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Sensitivity analysis of the total reinjection geothermal plant in Castelnuovo

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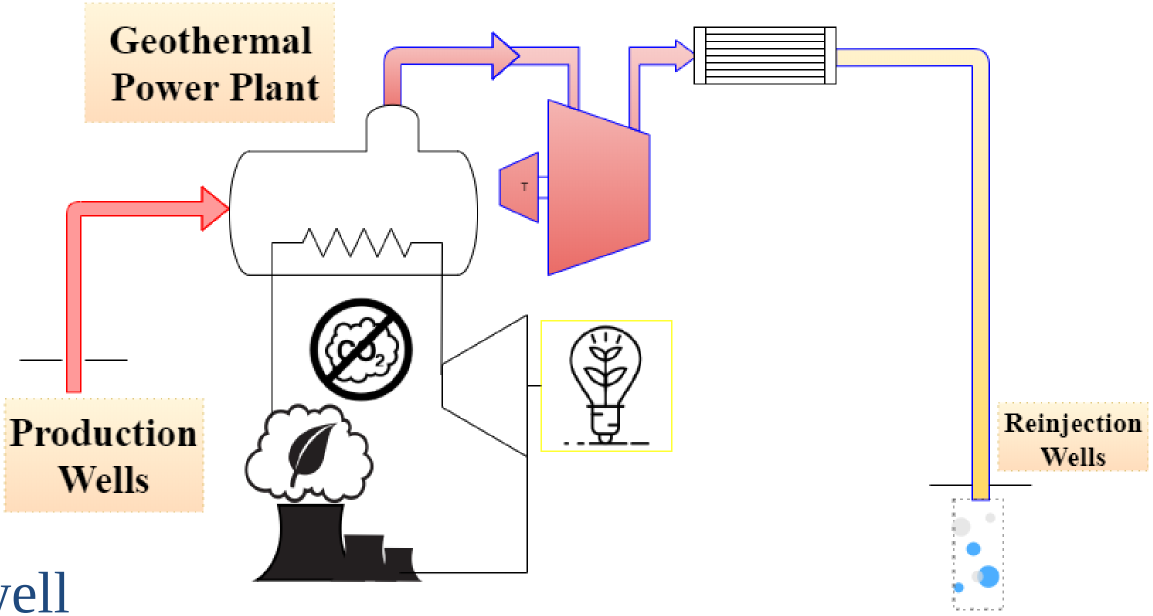
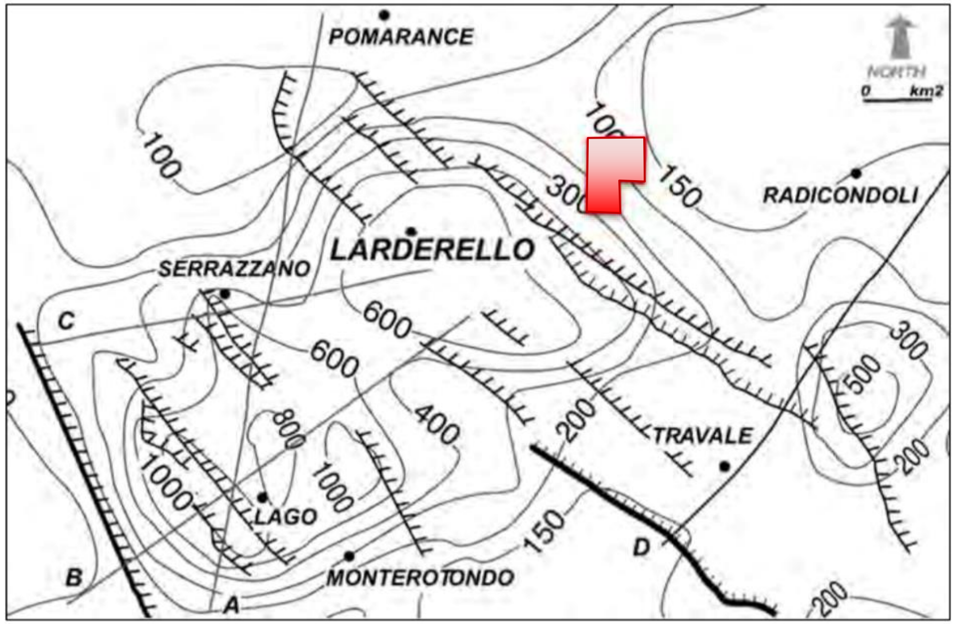


Resource conditions

- The Montecastelli Pisano area (in which the "Castelnuovo" permit falls) is characterized by values between **100 and 300 mW/m²** on average.
- Saturated vapour at a pressure within the **60-80 bar** range, **280°C** temperature at about **3500 m depth**.
- **At well head**, the expected resource conditions are **10.3 bars** pressure and **180 °C** temperature.
- The **NCG** mass content is estimated at about **8%**, of which about **7.8% is CO_2 and 0.2% H_2S**.

