Advanced systems for power production from geothermal low-enthalpy resources

Improving ORC power generation systems' performance and cost-effectiveness

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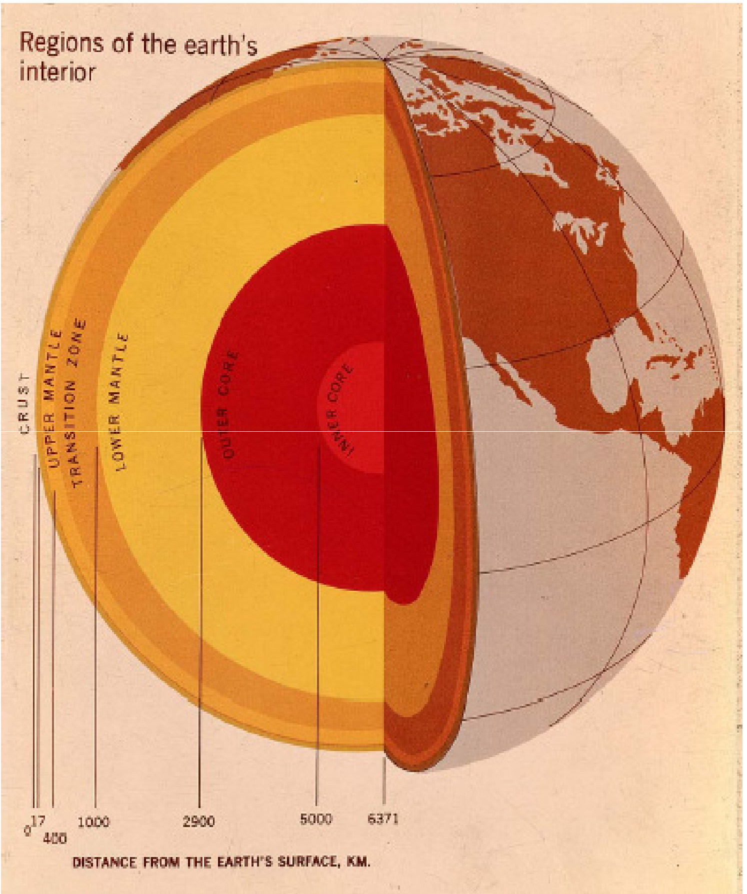
Geothermal energy: a big potential



- **Hydrothermal systems** – situated at a slight depth within the earth's surface.

  dry steam systems – steam is the continuous phase which controls the reservoir pressure.

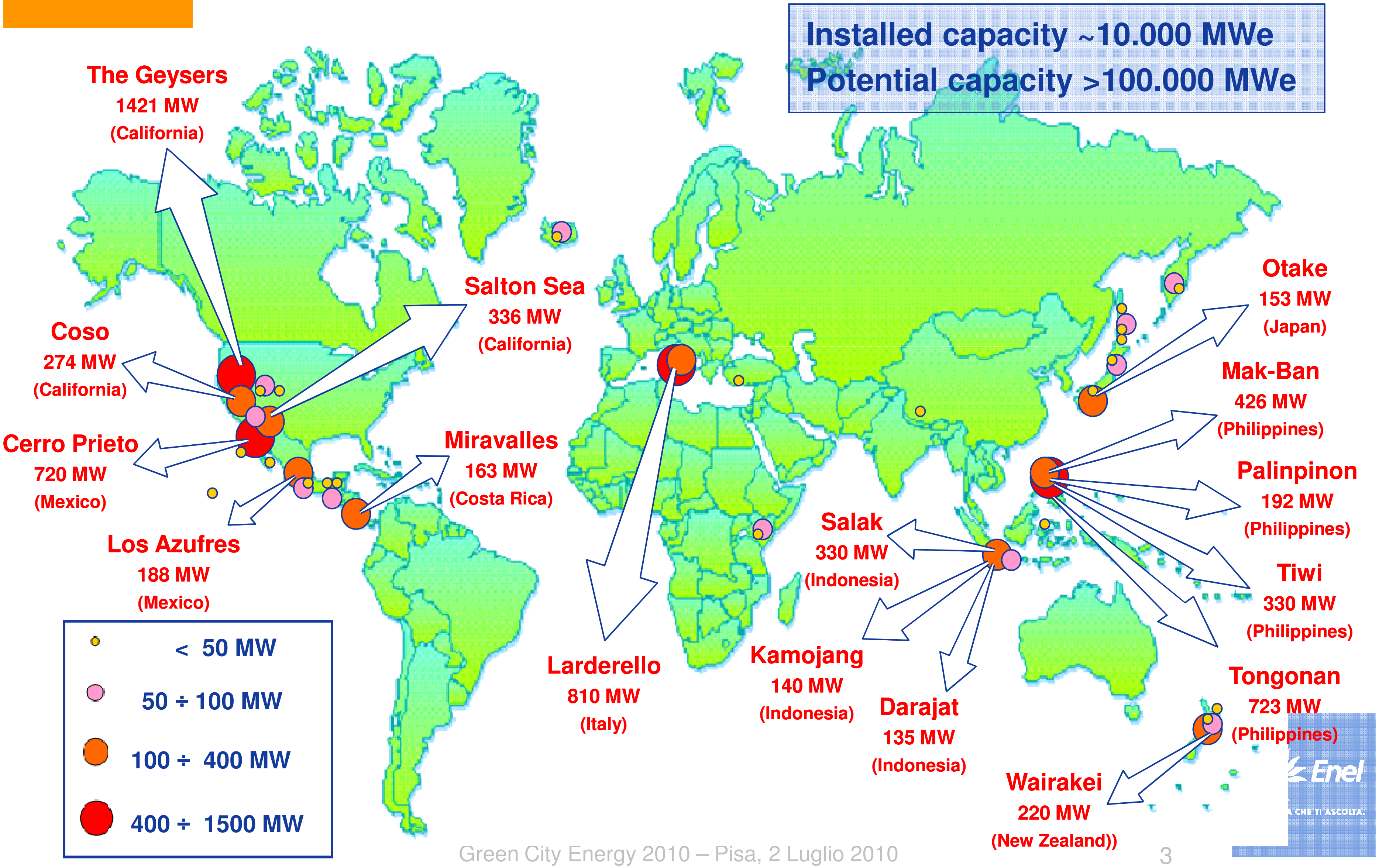
  water dominant systems - water is the continuous phase and controls the reservoir pressure.

  hot water reservoirs - water reservoirs with temperature ranging from 30℃ to 85℃.

  wet steam reservoirs – this kind of reservoir erogates water, or a mixture of water and steam, and gases characterized by high temperature (100÷370℃) and pressure.
- **Hot dry rocks** – rocky masses situated at a considerable depth beneath the earth's crust and characterized by high temperature and total absence of circulation fluids.
- **Geo-pressurized reservoirs** – made up of water characterized by high temperature (200℃) and a level of pressure near to the litostatic one (depths>4000m).
- **Magmatic systems** – magma bodies relatively close to the earth's surface.

