Utilization factor	90	%
Lifetime	30	years
Specific heat of rock	850	J/kg°C
Specific heat of liquid	4186	J/kg°C
Thermal recovery factor	15	%
Porosity	5	%
Rock density	2600	kg/m^3
Initial Separation pressure	$20\ 10^5$	Pa

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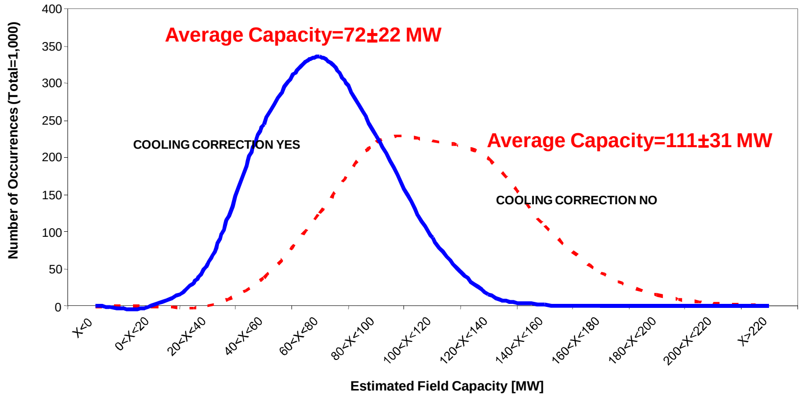
Uso: inserire classificazione

Geothermal Green Field Evaluation:

PARAMETER	MIN	MAX	UNIT	TYPE OF DISTRIBUTION
Reservoir area	10	14	km^2	Gaussian with μ=12 km^2 and σ =1 km^2
Reservoir thickness	1500	2500	m	Gaussian with μ=2000 m and σ =250 m
Reservoir temperature	290	310	°C	Gaussian with μ=300 °C and σ =5 °C
Recovery Factor	5	25	%	Gaussian with μ=15 % and σ =5 %
Porosity	4	6	%	Gaussian with μ=5 % and σ =0.5 %

Calculated Frequency Distribution of Field Capacity FLASH



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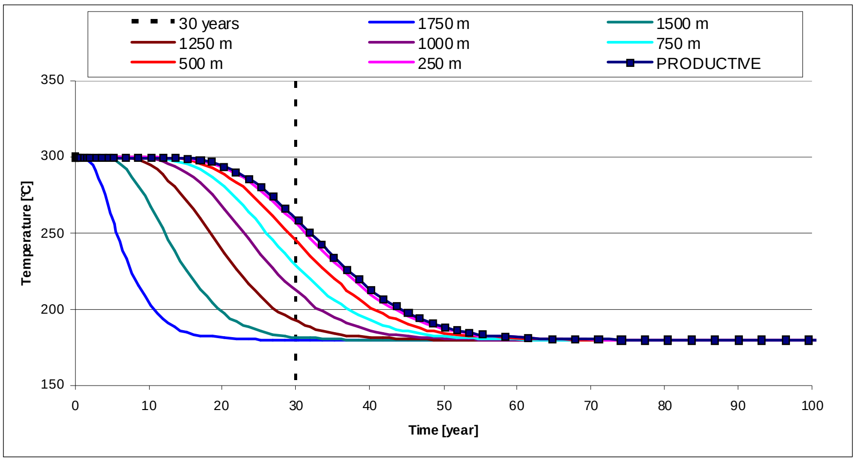
Geothermal Green Field Evaluation



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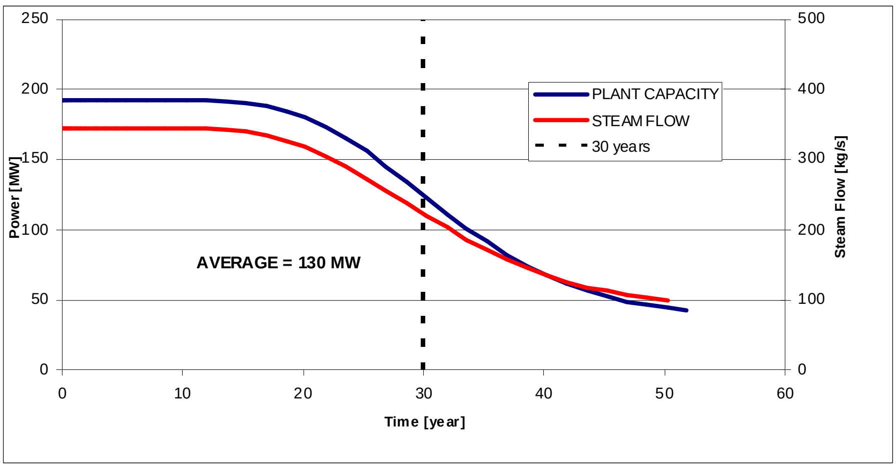
Geothermal Green Field Evaluation

Average Capacity Stored Heat=111±31 MW



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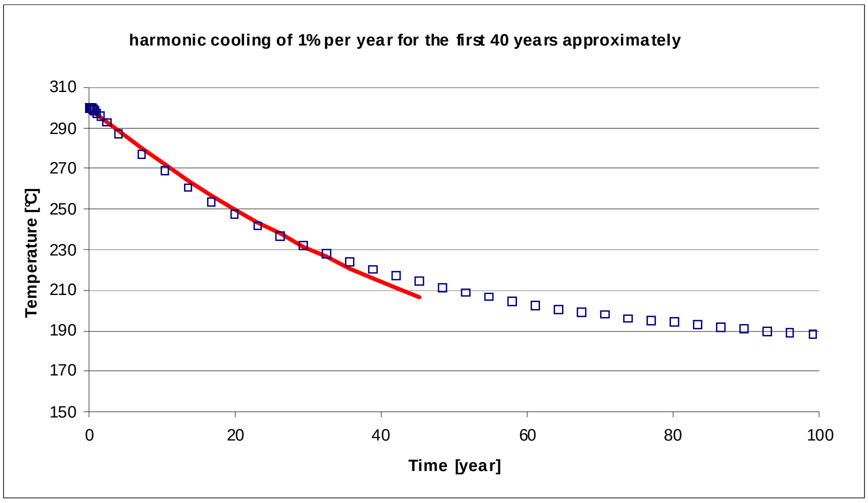
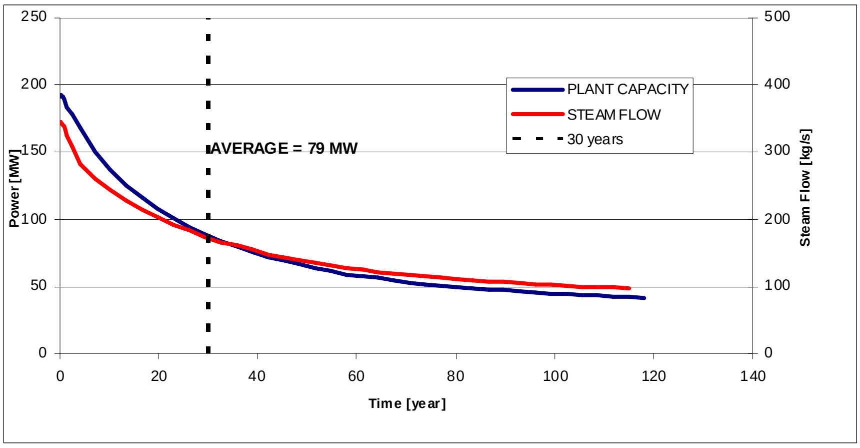
Geothermal Green Field Evaluation

