Tecnologie per conversione e utilizzo sostenibile dell'energia geotermica

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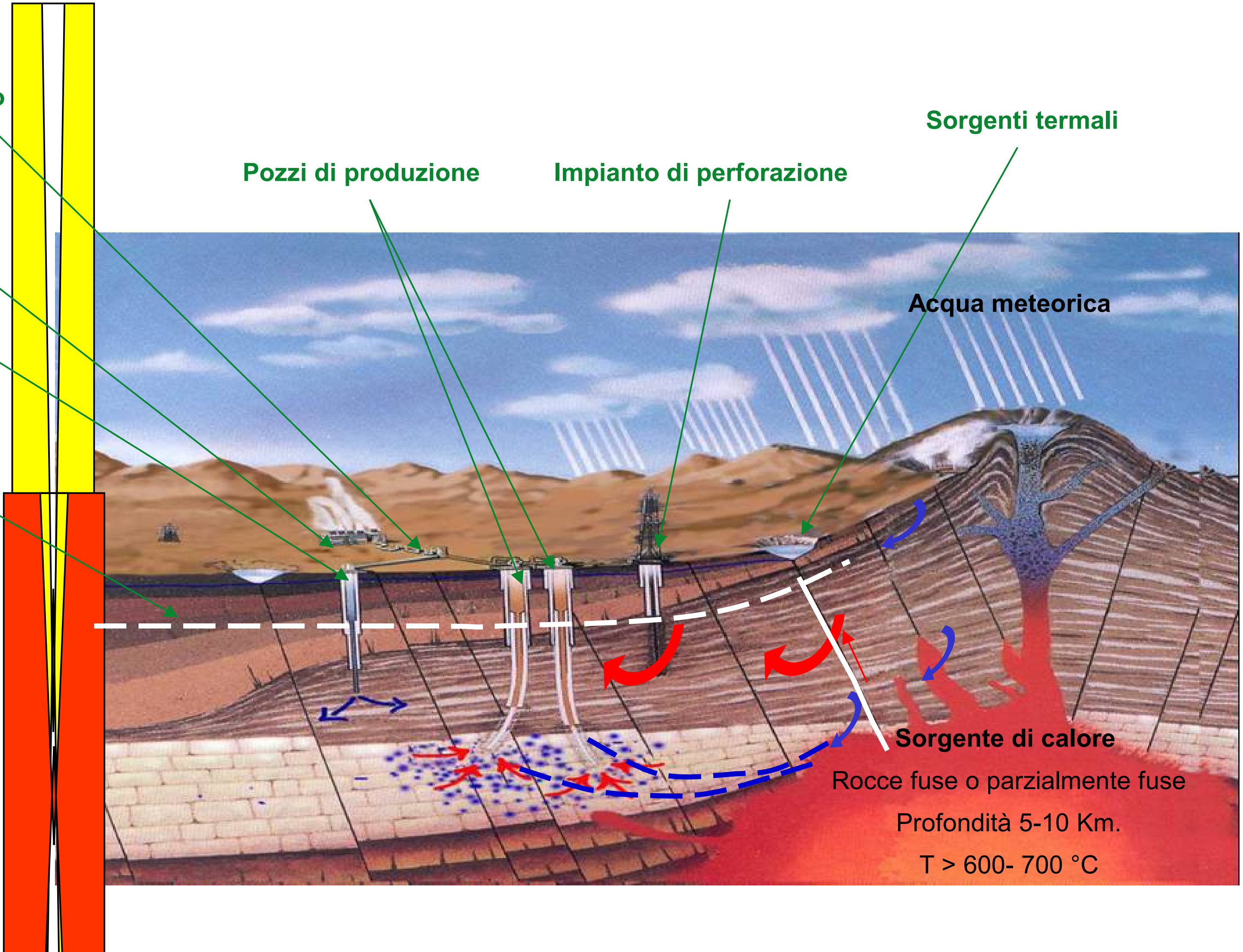
DISTRETTO DELLE
ENERGIE RINNOVABILI

:: ENERGY MADE IN TUSCANY ::

COSVIG

**Consorzio per lo Sviluppo delle
Aree Geotermiche**

Schema concettuale di un sistema geotermico idrotermale



Vapordotto

Centrale

Pozzo si reiniezione

Falda acquifera

Rocce impermebili c
Spessore 500 – 2000 m

Serbatoio
Rocce porose e fratturate
Spessore : 500 – 1500 m
Temp. = 150 – 300 °C

Pozzi di produzione

Impianto di perforazione

Sorgenti termali

Acqua meteorica

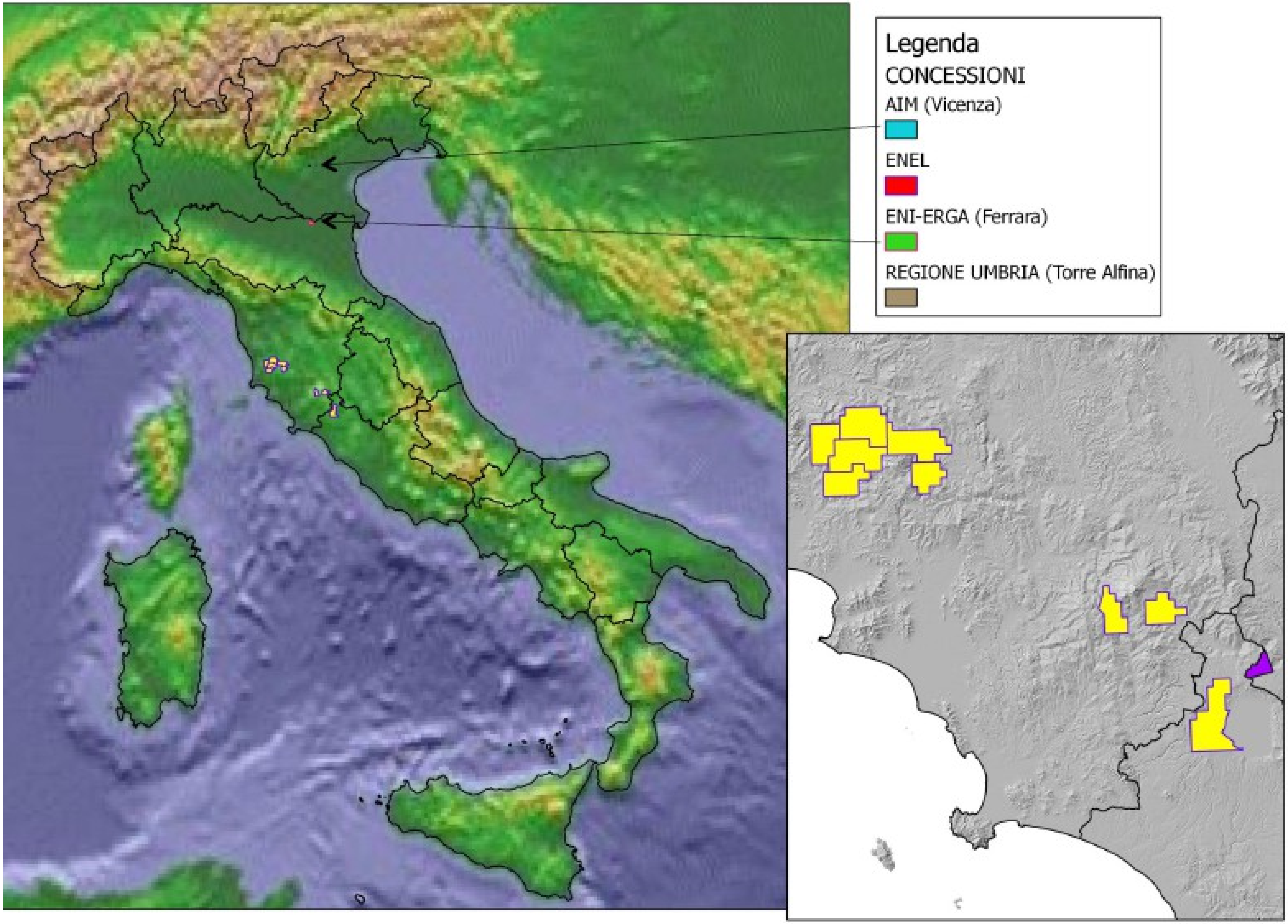
Sorgente di calore

Rocce fuse o parzialmente fuse

Profondità 5-10 Km.

T > 600- 700 °C

SITUAZIONE PRE D.Lgs 22/2010



SITUAZIONE Post D.Lgs 22/2010

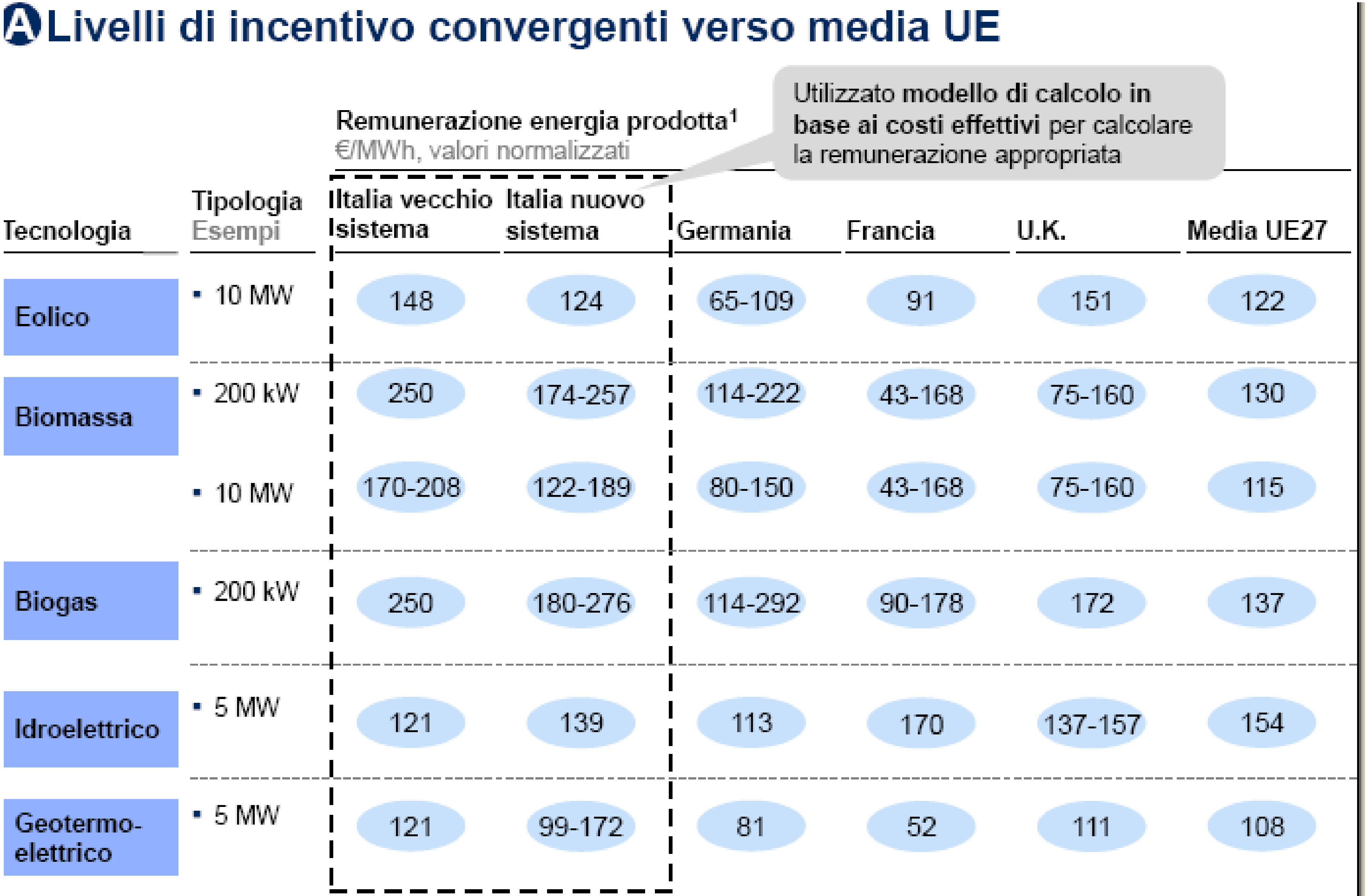
Legenda

Permessi di ricerca per Regione

- 🟥 Emilia Romagna
- 🟧 Lazio
- 🟦 Lombardia
- 🟩 Mar Tirreno
- 🟪 Sardegna
- 🟦 Sicilia
- 🟨 Toscana
- 🟩 Veneto