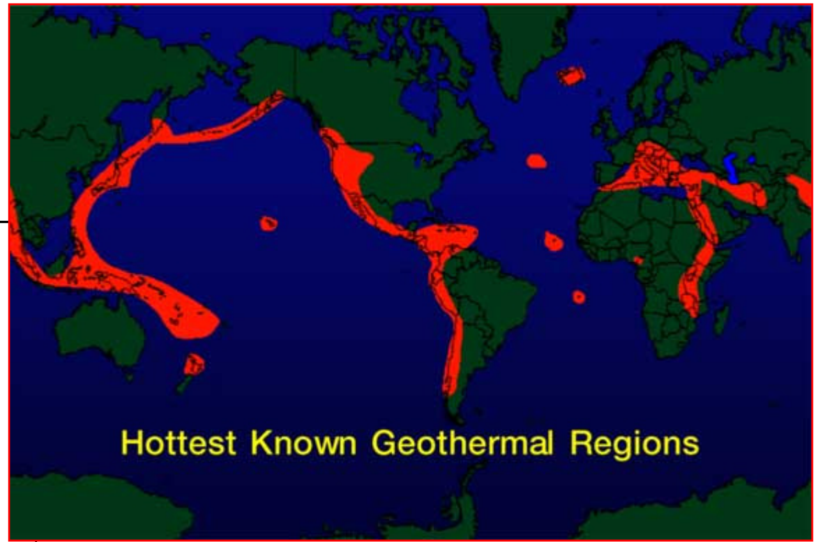
With wind and solar energy we look at the sky, but there is a lot of energy under our feet. *(J. Tester, MIT)*

Main geothermal fields worldwide



Low enthalpy geothermal resources

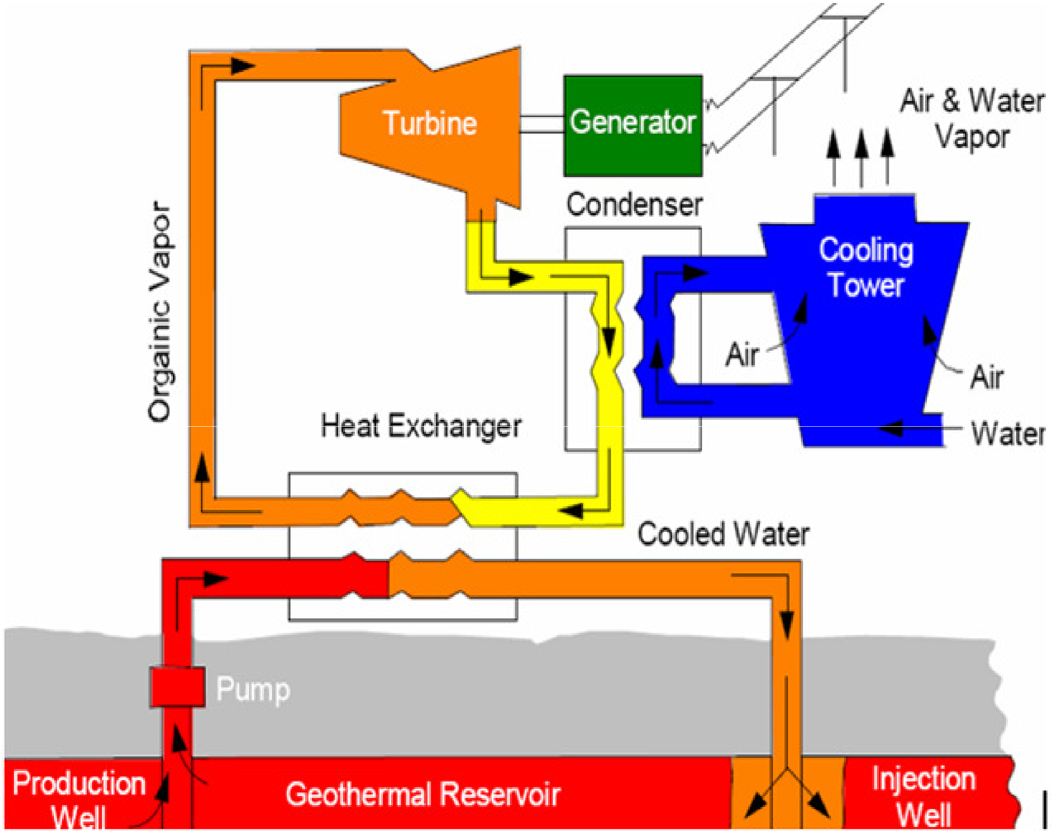
High temperature geothermal resources naturally occur in geologically active areas

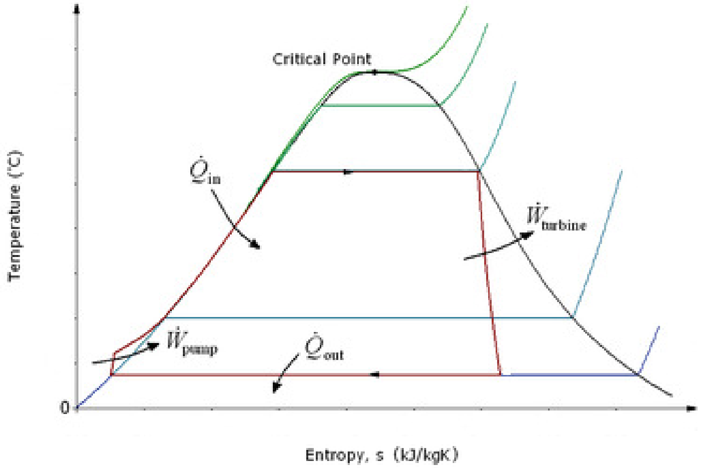


Medium/low temperature hydrothermal reservoirs are abundantly available and have by far the biggest electricity generation potential throughout Europe and worldwide

ORC technology represents best way to put into a productive way low-enthalpy geothermal resources