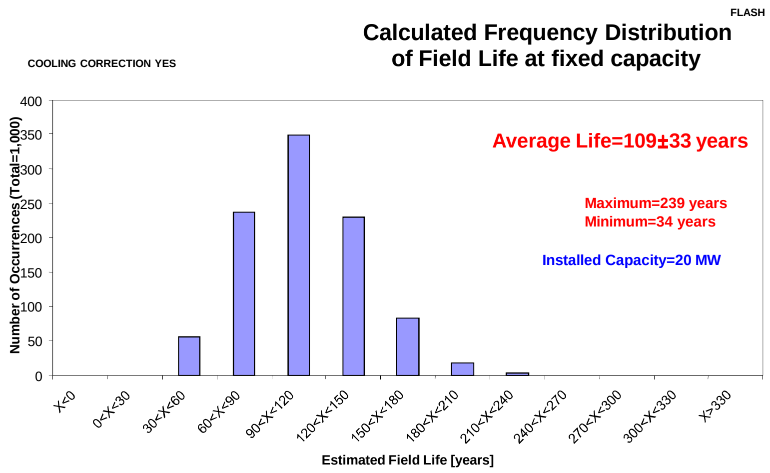


Geothermal Green Field Evaluation

Average Capacity Stored Heat-Cooling Correction=72±22 MW



Geothermal Green Field Evaluation



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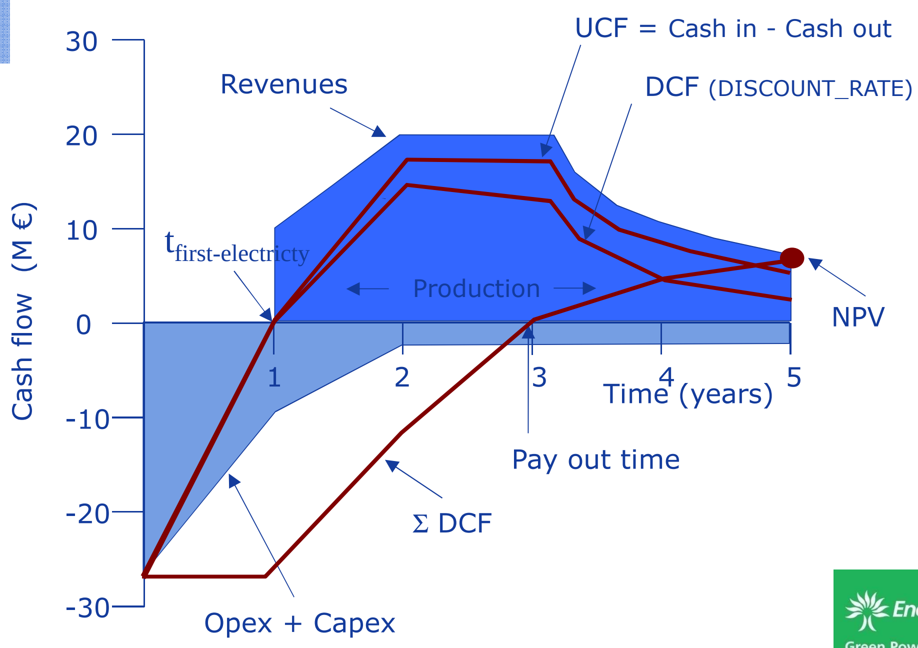
Geothermal Green Field Evaluation: DSS



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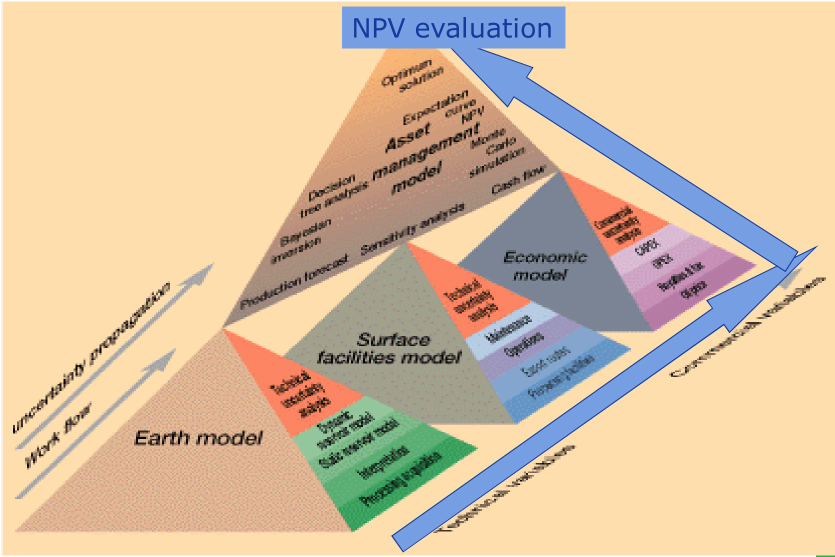
Uso: inserire classificazione

Geothermal Green Field Evaluation: DSS



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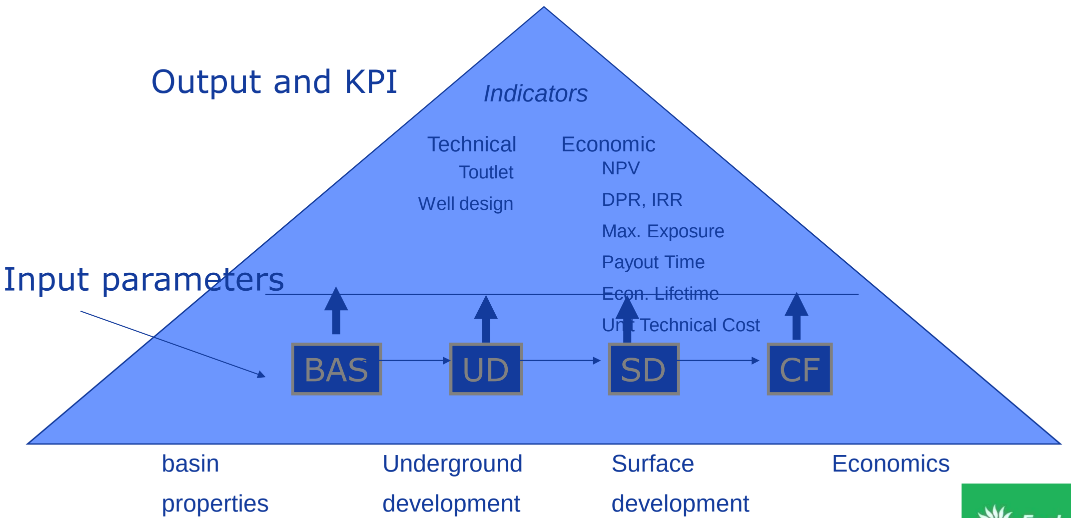
Uso: inserire classificazione

Techno-economic calculation→ Geothermal Fast computational models



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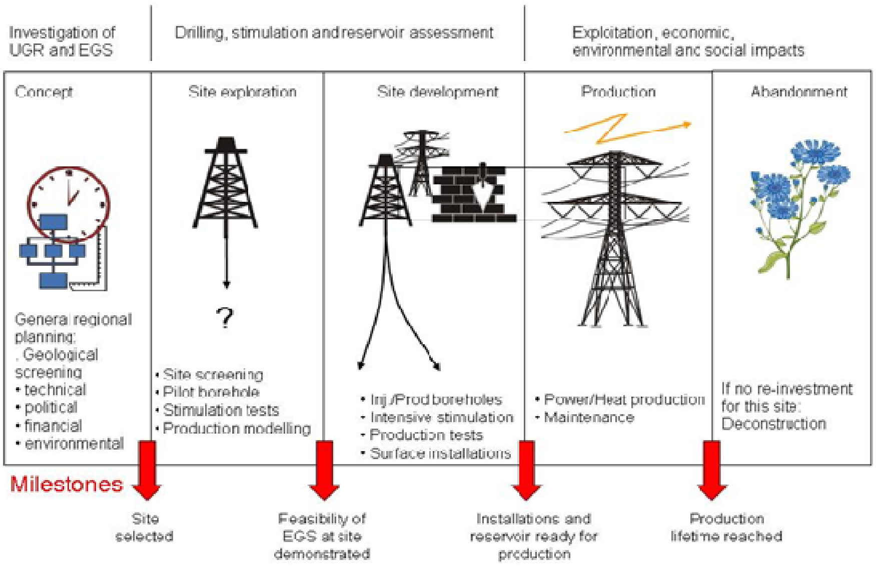
Uso: inserire classificazione

