Geothermal Electric Power Plants

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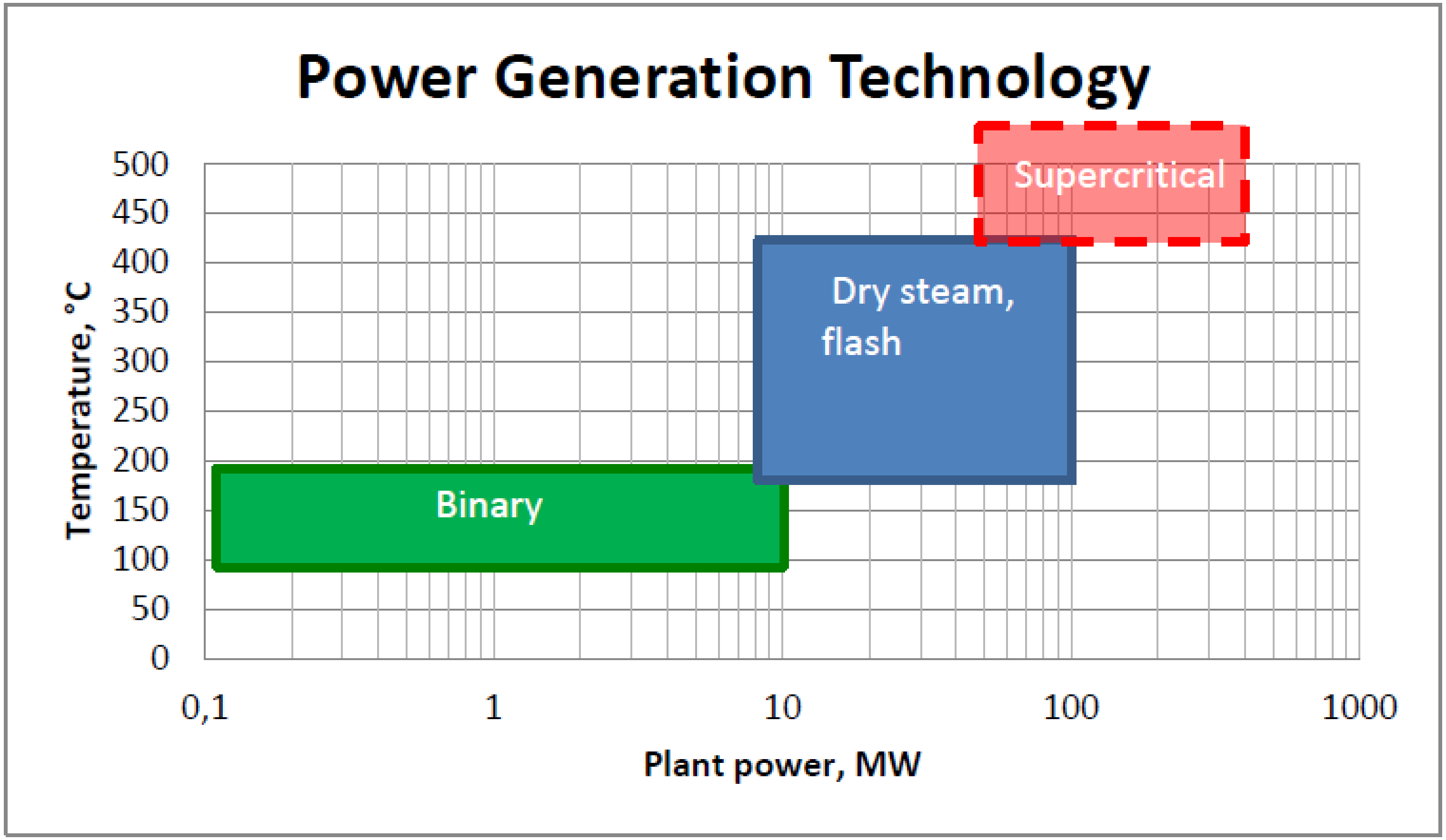
Presentation overview

Presentations outlining basic aspects of geothermal power generation, sketching similarities and differences with conventional power generation technology

Outline:

- plant schemes
- main design aspects
- main operating parameters

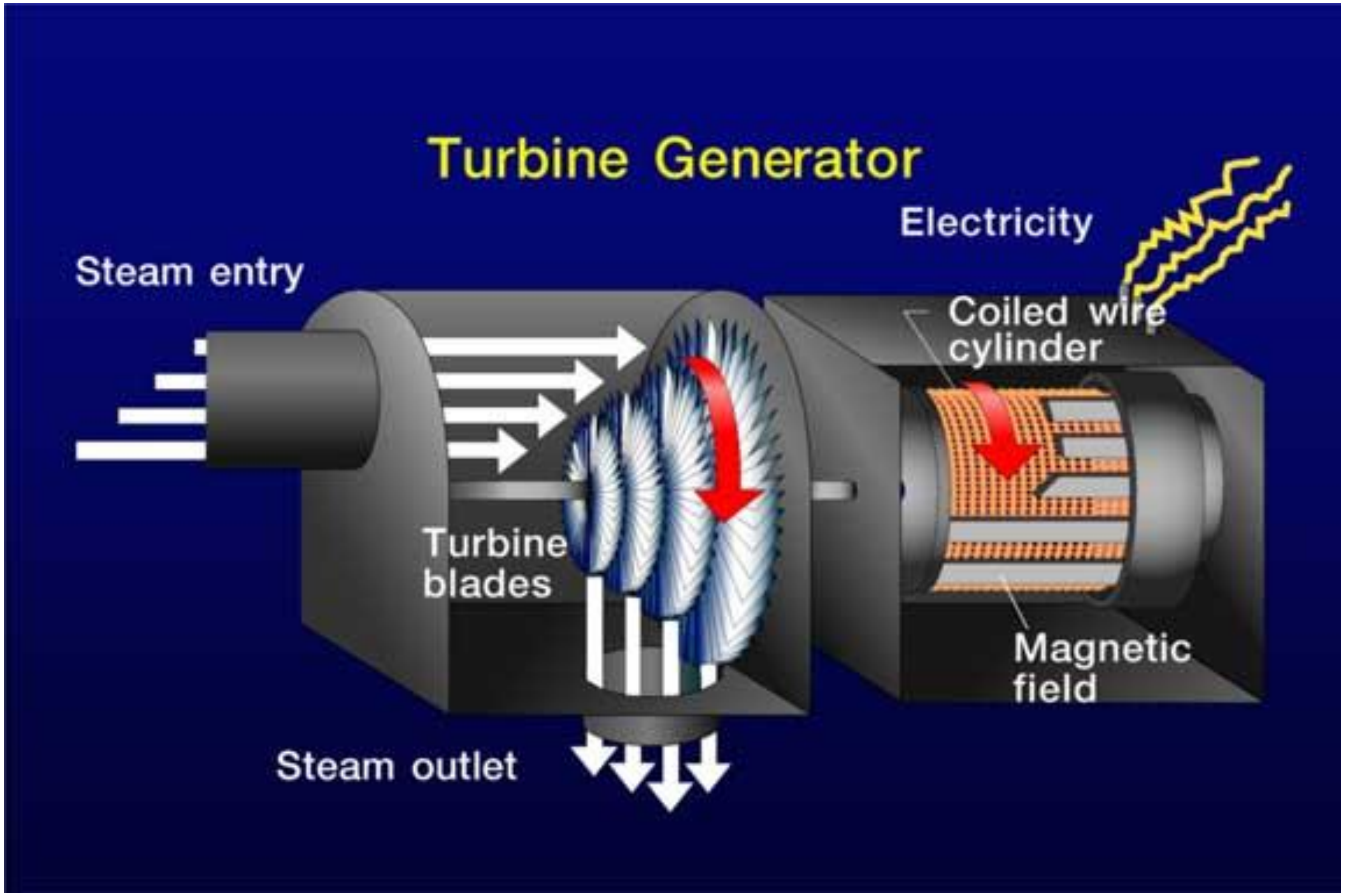
Choice of the power generation technology



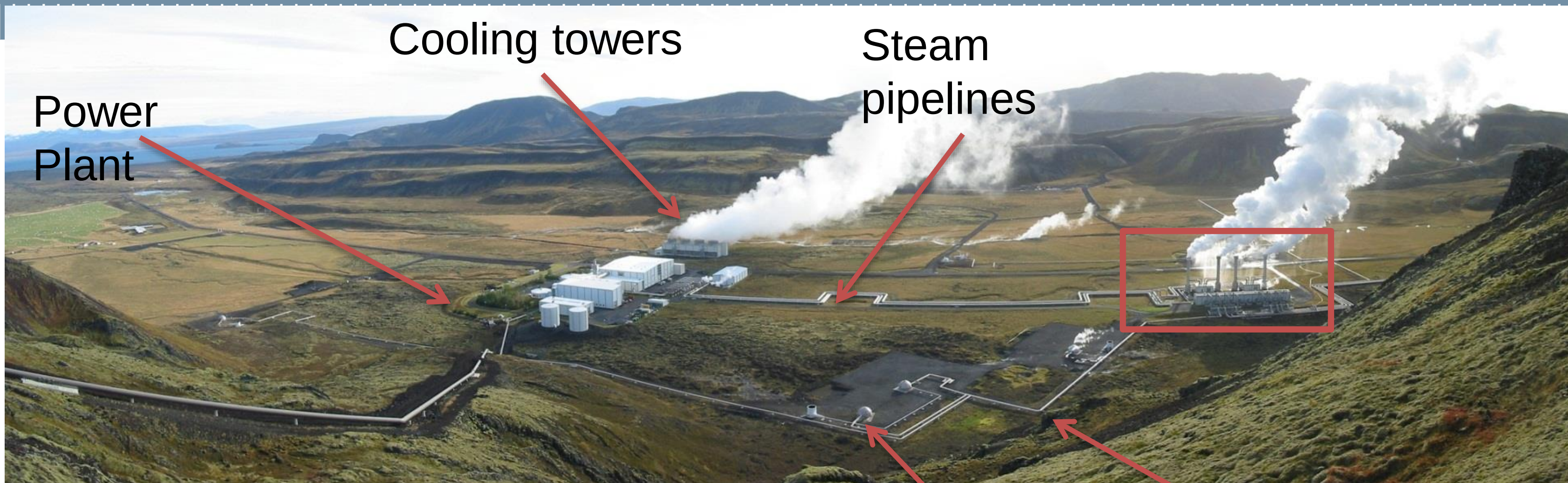
Geothermal power plants

- Wellhead installations and gathering system
- Geothermal fluid treatment
- Power station (and emissions treatment)
- Heat rejection system

Geothermal steam power plants:
the turbogenerator



Nesjavellir Power Plant



Well

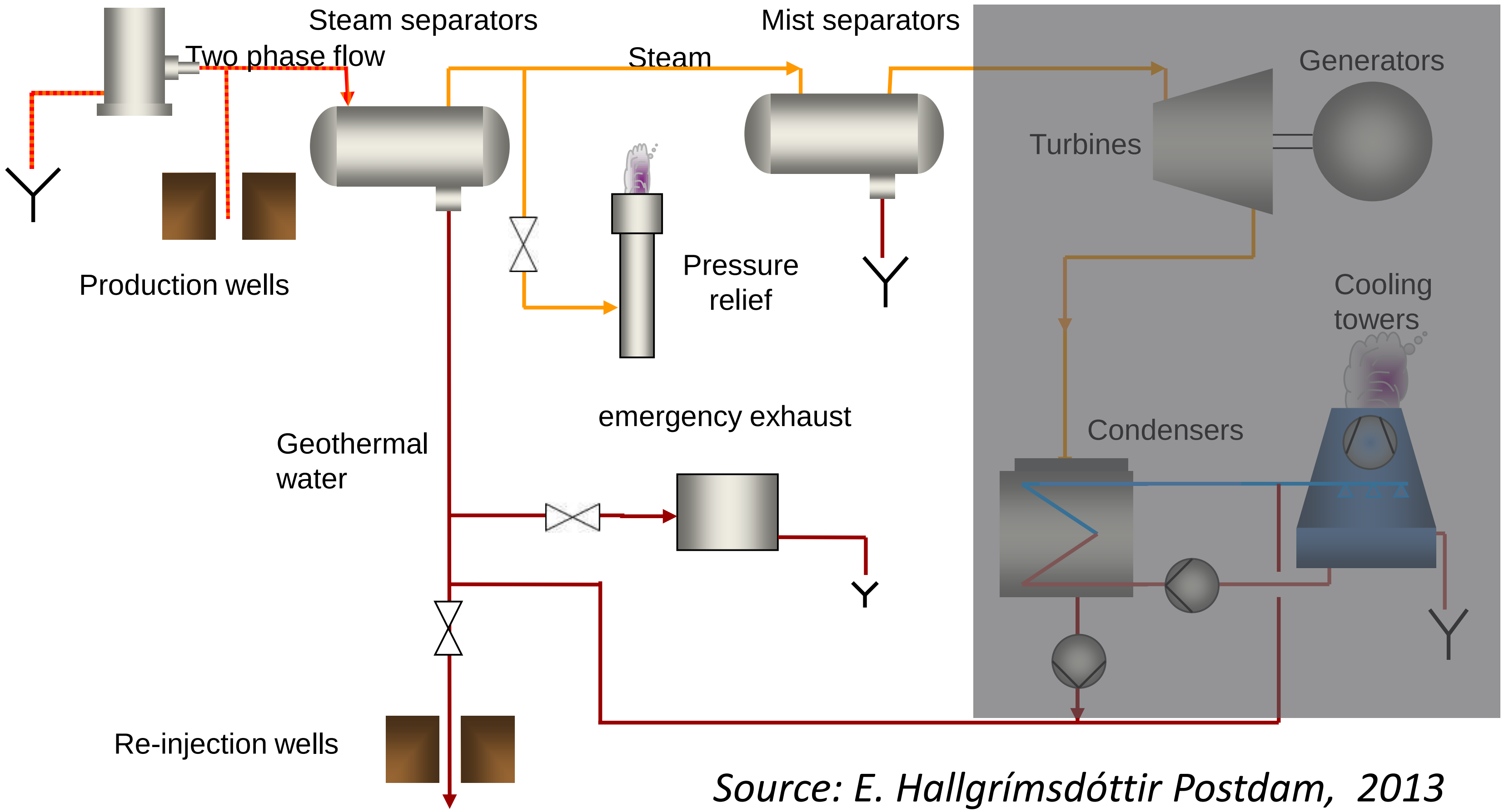
Two phase flow

Steam vent station

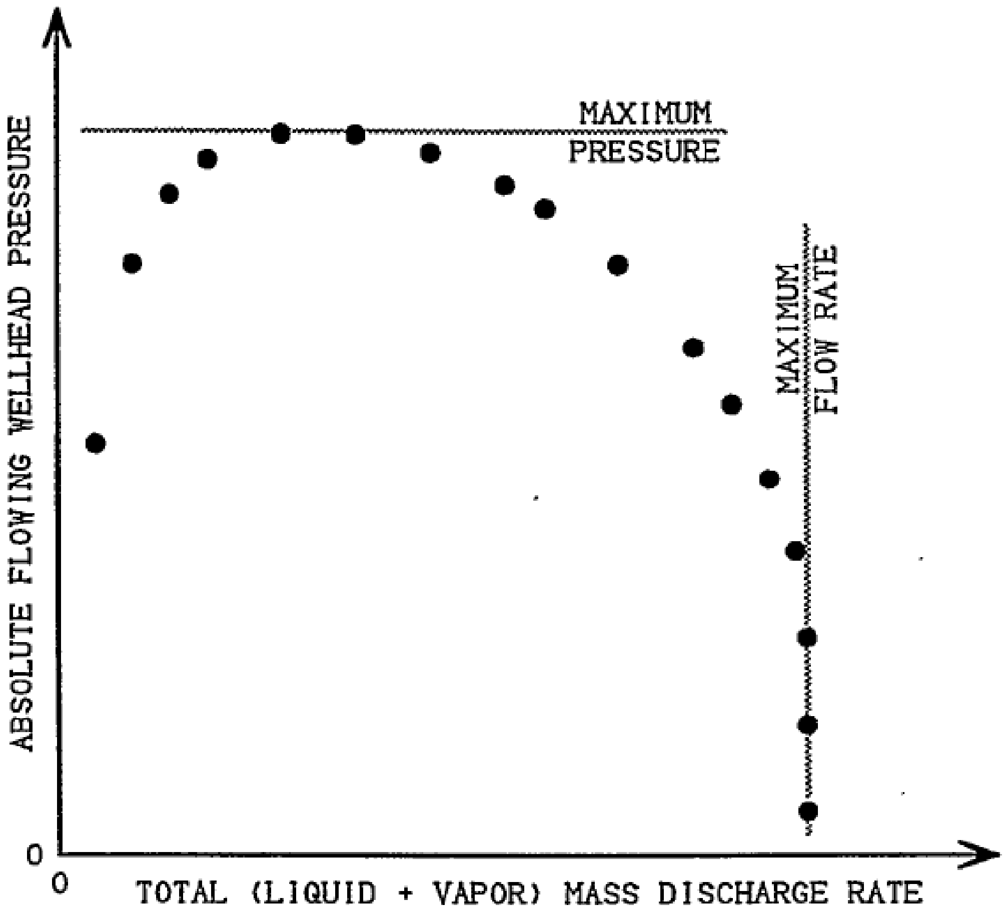
Separation station

Source: E. Hallgrímsdóttir Postdam, 2013
GEOELEC Training Course on Geothermal Elec