Regione	Km^2
Emilia Romagna	31,69
Lazio	2473
Lombardia	77,60
Mar Tirreno	681,90
Sardegna	1322
Sicilia	714,6
Toscana	3203,56
Veneto	2,4

Nuovo Decreto Energie Rinnovabili 2012 – 11/04/2012 - Geotermia



A Livelli di incentivo convergenti verso media UE

Utilizzato modello di calcolo in **base ai costi effettivi** per calcolare la remunerazione appropriata

Remunerazione energia prodotta[1]
€/MWh, valori normalizzati

Tecnologia	Tipologia Esempi	Italia vecchio sistema	Italia nuovo sistema	Germania	Francia	U.K.	Media UE27
Eolico	▪ 10 MW	148	124	65-109	91	151	122
Biomassa	▪ 200 kW	250	174-257	114-222	43-168	75-160	130
	▪ 10 MW	170-208	122-189	80-150	43-168	75-160	115
Biogas	▪ 200 kW	250	180-276	114-292	90-178	172	137
Idroelettrico	▪ 5 MW	121	139	113	170	137-157	154
Geotermo-elettrico	▪ 5 MW	121	99-172	81	52	111	108

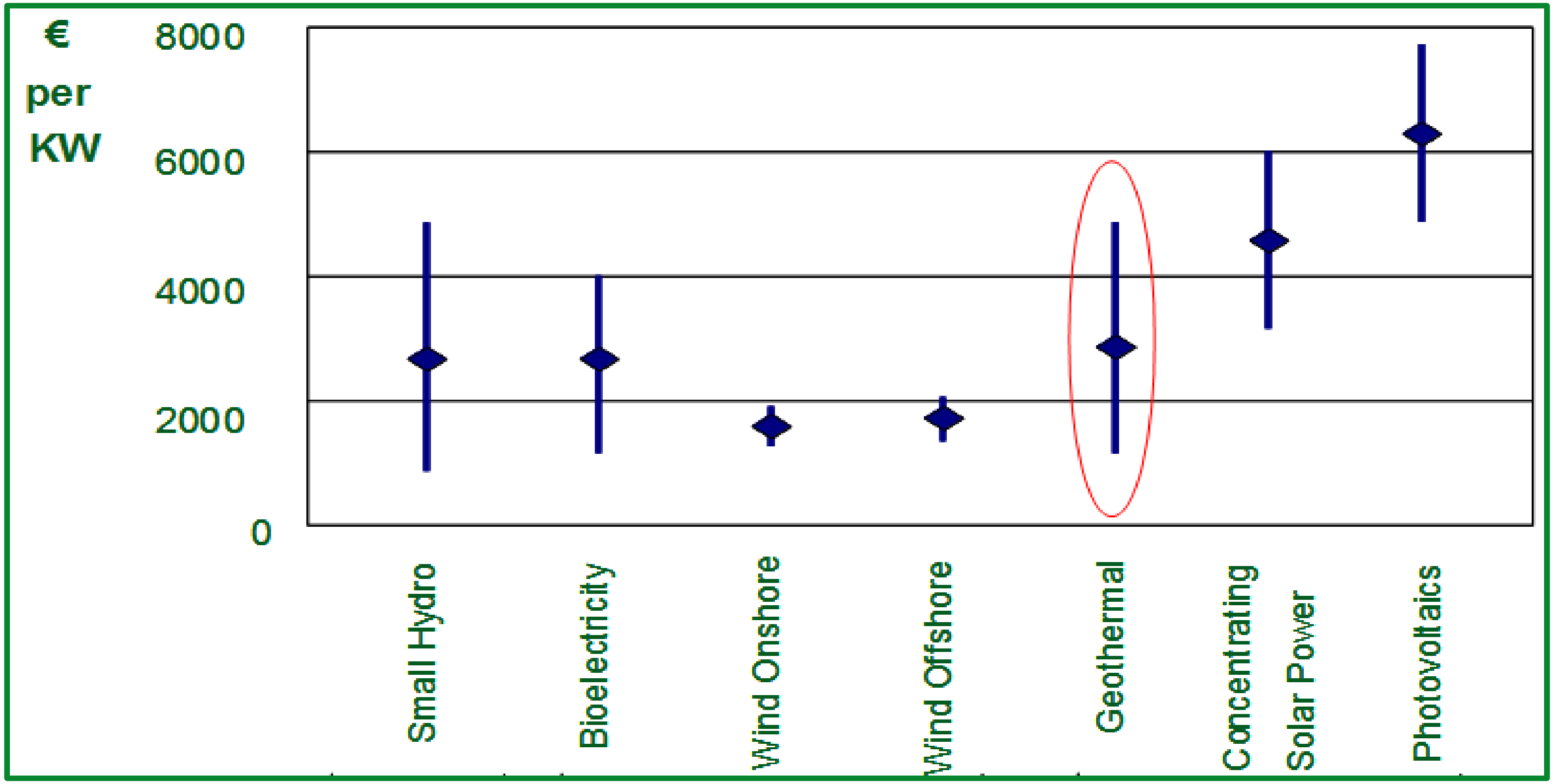
❸ Introduzione meccanismi per contingentare la potenza annua installata

Potenza	Meccanismi introdotti
> 5.000 kW (20.000 per idro e geo)	▪ Impianti accedono se vincono **procedura d’asta** al ribasso su incentivo nei limiti di quantitativi predeterminati di potenza annua
50 - 5.000 kW (50 - 20.000 per idro e geo)	▪ Impianti accedono previa **iscrizione a registro** nei limiti di quantitativi predeterminati di potenza annua
1 - 50 kW	▪ Impianti **liberi** di accedere ad incentivo dopo l’entrata in esercizio (il quantitativo di questa categoria viene detratto dal contingente a registro nell’anno successivo)

Spinta verso mix di tecnologie 'virtuose'

Impatti attesi	Esempi
Impatto su filiera economica nazionale e stimolo a innovazione	▪ Premi per **biomassa da filiera** ▪ Premi per limitate **emissioni CO2** (trasporto a breve raggio) ▪ Premi per impianti **geotermici innovativi** a emissioni nulle ▪ Premi per impianti **solari a concentrazione** e **fotovoltaici con caratteristiche innovative*** ▪ Trattamento specifico per riconversione **zuccherifici** (no aste e registri, tariffa incentivante fissa)
Impatto ambientale	▪ Premi per limitate emissioni **polveri sottili e altri inquinanti** locali ▪ Premi per riduzione **nitrati** in impianti a **biogas** ▪ Impianti che sostituiscono **Eternit*** ▪ Prioritizzazione impianti **fotovoltaici su edifici con elevata efficienza energetica***
Benefici su settori strategici contigui	▪ Specifica considerazione per **impianti a rifiuti urbani** (al 50% biodegradabili) ▪ Integrazione di impianti a biomasse e biogas con **settore agricolo**
Piccoli impianti	▪ Maggior supporto a impianti di **piccole dimensioni**, favoriti in varie modalità (es. esenzione da o prioritizzazione nei registri, tariffe più alte)

Fonti rinnovabili: Confronto tra le performance (2009)

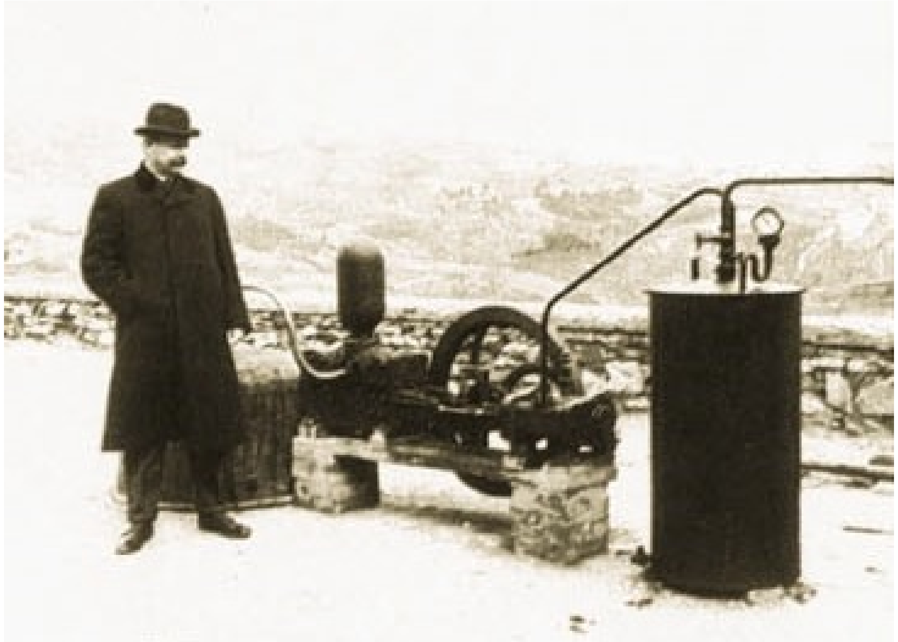


A fronte di costi di investimento più elevati rispetto alle altre forme di energia rinnovabili, **la geotermia garantisce una produzione costante** durante tutto l'anno con un fattore di capacità prossimo ad 1