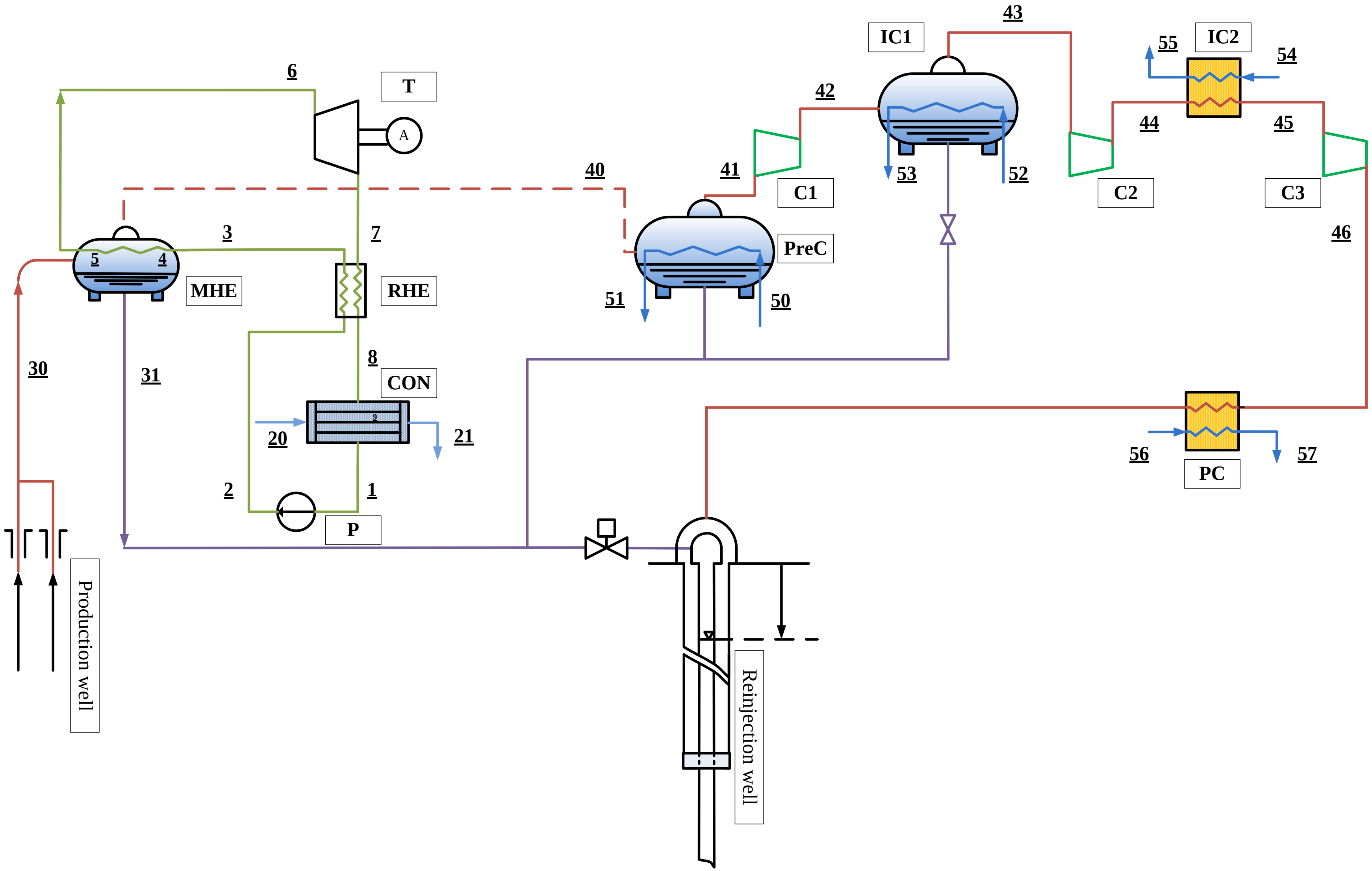


Heat flow distribution expressed in mW/m² (Bellani et al., 2004)

Bellani, S., Brogi, A., Lazzarotto, A., Liotta, D., Ranalli, G., 2004. Heat flow, deep temperatures and extensional structures in the Larderello geothermal field (Italy): constraints on geothermal fluid flow. J. Volcanol. Geotherm. Res. 132, 15– 29.

Power plant schematic

- The well layout consists of 2 production and 1 reinjection wells.
- The ORC is a recuperative power cycle using **R1233zd(E)** as working fluid.
- A **three-stage compressor** with intercoolers to reduce the power consumption is considered.

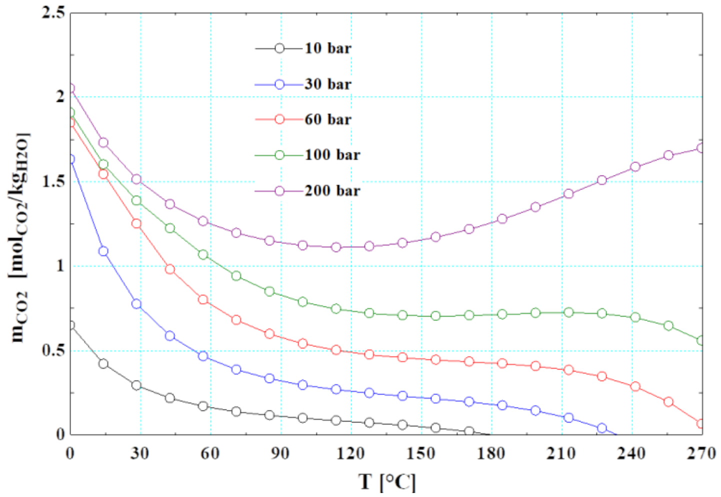


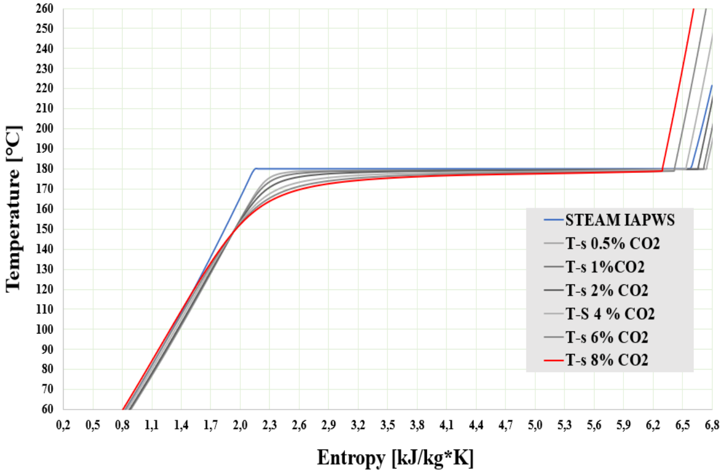
Thermodynamic models

$$\sum \dot{m}_i = \sum \dot{m}_e$$

$$\sum \dot{Q} + \sum \dot{m}_i h_i = \sum \dot{W} + \sum \dot{m}_e h_e$$

- All the processes for system and sub-systems are steady state.
- Turbines and pumps are considered as adiabatic devices.
- For design point conditions, the mass flow rate of the ORC was obtained fixing the net power output of the turbine at 5 MW_e.