Steam Supply - Preliminary P&ID



Source: E. Hallgrímsdóttir Postdam, 2013
GEOELEC Training Course on Geothermal Electricity



Source:
Sinistra:Pritchett , electrical generating capacity of geothermal slim holes, DOE/ID/13455
Destra: GEOELEC course, Mechanical equipment and operation and maintenance, session VI, Potsdam, 2013

Geothermal fluid

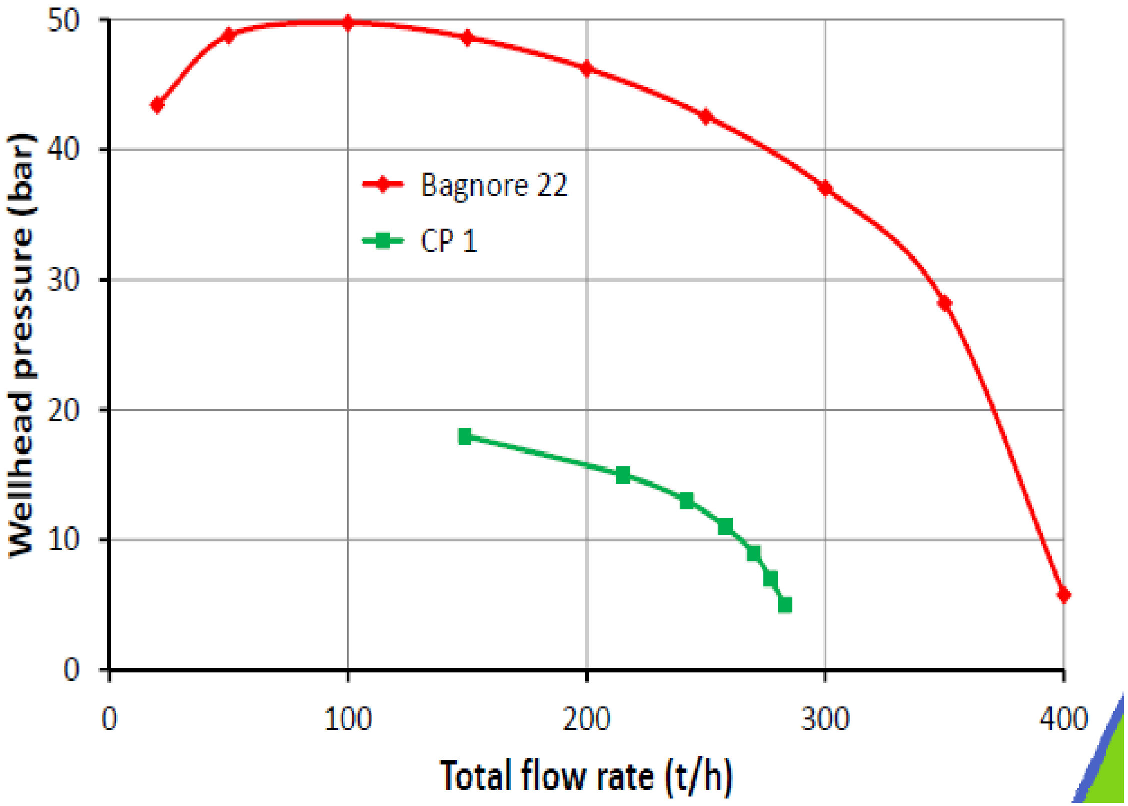
Geofluid contains dissolved salts and gases

Chemical composition is site dependent

LIQUID phase		GASEOUS phase
H_2O		H_2O
Na^+, Ca^{++}, Cl^-,	HCO_3^-, SO_4^{--}	CO_2
Fe, Mn, Pb, Zn,	Hg, Cu, A s	H_2S
SiO_2,		CH_4, N_2, HN_3, He, H_2
Others		Others

=> Geothermal fluid: usually chemically aggressive and corrosive

Typical productivity curves



Total mass flow=
Liquid + steam flow

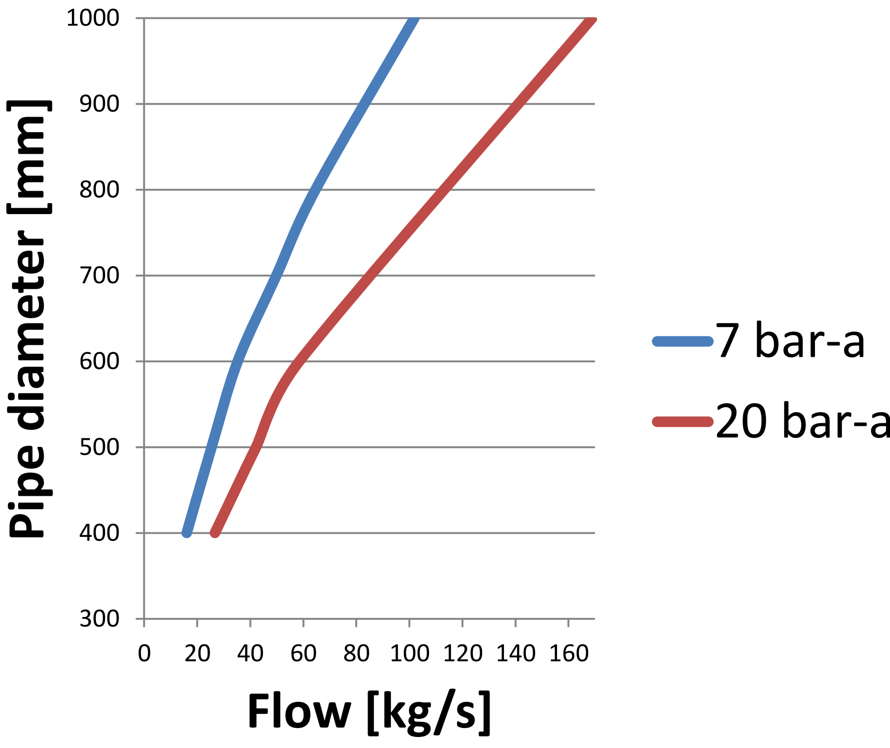
Source: F. Sabatelli, Pisa, 2013
GEOELEC Training Course on Geothermal Electricity

Pipeline design

Constant load
- Weight
- Pressure

Variable load (depending on location)
- Wind
- Snow
- Earthquake
- Ash

Other loads
- Thermal expansion
- Dynamic loads (esp.two-phase flow)
- Friction on supports



Pipeline design

Pipeline optimization

- CapEx increases with diameter (approx. linear) and thermal insulation thickness
- Thermal loss increases with external diameter and decreases with insulation thickness
- Pressure drop (power loss) decreases with diameter (5th power: $\Delta p = 4fL\rho u2/d$)
- Optimum at the lowest total lifecycle cost (strongly dependent on electricity FIT)

Steam Supply - Layout

- Central separation station
- Satellite separation stations
- Individual separators

Separation at wellhead

– Separate steam and (saturated) water flows

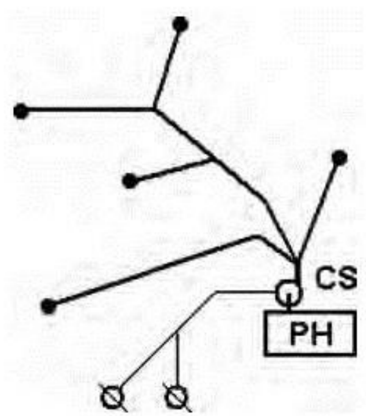
- Separation at satellite stations

– Two-phase flow + separate flows

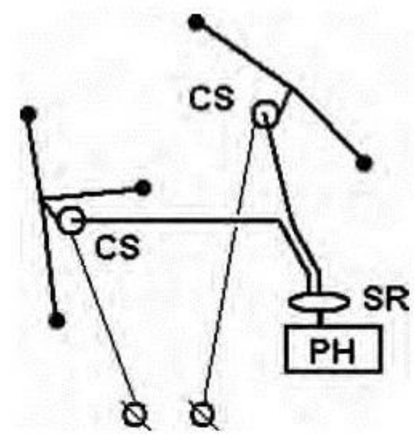
- Separation at the power plant

– Two-phase flow

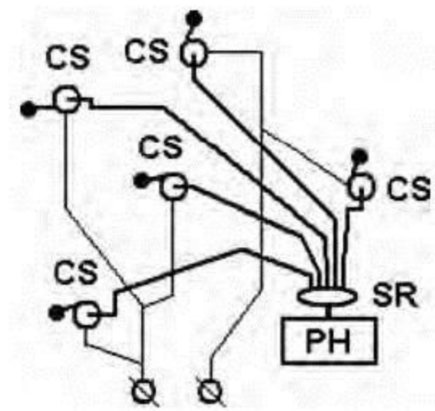
Central



Satellite



Individual



Source: Di Pippo

Steam gathering system – route selection

- Public safety
- Environmental impact
- Restriction on land
- Cost efficiency

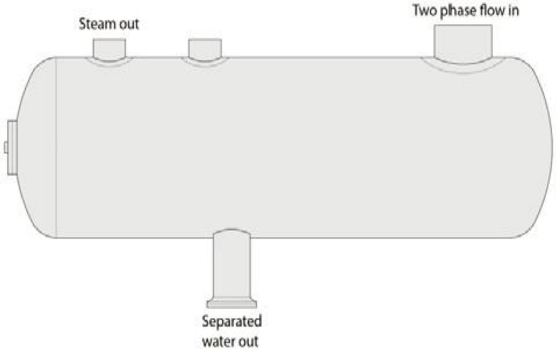
The Hellisheiði Power Plant

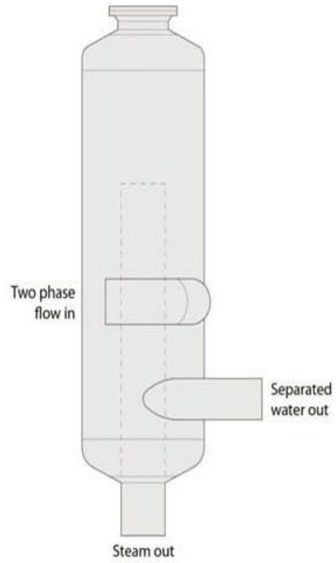
Adapted from : E. Hallgrímsdóttir Postdam, 2013
GEOELEC Training Course on Geothermal Electricity

Steam pipelines

Steam Supply - Separators

- Cyclone separators
- Gravity separators

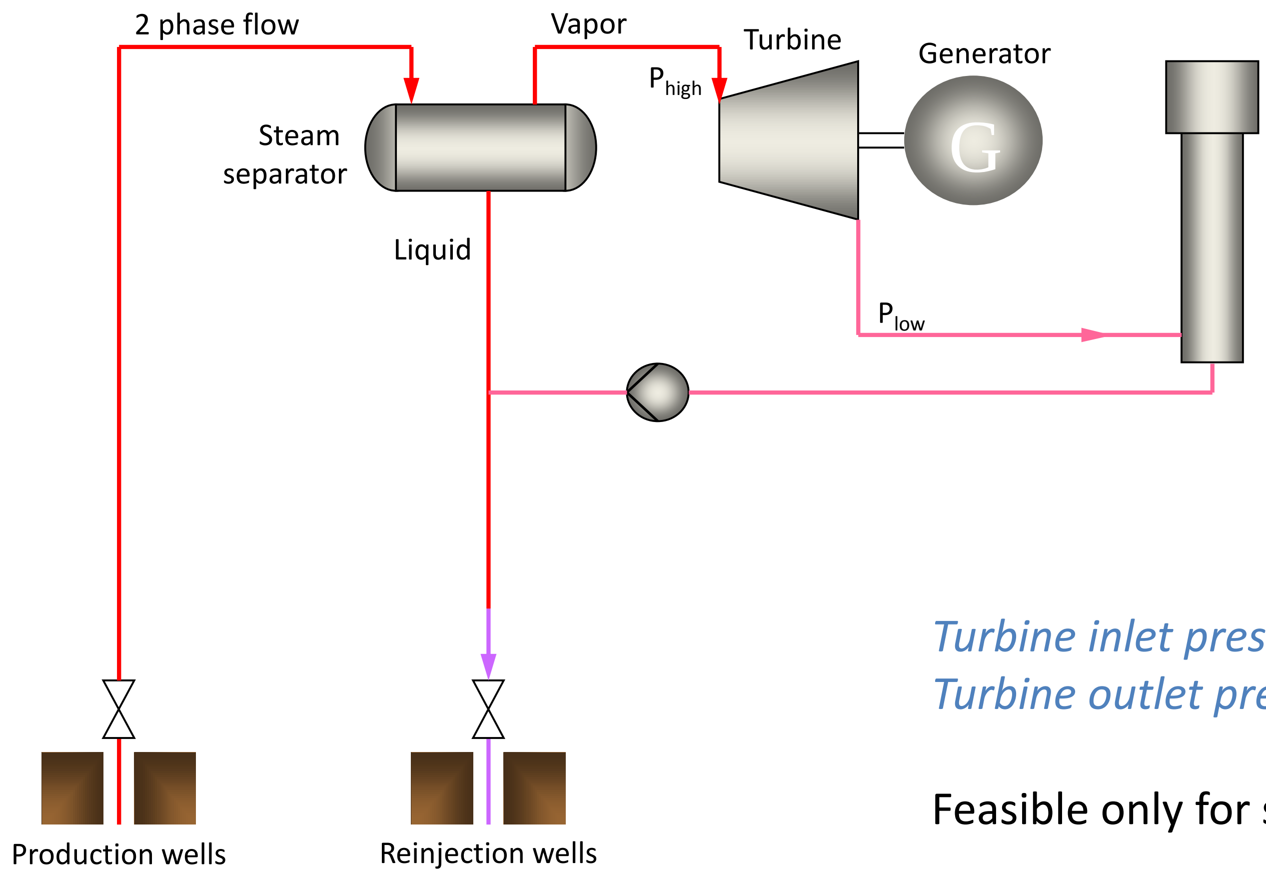




- Efficiency
  - Steam separator and moisture separator should together achieve 99,99 % bw. liquid removal or better

Separation station

Atmospheric discharge steam power Plant



Turbine inlet pressure=separator pressure
Turbine outlet pressure=atmospheric pressure

Feasible only for special applications

Condensing dry steam power plant (with direct contact condenser)