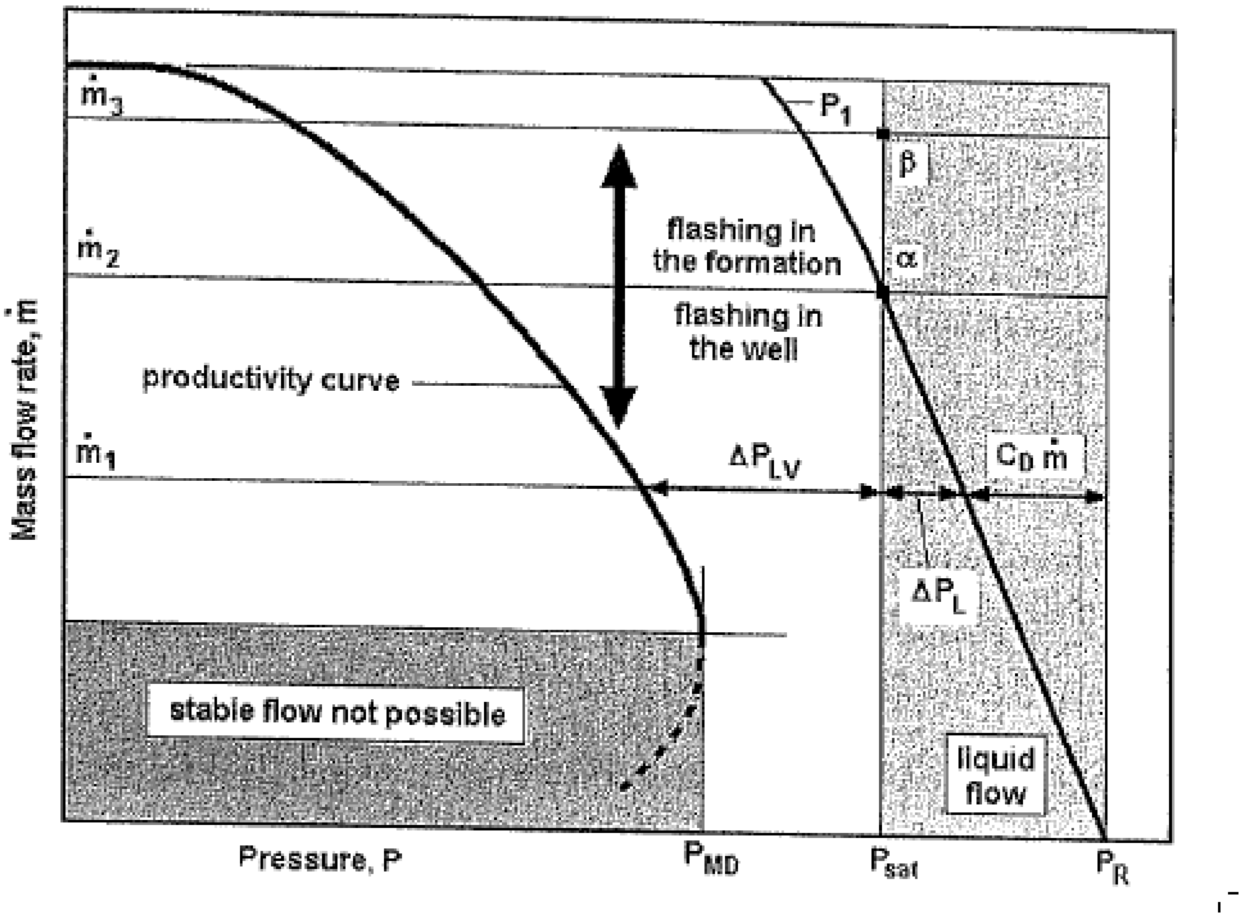
10 MW geotermici equivalgono a 40-50 MW eolici

Toscana

- Historically first in geothermal energy conversion (1904)
- Two main reservoirs:
  - Larderello (Dry Steam)
  - Monte Amiata (Pressurized water)
- Max temperatures in deep reservoir 300-350°C
- Installed capacity 772 MW (2012)



Typical **well productivity curve**, mass flow vs. well head pressure. Water-dominated system.



Thermodynamic conversion of Geothermal Energy (¨10000 Mwe worldwide)

High/Medium Enthalpy (90°C /150°C/200°C)

- Single-Flash (42% Power)
- Double-Flash (23% Power)

Water-dominated systems

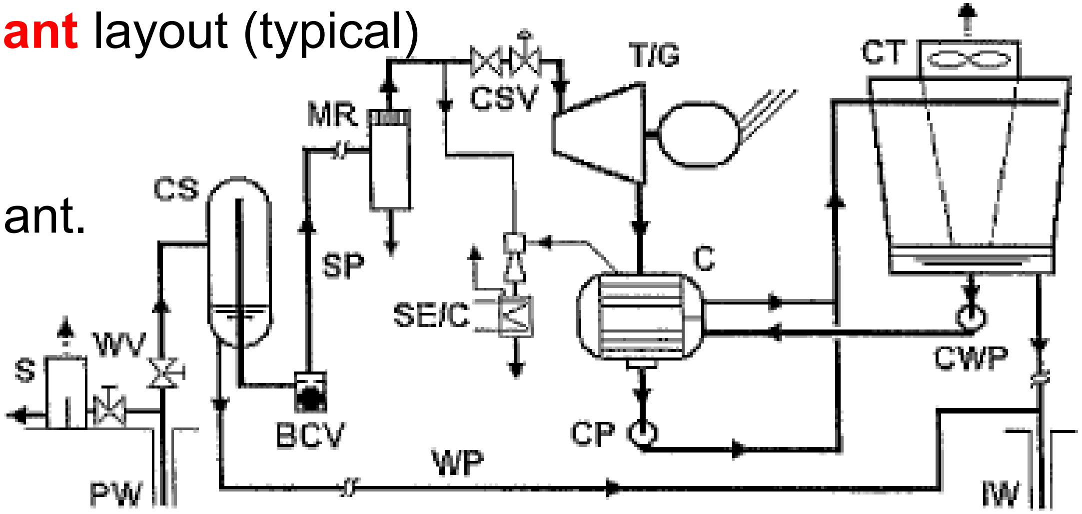
- Direct-Steam (27% Power)

Steam-dominated systems (e.g. Larderello)

Low/Medium Enthalpy (less than 90°C <150°C)

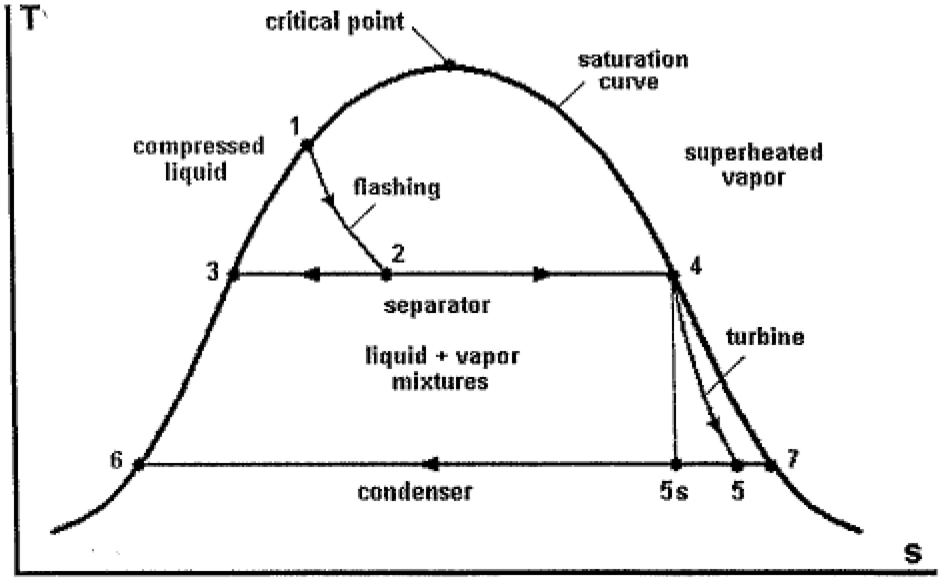
- Binary (Organic Rankine Cycle = ORC) (4% power)
- Hybrid Flash/Binary (4% Power)
- Kalina (water/ammonia with variable formulation)
- Pre-heating of fossil-fuel power plants (steam/gas /combined cycle)
- Integration with other energy sources (solar,…)

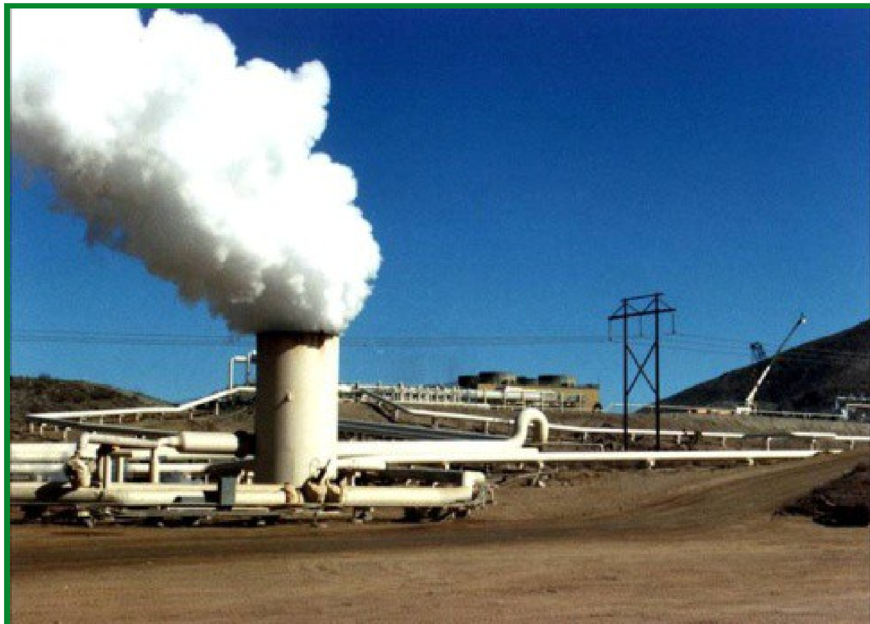
Single-flash geothermal power plant layout (typical)



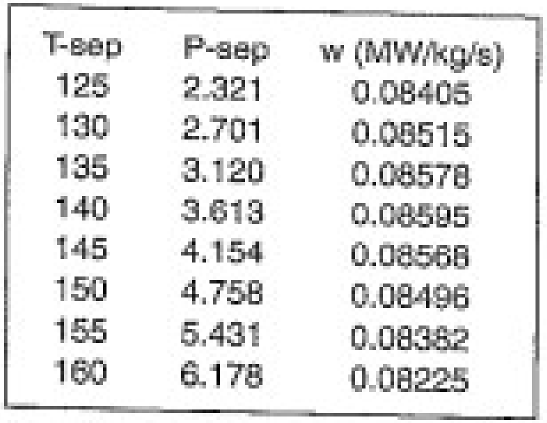
Single-flash geothermal power plant.

T-s cycle diagram

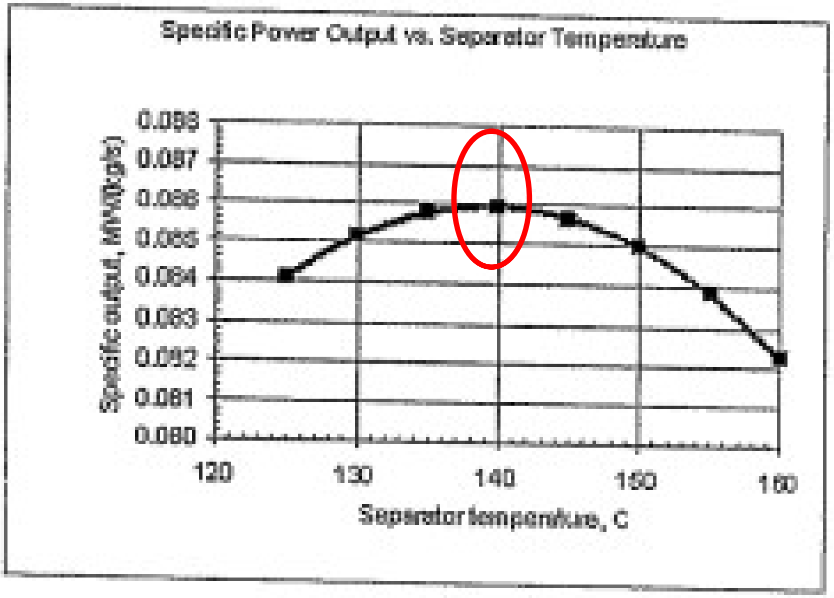


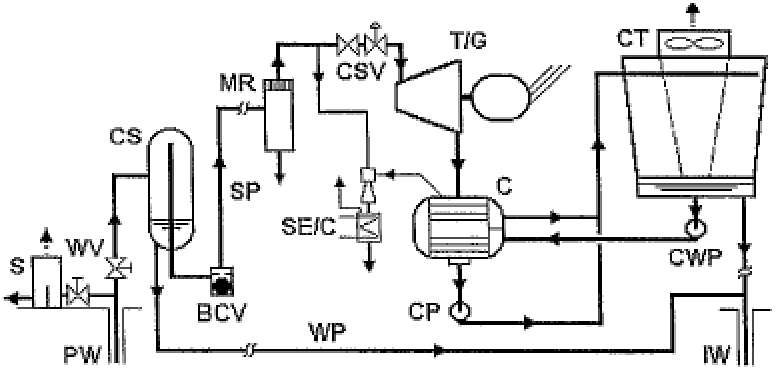


The combined effect of well productivity curve and power cycle efficiency can determine optimized conditions for power output:



T-sep	P-sep	w (MW/kg/s)
125	2.321	0.08405
130	2.701	0.08515
135	3.120	0.08578
140	3.613	0.08595
145	4.154	0.08568
150	4.758	0.08496
155	5.431	0.08382
160	6.178	0.08225

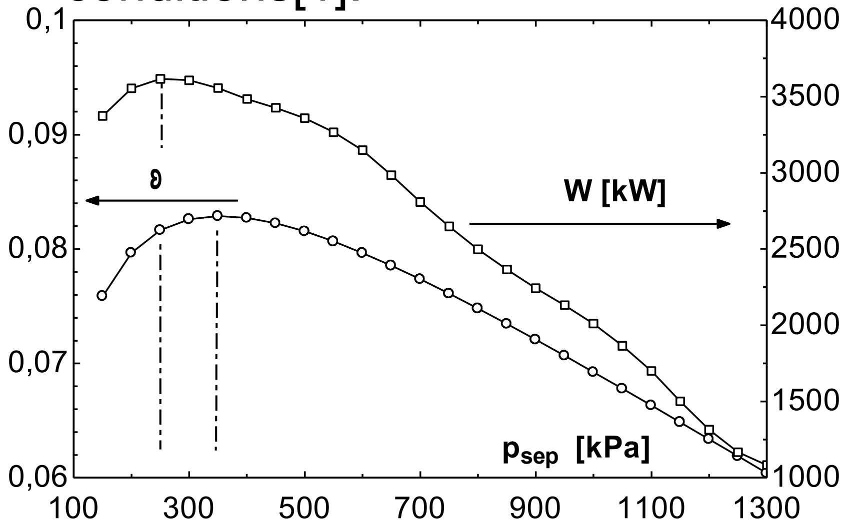




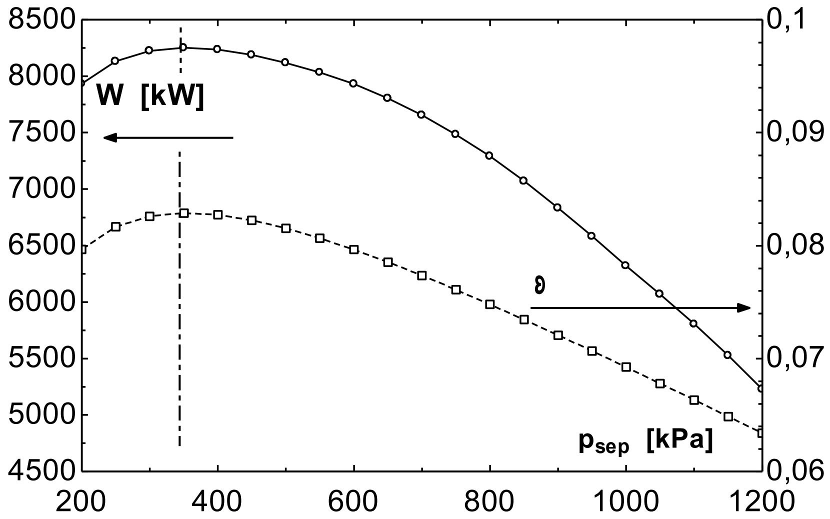
Single-flash geothermal power plant (example)

Single-flash systems

A parametric analysis in function of the separator pressure, leading to results shown in Figure 3 a and b, respectively for non-choked and choked well operating conditions[1].

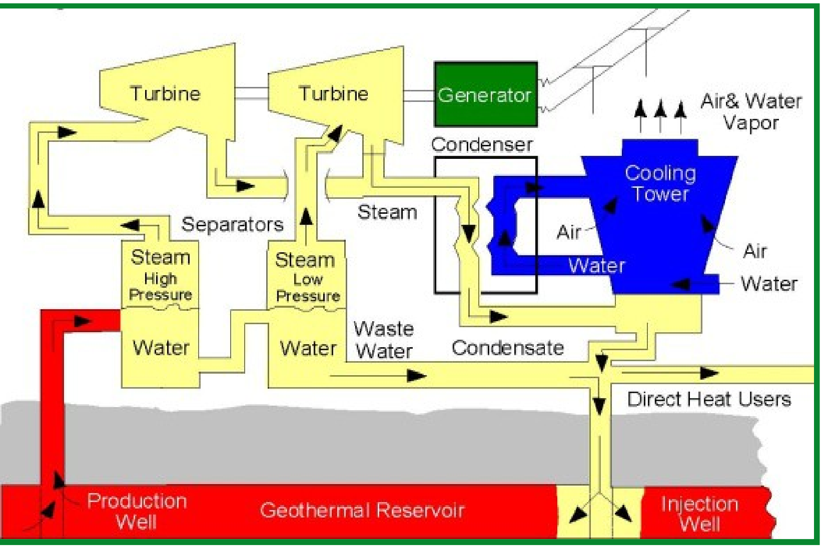


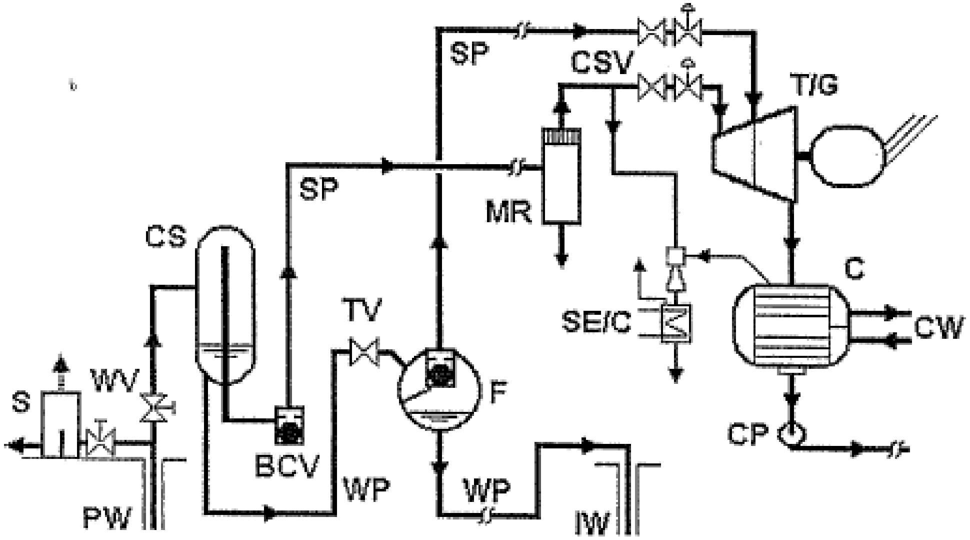
Single-Flash – Power and efficiency vs. psep;
(a) ***Non-choked well.***



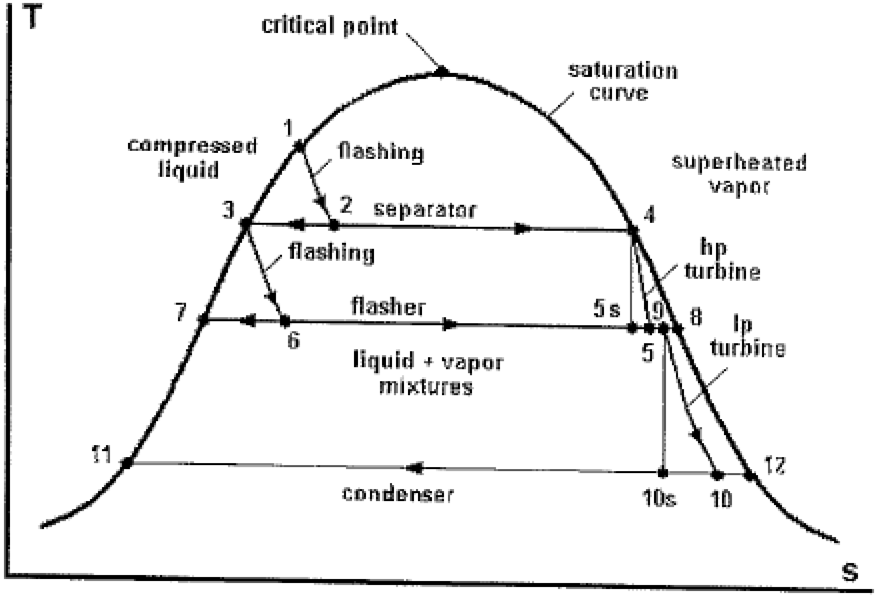
Single-Flash – Power and efficiency vs. psep;
(b) ***Choked well.***

[1] A well is defined as Choked or Non-Choked depending on whether the flash of the pressurized geothermal fluid in liquid conditions produces respectively choked or non-choked conditions for the steam flow rate



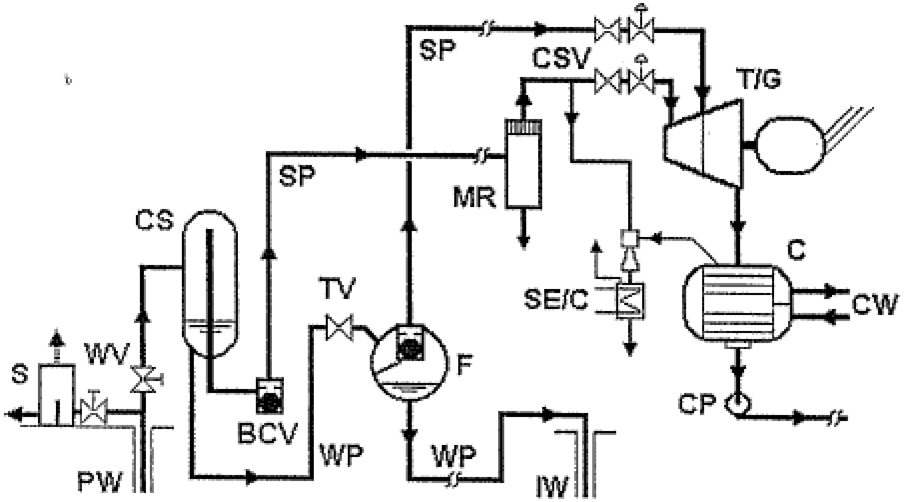


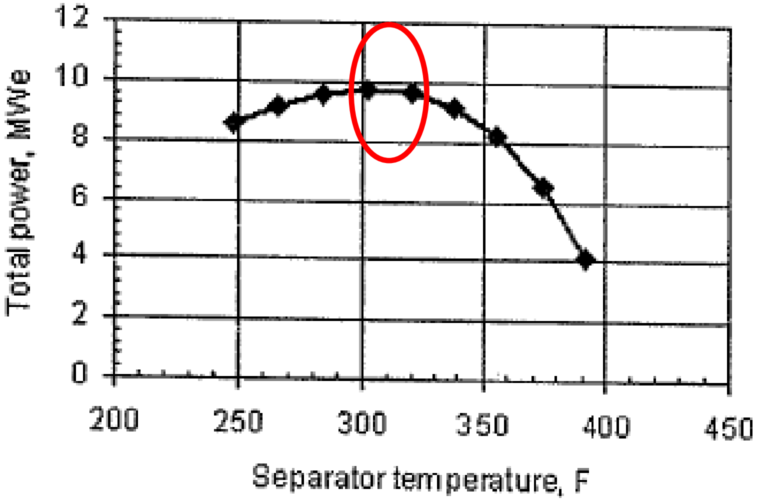
Double-flash geothermal power plant (Layout)