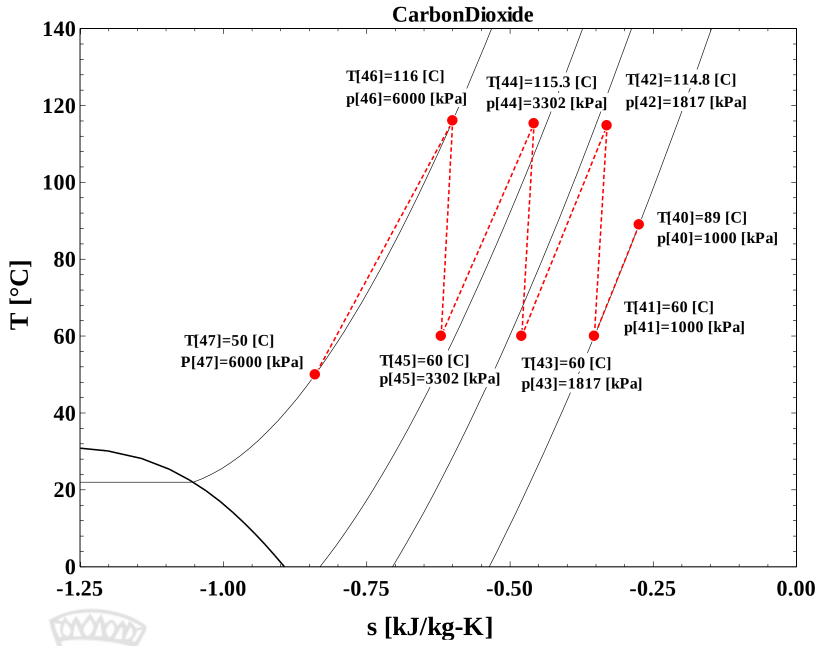


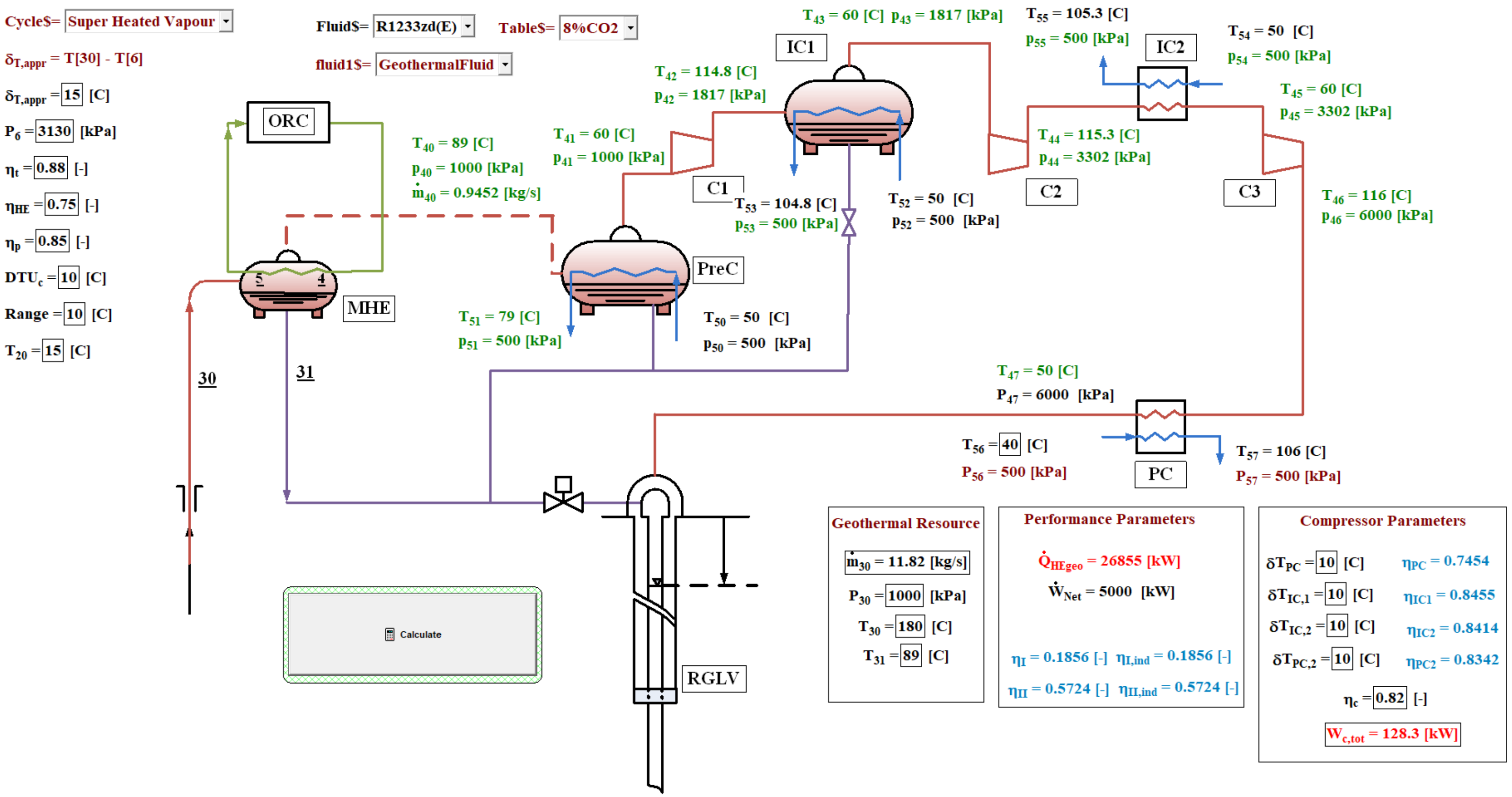
- Geothermal fluid are considered as a mixture of H_2O and CO_2.
- CO_2-H_2O mixture properties are estimated with a third-order EOS model.
- A CO_2 Solubility model (Duan and Sun, 2003) is implemented in the in-house code for THD properties.