Geothermal Green Field Evaluation: DSS



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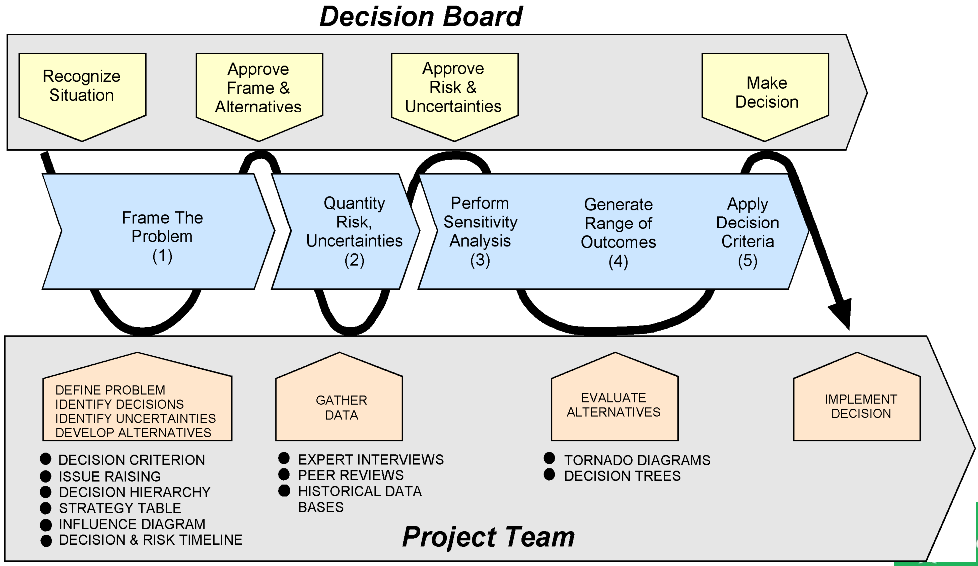
Uso: inserire classificazione

The D&RA Process, how mgt & staff create synergy: *team work!*



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Geothermal Energy 110

Uso: inserire classificazione

Steps to delineating a geothermal resource

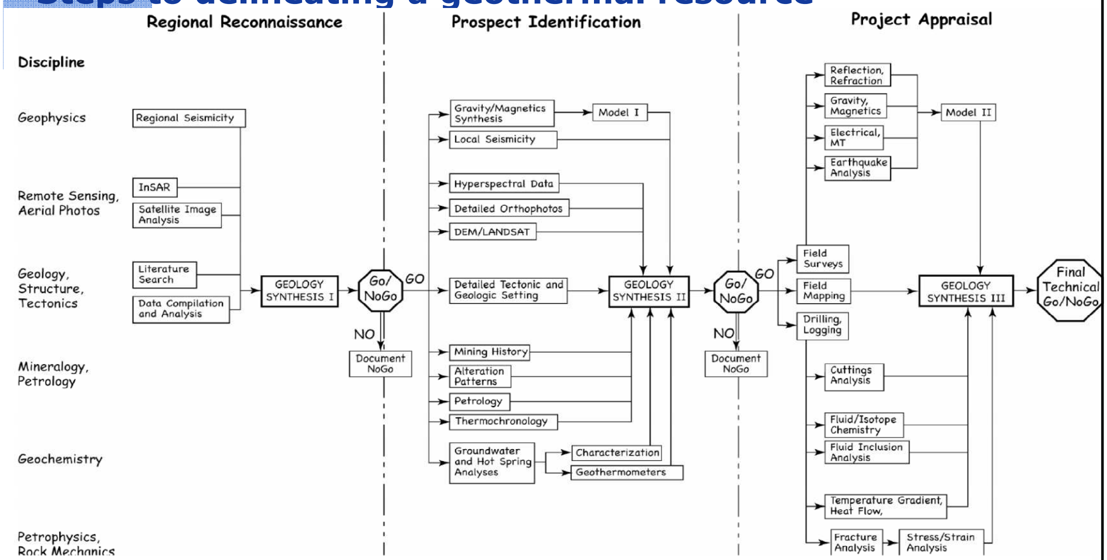


Figure 3. Exploration program screening protocols. This flow chart graphically lists the tools, data, and geologic features that can be assessed during geothermal exploration as it progresses from regional reconnaissance to a project level-appraisal. Once a prospect has been identified via the screening protocols described above or any other methods, a project appraisal typically includes many or all of the disciplines listed in this chart.

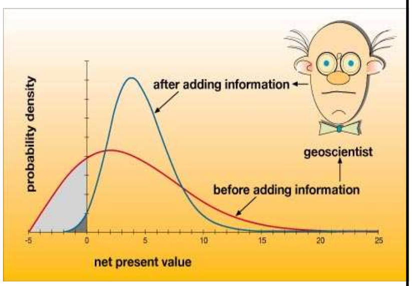
Genetic Occurrence Models for Geothermal Prospecting

ITSI Innovative Technical Solutions, Inc.

Uso: inserire classificazione

Using "Risk-tolerance" as optimisation constraint

- The decision-maker should then specify his/her risk-tolerance: for the project in question, and given other (portfolio) considerations, which cumprob x average NPV, i.e. if it is <0, am I prepared to accept?



- **Risk-tolerance criterion can then be used as optimisation constraint to cut out bad decision-alternatives**

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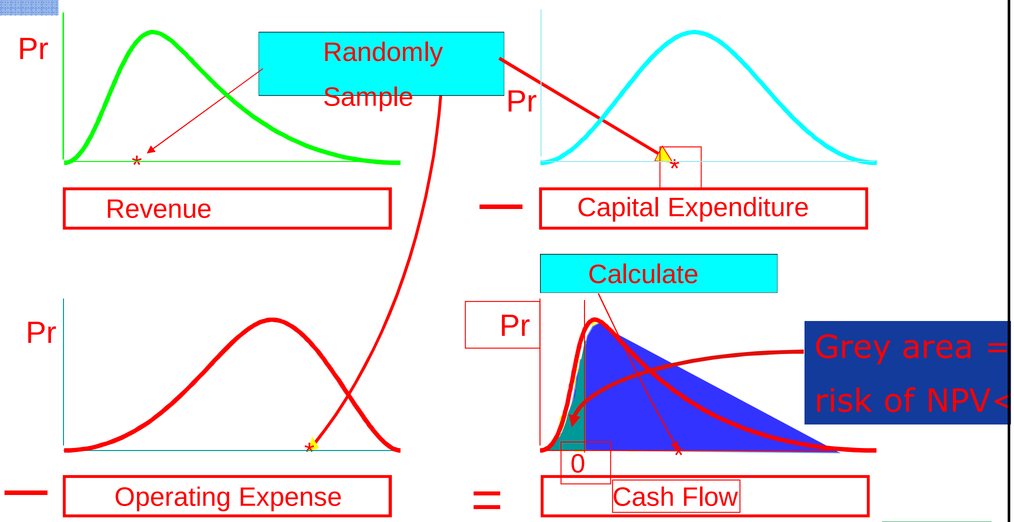
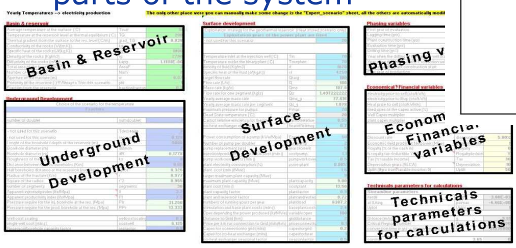
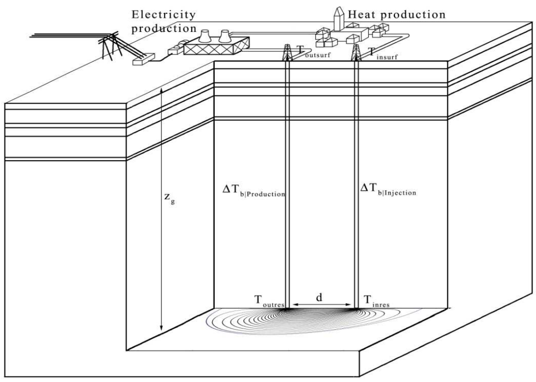
Monte Carlo Simulation Methodology, uncorrelated