Double-flash geothermal power plant.
T-s diagram of thermodynamic cycle

Double-flash geothermal power plant



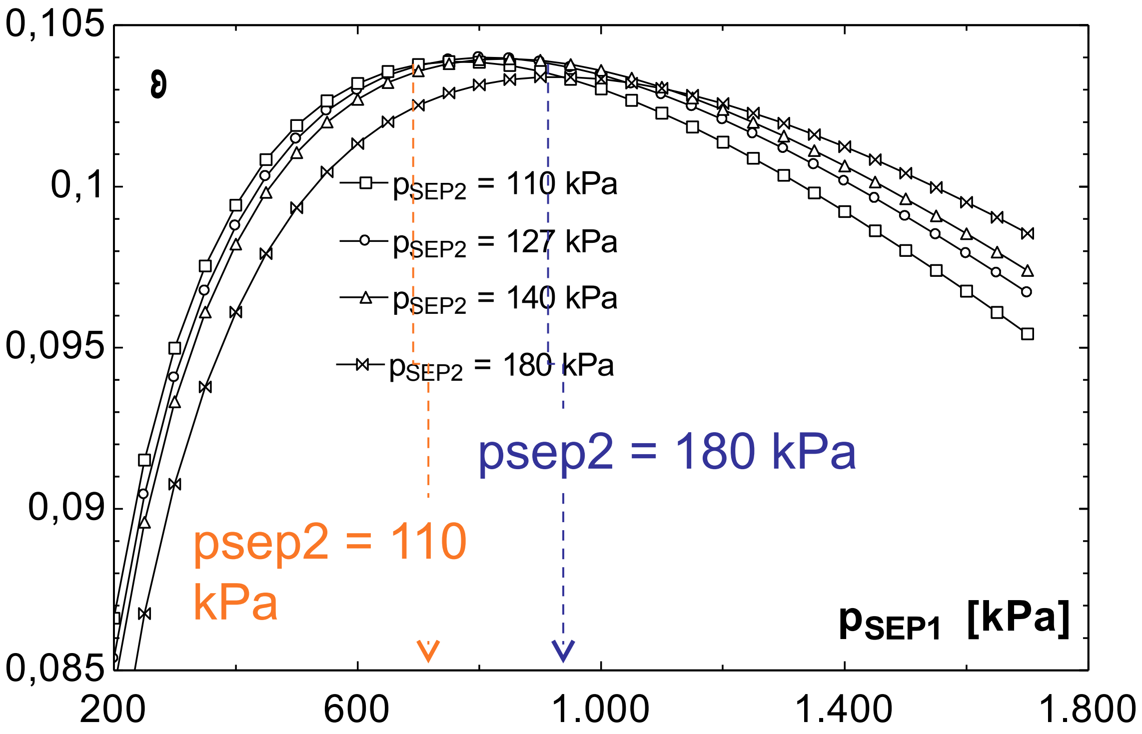


The improved cycle efficiency determines a higher power output with respect to a single-flash layout.

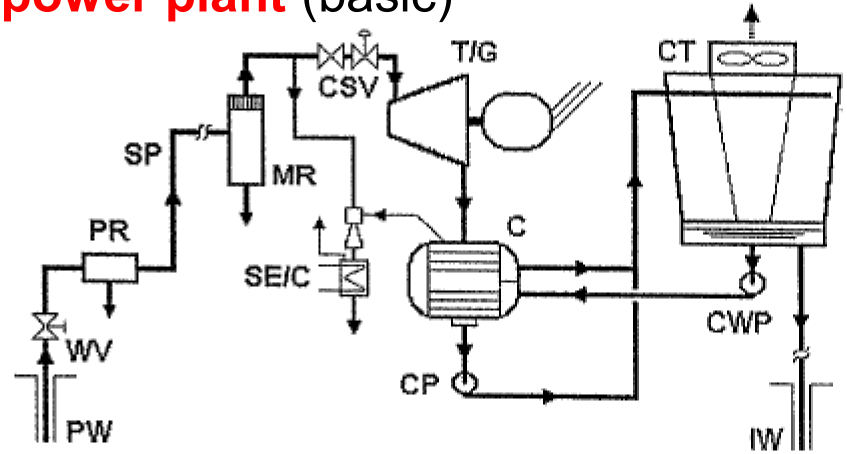
Again, matching with the well productivity curve can determine optimized operating conditions, which have to be carefully evaluated at the design stage and are liable to change during the expected power plant life span.

Double-flash systems

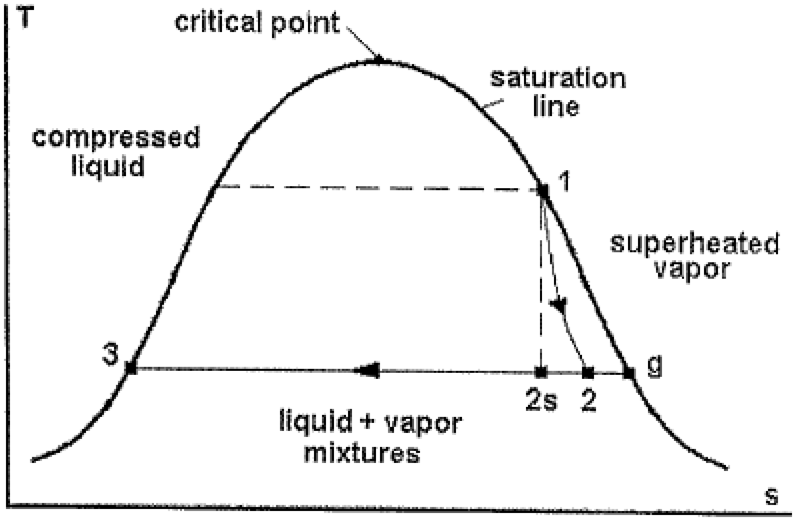
Double-flash plant: the values of psep1 and psep2 are inter-dependent, so that the choice of the second flash pressure must be adjusted to that of the first one:



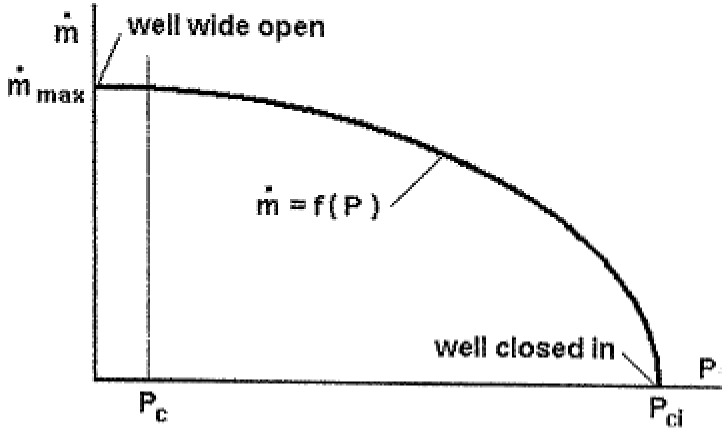
Dry (direct) steam geothermal power plant (basic)



Plant layout



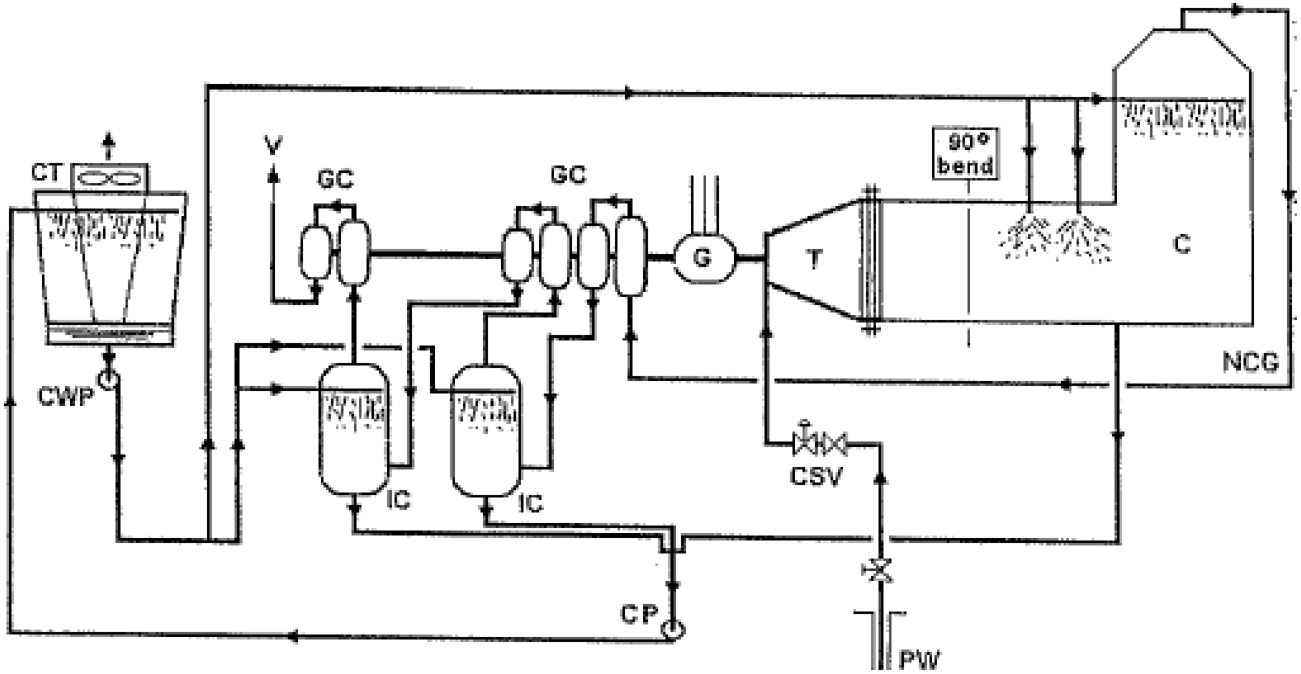
Thermodynamic cycle (T-s) diagram



Well productivity curve

The simple configuration of basic dry - steam geothermal power plants is complicated in practice by :

a) The necessity of removing incondensable gases (mainly CO2, about 5% in volume at Larderello). This involves the use of large compressor/extractor trains (4-6 MWe for the largest 100 Mwe power plants), with a clever (mixing type) intercooling arrangement
b) The necessity of providing condenser cooling, which implies the use of large cooling towers with extensive recirculation of the condensed drain before well reinjection