Duan Z., Sun R., An improved model calculating CO_2 solubility in pure water and aqueous NaCl solutions from 273 to 533 K and from 0 to 2000 bar, Chemical Geology, 193, 2003, 257 – 271

Thermodynamic model results

Parameter	Unit	Value
Geothermal mass flow rate	kg/s	11.82
CO_2 mass flow rate	kg/s	0.9452
Power plant efficiency	%	18.56
Heat input from Geothermal Fluid	kW	26855



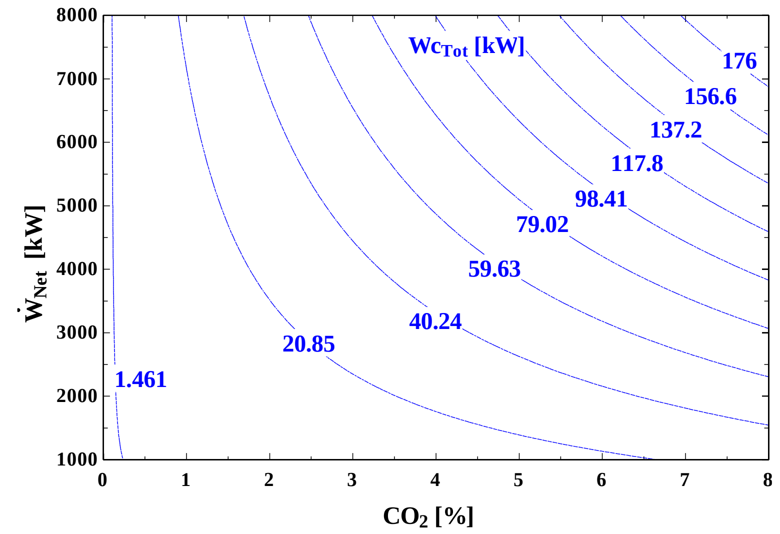


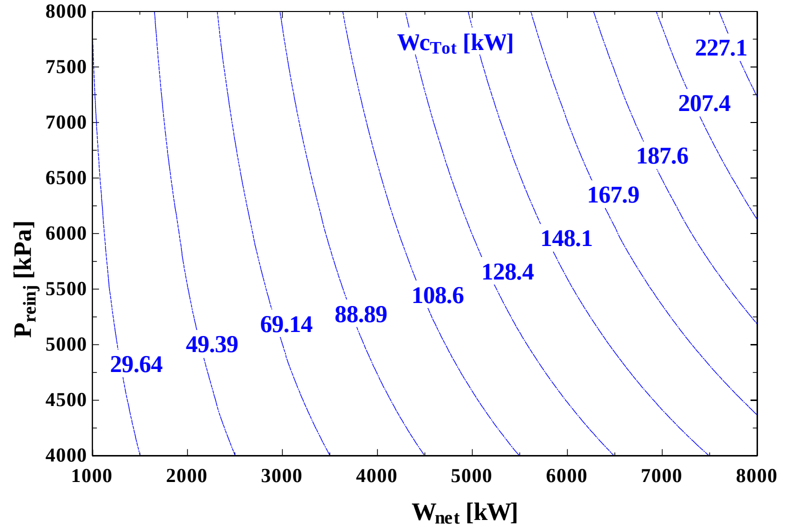
Sensitivity Analysis (CO_2 content)

Cases		W_c [kW]	$\dot{m}_{GEO}$ [kg/s]	$\dot{m}_{CO_2}$ [kg/s]	$\dot{Q}_{HE,GEO}$ [kW]	η_I --	η_{II} --
$\%CO_2$ Variation, W_{net} = 5 MW, P_{reinj} = 60 bar, η_c = 0.82	0.5%CO_2	7.307	10.77	0.05384	26221	0.1906	0.5443
	1%CO_2	14.7	10.83	0.1083	26260	0.1903	0.5462
	2%CO_2	29.76	10.97	0.2193	26339	0.1897	0.5498
	4%CO_2	61.02	11.24	0.4496	26503	0.1884	0.557
	6%CO_2	93.89	11.53	0.6918	26675	0.187	0.5645
	8%CO_2	128.5	11.84	0.947	26856	0.1856	0.5721

- Lower %CO_2 => lower $\boldsymbol{W_c}$ => higher $\boldsymbol{\eta_I}$.

- **Conversely**, due to the better match between the main heat exchanger curves, the **exergy efficiency increases with an increase of CO_2 content** within the geothermal fluid stream (the input exergy is lower).