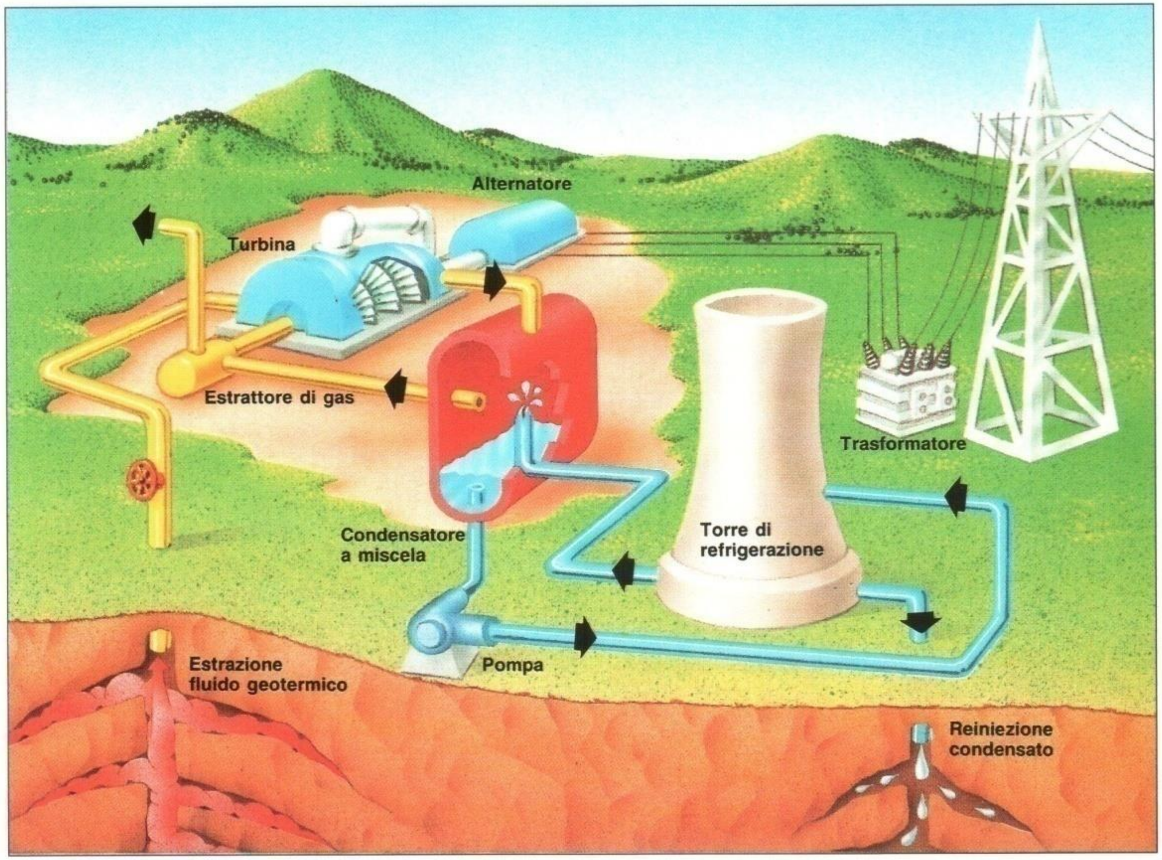


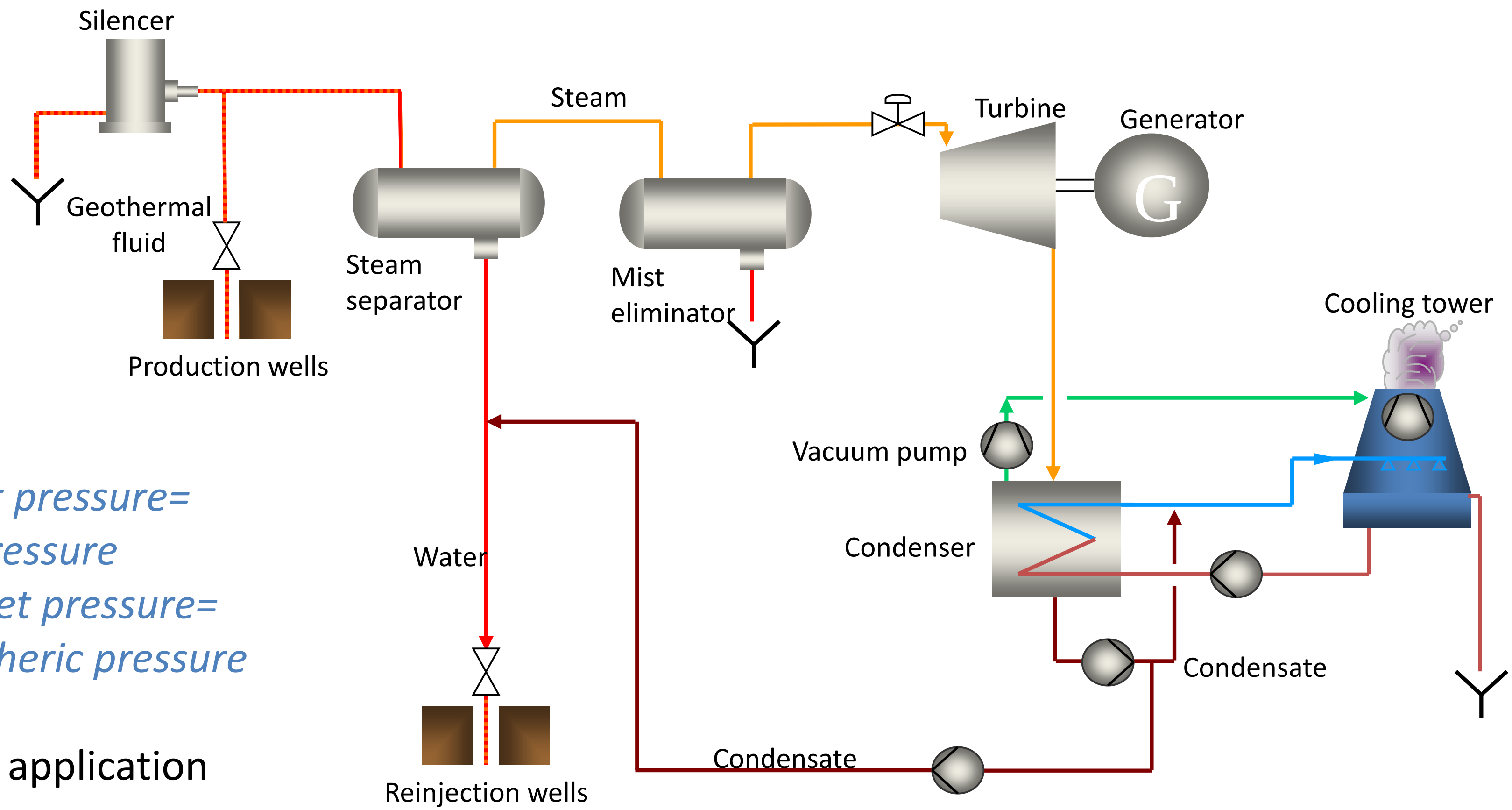
Fig. 30 - Una centrale geotermoelettrica con i suoi principali componenti.
Main components of a geothermal power plant.

Fonte:UGI, La Geotermia ieri, oggi, domani

Turbine inlet pressure=wellhead pressure

Turbine outlet pressure=sub-atmospheric pressure

Steam Power Plant with Condenser (with surface condenser)



Turbine inlet pressure= separator pressure
Turbine outlet pressure= Sub-atmospheric pressure

Widespread application

Condensing steam plants

Advantages

- Higher work extraction
- Power size about 20-120 MW
- Partial or full reinjection feasible, depending on the condensation system

Disadvantages

- Condensing system required
- Noncondensable Gas (NCG) removal system required

Single flash Steam power plants

Hot water “flashes” as a consequence of an imposed pressure drop

- Steam is fed to the turbine from a surface separator
- The power plant scheme is roughly the same

This is by far the most common technology, developed in New Zealand in the 1950s

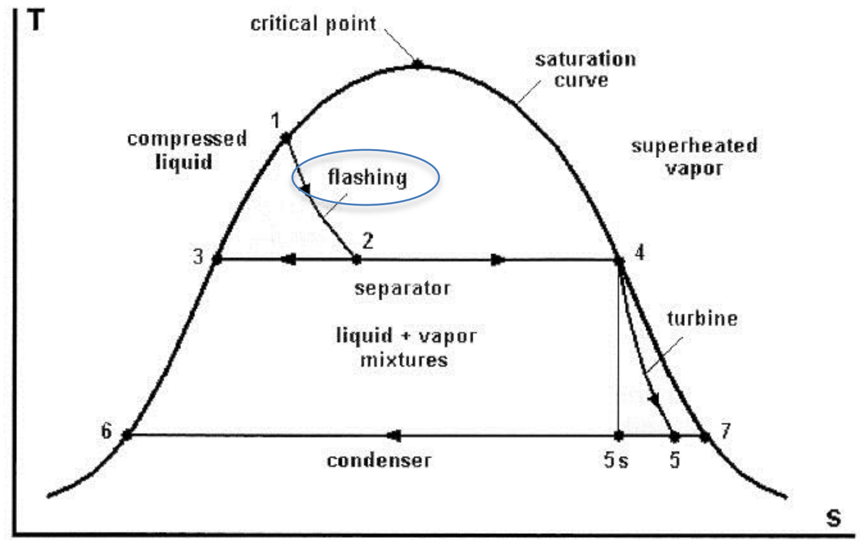
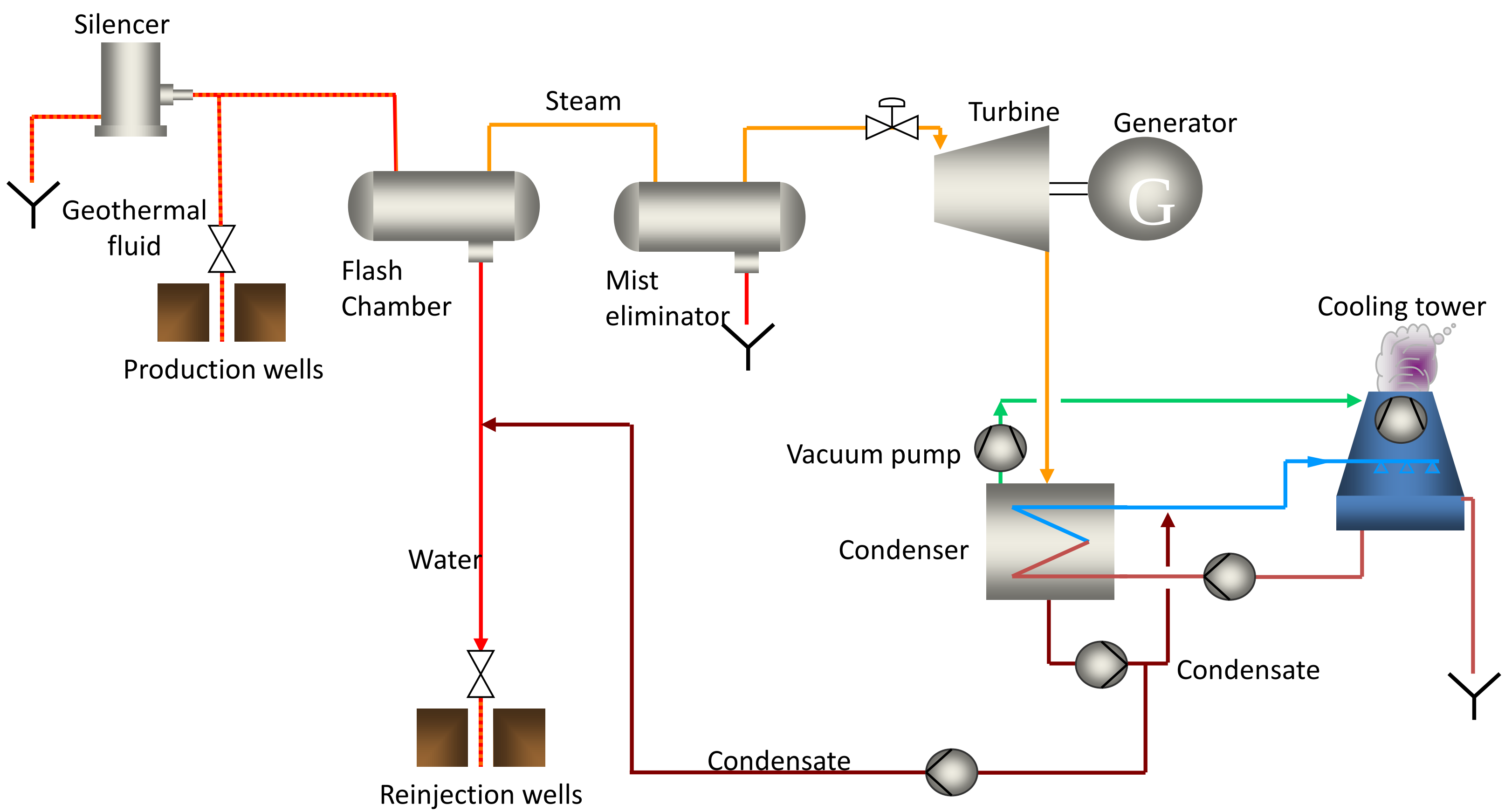


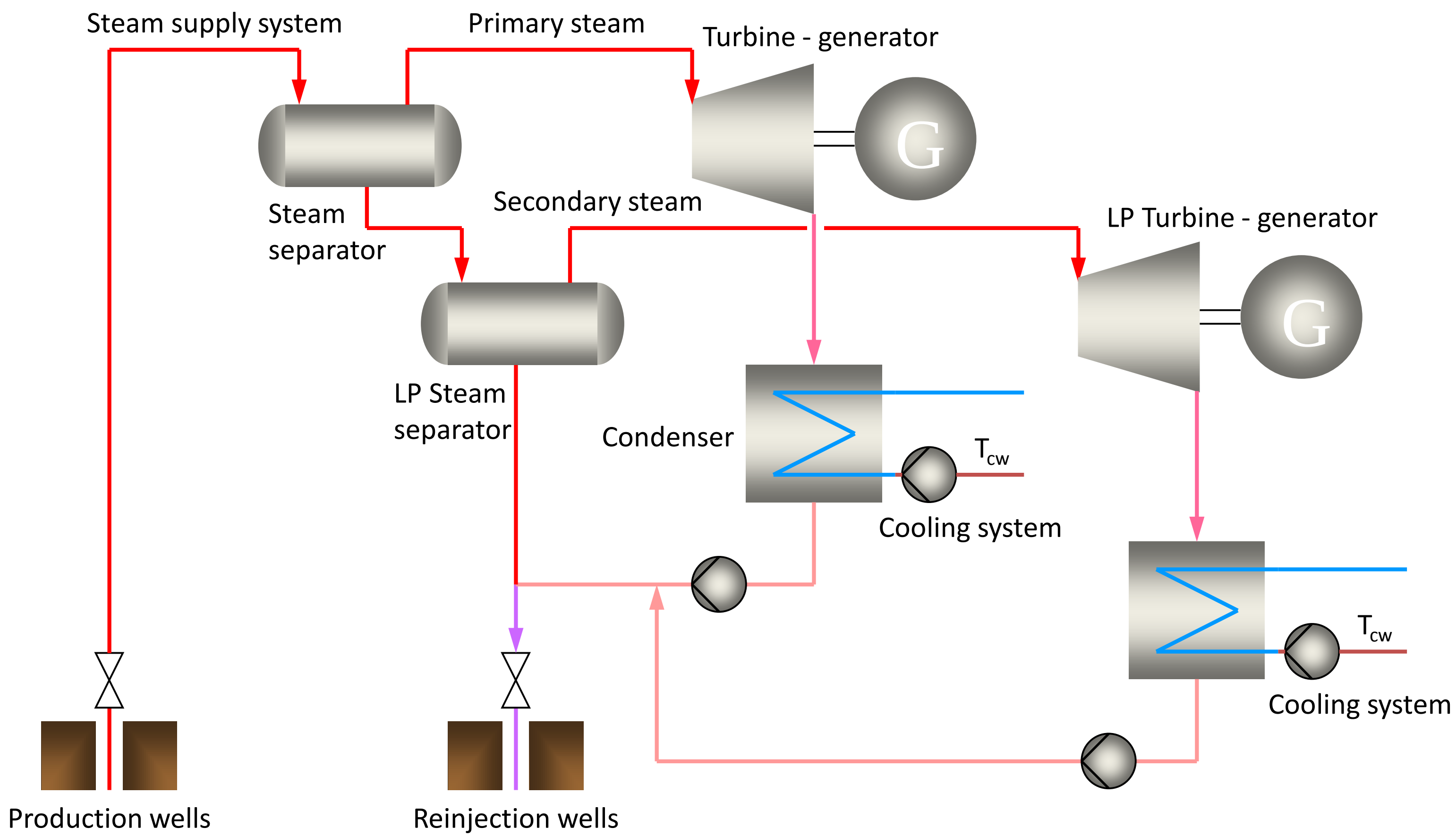
Fig. 5.9 Temperature-entropy state diagram for single-flash plants.

Source: Di Pippo, Geothermal power plants

Single flash Steam power plants



Steam Power Plant – Double Flash



Double flash steam power plants

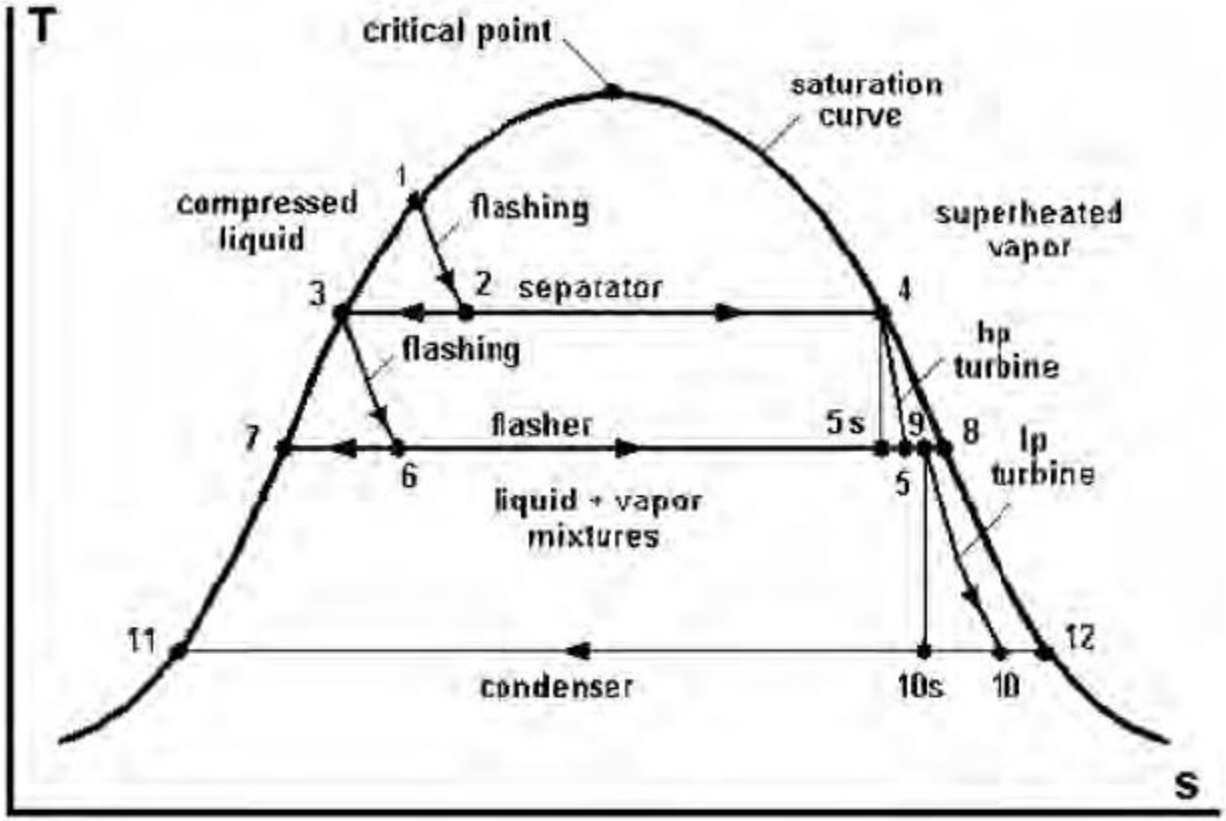


Fig. 6.8 Temperature-entropy process diagram for double-flash plant with a dual admission turbine.