Binary cycles for low enthalpy geo-resources



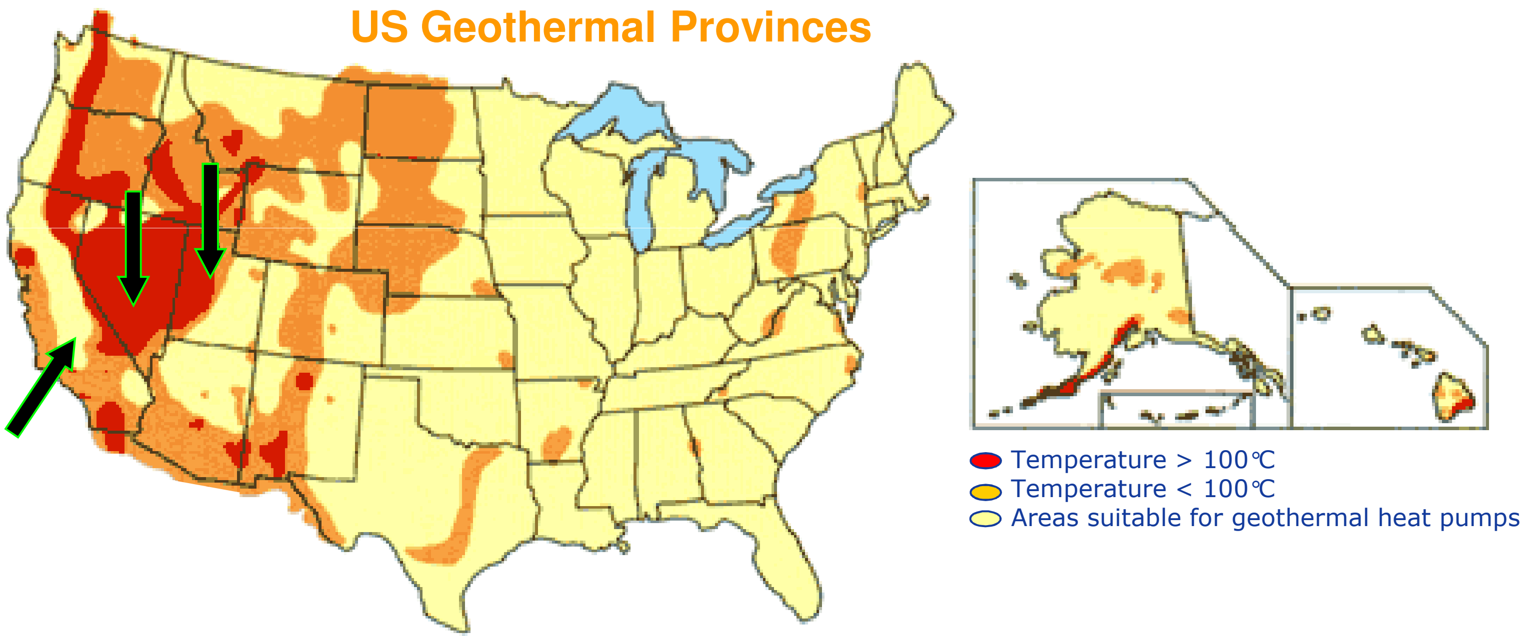


- For water dominant resources with temperature lower than 180°C, the binary cycle technology is the most efficient.
- The geo-fluid energy is transferred through a heat exchanger to a secondary fluid that works in a closed ORC cycle.
- The binary power plants have the least environmental impact due to the "confinement" of the geo-fluid.

Conventional working fluid: ***-Isobutane***
-Isopentane
-Butane
-Pentane

ENEL's interest in low enthalpy geothermal resources

- In early 2007 Enel North America acquired the rights to develop 4 geothermal fields in, California, Nevada and Utah.
- Approximately 65MWe from low enthalpy geo-resources are now in operation (Stillwater and Salt Wells Plants).



	Salt Wells	Stillwater	Surprise Valley	Cove Fort II
Brine mass flow [kg/s]	504 ÷ 560	877	756	756
Brine Temperature [°C]	135	154	165	152

Innovation in binary cycle technology

STATE OF THE ART

ORC CYCLE EFFECTIVENESS

7% ÷ 12%

ORC power production from low temperature resources has a low thermal efficiency

BYNARY PLANT CAPITAL COST

1200 ÷1600 €/KW
(1 ÷ 5 MWe unit)

2300 €/kW
(400 ÷ 500 kWe unit)

Low efficiency requires increased power plant equipment size that can become cost prohibitive

INNOVATION MAINSTAYS

ENHANCED PERFORMANCES & OPERATIONAL FLEXIBILITY

- To upgrade geothermal resources exploitation (electric generation more profitable)
- To better match the intrinsic characteristics of geothermal reservoirs
- To avoid performance decline due to the natural resources depletion and temperature drop

Project "Geotermia Innovativa"

Efficiency

18%

15%

12%

PHASE 2 - Development of a protoripal Hybrid Plant

Detection of the configuration which optimize the efficiency and the productivity of binary plants

PHASE 1 - Development of a innovative supercritical pilot binary plant (500 kWe)

- Optimization of the cycle's configuration to aim the maximum **flexibility**
- Detection of the best working fluid

State of art

- 1-5 MWe subcritical binary ORC
- Net specific work 35÷40 kJ/kg brine

1 year **Time** **3-4 year**

Project "Geotermia Innovativa" - Objectives

- To develop an advanced, supercritical, ORC technology in order to improve ENEL's geothermal production from low enthalpy geothermal resources worldwide (with a specific focus to USA).
  - Net specific work > 44 kJ/kg brine (~ +30% respect to actual technology).
  - High operation flexibility (capability to work with high performances in a wide range of brine temperatures).
  - Contained costs of investment.
- To demonstrate an advanced ORC at the pilot scale (500kWe).
  - Cycle thermodynamic performance.
  - Operating flexibility.
  - Component design and scale-up criteria (with a particular focus on turbo - expander).
  - Component reliability during long term operation (some thousands hours).
- To evaluate the feasibility to increase the productivity of ENEL's ORC geothermal plants in the USA thorough integration with solar energy.

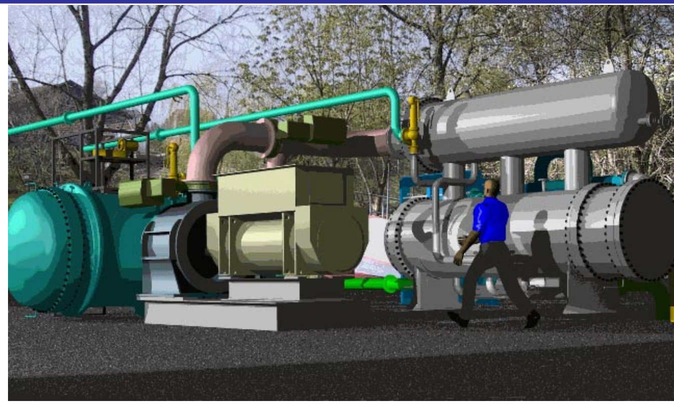
Project "Geotermia Innovativa" - Overview

Project time schedule

	2009	2010	2011	2012	2013
Fase 1	Agreement and Design of an Advanced ORC	Permitting Process for ORC Pilot Plant	Pilot Plant Procurement and Costruction	Cycle and Components Testing at the Pilot Scale	
Fase 2	Feasibility Study for Hybrid Cycles including Stillwater Power Plant (NV, USA)	Decision for the Demo Phase	Demo Plant Engineering Procurement and Costruction		

Short - Middle Term Activities

- TD cycle and working fluid have been selected.
- Basic design of pilot plant SC ORC (Apr. '10).
- Permitting procedure start-up (Dec. '09).
- Construction works at ENEL's Livorno experimental area (Sep. '11).
- Pre-feasibility study completion for geo-solar hybrid cycles (Sep. '10).