Exergo-Economic model

- **Exergy** is defined as the maximum work that can be obtained by bringing the state of a system to equilibrium with the environment (Kotas, 1985).

$$\chi_k = \frac{\dot{E}x_D}{\dot{E}x_{D,tot}}$$ Exergy destruction ratio

$$\sum_{e}^{N_e} \dot{C}_{P,e,k} = \sum_{i}^{N_i} \dot{C}_{F,i,k} + \dot{Z}_k$$ Exergy cost balance

- The **Exergo-Economic Analysis** (EEA) combines the exergy and the economic analyses, in order to provide a clear and efficient evaluation of the cost effectiveness of each component of the power plant, introducing the costs per exergy unit (Bejan et al., 1996).

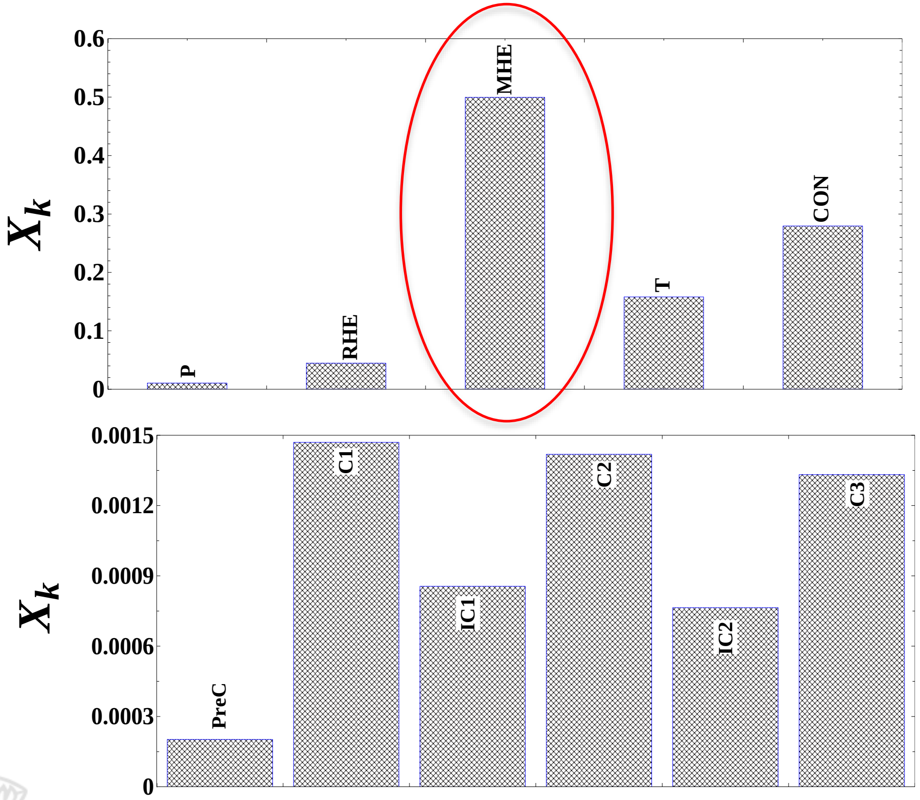
k	Component	Cost balance equations	Auxiliary equations
1	P	$c_2\dot{E}x_2 = c_1\dot{E}x_1 + c_{W_p}\dot{W}_p + \dot{Z}_p$	$c_{W_p}=c_{W_t}$
2	RHE	$c_3\dot{E}x_3 + c_8\dot{E}x_8 = c_2\dot{E}x_2 + c_7\dot{E}x_7 + \dot{Z}_{HE}$	$c_7 = c_8$
3	MHE	$c_6\dot{E}x_6 + c_{31}\dot{E}x_{31} + c_{40}\dot{E}x_{40} = c_3\dot{E}x_3 + c_{30}\dot{E}x_{30} + \dot{Z}_{HEgeo}$	$c_{30} = c_{31}$ $c_{40} = c_{30}$
4	T	$c_7\dot{E}x_7 + c_{W_t}\dot{W}_t = c_6\dot{E}x_6 + \dot{Z}_t$	$c_6 = c_7$
5	CON	$c_1\dot{E}x_1 + c_{21}\dot{E}x_{21} = c_8\dot{E}x_8 + c_{20}\dot{E}x_{20} + \dot{Z}_{cond}$	$c_{20}=0$ $c_{21} = c_{20}$
6	PreC	$c_{41}\dot{E}x_{41} + c_{51}\dot{E}x_{51} = c_{40}\dot{E}x_{40} + c_{50}\dot{E}x_{50} + \dot{Z}_{PC1}$	$c_{50}=0$ $c_{40} = c_{41}$
7	C1	$c_{42}\dot{E}x_{42} = c_{41}\dot{E}x_{41} + c_{W_{c1}}\dot{W}_{c1} + \dot{Z}_{c1}$	$c_{W_{c1}}=c_{W_t}$
8	IC1	$c_{43}\dot{E}x_{43} + c_{53}\dot{E}x_{53} = c_{42}\dot{E}x_{42} + c_{52}\dot{E}x_{52} + \dot{Z}_{IC1}$	$c_{52} = c_{50}$ $c_{43} = c_{42}$
9	C2	$c_{44}\dot{E}x_{44} = c_{43}\dot{E}x_{43} + c_{W_{c2}}\dot{W}_{c2} + \dot{Z}_{c2}$	$c_{W_{c2}}=c_{W_t}$
10	IC2	$c_{45}\dot{E}x_{45} + c_{55}\dot{E}x_{55} = c_{44}\dot{E}x_{44} + c_{54}\dot{E}x_{54} + \dot{Z}_{IC2}$	$c_{54} = c_{50}$ $c_{45} = c_{44}$
11	C3	$c_{46}\dot{E}x_{46} = c_{45}\dot{E}x_{45} + c_{W_{c3}}\dot{W}_{c3} + \dot{Z}_{c3}$	$c_{W_{c3}}=c_{W_t}$

Bejan A., Tsatsaronis G., Moran M.J.: Thermal Design and Optimization, John Wiley & Sons, (1996).