Source: Di Pippo, Geothermal power plants

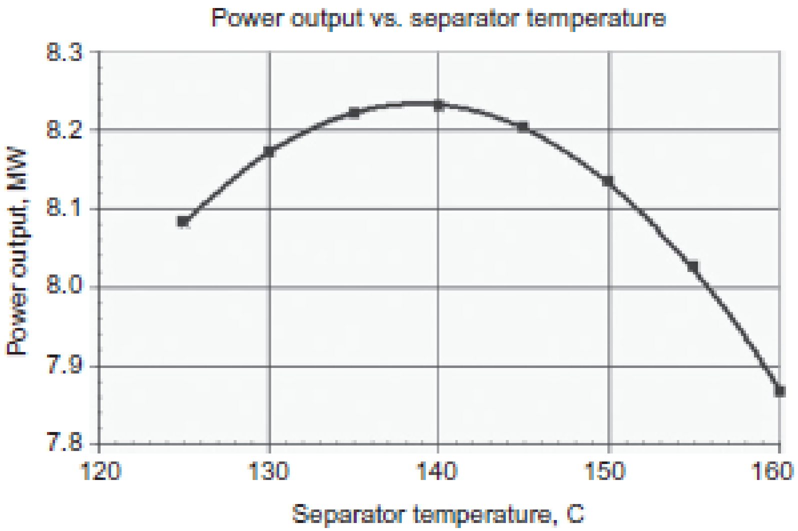
Nga Awa Purua, New Zealand

Location:	Taupo, Auckland, New Zealand
Date Commissioned:	2010
Rated Capacity:	140 MW
Annual Production:	1,100 GWh per year
Capacity Factor:	89.7%
Carbon Offset:	Unknown
Owner:	Mighty River Power + Tauhara North No.2 Trust joint venture. Construction: Sumitomo
Generation Offtaker:	Mighty River Power
Generation Technology:	Triple-flashed steam turbine power plant: (1) 140 MW Fuji Electric Systems triple-flash steam turbine. (6) 8,200 feet wells
Cost:	$303 million

Flash optimization: flash pressure is a key parameter

- Steam mass flow (kg/s) decreases with increasing flash pressure
- Specific work extraction (J/kg), at constant condensing pressure, increases with flash pressure

=> optimum flash pressure maximizes the power produced (W)



Note that T=Tsat(pflash)

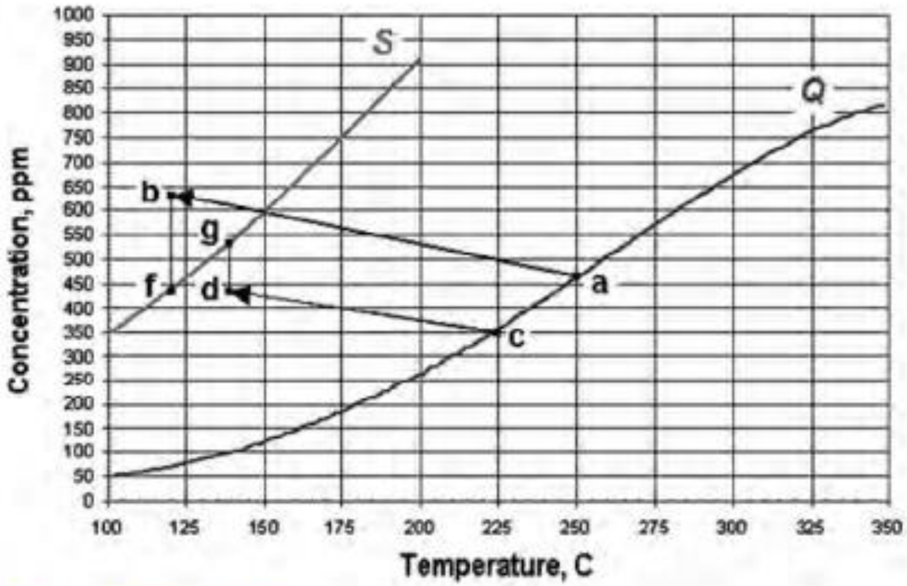
Source: Di Pippo, Geothermal power plants

Flash optimization

- Thermodynamic calculations
- Rule of thumb (equal temperature split)
  - $T_{flash\ opt} = (T_{res} - T_{cond})/2$ (single flash)
  - $T_{flash\ 1\ opt} = T_{res} - (T_{res} - T_{cond})/3$
  - $T_{flash\ 2\ opt} = T_{res} - 2(T_{res} - T_{cond})/3$ (double flash)
- Bottoming binary cycle using flashed water

Flash optimization constraints

- Technical issues: minimum pressure, silica scaling (for high T_{res})
- CapEx issue (increase at lower pressures)



Source: DiPippo

GEOELEC

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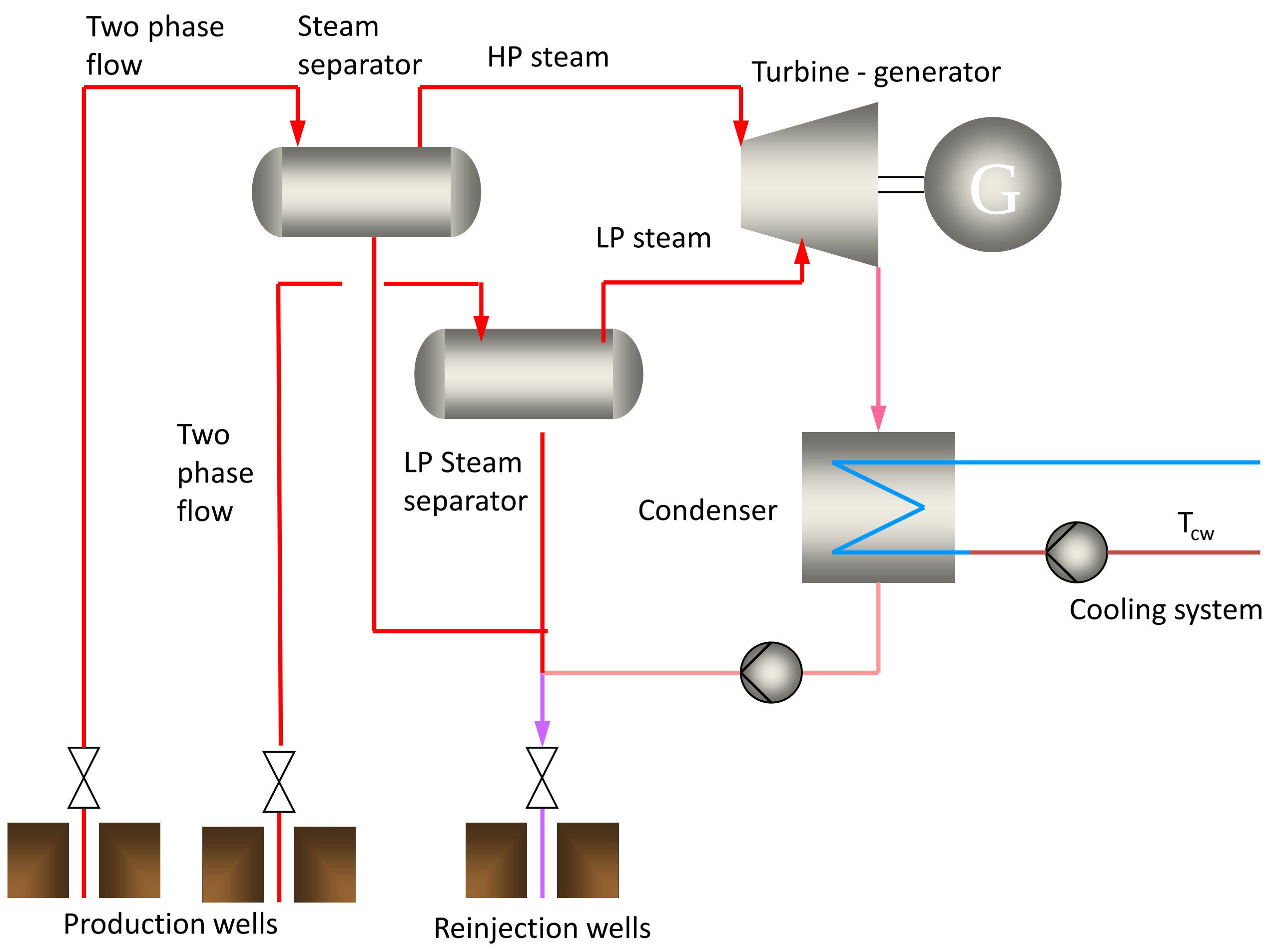
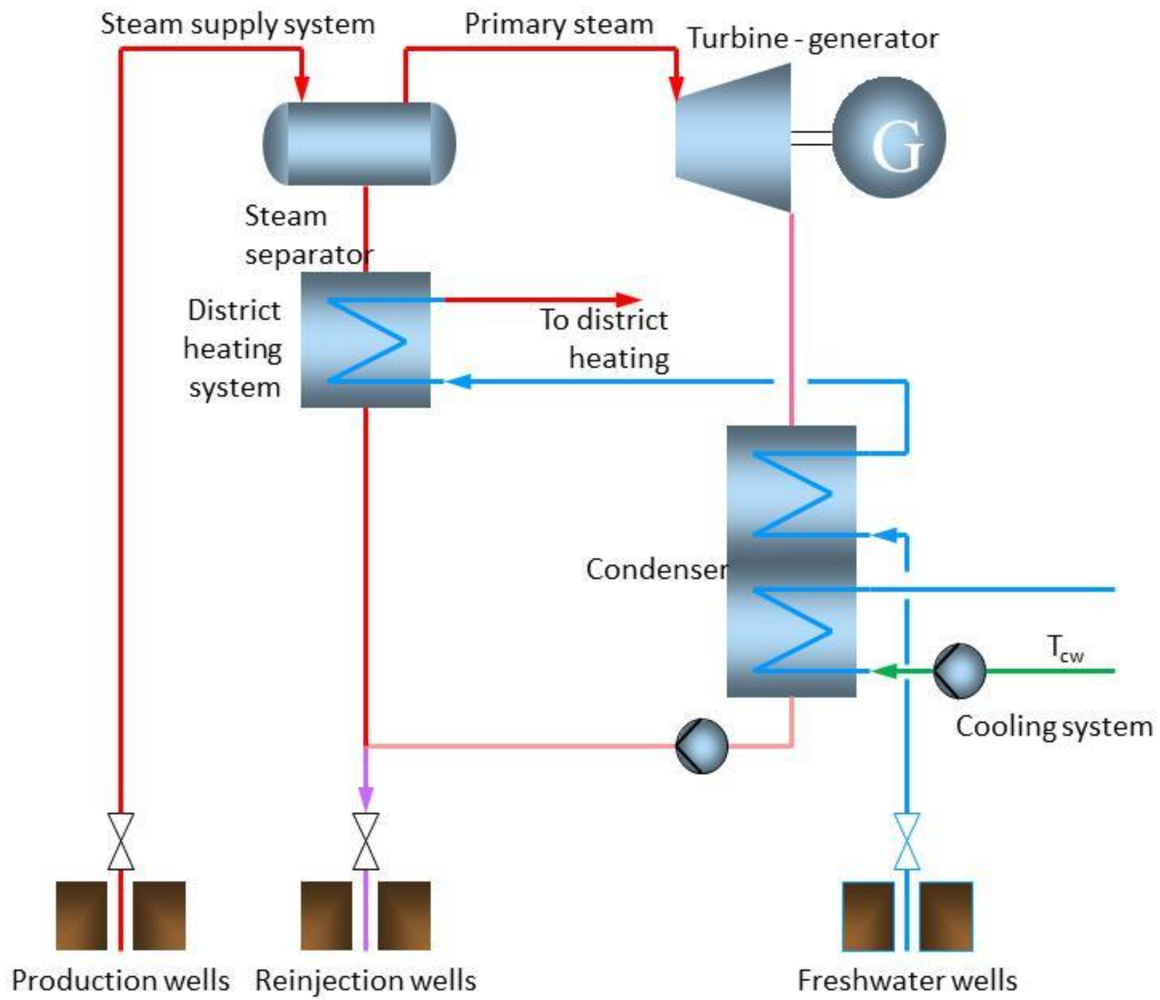
Other plant schemes: tailored on the geothermal source and the application – Double Pressure - Steam Power Plant



Other plant schemes:
tailored on the geothermal source and the application
Steam Power Plant w. District Heating



Main machinery

- Steam turbine
  - Single flow/Double flow
- Generator
- Condenser
  - Direct-contact/Surface
- Hotwell pump
- NCG extraction system
  - Ejectors/LRVP/Compressor
- Cooling tower
  - Wet/Hybrid/Dry

Impianto a vapore

Steam turbine features

- Wet (saturated) steam at turbine inlet

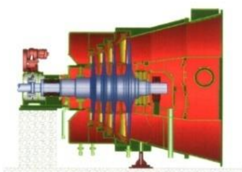
– Vane-type demister to minimize erosion
– Efficient water removal system in the turbine
– Blade coating/protection (erosion)
– Bla\de materials (corrosion)
– Entrained water contains dissolves salts that may precipitate after expansion (first stage nozzles, HP shaft labyrinth seals)
– Double steam inlet (inlet valve testing)
– Low p & T (no creep, low efficiency)

Standard Turbine Module

- High efficiency impulse technology
- Unit size ranging from 20MW to 200MW with various turbine types of single flow, double flow, triple flow or four flow
- Applicable to wide range of resource conditions, i.e., steam pressure from 2bar to 30bar and for various types of systems, such as;
  - Dry steam plants
  - Single, double and triple flash systems
  - Hot Dry Rock/Enhanced Geothermal Systems
- Axial or top exhaust arrangement for low profile, in addition to conventional down exhaust arrangement

Output Range | **Basic Configuration** | **Application**

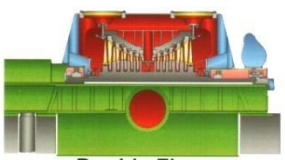
20-70MW



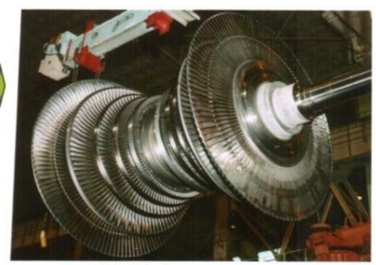
Single Flow

33.6MW Hellisheidi, Iceland

40-140MW

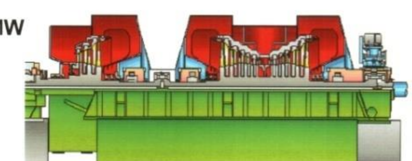


Double Flow



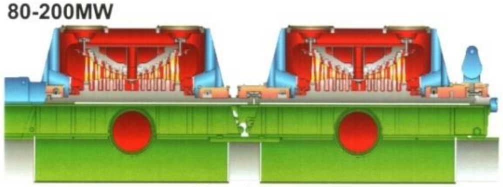
39MW Geysers, USA

75-160MW



Triple Flow

80-200MW

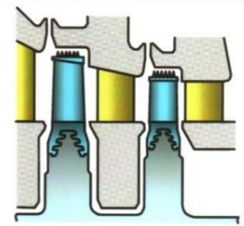
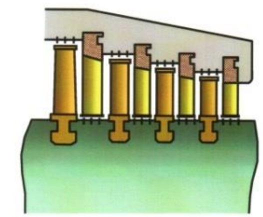
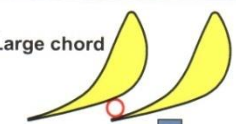
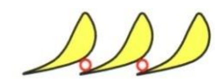
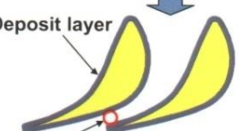


Four Flow

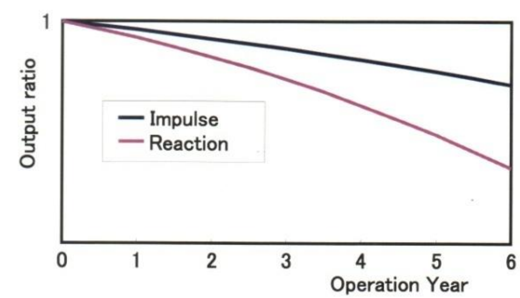
110MW Cerro Prieto, Mexico

Impulse Technology

- Smaller number of stages
  - Robust wide chord nozzles and blades
  - Moisture extracting traps equipped in the steam-path
  - Easy maintenance
- Widely spaced large chord nozzles and blades
  - Highly resistant to fouling from deposits --- Sustained performance
  - Superior protection against solid particle attack entering the steam-path
  - Longer overhaul interval
- Coated rotor and nozzles to protect against erosion/corrosion attack
- Low thrust force
  - Large single flow (20-70MW) skid-mounted turbine available