Starting with Engine.xls: a geothermal system description

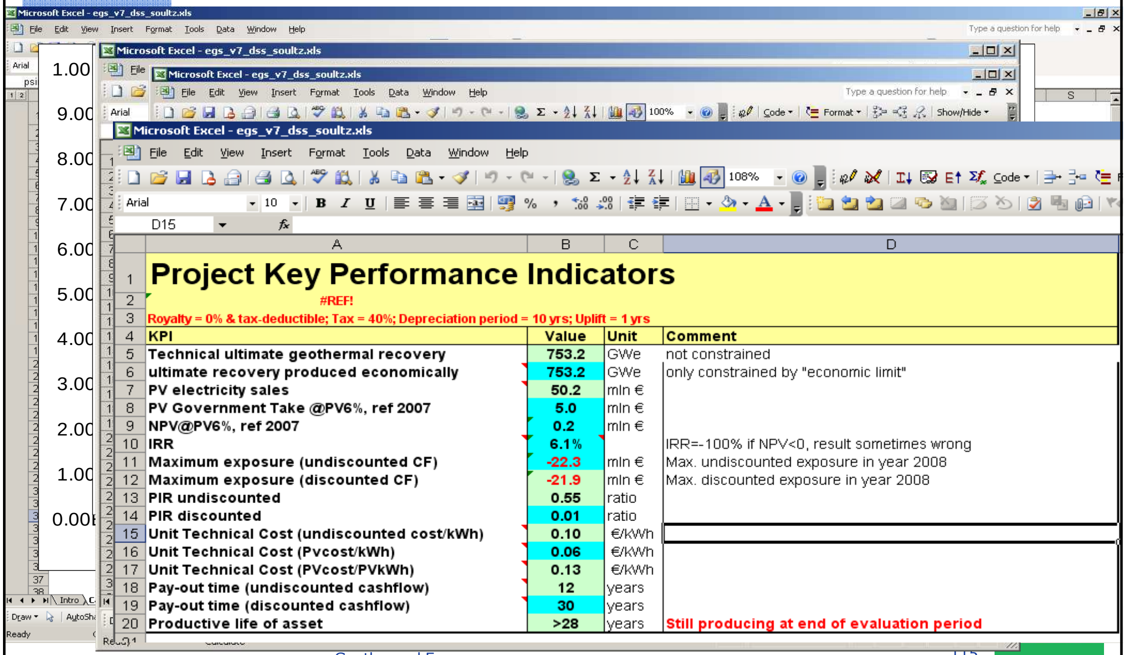
Input parameters are regrouped in the "Cashflow" spreadsheet classified intro 4 main categories representatives of the parts of the system





EXCEL

Uso: inserire classificazione



	A	B	C	D
1	Project Key Performance Indicators			
2	#REF!			
3	Royalty = 0% & tax-deductible; Tax = 40%; Depreciation period = 10 yrs; Uplift = 1 yrs			
4	KPI	Value	Unit	Comment
5	Technical ultimate geothermal recovery	753.2	GWe	not constrained
6	ultimate recovery produced economically	753.2	GWe	only constrained by "economic limit"
7	PV electricity sales	50.2	mln €	
8	PV Government Take @PV6%, ref 2007	5.0	mln €	
9	NPV@PV6%, ref 2007	0.2	mln €	
10	IRR	6.1%		IRR=-100% if NPV<0, result sometimes wrong
11	Maximum exposure (undiscounted CF)	-22.3	mln €	Max. undiscounted exposure in year 2008
12	Maximum exposure (discounted CF)	-21.9	mln €	Max. discounted exposure in year 2008
13	PIR undiscounted	0.55	ratio	
14	PIR discounted	0.01	ratio	
15	Unit Technical Cost (undiscounted cost/kWh)	0.10	€/kWh	
16	Unit Technical Cost (Pvcost/kWh)	0.06	€/kWh	
17	Unit Technical Cost (PVcost/PVkWh)	0.13	€/kWh	
18	Pay-out time (undiscounted cashflow)	12	years	
19	Pay-out time (discounted cashflow)	30	years	
20	Productive life of asset	>28	years	Still producing at end of evaluation period

Uso: inserire classificazione

Discrete uncertainties (scenario trees)

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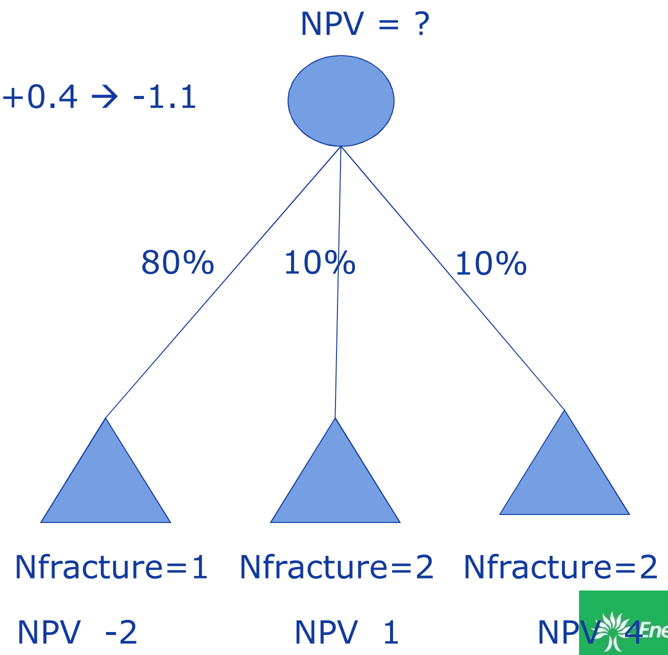
Scenario/Logic Tree

Uso: inserire classificazione

-1.6+0.1+0.4 → -1.1



scenario not under control of company

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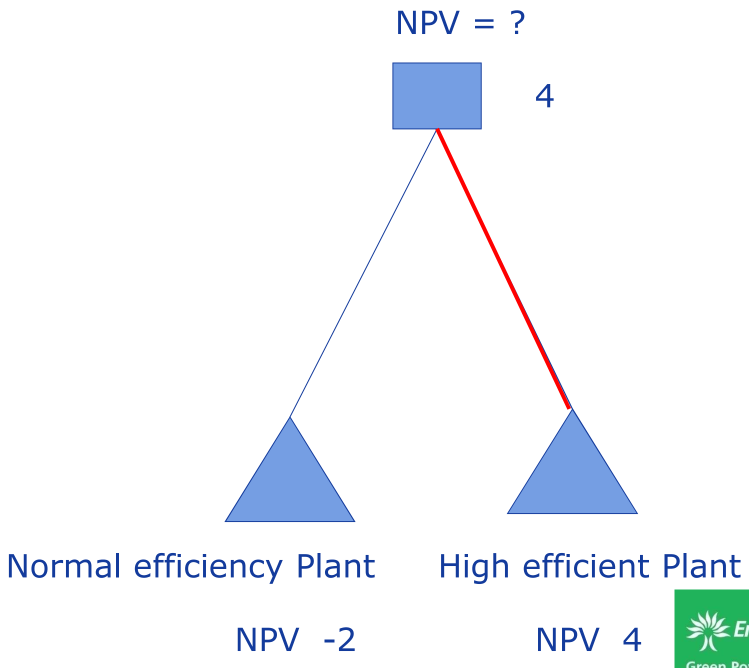
Scenario/Option Tree