Kotas, T., The Exergy Method of Thermal Plant Analysis, Elsevier, 1985.

Exergo-economic Results

Exergy destruction ratio

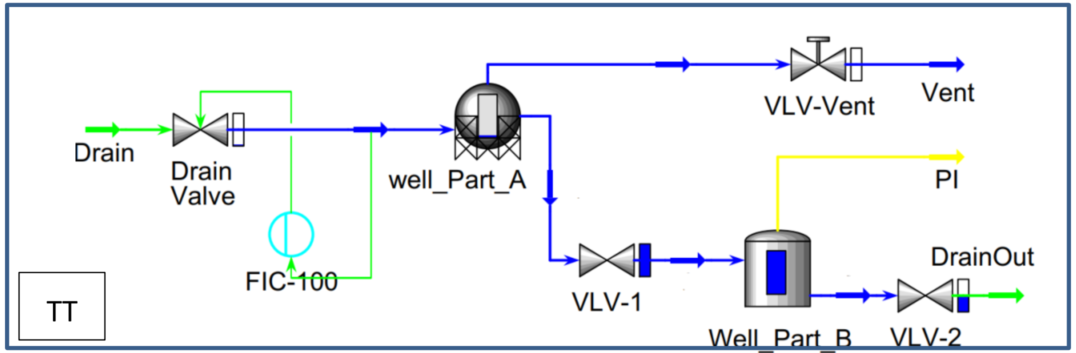


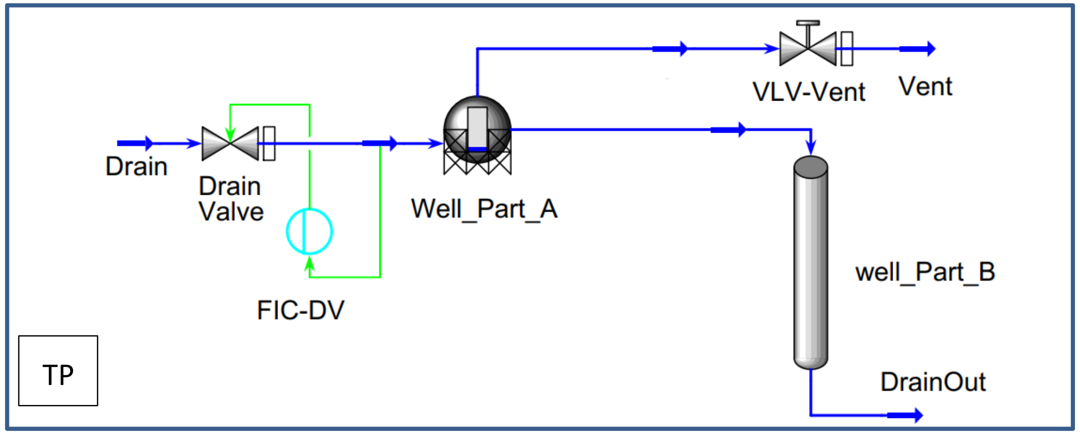
Component	PEC (€)	$\dot{Z}_k$ (€/s)	$\dot{C}_{D,k}$ (€/s)	$c_{F,k}$ (€/kWh)	$c_{P,k}$ (€/kWh)
P	193464	0.001558	0.0008032	0.07148	0.1056
RHE	438204	0.00353	0.00242	0.05154	0.1009
MHE	2.920E+06	0.02352	0.009514	0.01804	0.03419
T	2.651E+06	0.02136	0.008596	0.05154	**0.07148**
CON	656282	0.005286	0.01634	0.05538	0.2662
PreC	181662	0.001463	0.000003835	0.01804	1.819
C1	126231	0.001017	0.0001109	0.07148	0.1835
IC1	185022	0.00149	0.000053	0.05869	0.8226
C2	120236	0.0009685	0.0001071	0.07148	0.1837
IC2	219831	0.001771	0.00006767	0.08384	1.008
C3	113008	0.0009102	0.0001005	0.07148	0.1834

- **PEC** = Purchased Equipment Cost
- $\dot{Z}_k$ = Sum of the cost rates associated with investments and operation and maintenance for the k-th component
- $\dot{C}_{D,k}$ = Exergy destruction cost rate
- $c_{F,k}$ = costs per exergy unit of fuel
- $c_{P,k}$ =costs per exergy unit of product

Dynamic Simulation of the Reinjection Well

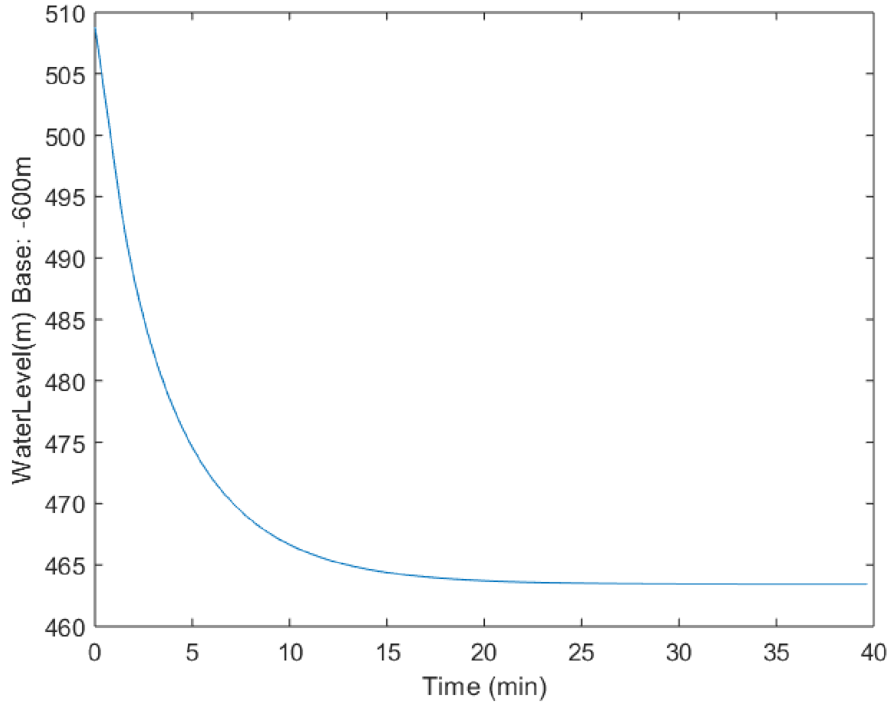
- The model was developed in Honeywell UniSim®, including control of the flow rate by valve throttling and estimation of the water level.
- Two approaches are considered for the simulation of the drain injection process.
- In the first design (**Tank-Tank: TT**), the well is simplified with two cascade tanks and a valve.
- In the second design a preliminary cylindrical tank and a pipe segment are utilized (**Tank-Pipe: TP**).