	Impulse Turbine	Reaction Turbine
Turbine Stages		
Brand New Nozzle	Large chord 	 Small chord
Deposited Nozzle	Deposit layer  Wide open throat even at accumulation of deposits	Deposit layer  Almost clogged up throat Reduced nozzle area causes output decrease

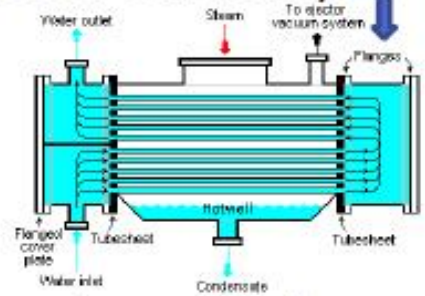
Turbine output degradation due to impurity deposit
- Impulse vs. Reaction -



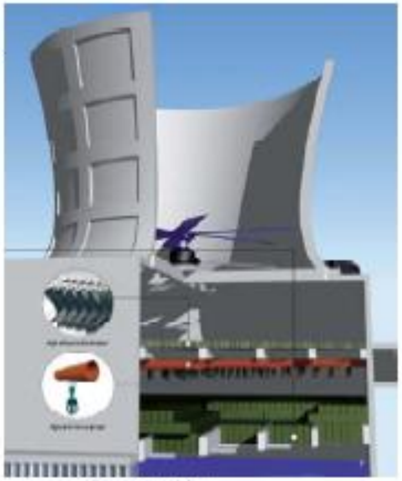
Source Toshiba website

Power plant features

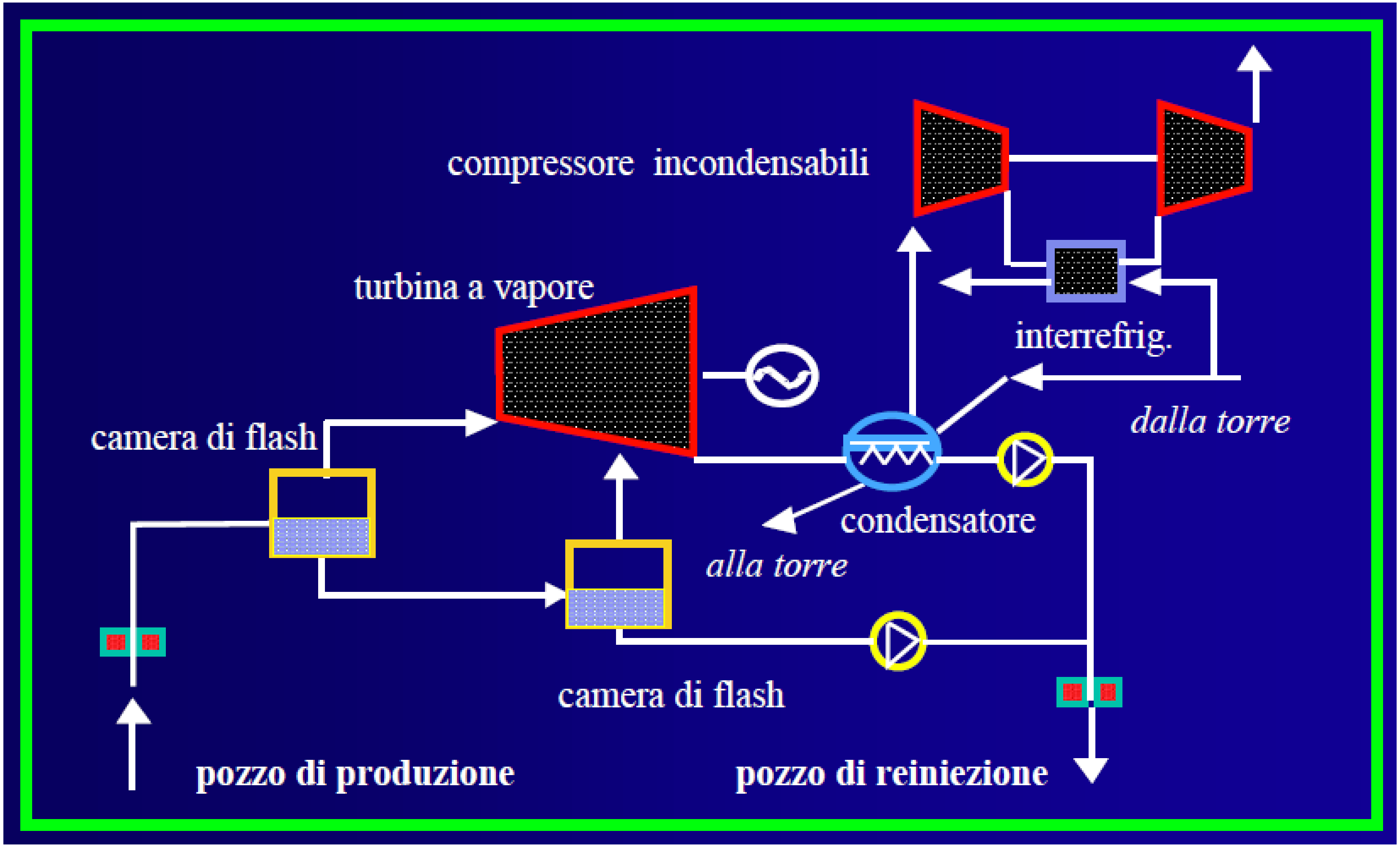
- NCG in steam
  - Condenser selection (direct-contact or surface)
  - Gas cooling section in condenser
  - NCG extraction system



- Heat rejection
  - Wet cooling towers (steam condensate as make-up water)
    - counter-flow
    - cross-flow
  - Hybrid cooling towers
  - Dry cooling towers
  - Air cooled condenser

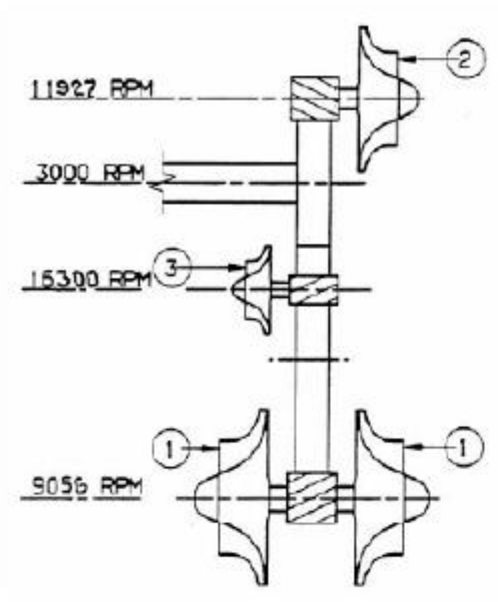


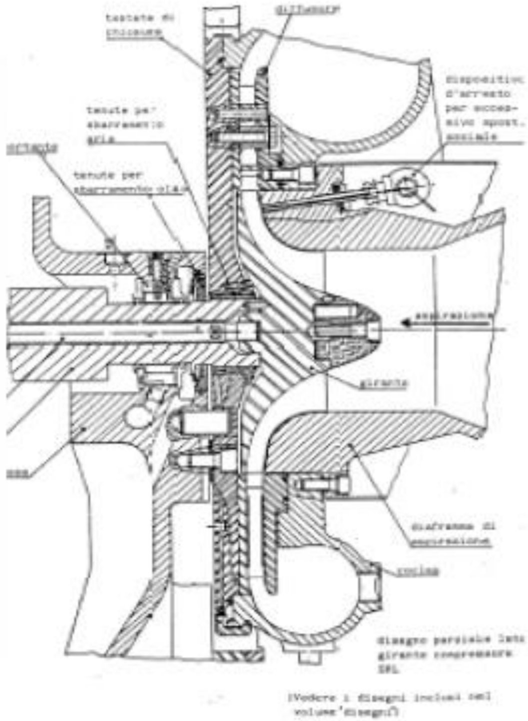
Double flash steam power plant with NCG extraction system



NCG extraction from condenser

- Centrifugal compressor





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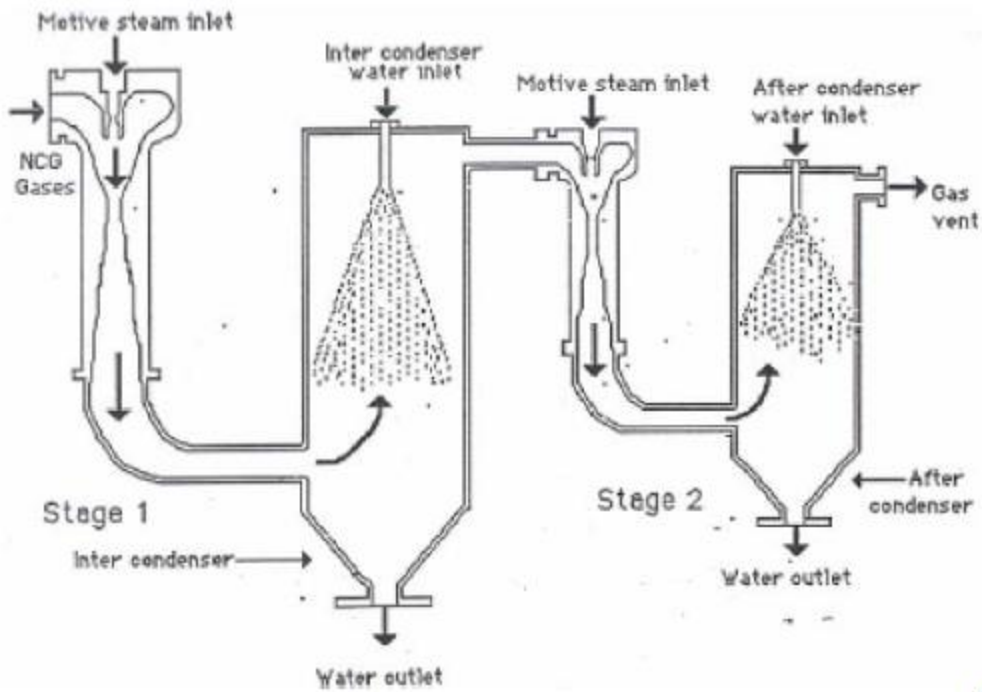
NCG extraction from condenser

- Steam ejectors (2 or 3 stages)



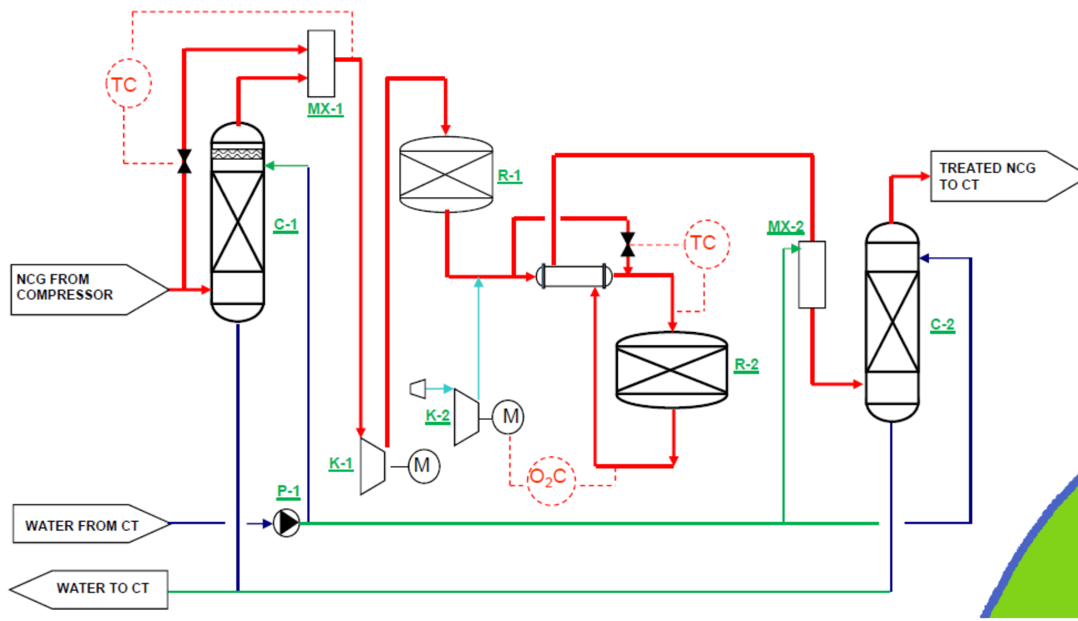
AMIS plants

AMIS abatment system: abatement of H2S and Hg

AMIS process, developed by Enel, is suitable for:

- Direct-contact condensers
- NCG with low calorific value (over 95% w. CO2)
- Unattended operation (sulfur sludge filtration, chemistry control)
- Small size units: low O&M requirements, reliable operation

AMIS simplified scheme



Binary technology

Main features:

Power generation by means of closed thermodynamic cycle (binary cycle)

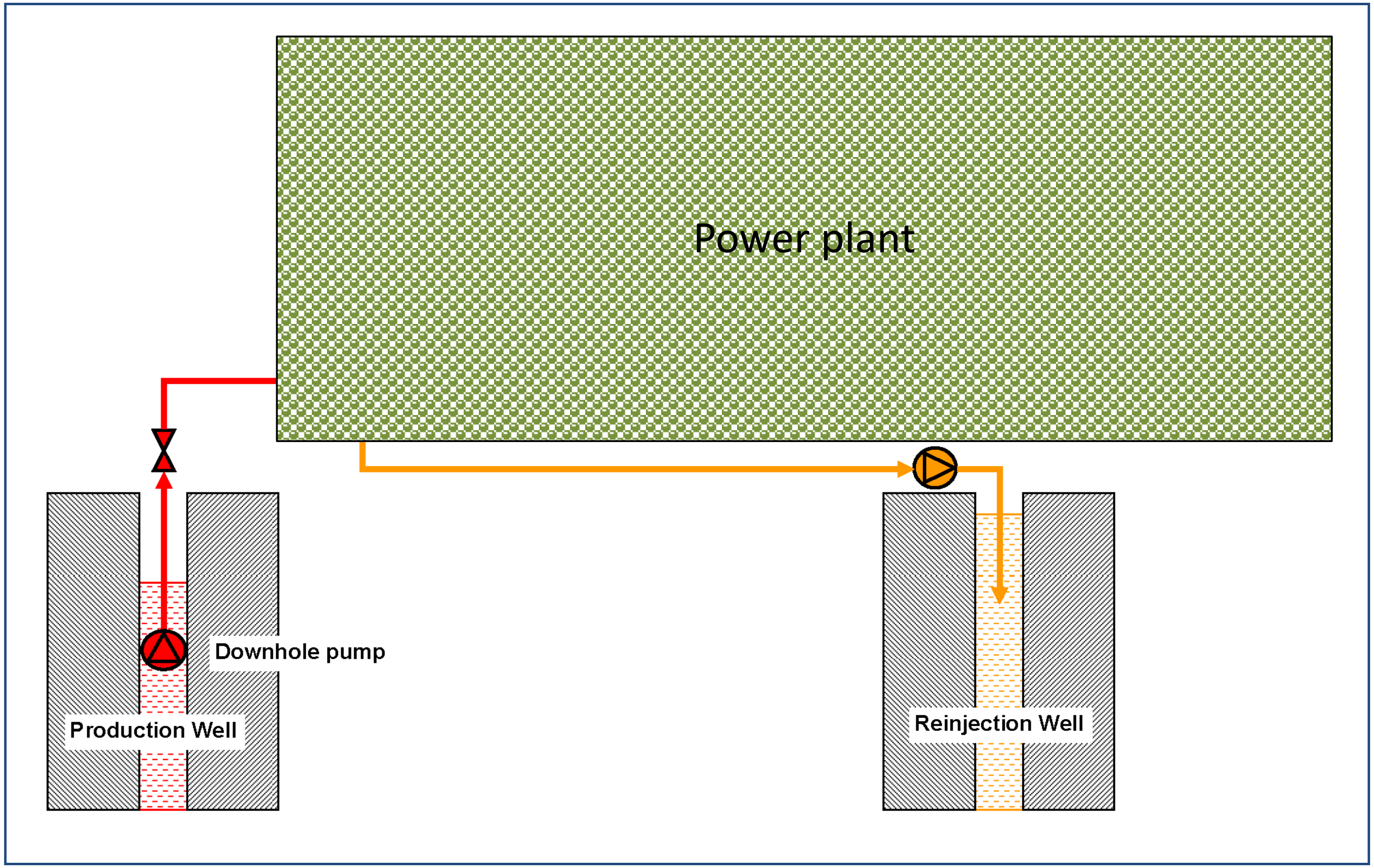
Geotherml fluid loop and power cycle are completely separated

Nearly zero emission plant (for all-liquid geofluid)

Suitable for integration with other energy sources

(solar, biomass, waste....)