Uso: inserire classificazione



scenario under control of company

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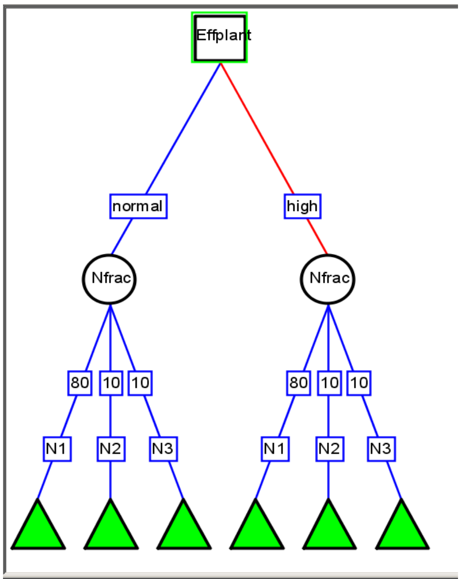
Uso: inserire classificazione

Combining controllable and not controllable



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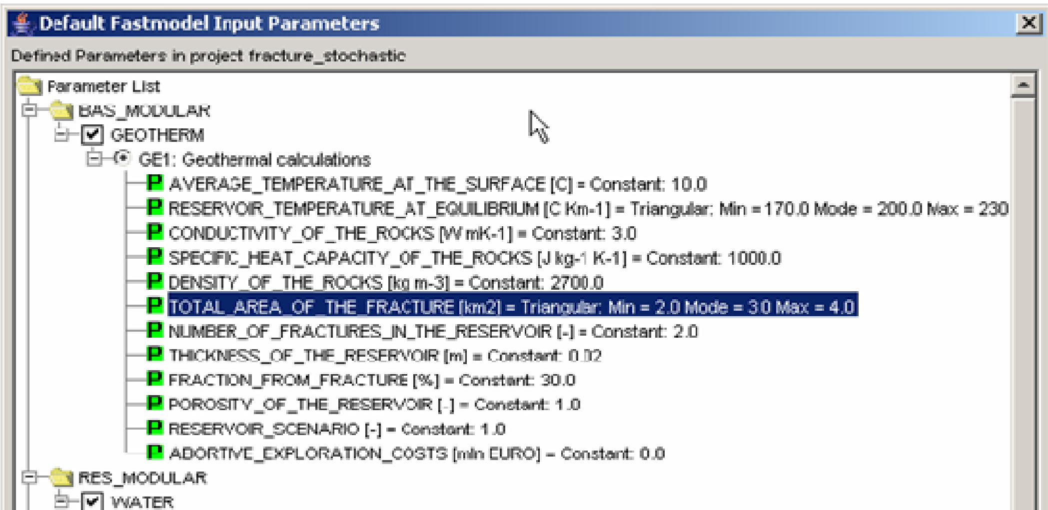
Uso: inserire classificazione

Example of INPUT



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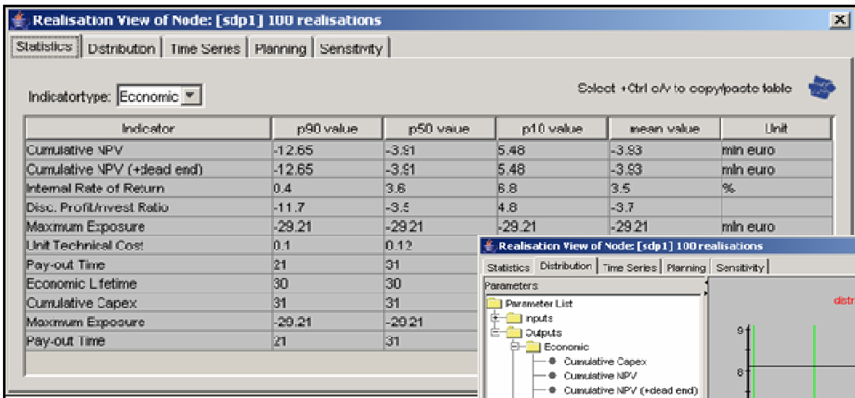
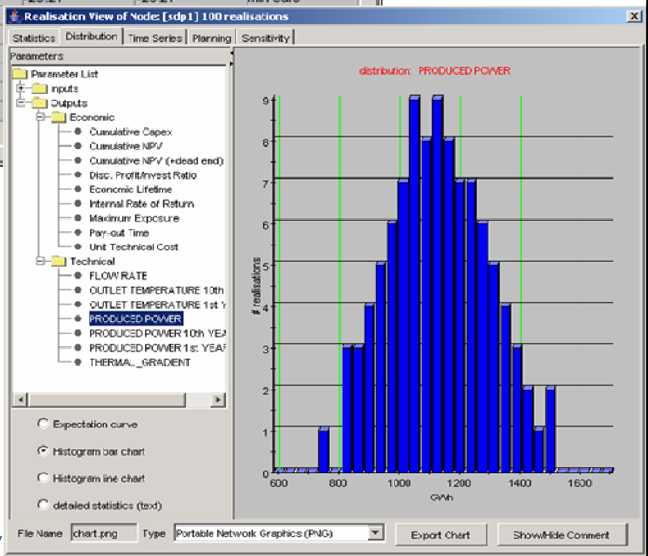
Uso: inserire classificazione



Indicator	p90 value	p50 value	p10 value	mean value	Unit
Cumulative NPV	-12.65	-3.91	5.48	-3.93	mln euro
Cumulative NPV (+dead end)	-12.65	-3.91	5.48	-3.93	mln euro
Internal Rate of Return	0.4	3.6	6.8	3.5	%
Disc. Profit/Invest Ratio	-11.7	-3.5	4.8	-3.7	
Maximum Exposure	-29.21	-29.21	-29.21	-29.21	mln euro
Unit Technical Cost	0.1	0.12			
Pay-out Time	21	31			
Economic Lifetime	30	30			
Cumulative Capex	31	31			
Maximum Exposure	-29.21	-29.21			
Pay-out Time	21	31			