- **An agreement has been signed with Turboden and Politecnico of Milan for advanced ORC development, pilot plant EPC and ORC testing (Phase 1) on April the 24th of 2009.**
- **A cooperation has been activated with MIT in order to evaluate the feasibility of geo-solar integration in USA geothermal fields.**

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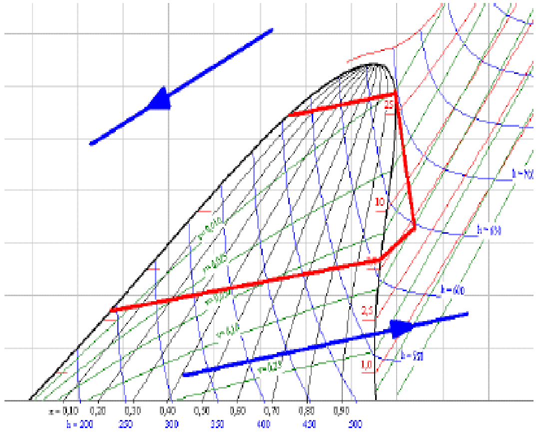
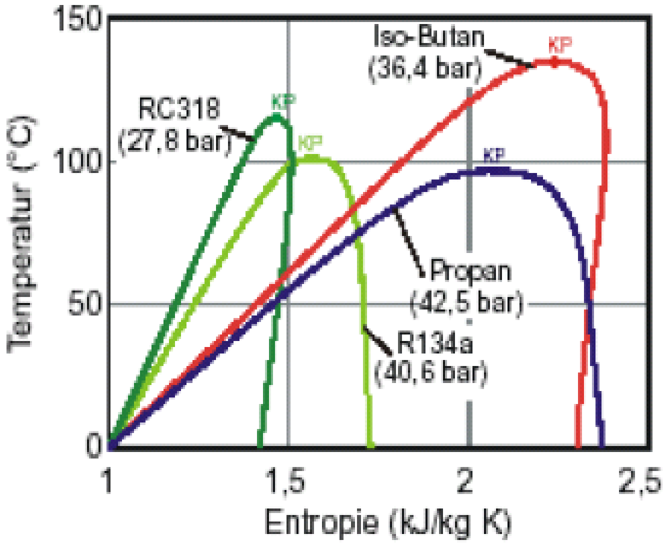
Cycle optimization and working fluid selection

- **Cycle modelling**
  - Sub-critical cycles (saturated, superheated)
  - Super-critical cycles



- **Working fluid screening criteria**
  - **6** Hydrocarbons tested
  - **4** Refrigerants tested

- Low boiling point and high vapor pressure fluids related to operating T and P
- Heavy fluid, characterized by little enthalpy drop, therefore the turbo-machinery is little mechanically stressed



Calculation Hypotesys

Constraints of the models

INPUT DATA

Brine inlet temperature: 100°C ÷ 200°C
Brine reinjection temperature: ≥70°C
Cooling water: NOT AVAILABLE
Geothermal fluid mass flow: 100 kg/s
Dead-state temperature (Air ambient temperature): 20°C
Turbine isentropic efficiency:
85% for fully-vapor expansions
<85% when liquid present (calculated from the Baumann equation)
Turbine exit vapor quality: 90%
Mechanical/generator efficiency: 98%
Pump efficiency: 80%
Condenser subcooling: 2°C
Main heat exchanger LMTD: 10°C (only for supercritical cycles)
Evaporator heat exchanger pinch temperature: 5°C (only for subcritical cycle)
Pre-heater heat exchanger LMTD: >5°C (only for subcritical cycle)
Regenerator pinch temperature difference: 5°C
Regenerator effectiveness (where appropriate): 50%
No pressure drop in heat exchangers

Cycle optimization criteria

Maximise the overall net conversion efficiency of the modelled power system

OPTIMIZATION VARIABLES

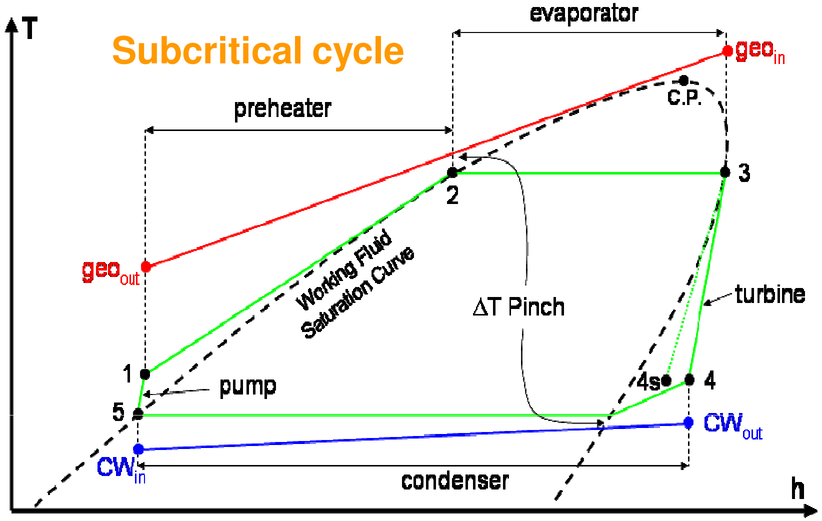
- Working fluid mass flow rate
- Working fluid turbine inlet pressure
- Working fluid condensing pressure