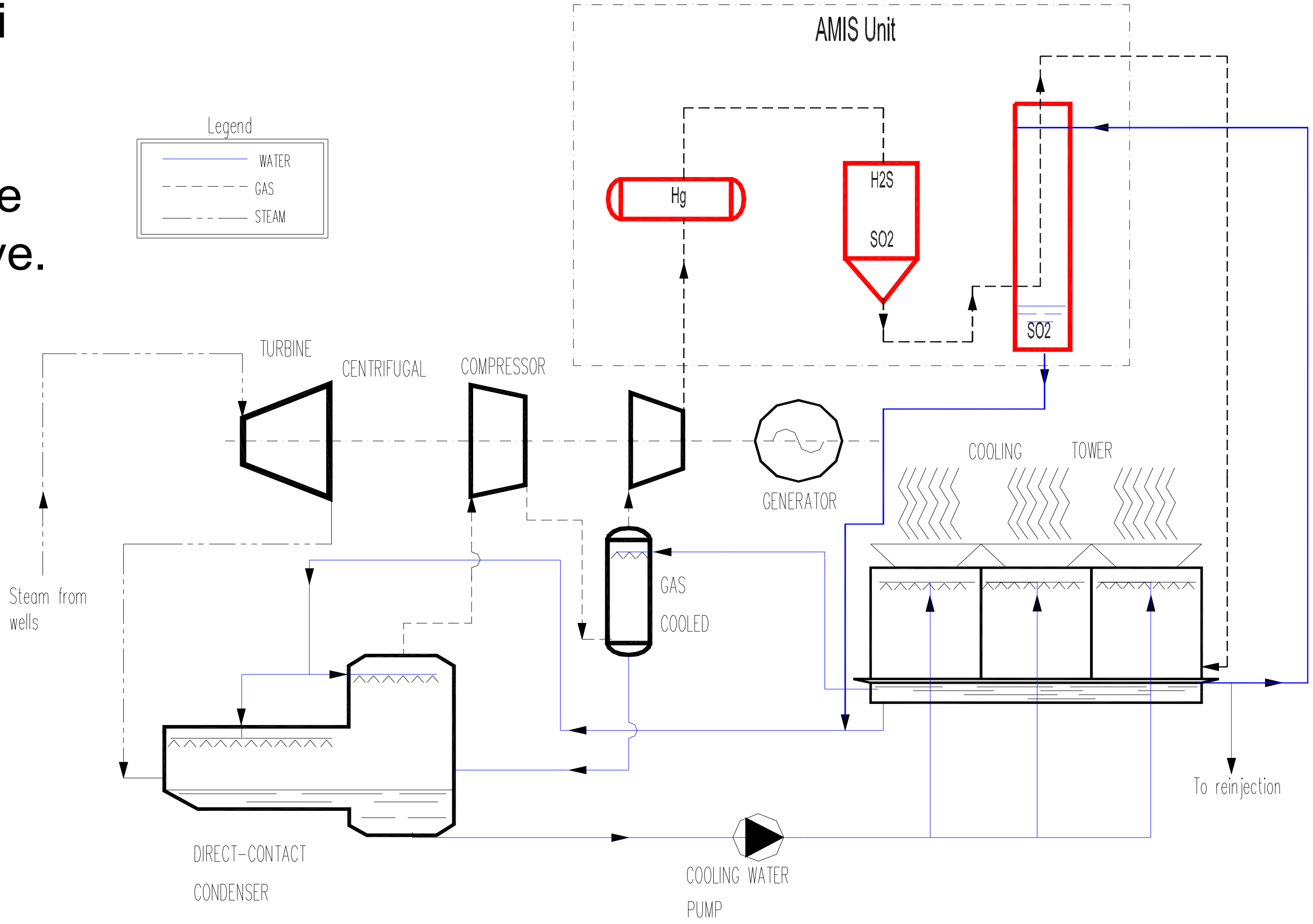


“Greening” Geothermal Power Plants

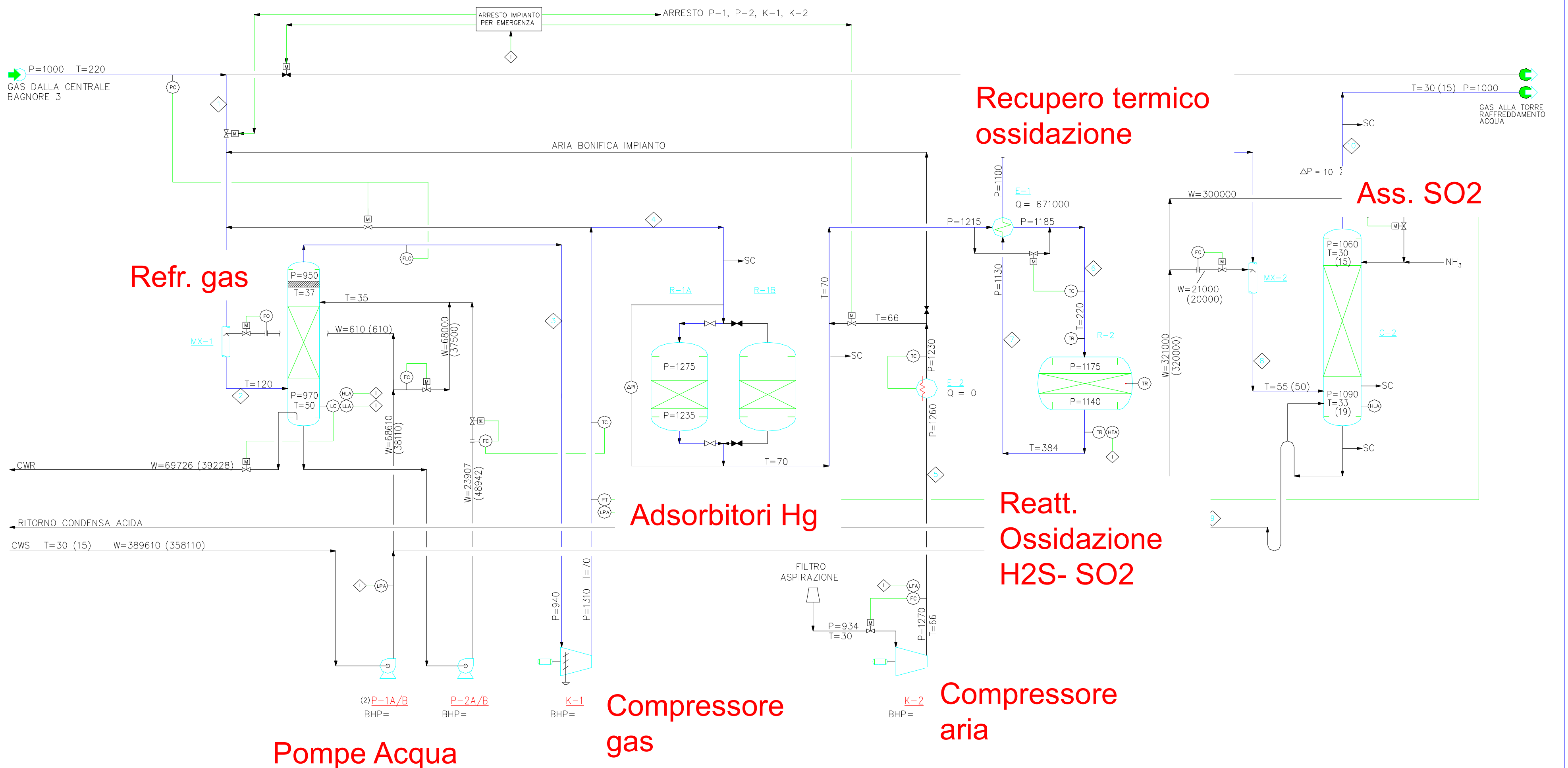
- Conventional Geothermal Power Plants (1-flash, 2-flash, Dry-steam direct expansion) use the Geothermal Resource allowing contact of large discharge flows with the atmospheric environment
- The Geothermal resource fluid is often contaminated with chemical pollutants (e.g. H_2S, possibly Hg and/or traces of heavy metals). Moreover, extensive flows of CO_2 are involved and finally discharged to the atmosphere (this last is often only an extension of the “natural emission” from non-exploited geothermal or volcanic areas)
- There exists a problem of pollution from Geothermal power plants
- A radical solution is to switch to “Binary plants” , which avoid almost completely contact of the geothermal fluid with the atmosphere (the fluid is completely re-injected into the field, after cooling)
- The present technology offers options for “greening” existing plants of the traditional type (AMIS ®)

L'impianto AMIS ® di Bagnore è in grado di trattare una corrente gassosa fino alla portata max di 15600 kg/h, rimuovendo fino a 200 kg/h di H_2S

La scelta fatta finora è stata quella di introdurre sistemi di trattamento chimico, di tipo industriale, per rimuovere efficacemente le specie inquinanti più nocive.



Schema di processo trattamento AMIS® gas incondensabili (cattura H2S, Hg)



APPARECCHI

C–1	REFRIGERANTE GAS	P–1	POMPA ALIMENTAZIONE ACQUA DI RAFFREDDAMENTO
C–2	ASSORBITORE SO_2	P–2	POMPA CIRCOLAZIONE ACQUA DI RAFFREDDAMENTO
E–1	SCAMBIATORE CARICA/EFFLUENTE REATTORE OSSIDAZIONE H_2S	R–1A/B	ADSORBITORI Hg
E–2	PRERISCALDATORE AVVIAMENTO IMPIANTO	R–2	REATTORE OSSIDAZIONE H_2S
K–1	COMPRESSORE GAS		
K–2	COMPRESSORE ARIA		
MX–1	MISCELATORE STATICO COLONNA C–1		
MX–2	MISCELATORE STATICO COLONNA C–2		

NOTE

1.– GLI EQUILIBRI LIQUIDO/VAPORE ASSUMONO CHE TUTTA LA SO_2 E' RIGETTATA NELLA FASE LIQUIDA MENTRE TUTTI GLI ALTRI GAS (CO_2, H_2, CH_4, N_2, O_2, A, E H_2S) SONO RIGETTATI NELLA FASE VAPORE.

2.– DA INSTALLARE FUORI DEI L.B. DELL'IMPIANTO.

3.– I VALORI TRA PARENTESI SI RIFERISCONO ALLA TEMPERATURA MINIMA DELL'ACQUA DI RAFFREDDAMENTO.

LEGENDA

P	=	PRESSIONE	mBARa
ΔP	=	PERDITA DI CARICO	mBAR
T	=	TEMPERATURA	°C
W	=	PORTATA	Kg/hr
Q	=	CALORE SCAMBIATO	Kcal/hr
Q_L	=	PERDITA DI CALORE	Kcal/hr
BHP	=	POTENZA ASSORBITA	KW
CWS	=	ALIMENTAZ. ACQUA RAFFREDD.	
CWR	=	RITORNO ACQUA RAFFREDD.	
SC	=	PRESA CAMPIONE	

REVISIONI

REV.	DATA	DESCRIZIONE	DIS.	APPR.
0	.	PRIMA EMISSIONE	VM	

IMPIANTO
AMIS BG3
IMPIANTO ABBATTIMENTO
MARCIA GAS RICCO, MAX CAPACITA'
SCHEMA DI PROCESSO

CONSER
QUESTO DOCUMENTO E' PROPRIETA' DELLA:
CONSER S.p.A.
LA DIVULGAZIONE E' CONSENTITA SOLO DIETRO PERMESSO SCRITTO

CLIENTE
Erga
Gruppo Enel

PROGETTO	LOCALITA'
A051	BAGNORE

DISEGNATO	CONTROLL.	APPR.	DATA
VM	.	.	.