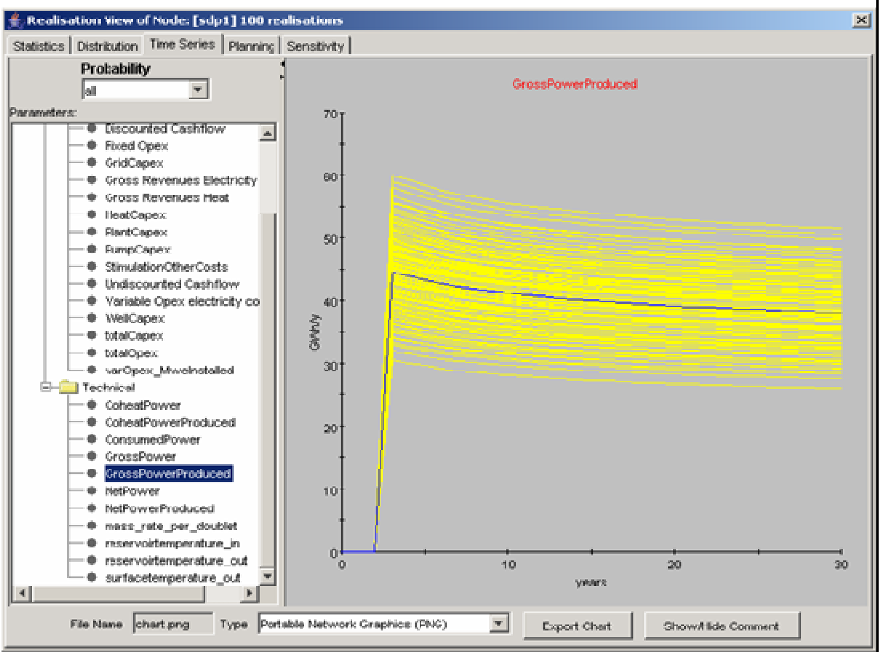


Examples of OUTPUT

Geothermal Energy

Uso: inserire classificazione

Examples of OUTPUT



Geothermal Energy

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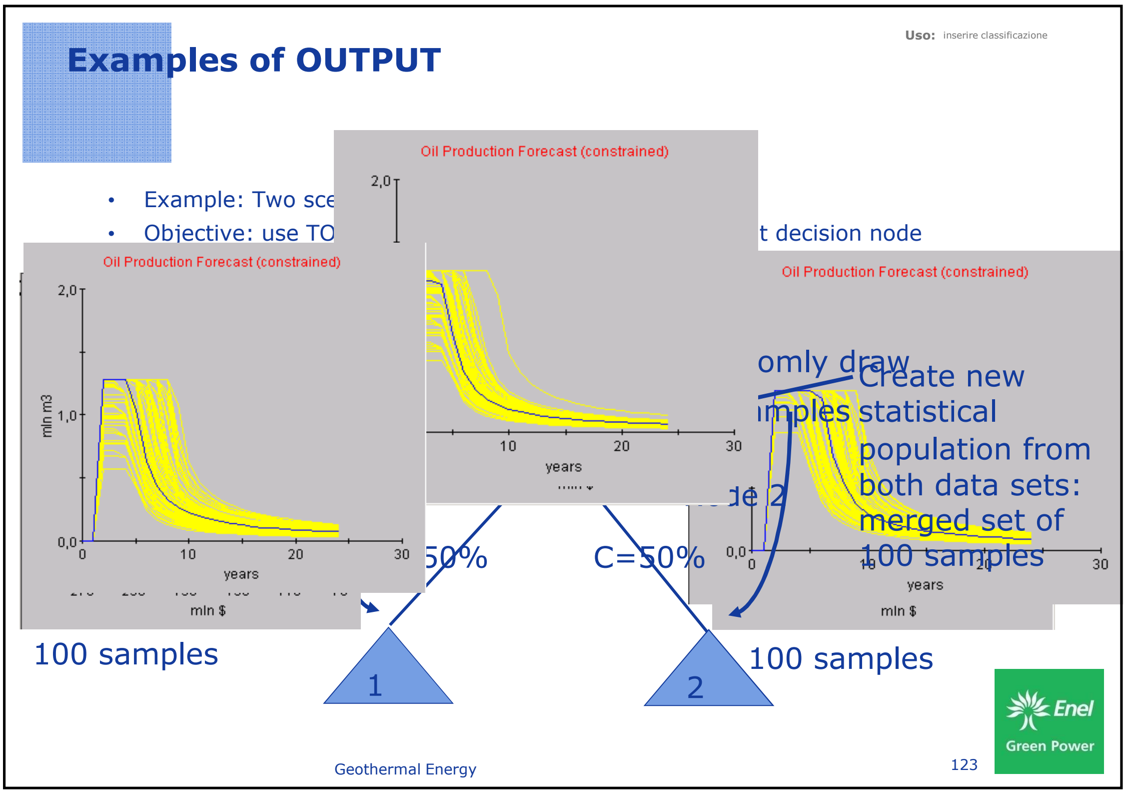
Uso: inserire classificazione
Examples of OUTPUT
Example: Two sce
Objective: use TO
t decision node
Oil Production Forecast (constrained)
Oil Production Forecast (constrained)
Oil Production Forecast (constrained)
mln m3
years
mln $
omly draw
mples
de 2
Create new statistical population from both data sets: merged set of 100 samples
50%
C=50%
100 samples
100 samples
1
2
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Geothermal Energy
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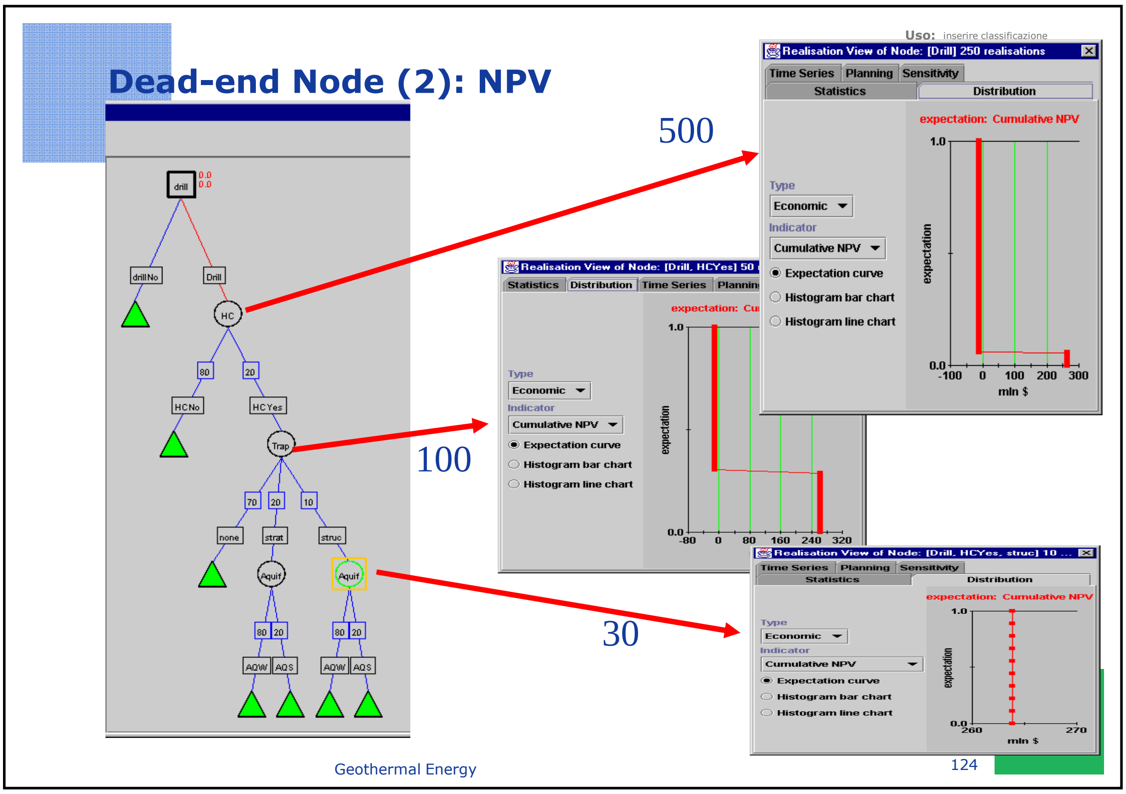
Uso: inserire classificazione
Dead-end Node (2): NPV
500
100
30
drill
drill No
Drill
HC
HC No
HC Yes
Trap
none
strat
struc
Aquif
AQW
AQS
Realisation View of Node: [Drill] 250 realisations
Time Series
Planning
Sensitivity
Statistics
Distribution
expectation: Cumulative NPV
Type
Economic
Indicator
Cumulative NPV
Expectation curve
Histogram bar chart
Histogram line chart
expectation
mln $
Realisation View of Node: [Drill, HCYes] 50
Realisation View of Node: [Drill, HCYes, struc] 10
Geothermal Energy
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Uso: inserire classificazione

DSS is a decision tree that combines discrete and continuous uncertainties

- Tree consists of branches
- Branches are interconnected by (any sequence of):
  - **Decision nodes: action under control of company**
  - **Chance nodes: scenario not under control of company**
  - **End nodes: the "leaves" at the end of the branch where concatenated fast model calculations are done**
- Special features
  - **Mutually exclusive and unique scenario combinations ("pruning of tree")**
  - **Dead-end nodes: to model abortive courses of action**
  - **Scenario dependencies: conditional probabilities using hierarchy**
  - **Expert data can be imported (to circumvent use of Fast Models)**