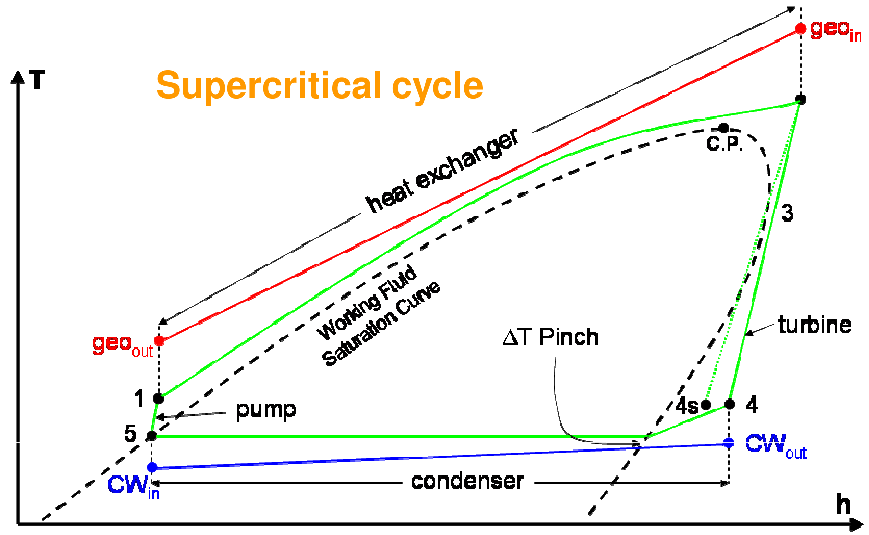
PERFORMANCE INDICATORS

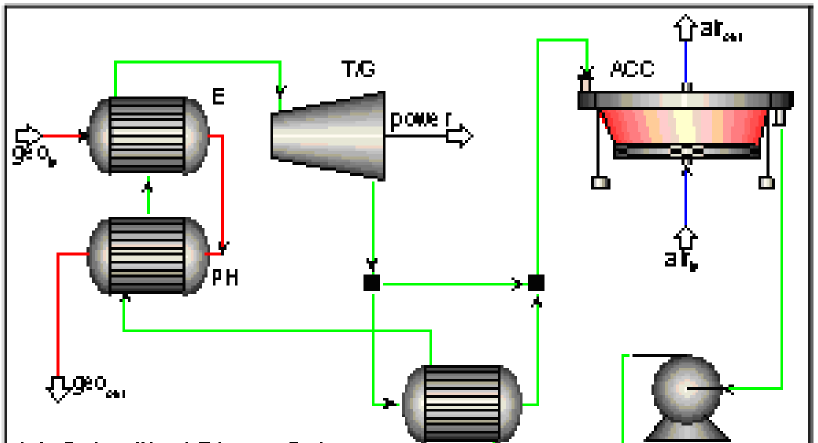
- Utilization efficiency → $\eta_u = \frac{W_{net}}{E_{in}}$
- Thermal efficiency → $\eta_{th} = \frac{W_{net}}{Q_{in}}$

Optimization variables were varied in order to reach the optimum in terms of cycle net conversion efficiency