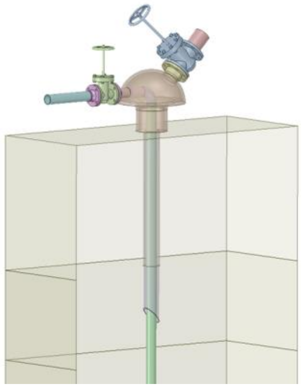




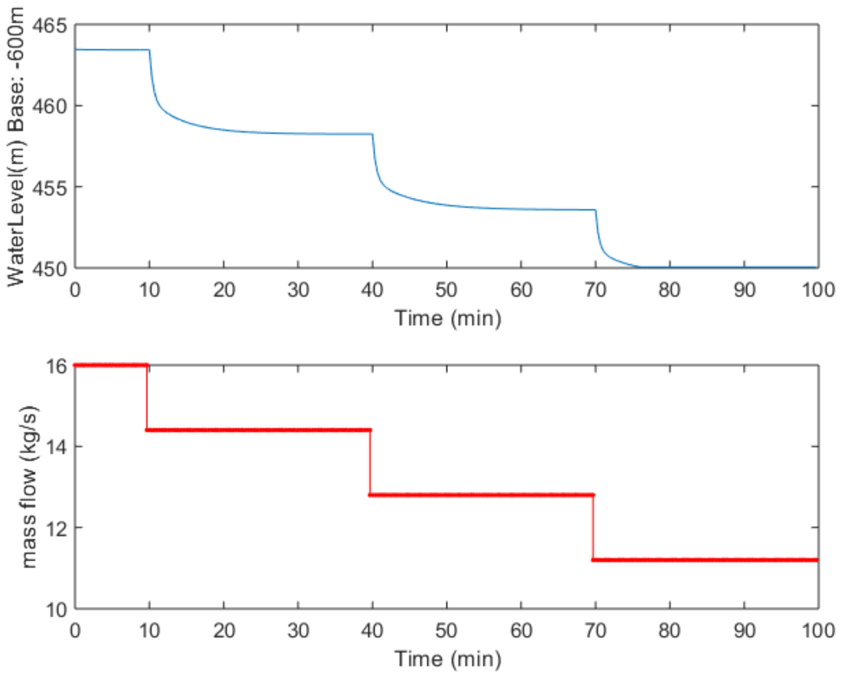
Response time of the reinjection well

- Stabilization time of water level in the start-up phase.



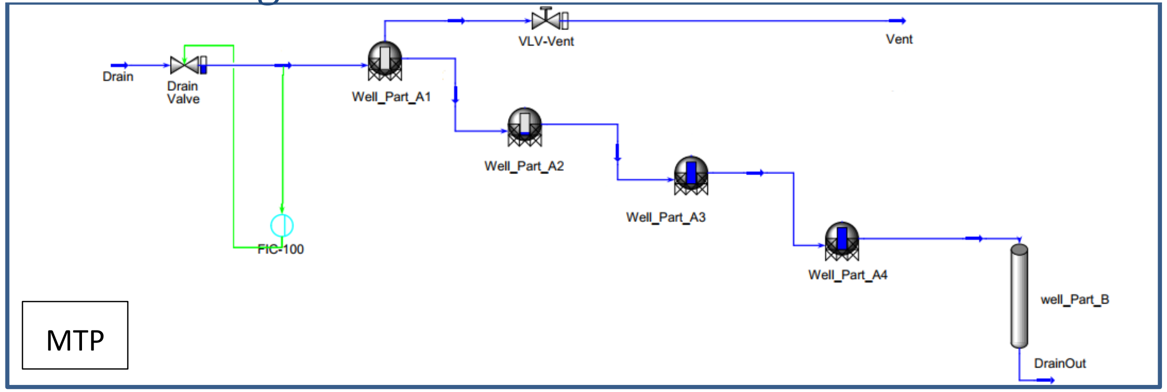


- Water level change as the result of reducing valve opening in three steps 10% each.