SCALA	FORMATO	FILE	DISEGNO N°	FG.	DI	REV.
--	--	A051 PFD 06	SP–05	1	1	0

Efficienze AMIS ® /BG3

SINGOLE FASI AMIS:

Filtri demercurizzanti: oltre il 99%

Ossidazione catalitica: oltre il 98%

Assorbimento SO2: oltre il 90%
(in funzione del rapporto NH3/H2S entrante)

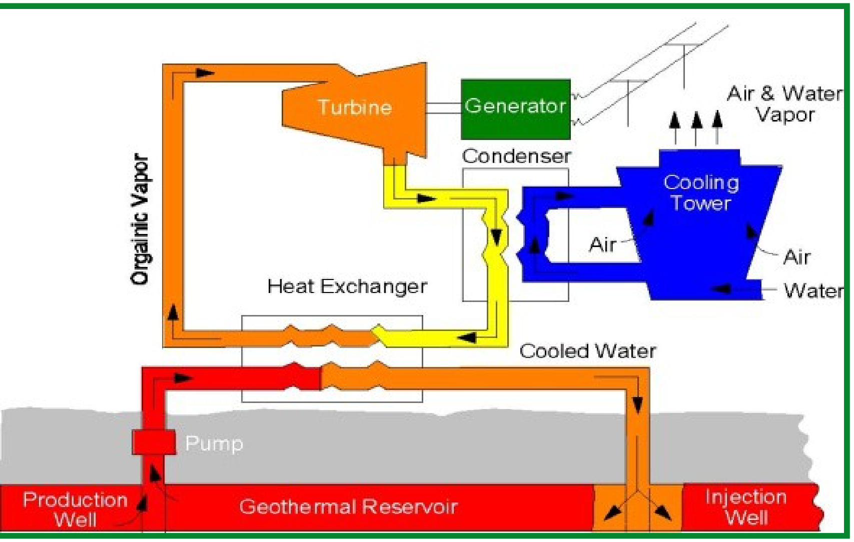
ABBATTIMENTO TOTALE:

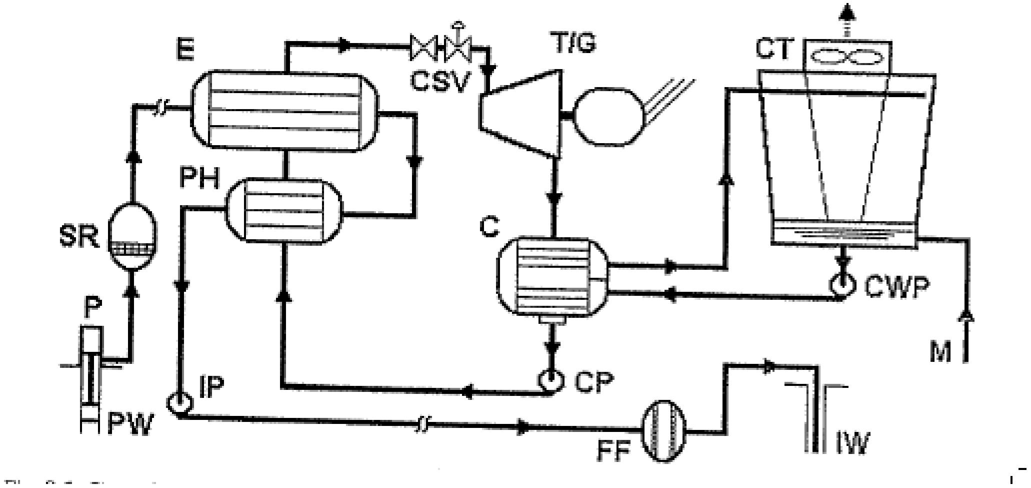
(rispetto al quantitativo in ingresso in centrale)

Overall reduction of plant emission was 95% or higher for mercury and 75% for H2S. The geo-fluid feeding Bagnore 3 plant contains a lot of ammonia (molar ratio H2S/ammonia about 1:3). This on the one hand allows a complete scrubbing of SO2 without chemicals addition and on the other hand increases the buffer capacity of geothermal water. As a consequence, pH decrease after SO2 scrubbing is moderate, limiting the partitioning change towards gaseous phase. This is the reason why overall H2S removal efficiency is limited to 75%.

At Travale 2-3 where chemicals are added (no NH3 in geofluid), both the Hg and H2S removal efficiencies exceed 99%.
Based on these results, since 2006 the AMIS® gas treatment has been systematically added to all relevant existing geothermal power plants operated by

Binary Cycle (ORC) geothermal power plant

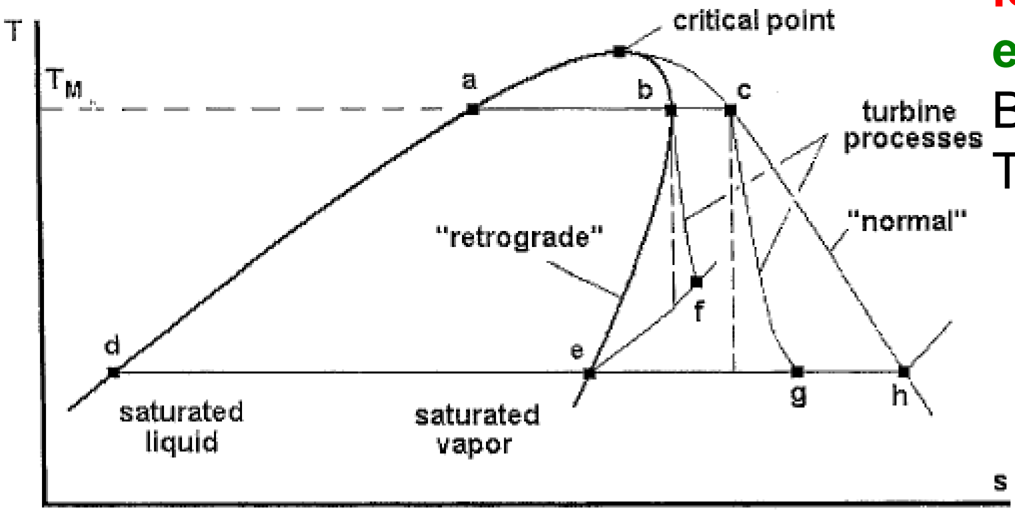




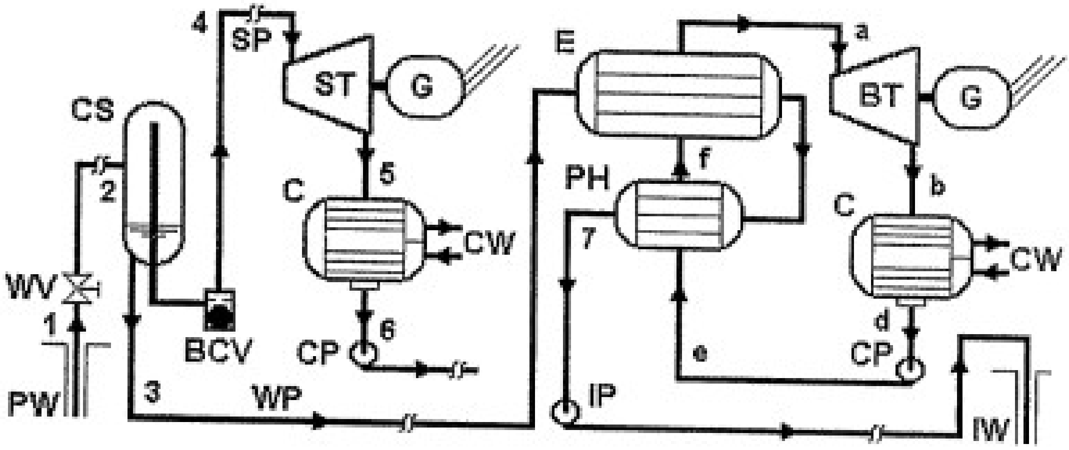
Binary plants operate on a **closed-loop**: **the geothermal fluid is not expanded in the atmosphere**.

Binary (ORC) geothermal power plant.

T-s diagram of thermodynamic cycle

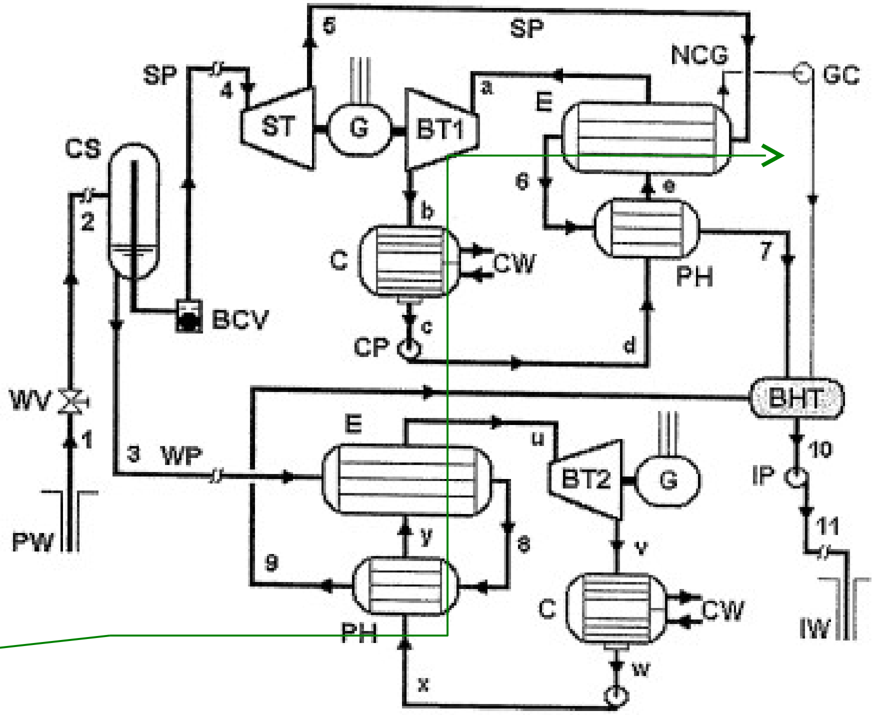


Hybrid single-flash/Binary Cycle (ORC) geothermal power plants



Hybrid binary plants can improve considerably the performance of single- or double-flash geothermal power plants, allowing extended heat recovery from the flash drain (which is re-injected in colder conditions).

Anche negli impianti ibridi si possono adottare soluzioni per evitare il contatto del geofluido con l’atmosfera.



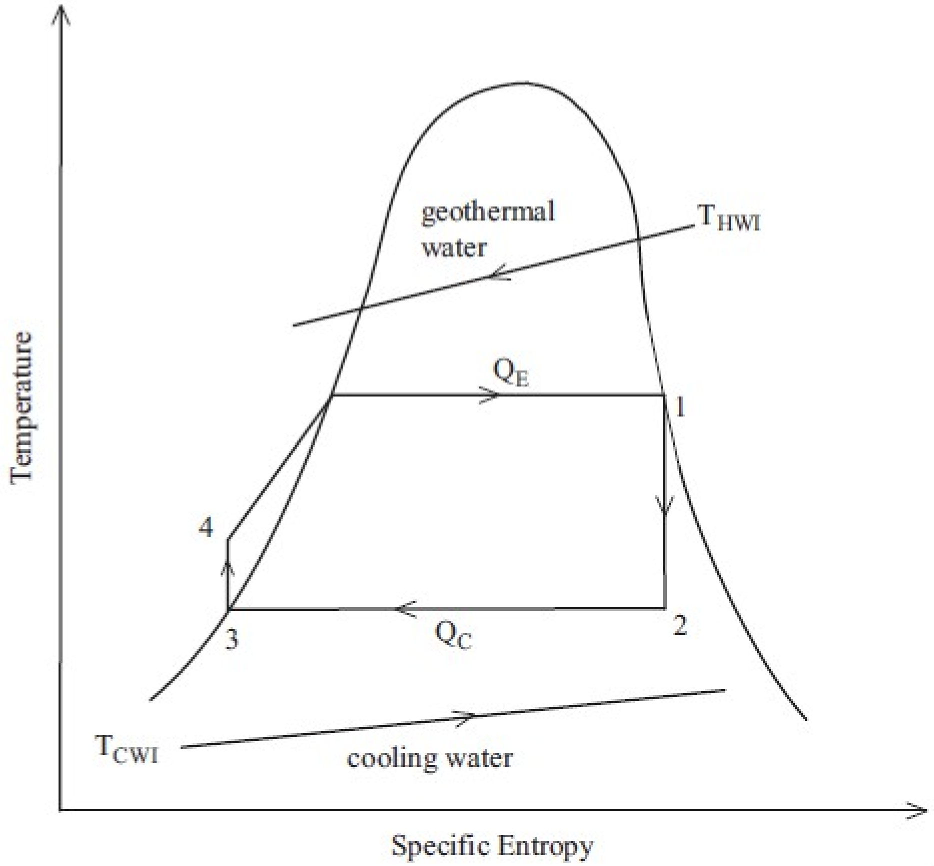
Il problema generale della conversione dell’energia geotermica