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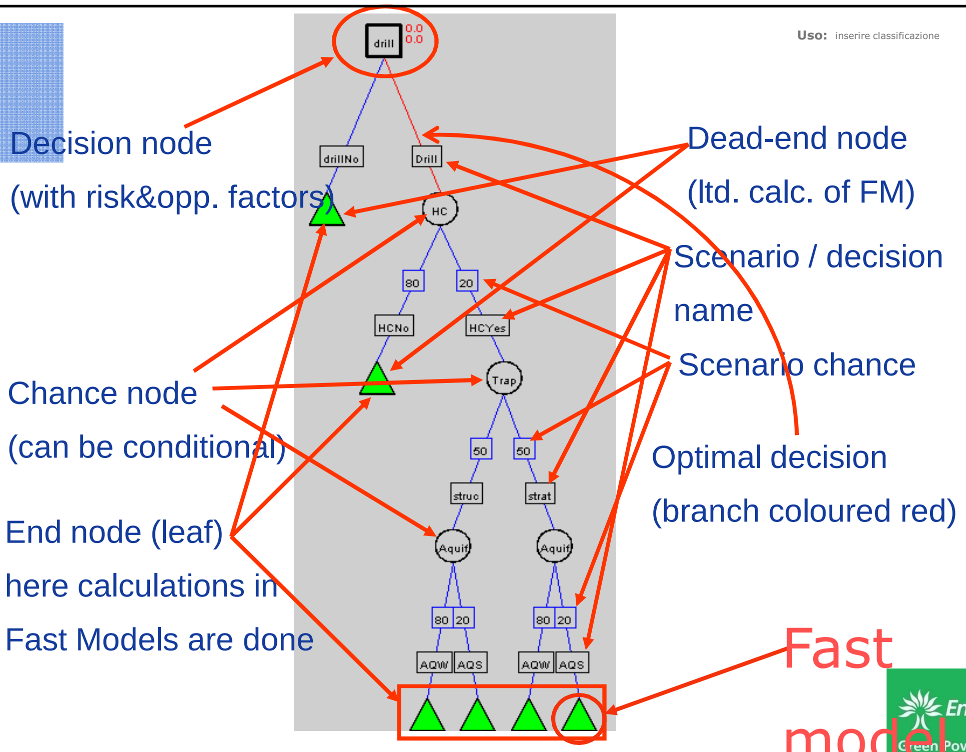
Uso: inserire classificazione



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EGS DSS Example : Mixing discrete and continuous uncertainties, decision trees

- Design decision (discrete)
  - Normal plant (costs 1.5 mln/ MWe, eff=0.55)
  - Higheff plant (costs 2 mln/ MWe, eff=0.6)
- Uncertainties (continuous)
  - Fracture area 2-4 km2
  - Inflow other than “connected” fracture 50-90%
- Uncertainties (discrete)
  - Having 1 (80%) ,2 or 3 fractures (each 10%)

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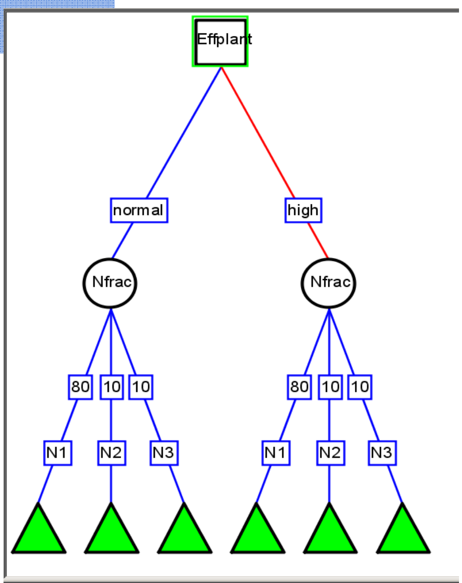

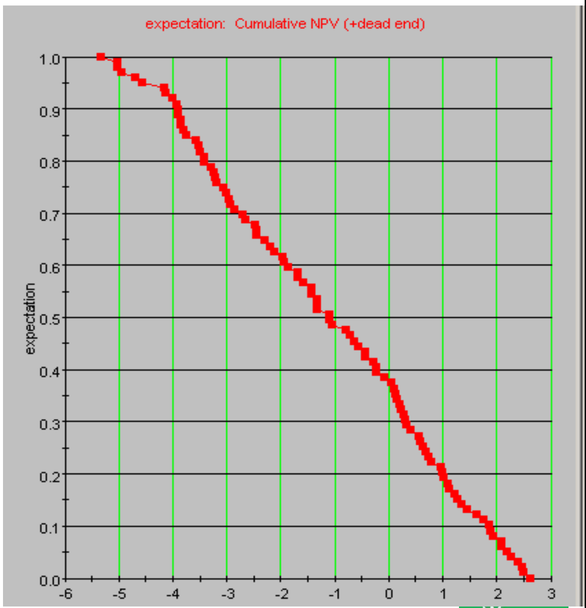

NPV

Engine DSS

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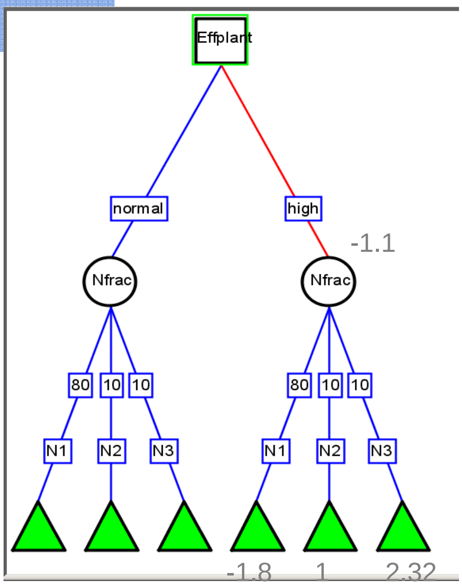
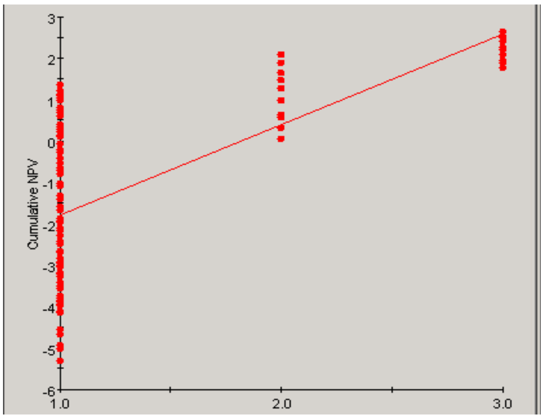
Uso: inserire classificazione





Geothermal Energy

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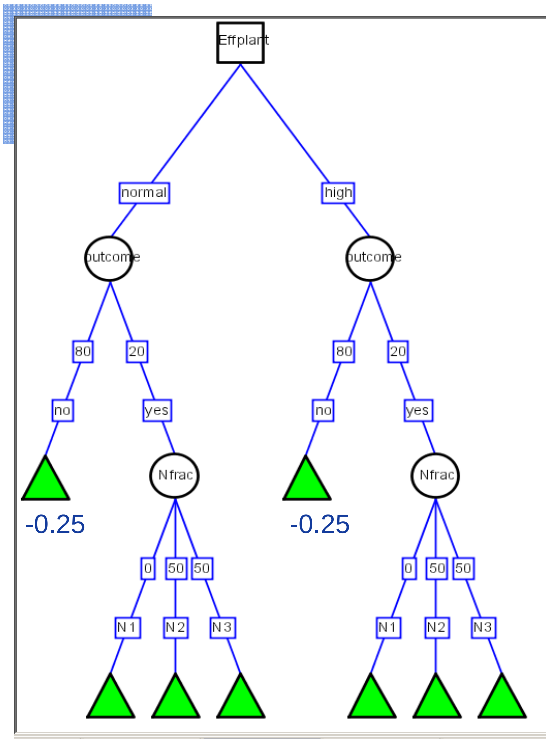
Uso: inserire classificazione