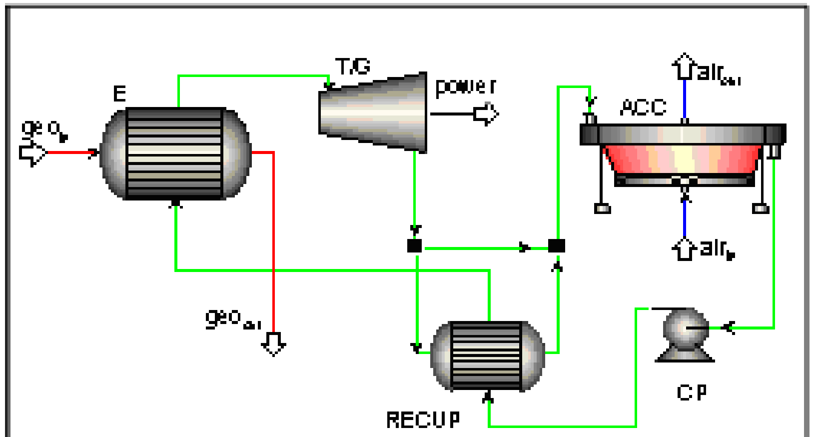
Subcritical vs. Supercritical Cycles





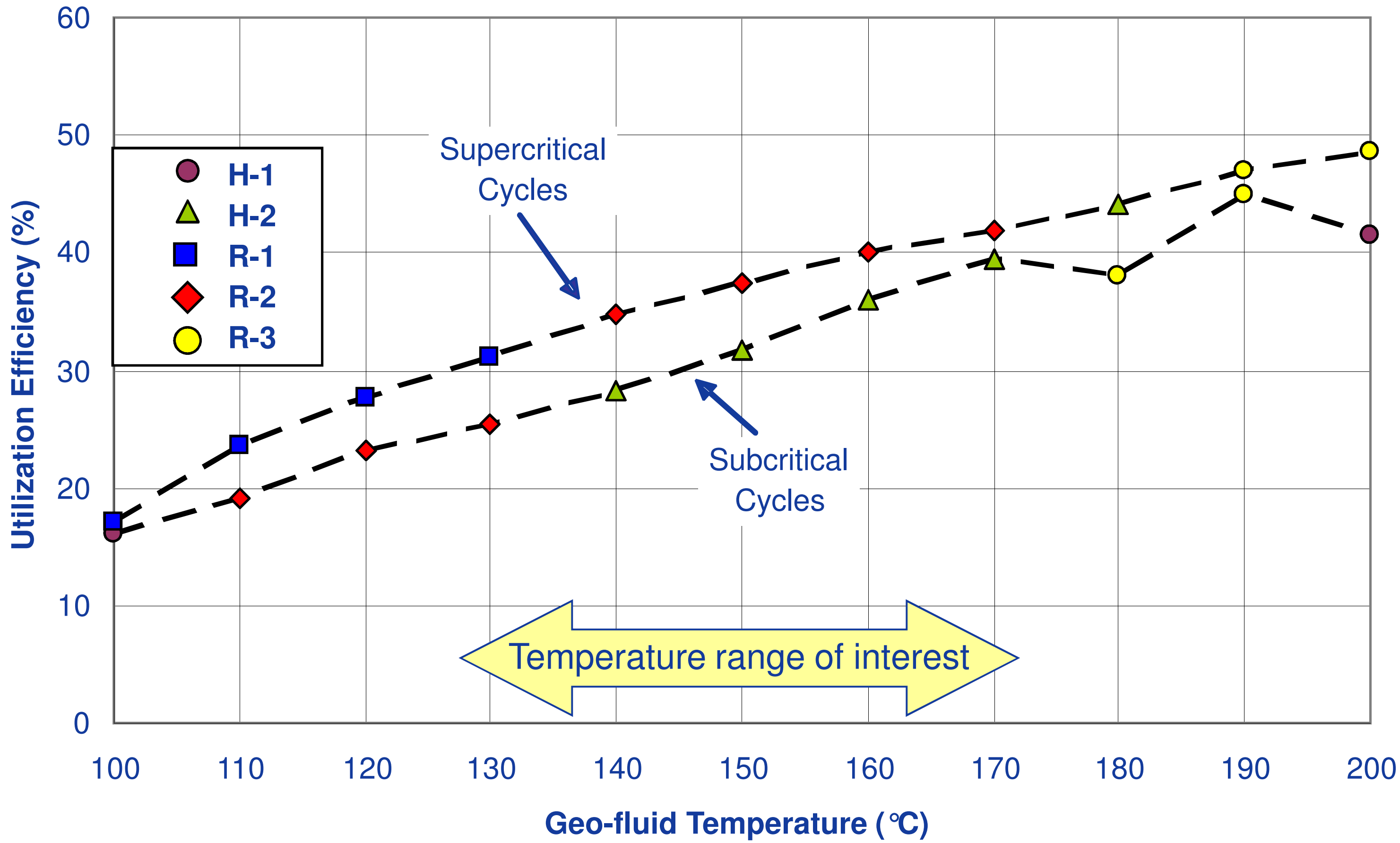


(a) Subcritical Binary Cyle



(b) Supercritical Binary Cyle

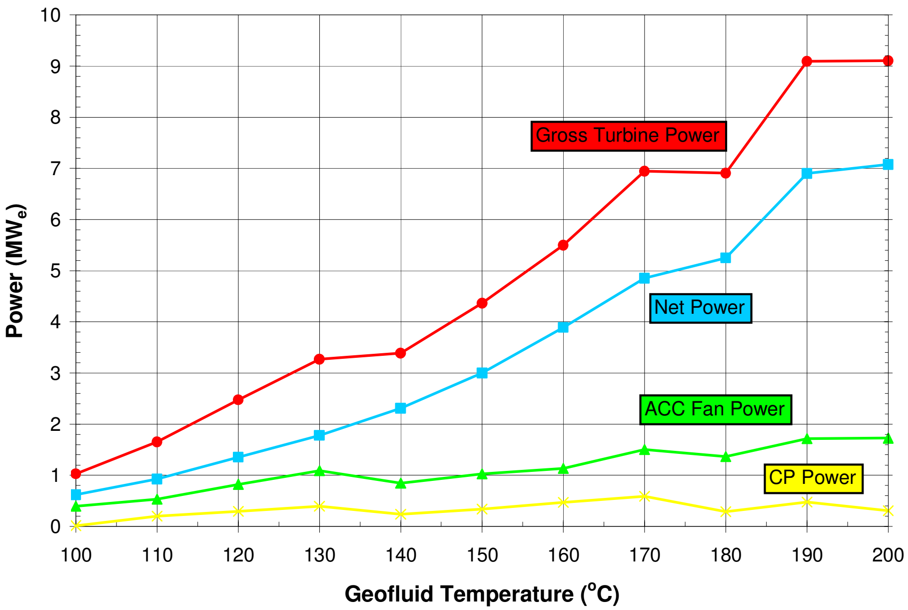
Simulation results 1/2



Supercritical cycles provide higher utilization efficiency for all geo-fluid temperature range, resulting in max 23% increase in net power.

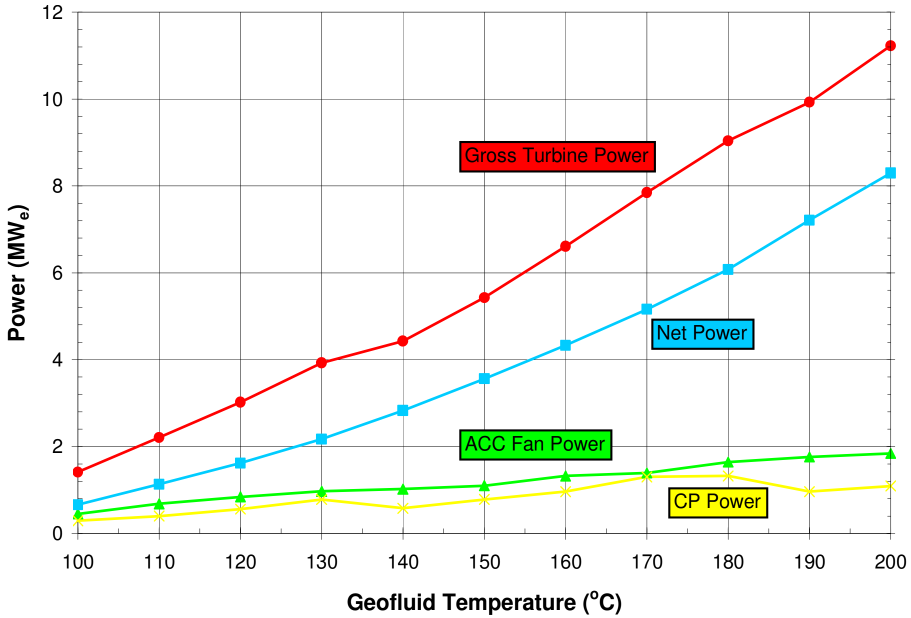
Simulation results 2/2

Subcritical cycle



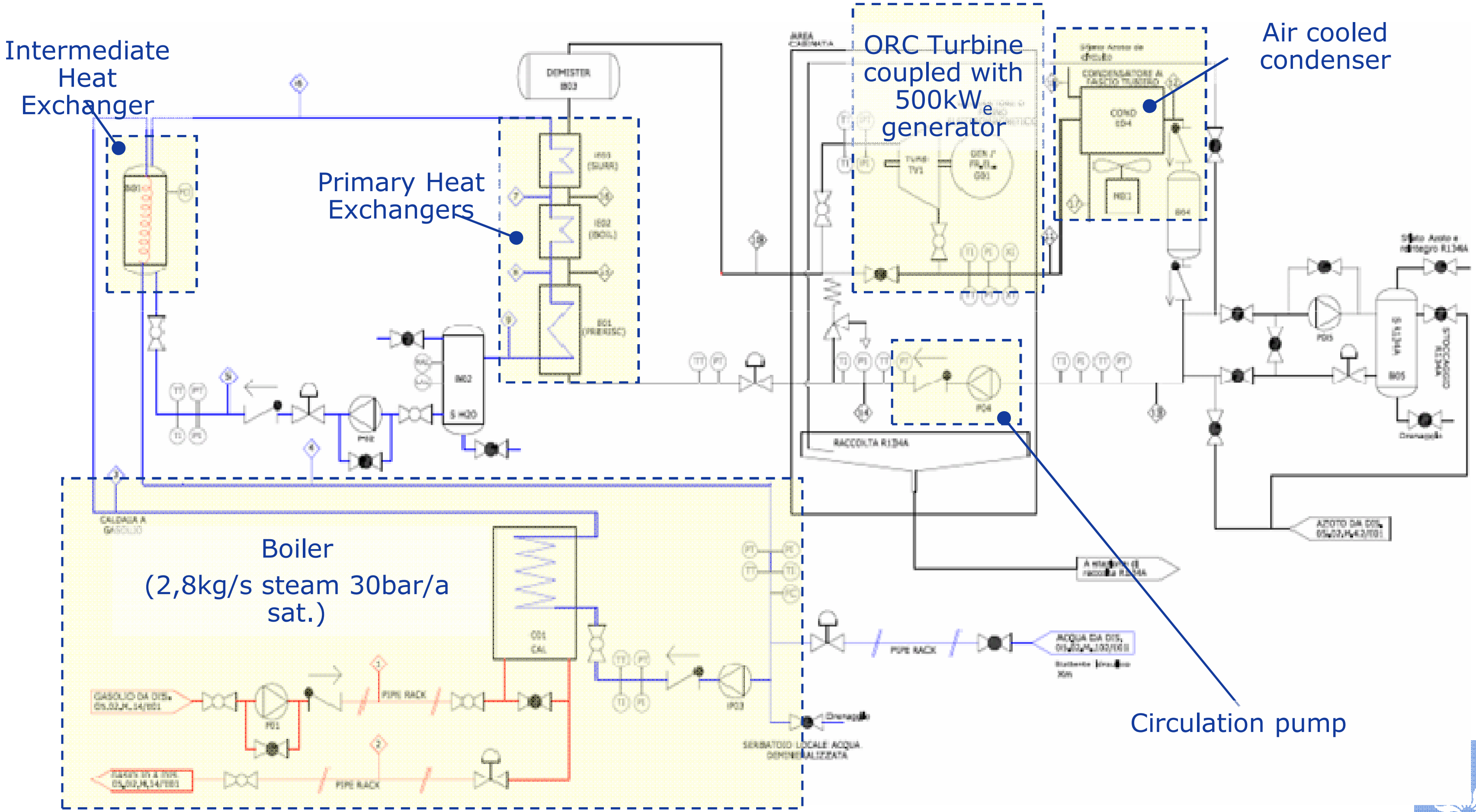
Power, MW	H-1 @ 100°C	H-2 @ 150°C	H-1 @ 200°C
Gross	1.03	4.37	9.12
Parasitic losses	40%	31%	22%
Net	0.62	3.00	7.07