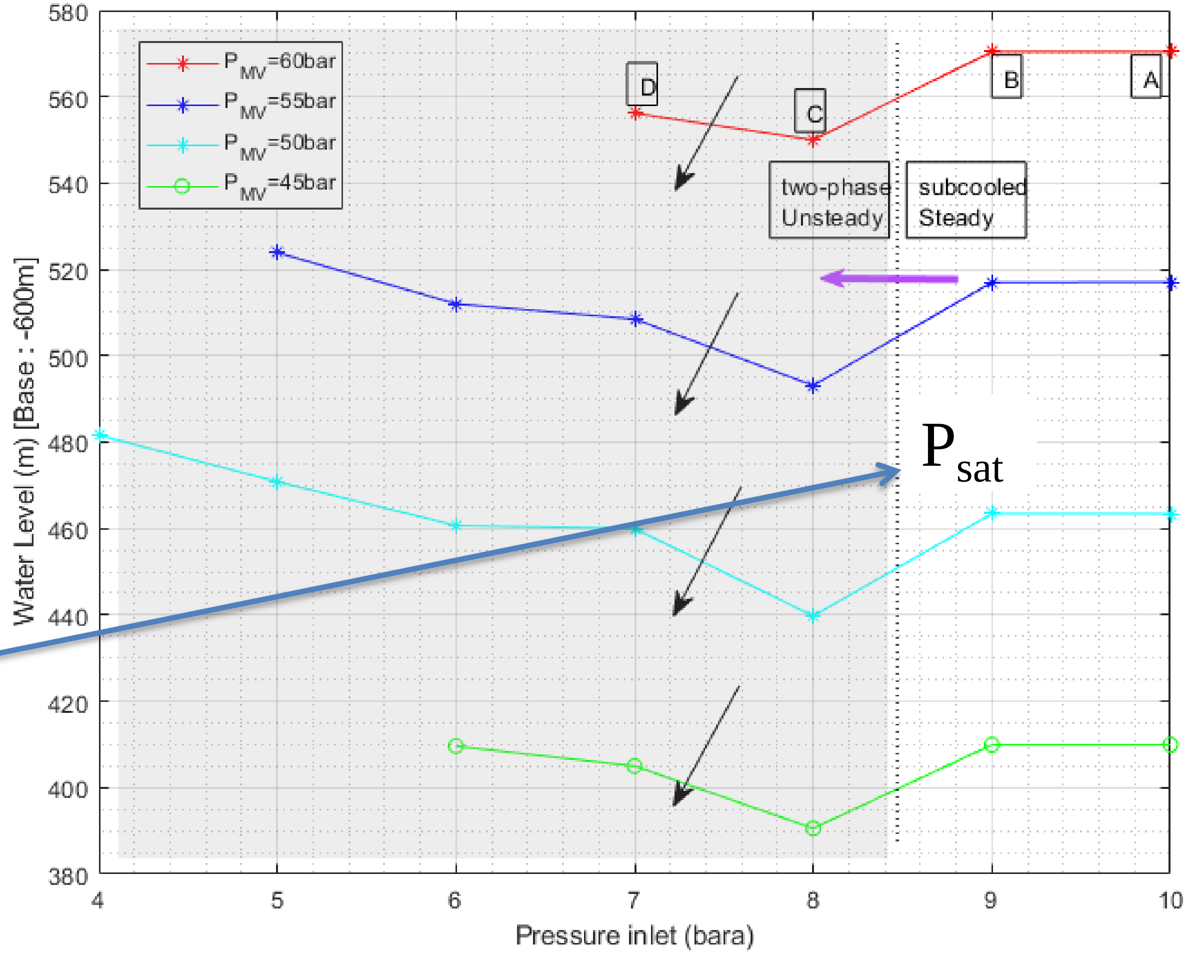
Flow-pressure variations in the reinjection well

- **Multi-stage array of tanks (MTP)** for the preliminary section => water level analysed over a wide range



- The safe lower pressure limit for re-injection is determined by **saturation conditions.**

- It is possible to guarantee adequate pressure at wellhead either by hydrostatic head or using a circulation pump on the condensate line.



Conclusions

- A model of the Castelnuovo power plant was presented with a focus on power generation performance (design) and on the reinjection process (including transients/dynamic simulation).

- Sensitivity analyses were performed: the performance of the system for the power generation (CO_2 content) and the compression train (delivery pressure and 2-phase reinjection depth) were assessed over a wide operating range.

- The dynamic simulation model provided information on the unsteady behaviour of the process with relevant info on how to manage two-phase flow conditions at the reinjection well head.

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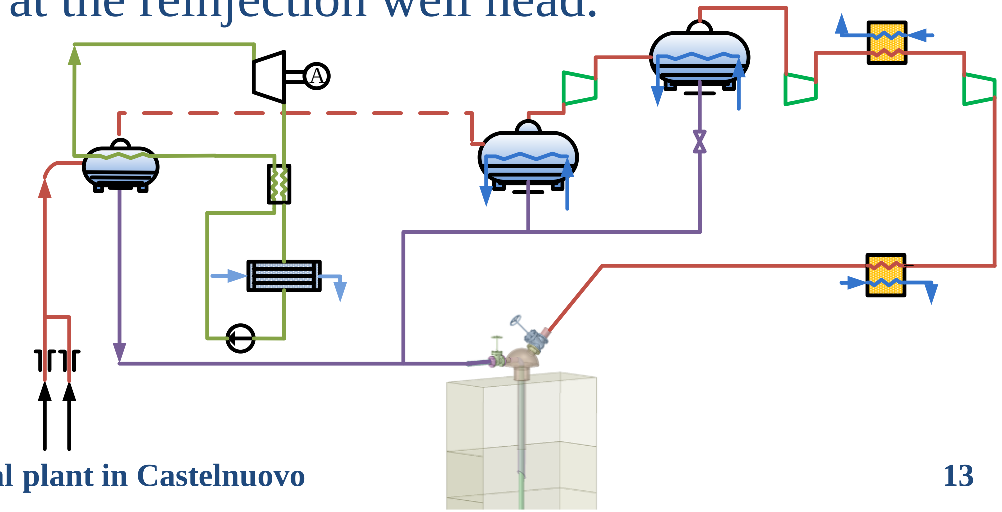

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