Introducing an information acquisition phase, which allows to rule out N1

Costs are 250 kEURO

Geothermal Energy

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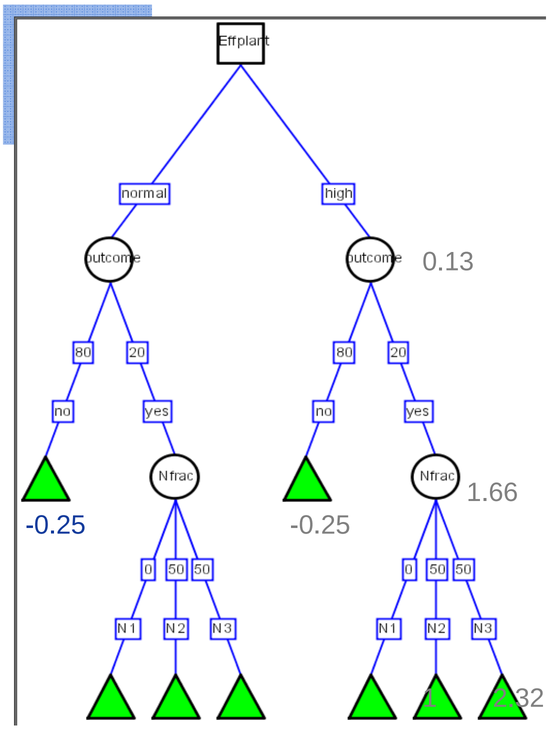
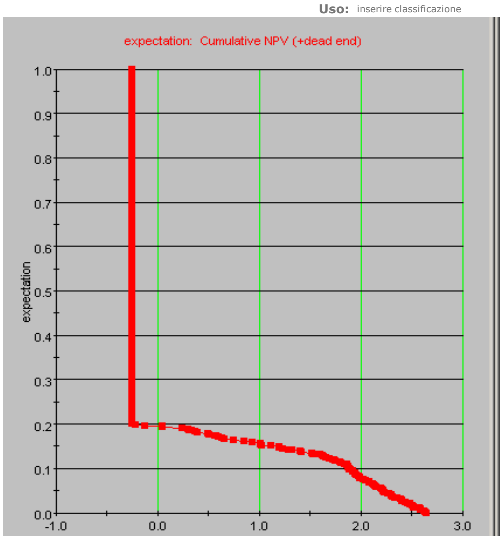
Uso: inserire classificazione





NPV

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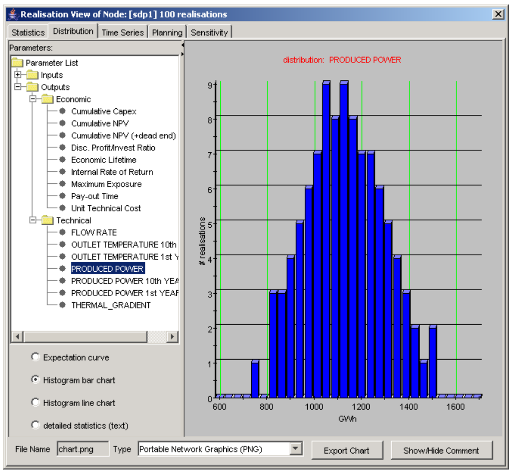
Uso: inserire classificazione

Geothermal Green Field Evaluation: DSS



Surface development

Exploitation strategy for the geothermal reservoir (Heat stored scenario only)	
Exploitation years of the power plant are fixed	
Numers of years planed for the exploitation (yrs)	20

Temperature inlet at the injection well (°C)	Tin	70
Temperature outlet the binary plant (°C)	Toutplant	70
density of fluid (Kg/m3)	rf	1078
Specific heat of the fluid (J/(kg.K))	cf	4250
target flow rate	Qtarg	100
Flow rate (L/s)	Q	213.8336193
Mass rate (kg/s)	Qms	230.5126416
Flow rate for one segment (kg/s)	Qs	3.201564467
Yearly average mass rate	Qms_y	165.9691019
Yearly average mass rate per segment	Qs_y	2.305126416
maximum pressure for pumps	Pmax	70
Dead State temperature (°C)	T0	20
Carnot relative efficiency for the plant	carnotrelative	0.55
co-heat exchanger efficiency	heatefficiency	0.7

Underground Development

Choice of the scenario for the temperature
Heat stored

number of doublet	numdoublet	1

Fixed decreasing temperature (°C/yr)	Tdecrease	0
recovery factor	recovery	0.125
Lenght of the borehole / depth of the reservoir (m)	zg	5000
Borehole diameter (inch)	dBinch	7
Borehole diameter (m)	dB	0.1778
Roughness of the pipes (mm)	ks	0
Distance between the two boreholes (Km)	Dist	0.65
Half boreholes distance at the reservoir level (Km)	aplot	0.325
Radius of the fracture (Km)	r	0.977
Square of the radius	r^2	0.955
number of segments	segments	36
Apparent injectivity index (l/s/Mpa)	II	3.2
Apparent productivity index (l/s/Mpa)	PI	7.5
Pressure require for the inj. borehole at the res. (Mpa)	PIr	57.897
Pressure require for the prod. borehole at the res. (Mpa)	PPr	24.703

Well cost scaling	wellcostscaling	0.7
single well cost (mln I)	costwell	6.125
Reservoir/borehole capacity factor	resfactor	0.8

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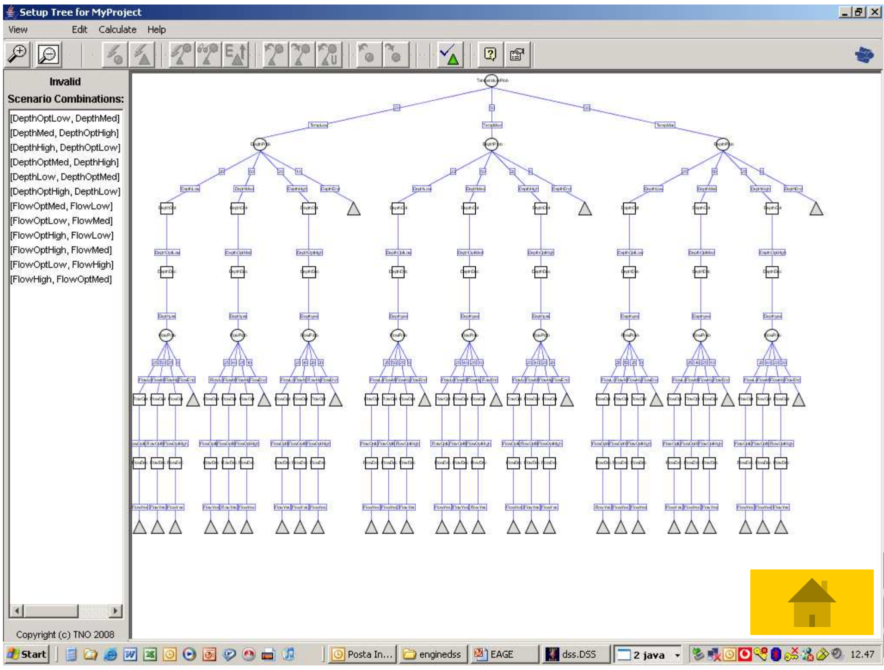
Uso: inserire classificazione

Geothermal Green Field Evaluation: DSS



Uso: inserire classificazione

Conclusion

Geothermal energy is **independent of weather conditions** and has an inherent storage capability which makes it especially suitable for supplying **base load power** in an economical way, and can thus serve as a partner with energy sources which are only available intermittently.

The renewable energy sources can contribute significantly to the mitigation of climate change, and more so by working as partners rather than competing with each other.

Uso: inserire classificazione

Conclusion

Presently the most growing geothermal utilisation sector is **heat pump applications**. This development is expected to continue in the future making heat pumps the main direct utilisation sector. The main reason for this is that geothermal heat pumps can be installed economically all over the world.

One of the strongest arguments for putting more emphasis on the development of geothermal resources worldwide is the **limited environmental impact** compared to most other energy sources.

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Uso: inserire classificazione

Conclusion

The geothermal exploitation techniques are under a rapid development and the understanding of the reservoirs has been improved considerably in the past years.

Combined heat and power plants are gaining increased popularity, improving the overall efficiency of the geothermal utilisation.

Also, low-temperature power generation with binary plants has opened the possibilities of producing electricity in countries which do not have high-temperature fields.

Enhanced Geothermal Systems (EGS) that extract heat from deeper parts of the reservoir than conventional systems are under development.

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Conclusion

Geothermal energy has established itself as a source of reliable and environmentally responsible power.

Its installed capacity is equivalent to 9 nuclear plants, with no atmospheric emissions nor hazardous wastes.

•**High Availability** and **Load Factors**,

•No Dependence on sunlight and weather,

•**Huge Resource Bases.**

Geothermal Energy is

a key resource in a sustainable energy future

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