The geothermal fluid loop



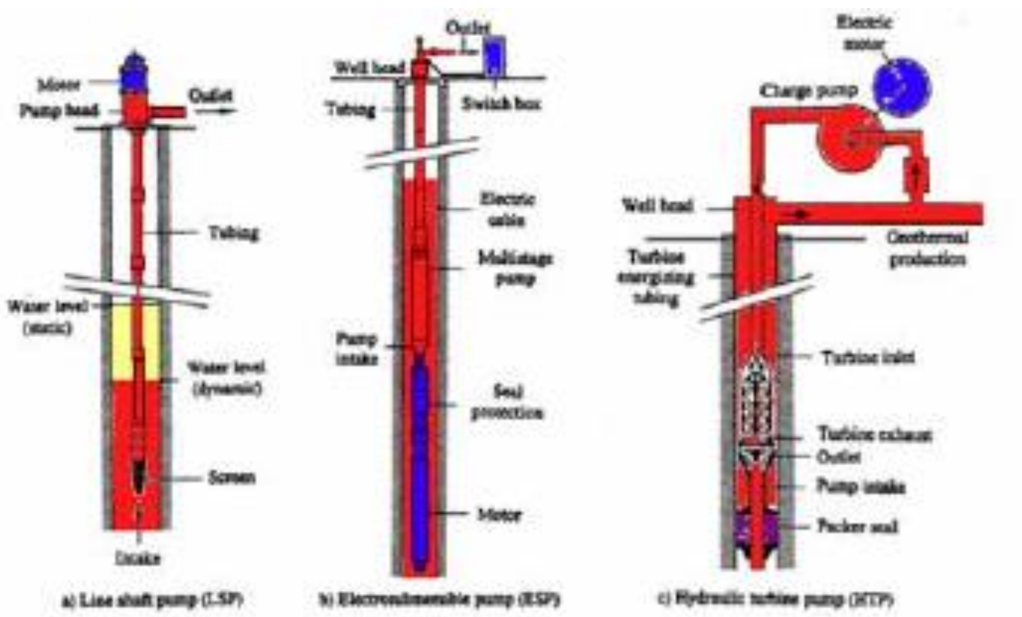
The geothermal fluid loop: gathering

Doublet: (1 production well, 1 injection well) is the typical layout

Triplet is also used

Multi-well, with several modules is being discussed

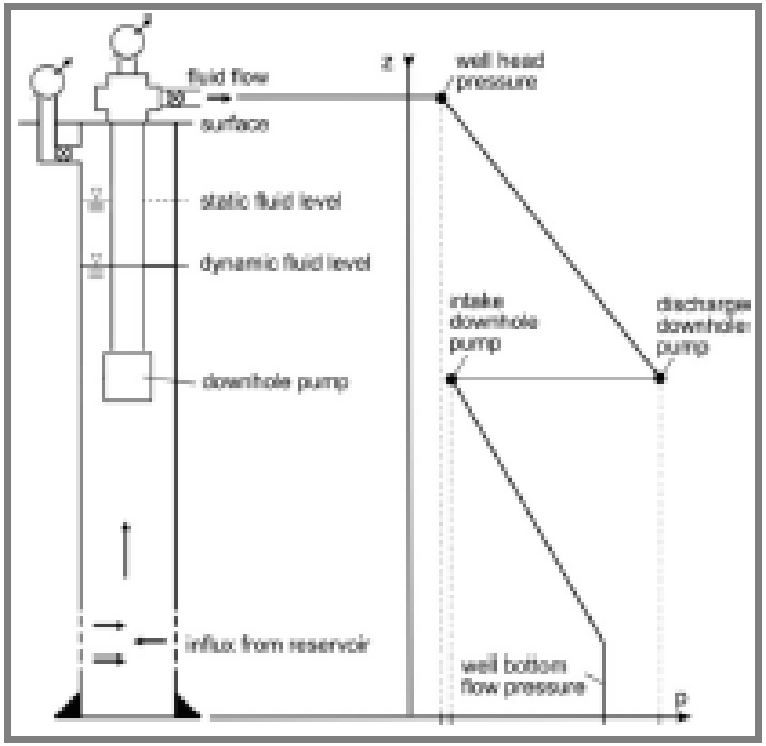
The downhole pump:lineshaft (LSP), submersible (ESP), hydraulically driven (HTP)



Source: TP-Geoelec "Strategic Research Priorities for Geothermal Electricity»

Main issues: depth, pumping head, temperature, reliability and availability

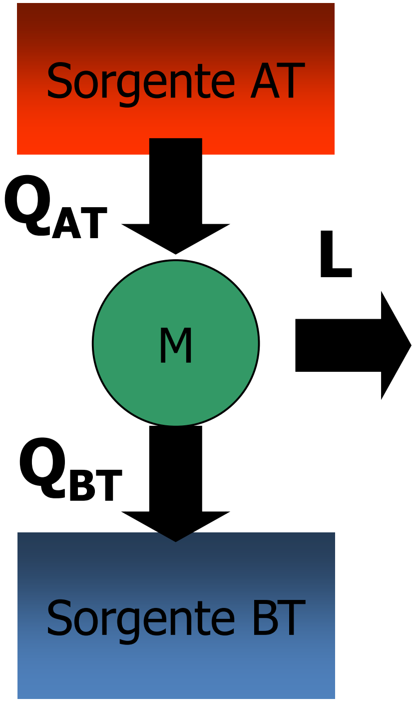
The geothermal fluid loop: pressure change in the production well



Rif. Frick et al., 2011

Figure 6. Scheme of a production well showing downhole pump, static fluid level and dynamic fluid level (left) and the pressure curve during fluid production (right).

The power cycle – remind from thermodynamics



$$\eta = \frac{L}{Q_{AT}}$$

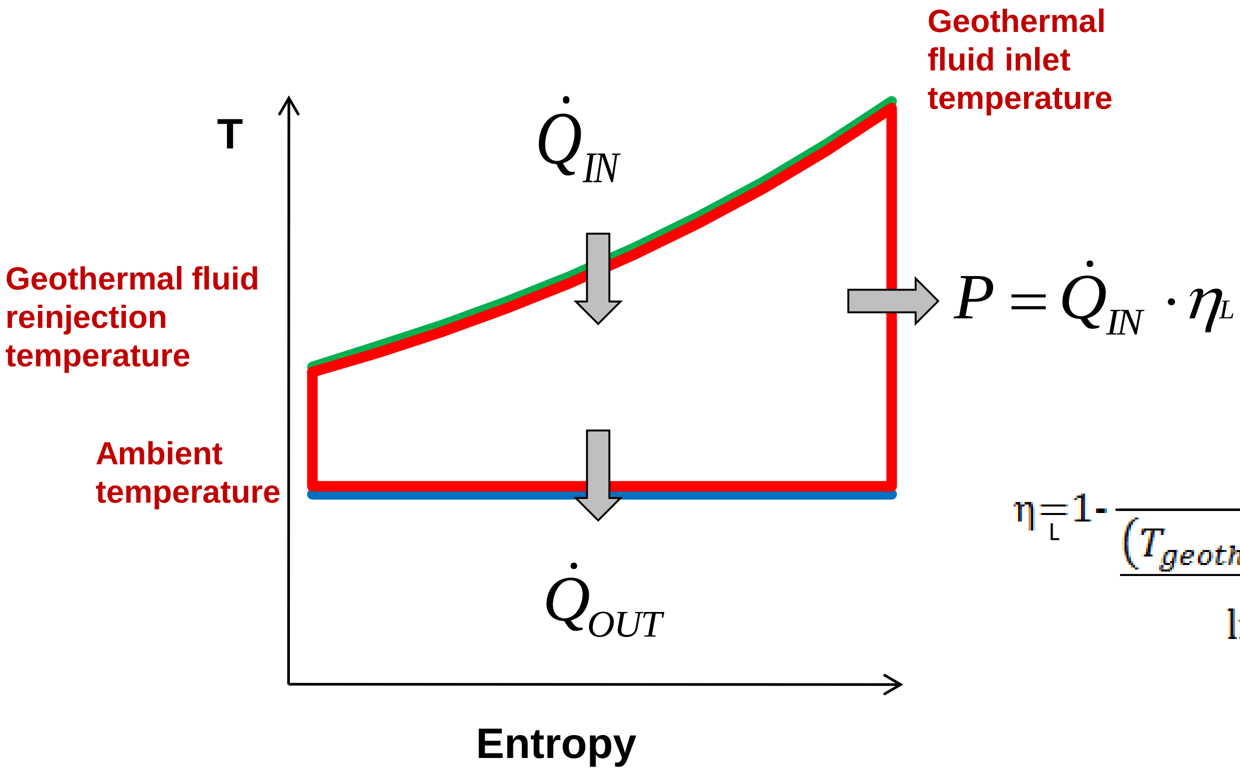
$$\eta_{id,C} = 1 - \frac{T_{BT}}{T_{AT}}$$

Only for Carnot cycles with constant temperatures

$$\eta < \eta_{id,C}$$

Power cycle: the reference ideal cycle

for all liquid heat source, with constant heat capacity



Lorenz cycle

REMIND: the cycle efficiency depends only on the geothermal source and ambient temperatures

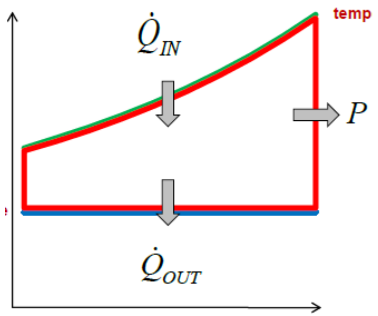
$$\eta_L = 1 - \frac{T_{amb}}{\dfrac{(T_{geoth,source} - T_{reinjection})}{\ln\left(\dfrac{T_{geoth,source}}{T_{renijection}}\right)}}$$

Case study: Soultz, ideal cycle
Nominal conditions: ambient 10°C; geothermal fluid salt content 100 g/l inlet temperature 175 °C, reinjection 70 °C

Thermal power: $\dot{Q}_{IN} = \dot{m} \cdot c \cdot \Delta T$

$$\dot{Q}_{IN} = 33.57\,\frac{kg}{s} \cdot 3.7\,\frac{kJ}{kgK} \cdot (175 - 79.1)K = 13MW$$

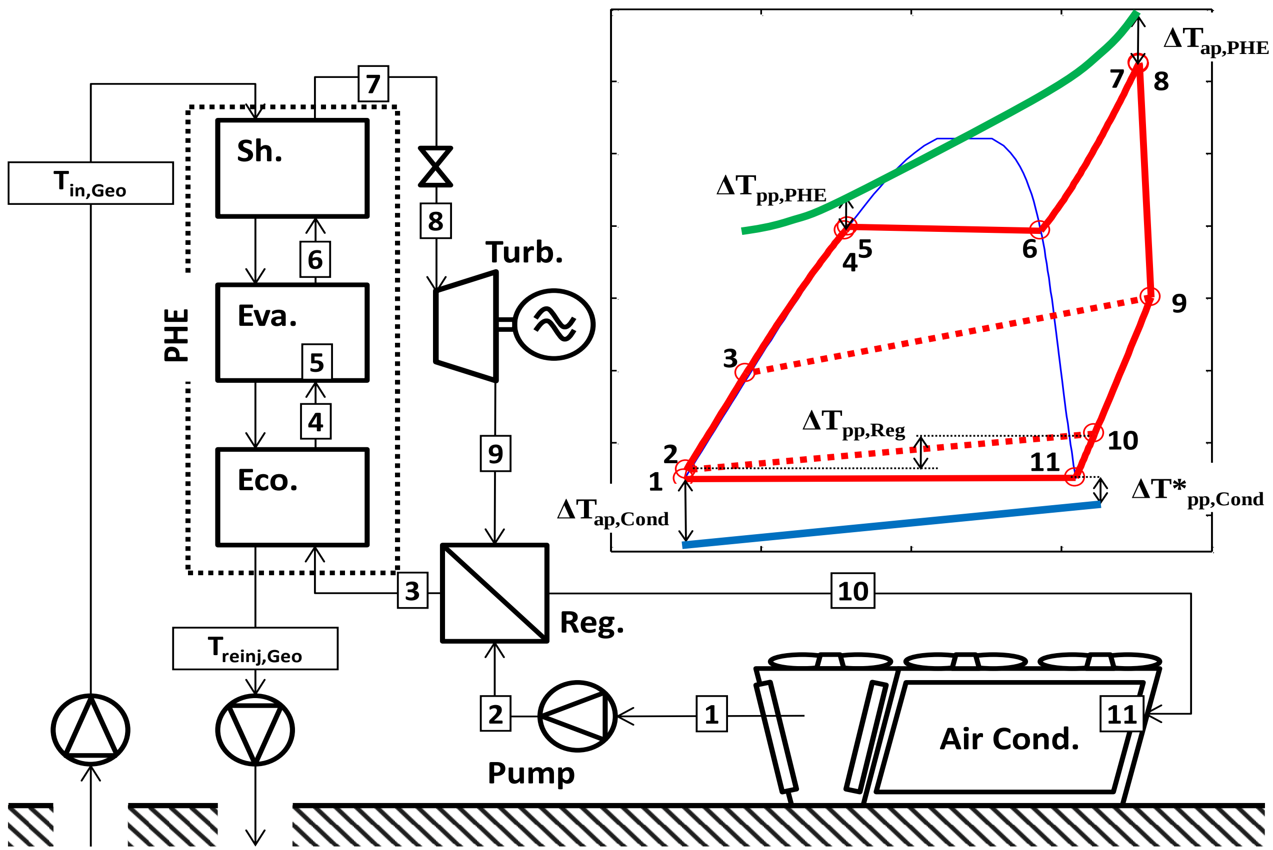
$$\eta = 1 - \frac{283.15}{\frac{(175 - 70,1)}{ln\frac{175+273,15}{70.1+273.15}}} = 0.28$$



$$P_{IDEAL} = \dot{Q}_{IN} \cdot \eta = 13MW \cdot 0.28 = 3.64MW$$

Power cycle: the real cycle

ORC, pure fluid



Concepts for binary cycle design

Objectives:

-high efficiency

-=> second law analisys: minimize second law losses

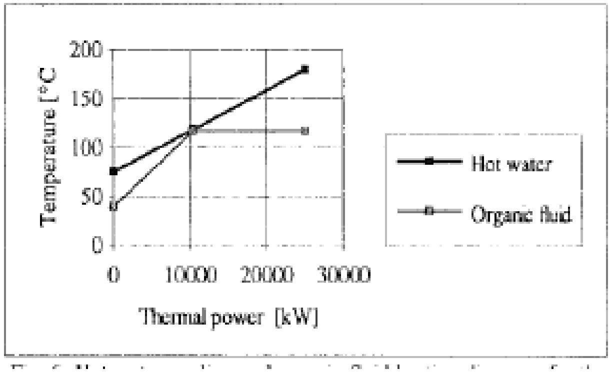
-low cost, €/kW

-=> optimize component design

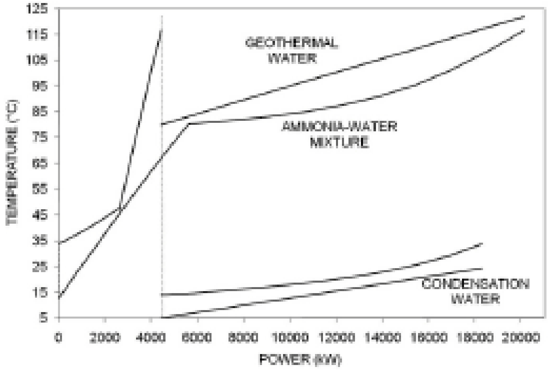
-Critical choice: the cycle working fluid