Supercritical cycle



Power, MW	R-1 @ 100°C	R-2 @ 150°C	R-3 @ 200°C
Gross	1.41	5.43	11.23
Parasitic losses	53%	34%	26%
Net	0.66	3.56	8.30

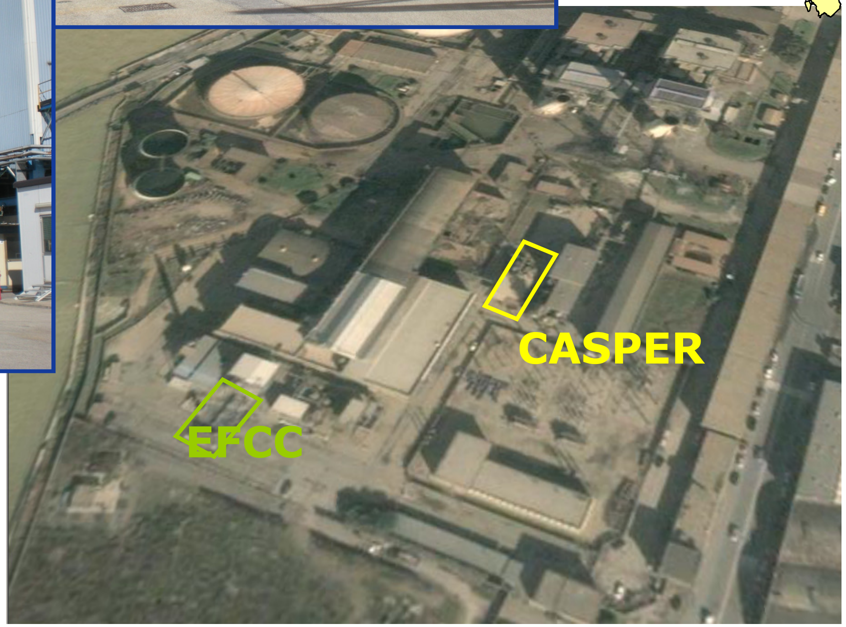
Advanced 500 KW_e ORC pilot plant PFD



Advanced 500 KW_e ORC pilot plant

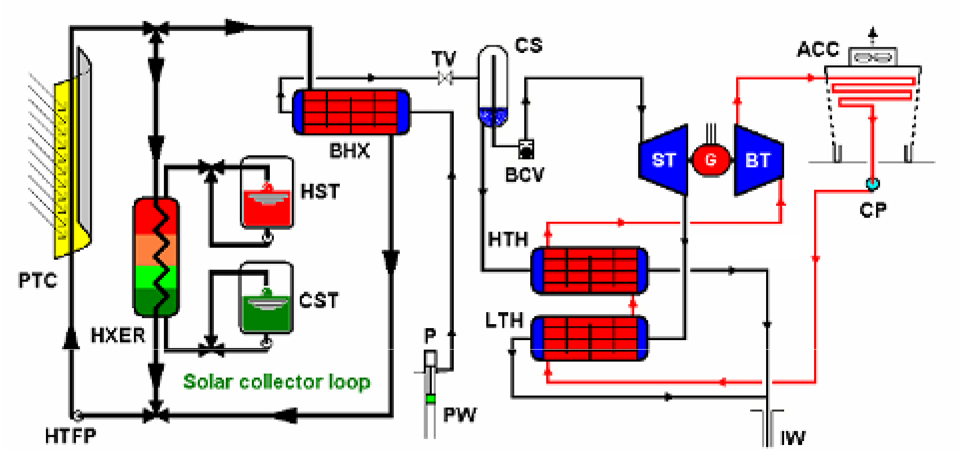
Auxiliary boiler already available 5,6 MW (8,5 t/h, 250°C)

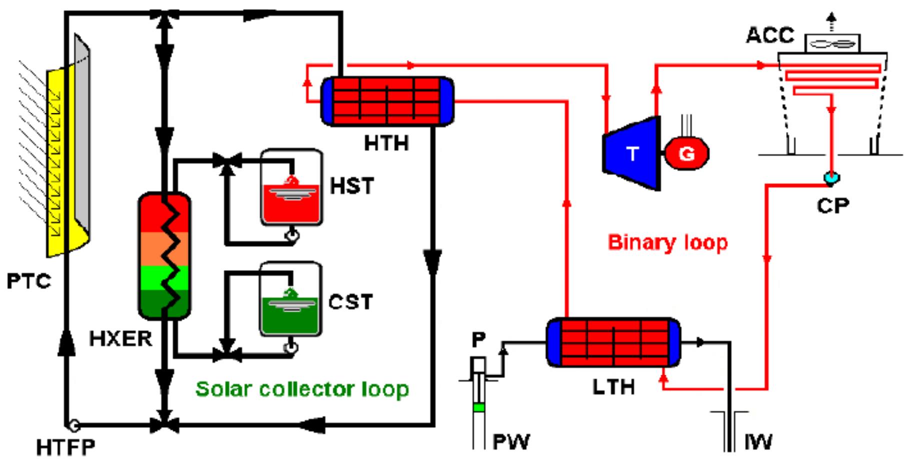
200 m² foundation platform for pilot plant installation