Concepts for binary cycle design

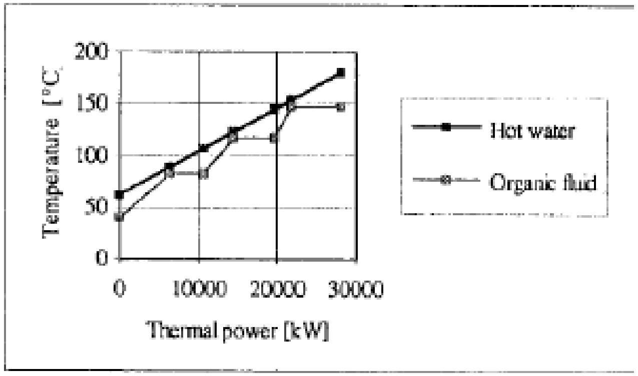
The heat introduction process



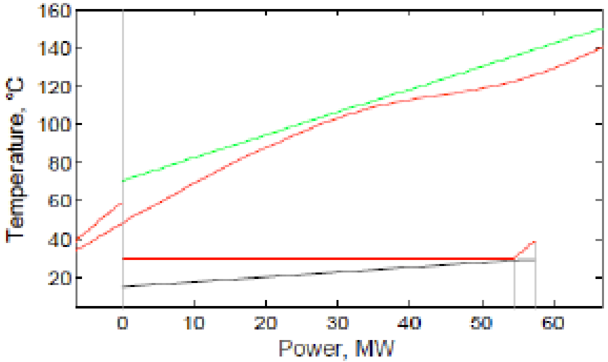
Single evaporation pressure



Kalina cycle



Multiple evaporation pressures

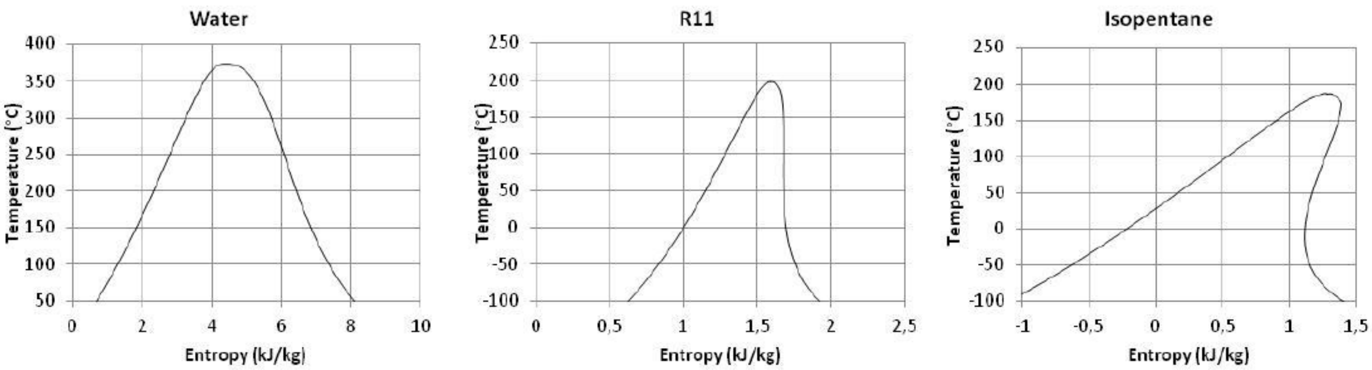


Supercritical cycle

ORC working fluid selection

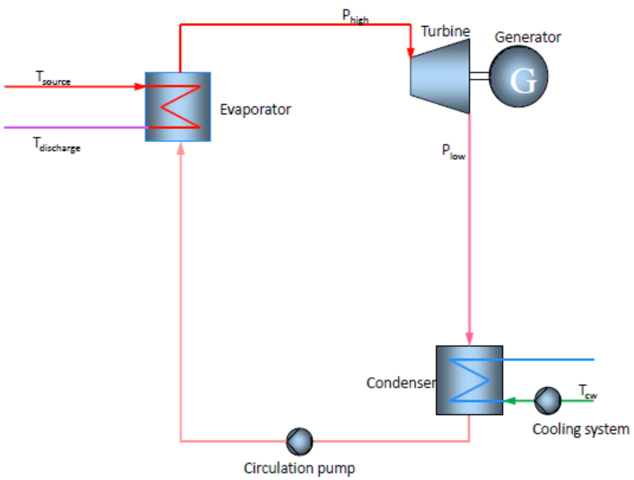
The fluid must be suitable for the selected geothermal source and plant size (Fluid critical temperature and pressure, molecular complexity and mass are relevant)

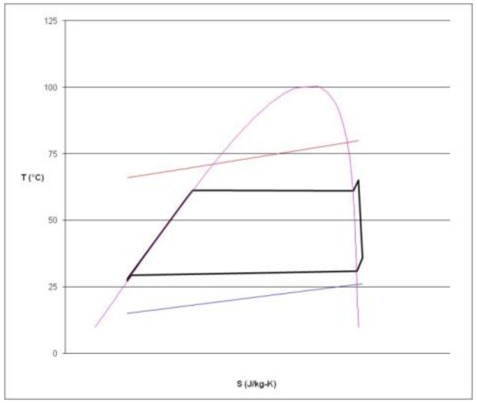
Hydrocarbons
Refrigerants
Others



Important issues: environmental, toxicity, flammability,material and lubricant compatibility, cost

ORC, pure fluid, simple cycle optimization: the evaporation temperature is a key parameter

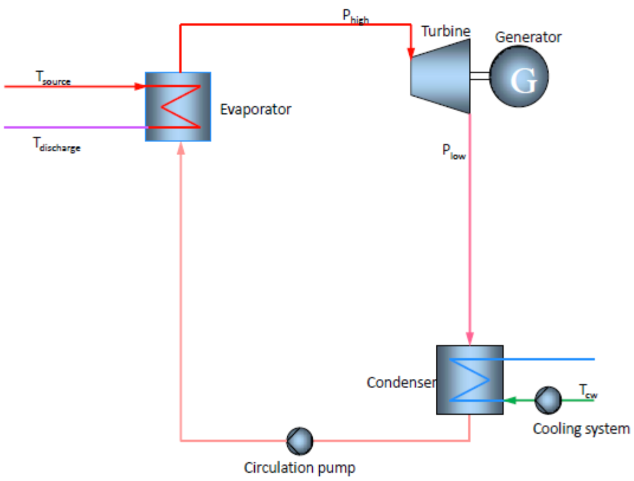


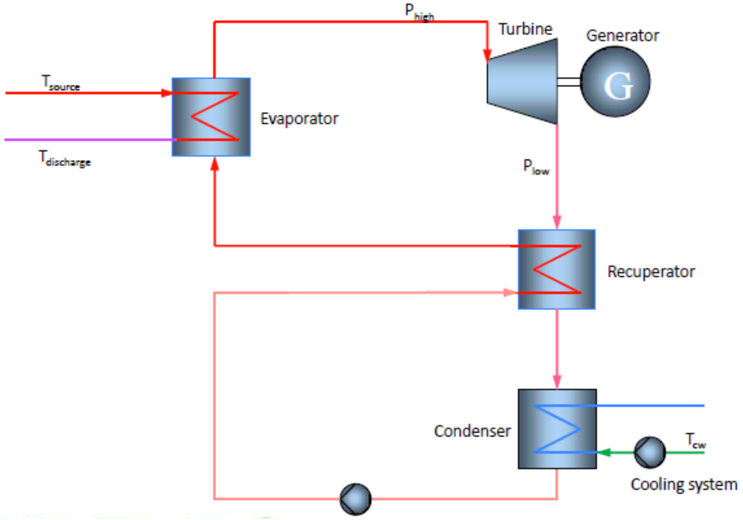


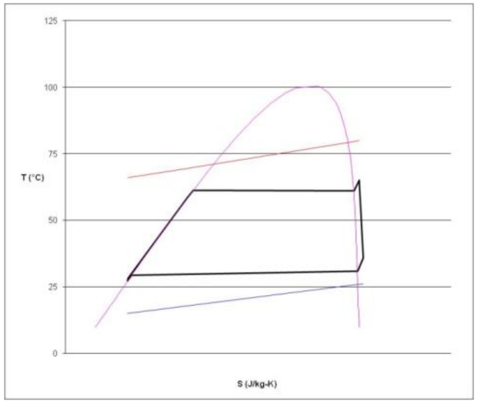
- Introduced thermal power decreases when evaporation temperature increases
- Cycle efficiency increases when evaporation temperature increases

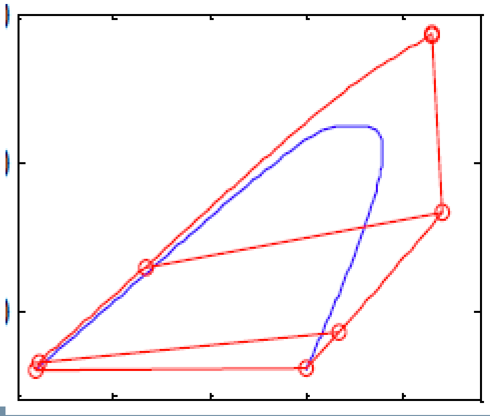
=> Maximum cycle power for the optimum evaporation temperature

Cycle selection: simple or recuperative subcritical or supercritical

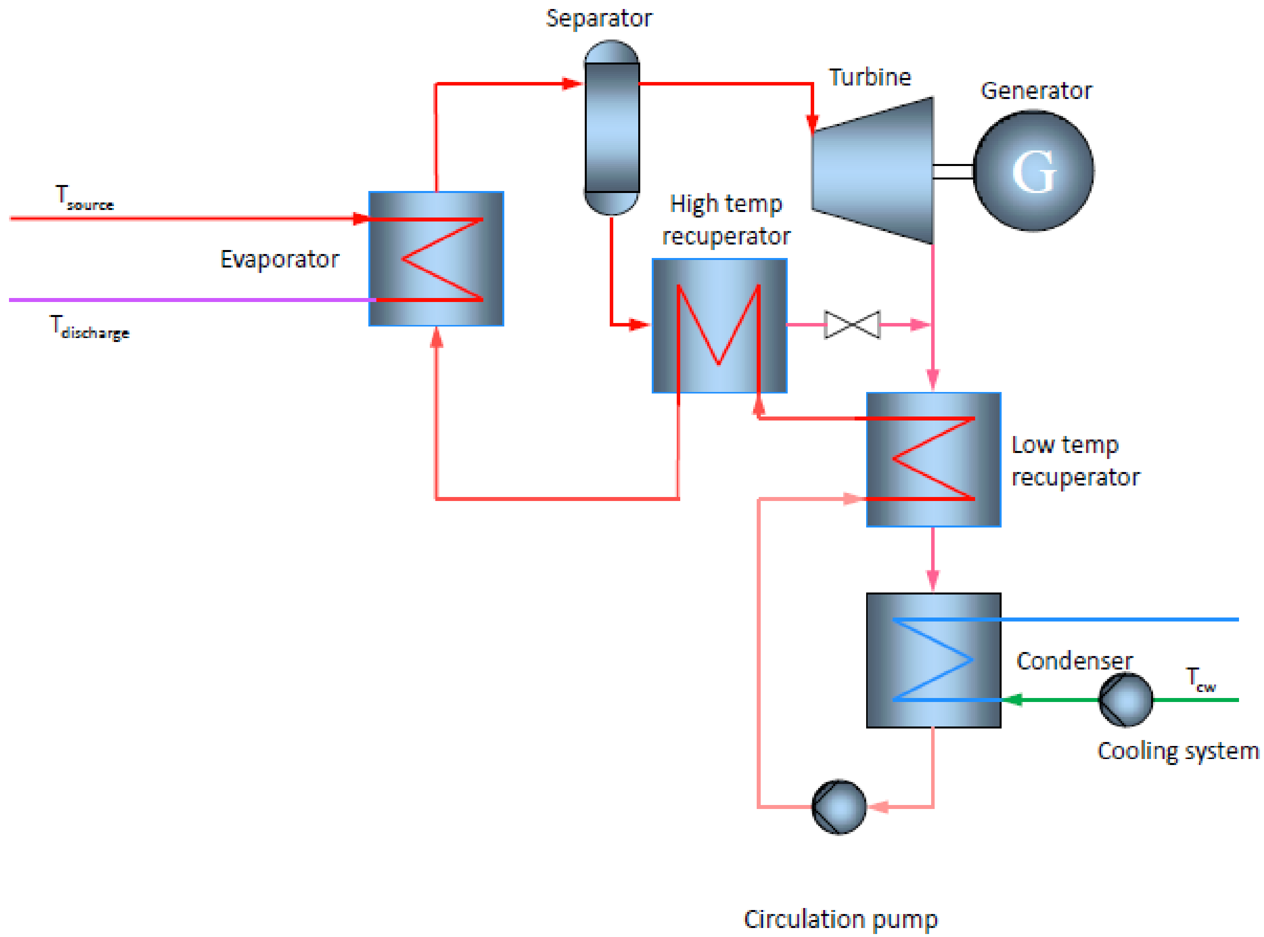






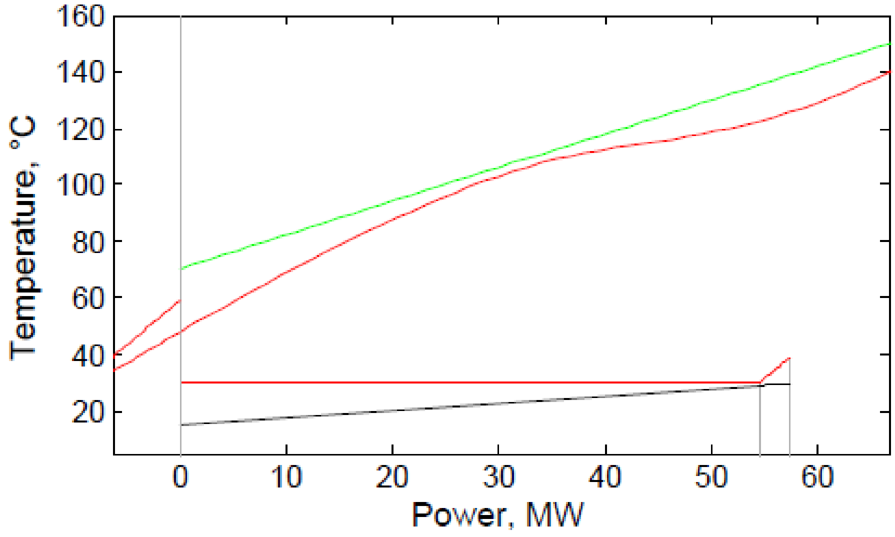


Kalina cycle
working fluid: ammonia-water mixture

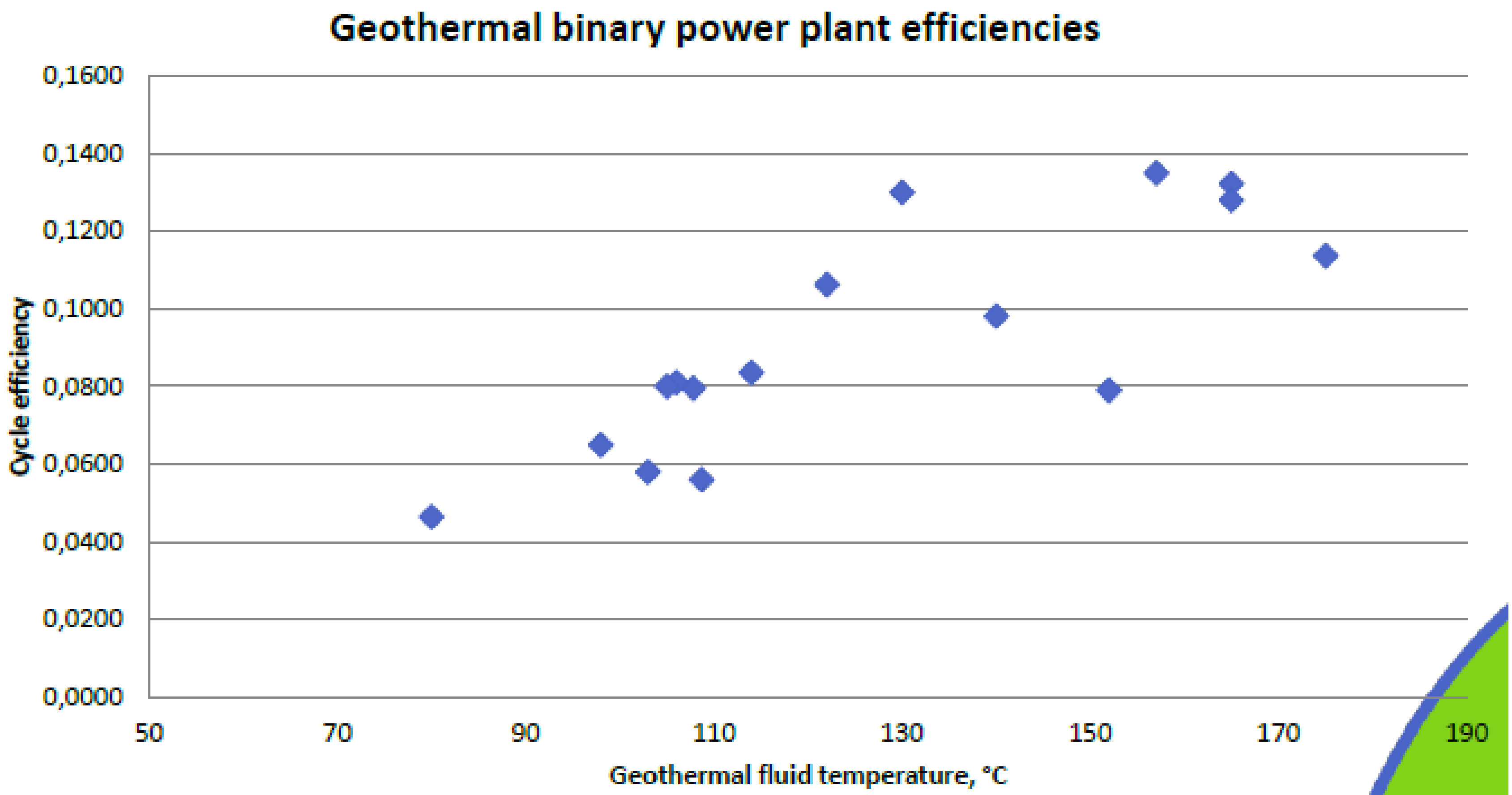


Cost & component sizing

- Turbine cost depends mainly on turbine size, and, therefore, on the working fluid selected
- Heat exchangers: selection of $\Delta T_{pinch\ point}$ for the heat exchangers is crucial : *the smaller the $\Delta T_{pinch\ point}$, the higher the efficiency but also the heat exchanger surface and cost*

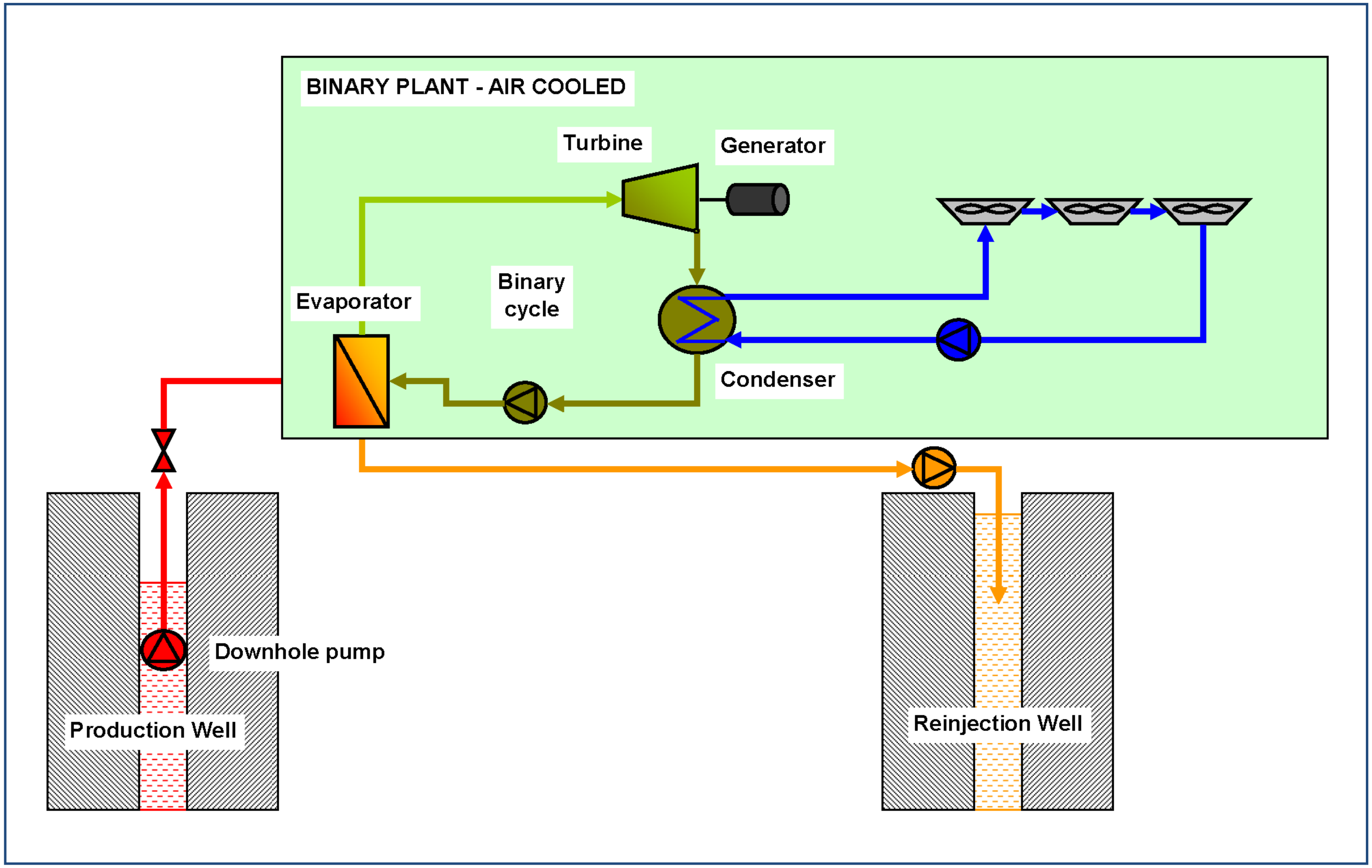


Binary plant performance



The plant power balance

Net plant power = (turbine power – pump power) -auxiliaries power consumption



Binary power plant schemes and main features

The plant comprises two separate section: the geothermal fluid loop and the power cycle

NCG and dissolved minerals are confined in geofluid loop

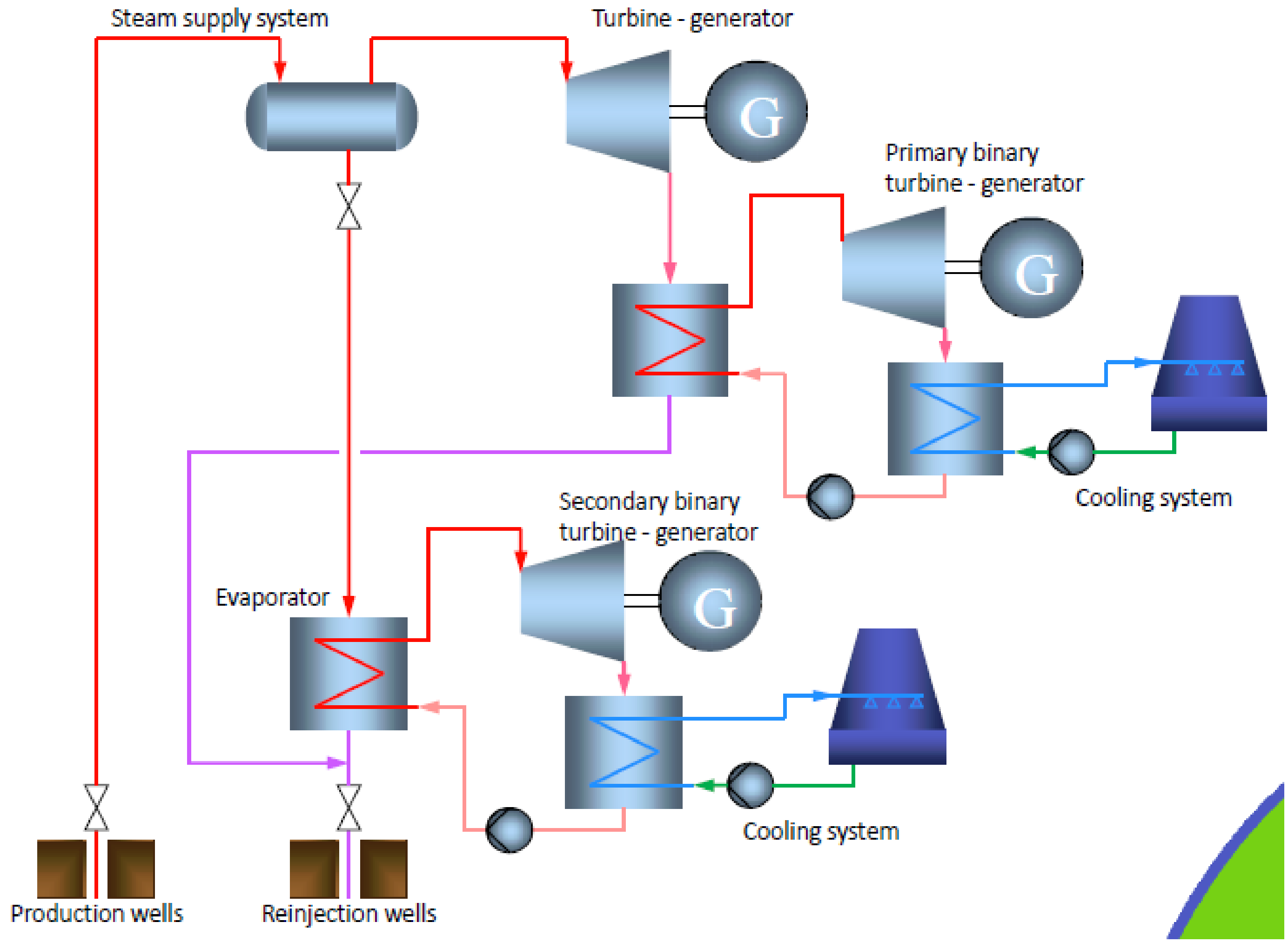
Power cycle arrangement depends on thermodynamic cycle selected

Conventional heat rejection (water/ air cooled condenser or hybrid system)

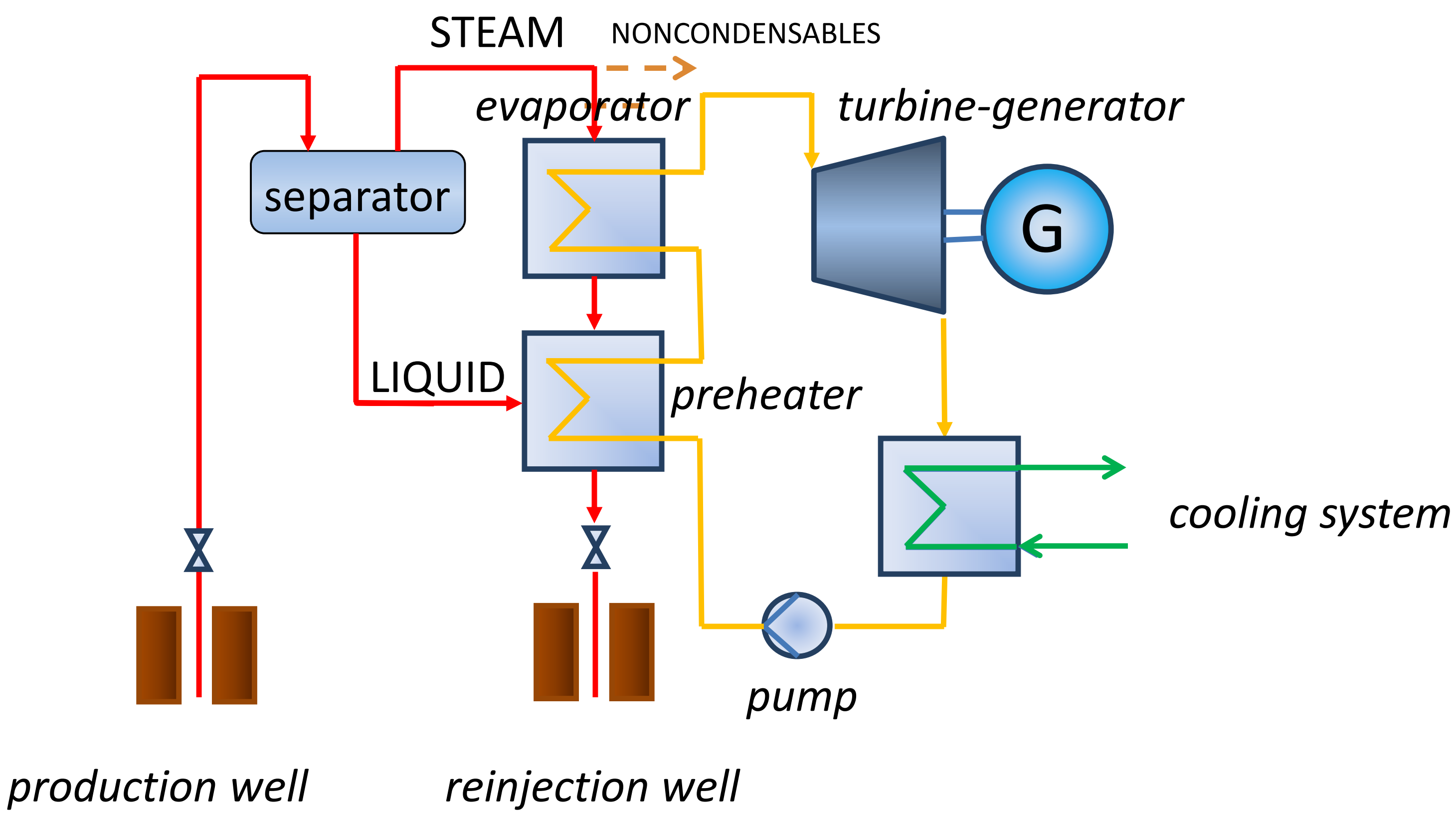
Cogeneration application and/or hybrid configuration is eligible

Plant scheme tailored on the geofluid also possible

Mixed steam-binary plant



High enthalpy geofluid binary plant scheme



Main machinery

- Heat exchangers (pre-heater, evaporator, condenser, recuperator)
- Turbine
- Generator
- Feed pump
- Down-hole pump

Power plant view

Turbine

Turbine requirements:

Work extraction

Suitability to accomodate increasing volumetric flow rate

High efficiency

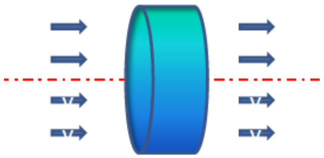
Low cost (=> reduced stage number)

Remark*: dry vapour expansion, no erosion of blades*

Binary power plant – turbine

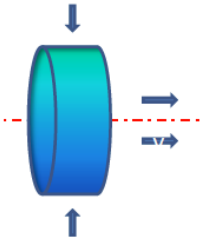
Axial, possibly multistage

most common



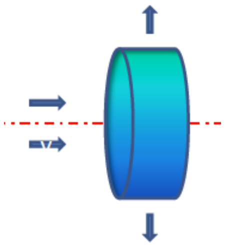
Radial, inflow, usually single stage

sometimes used

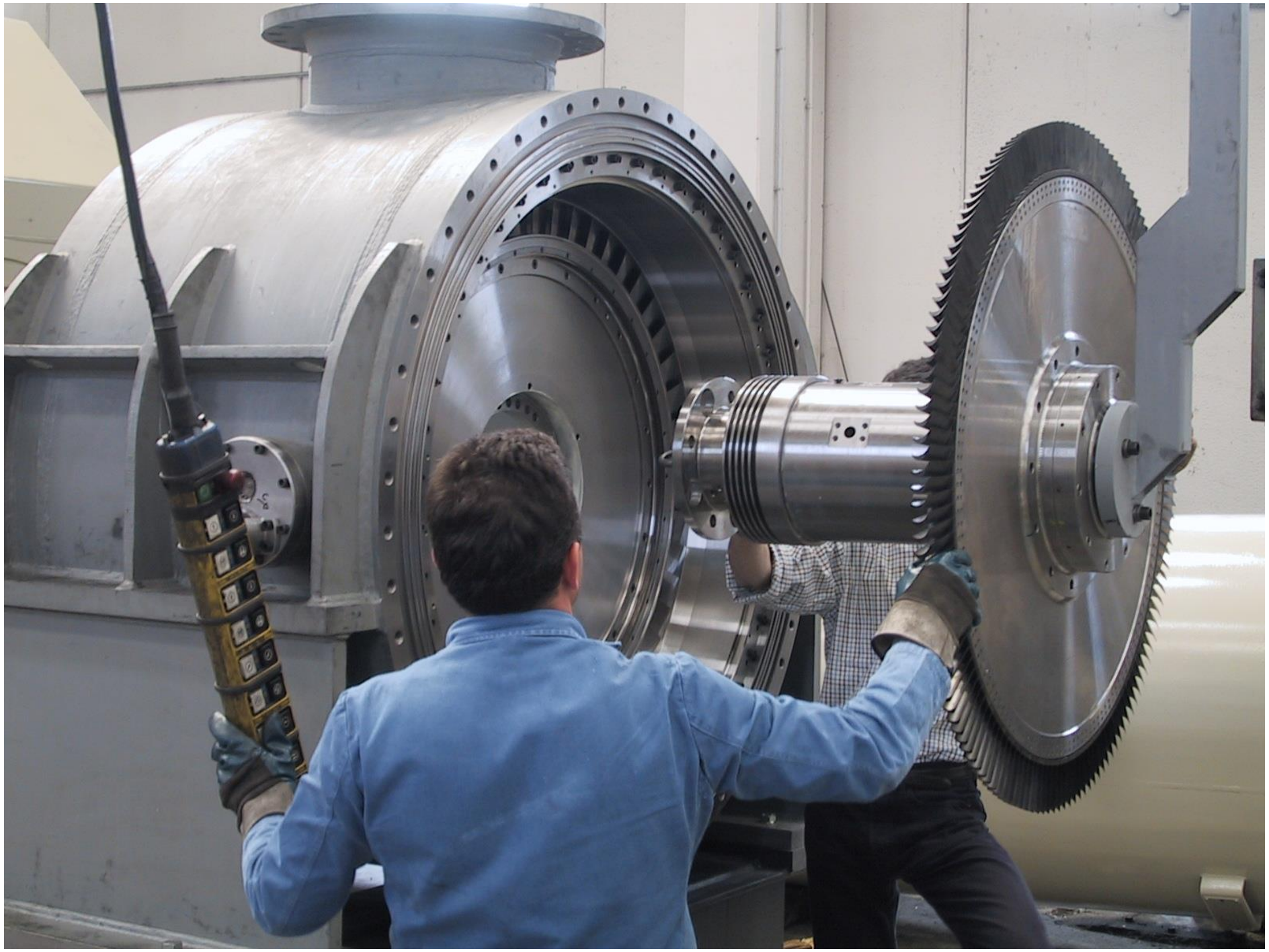


Radial, outflow, multistage

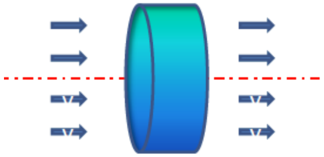
recently proposed again



Turbine, axial, single stage



Low rotational speed
Low peripheral speed, low mechanical stress
No reduction gear



By courtesy of Turboden

High rotational speed with reduction gear
High work extraction per stage
(centrifugal force potential increases work extraction)

Adapt to accommodate variable inlet nozzles


GROVE
CONVOI EXCEPTIONNEL
80 90
MANUTENTION
CRYO STAR

Binary plant – power cycle pump

- Centrifugal, multistage pump
- Operated at variable speed

Power Plant - Heat Exchangers

shell and tube or plate – possibly with phenolic coating

Soultz heat exchangers

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- Bombarda, P., Invernizzi, C., Pietra C., "Heat recovery from Diesel engines: A thermodynamic comparison between Kalina and ORC cycles" Applied Thermal Engineering 30 (2010) 212–219
- Di Pippo, R.: Second Law assessment of binary plants generating power from low-temperature geothermal fluids, *Geothermics, **33, (2004), 565-586.***

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