Future development

Phase 2: Geothermal & Solar Hybrid Cycle Advantages

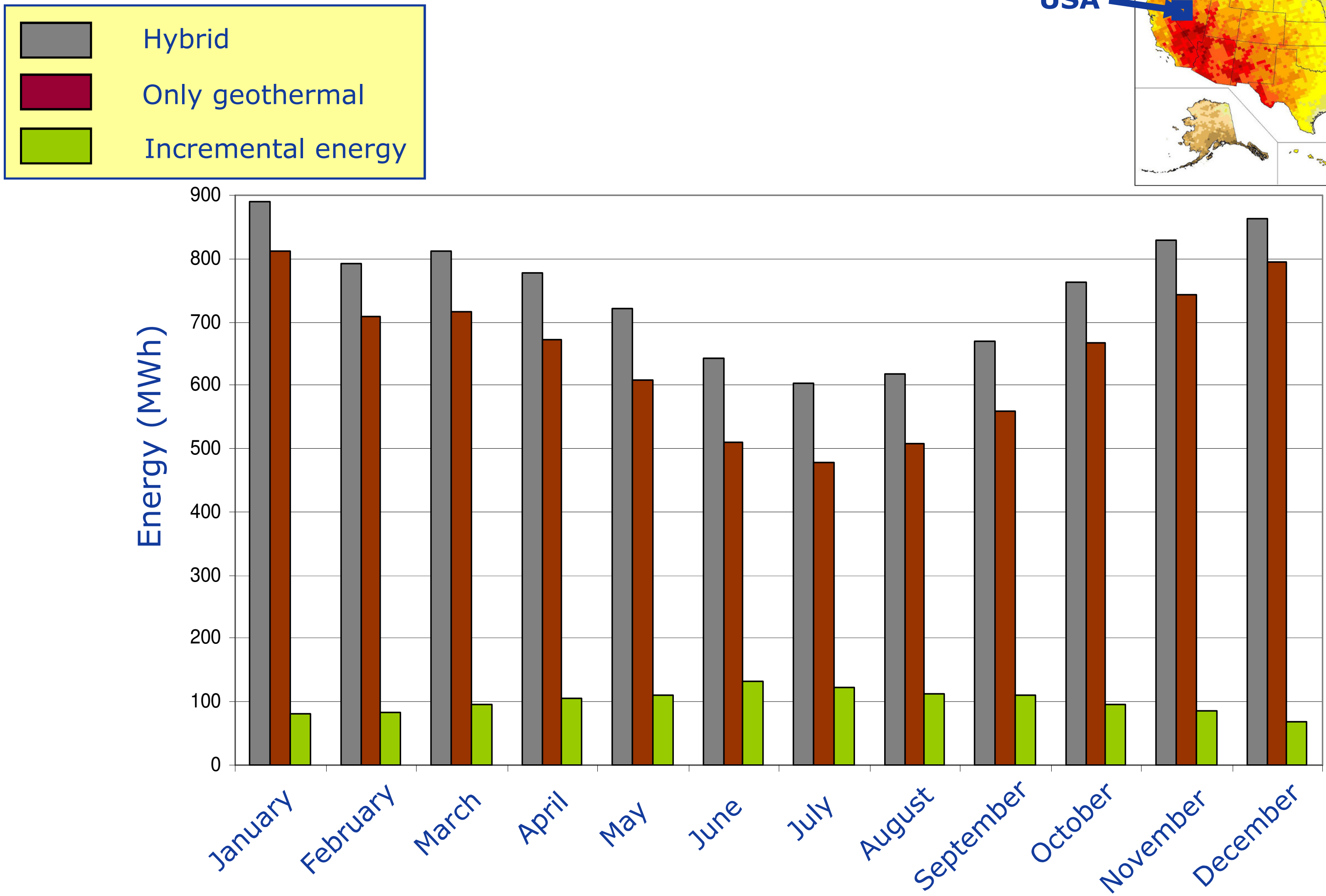


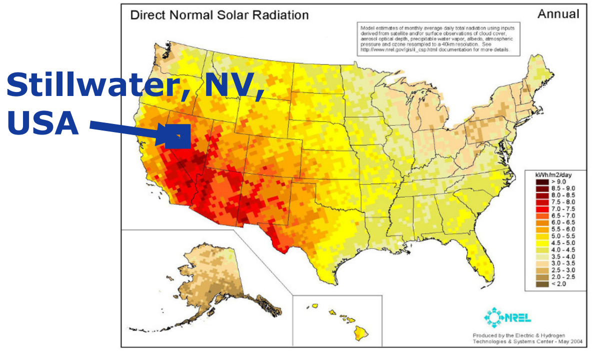


- Minimize geothermal technology problems and produce more electricity without expanding the use of the geo-resource
- Improve performance over a pure geothermal system
- More cost-effective than standalone solar facilities, also thanks to medium temperature and low-cost solar collectors
- To offset the risk of premature resource depletion
- To hedge risk associated with geothermal production (predictability of resource's temperature and flow rate)

Hybrid-cycles – First results

Old Stillwater Plant





Supercritical binary costs

Cost:	€ 8.7 Million
Power:	5 MW
Investment per MW:	~1700 €/kW

Brine Preheat Hybrid Results

Size:	1.9ac (7500m²)
Cost:	$1.45 Million
Incremental Electricity:	1200 MW-h
Investment per kW-h:	1.21 $/kW-h
Capacity Factor	34.1%

η = collector efficiency = 0.75
collector price = $193.25 / m2

25-Year Incremental Solar Levelized Cost:	interest=10%, 13.3 ¢/kW-h	interest=15%, 18.7 ¢/kW-h	interest=25%, 30.3 ¢/kW-h
O&M Included	interest=10%, 15.3 ¢/kW-h	interest=15%, 20.7 ¢/kW-h	interest=25%, 32.3 ¢/kW-h

Concluding remarks

- Over the temperature range studied and for the design specifications assumed, supercritical binary cycles are more efficient than subcritical cycles, producing up to **23% more net power**, despite parasitic pumping losses in the supercritical cases are 2-3 times higher than subcritical ones.
- Refrigerants performed very well as working fluids, especially for supercritical cycles.
- In a supercritical cycle the possibility of operating outside the fluid saturation diagram during the heat adduction phase guarantees a greater operational flexibility with respect to subcritical cycles.
- Based on the positive results of the undertaken work, ENEL has signed a cooperation agreement with Turboden and Milan Polytechnic aimed at designing and constructing a 500KWe pilot plant in its experimental area in Livorno in order to assess TD performance, component reliability and costs of the new technology.
- In the mean time the techno-economic feasibility of geo-solar integration for ENEL's binary plant in the USA is under evaluation in cooperation with Massachusetts Institute of Technology) aimed at increasing production, reducing risks and increasing flexibility.

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