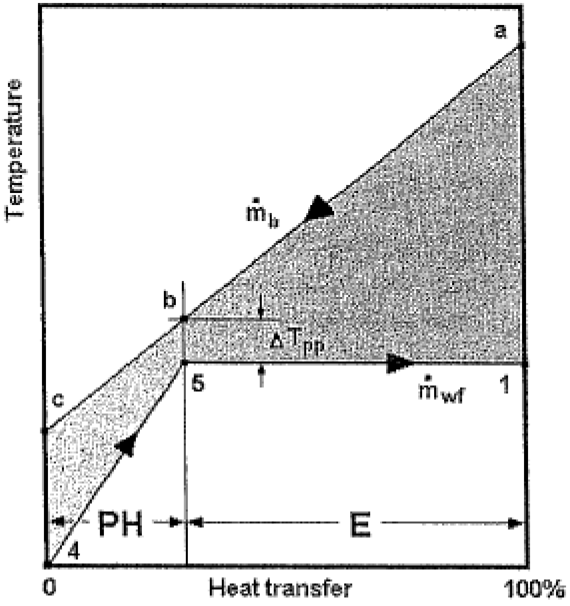
- NON si tratta di una risorsa infinita (serbatoio termodinamico)
- Si ha sempre a che fare con una portata definita entro certi limiti di geofluido, disponibile in certe condizioni (entalpia = circa temperatura) e restituibile in condizioni raffreddate al sistema geotermico
- Si deve sempre attuare un compromesso ottimale tra recupero di energia dalla risorsa e rendimento del ciclo termodinamico di conversione

Il problema generale della conversione dell’energia geotermica - 2

- Negli impianti convenzionali il compromesso equivale alla massimizzazione della potenza prodotta da un pozzo (il “ciclo termodinamico” viene adattato alla curva di producibilità del pozzo)
- Negli impianti binari il compromesso (che equivale alla massimizzazione della potenza) si traduce nel corretto accoppiamento delle capacità termiche tra geofluido e fluido di lavoro nel ciclo; od anche nell’ottimizzazione termodinamica complessiva (recupero energia * rendimento di conversione)
- In realtà il “compromesso” va trovato considerando altri benefici: la limitazione delle emissioni in atmosfera, la conservazione della risorsa, e la produzione di beni importanti collaterali oltre all’energia elettrica (es. calore, freddo)

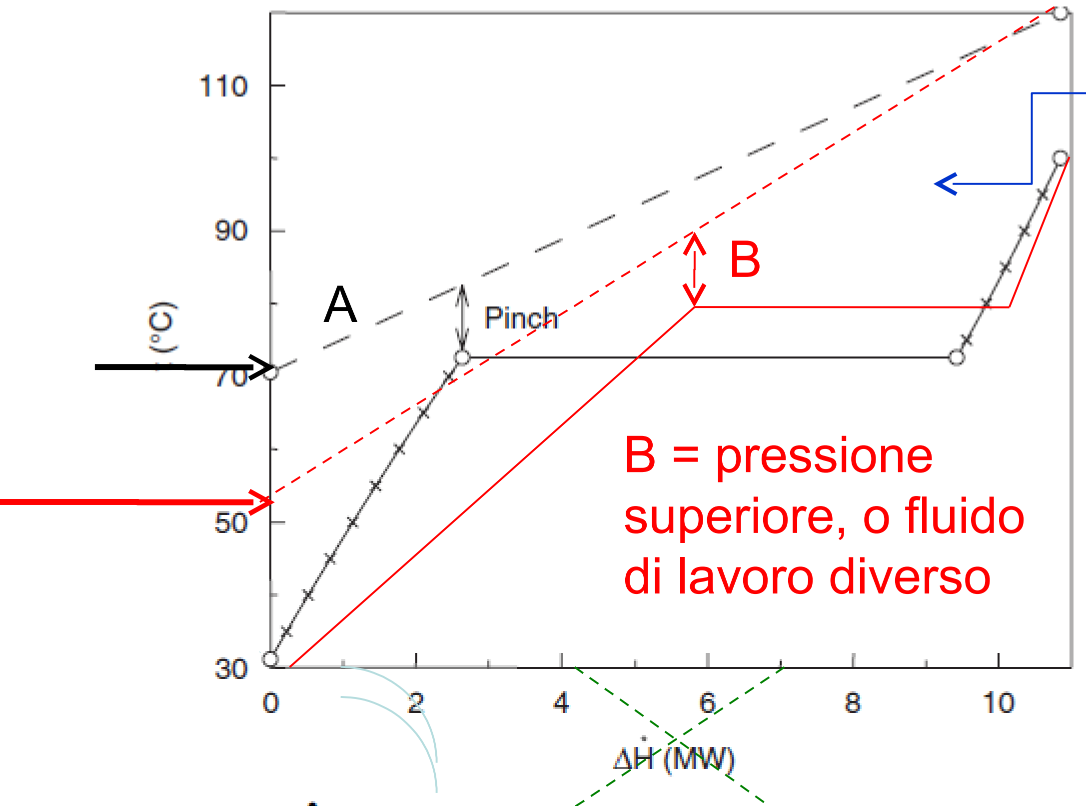
Common Problem in Binary cycles: **matching heat capacities**





One-pressure level
Subcritical cycle

One-pressure level ORC
Subcritical vs. supercritical



B = pressione superiore, o fluido di lavoro diverso

Fig. 9. $T, \Delta\dot{H}$ –diagram for heating R152a in a b3-cycle at 20 bar from state point 2 ($T = 31.16$ °C) to state point 3 (100 °C).

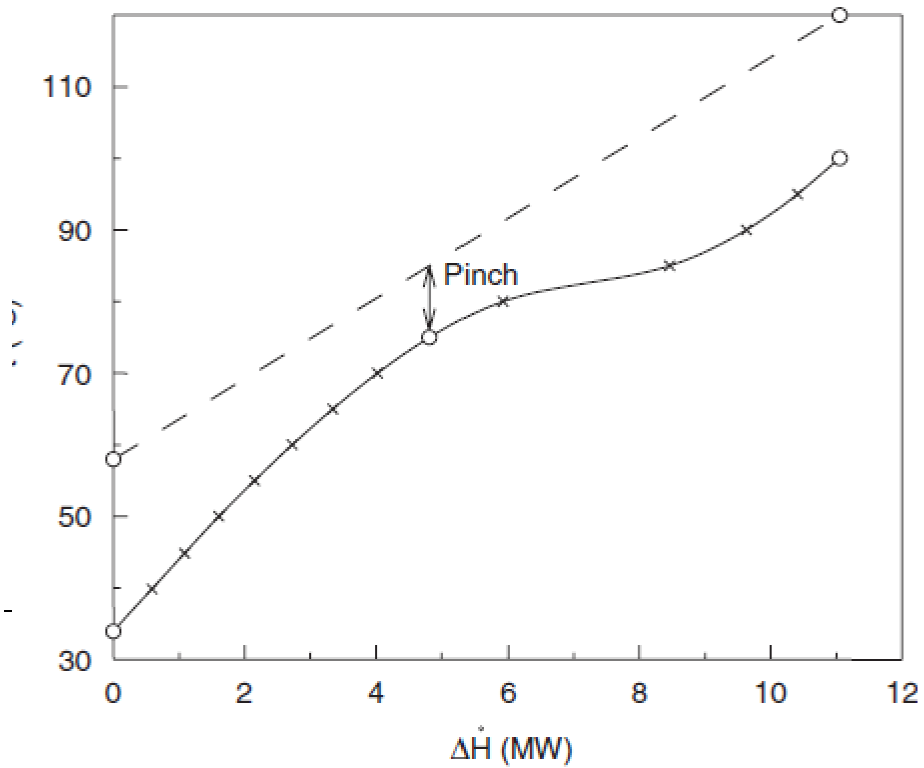
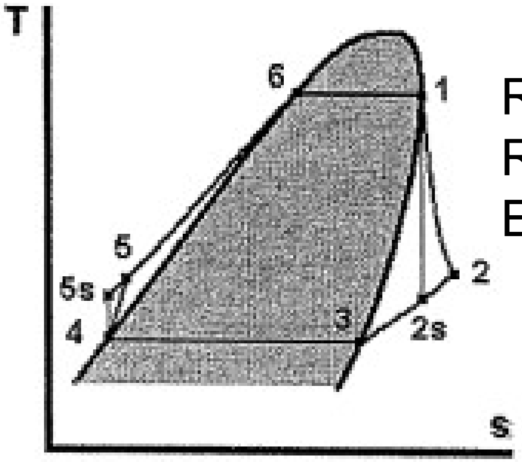


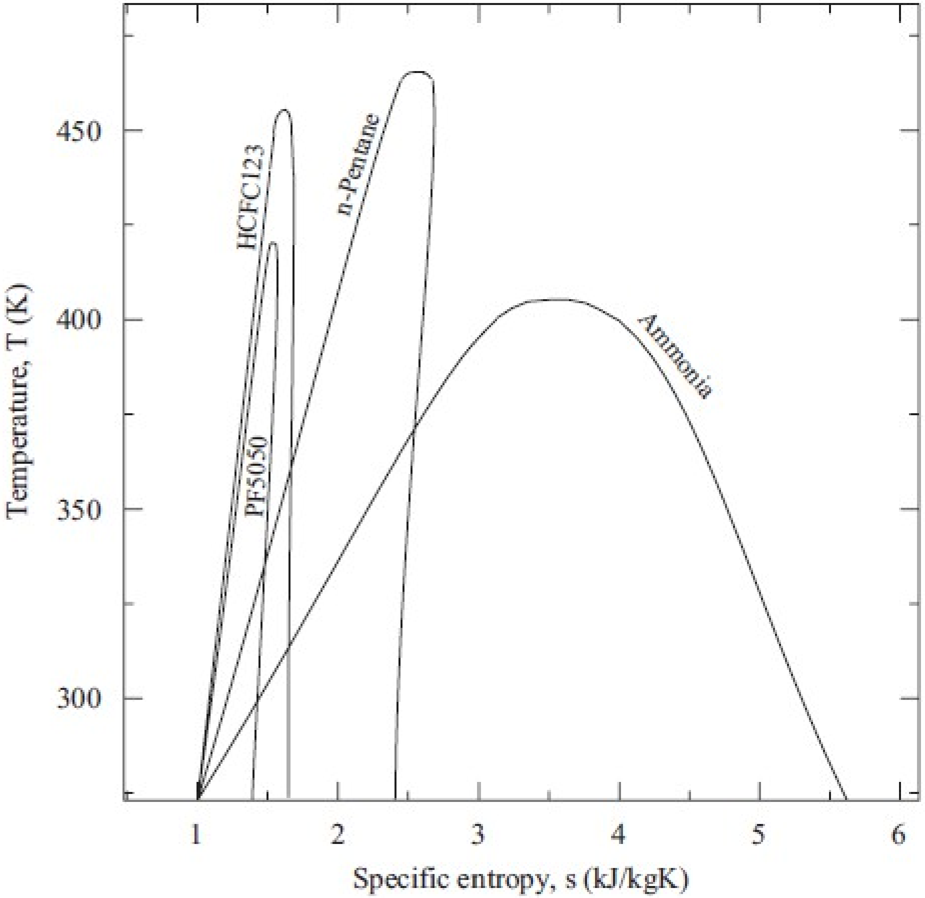
Fig. 10. $T, \Delta\dot{H}$ –diagram for heating R143a in a s2-cycle at 45 bar from state point 2 ($T = 33.93$ °C) to state point 3 (100 °C).

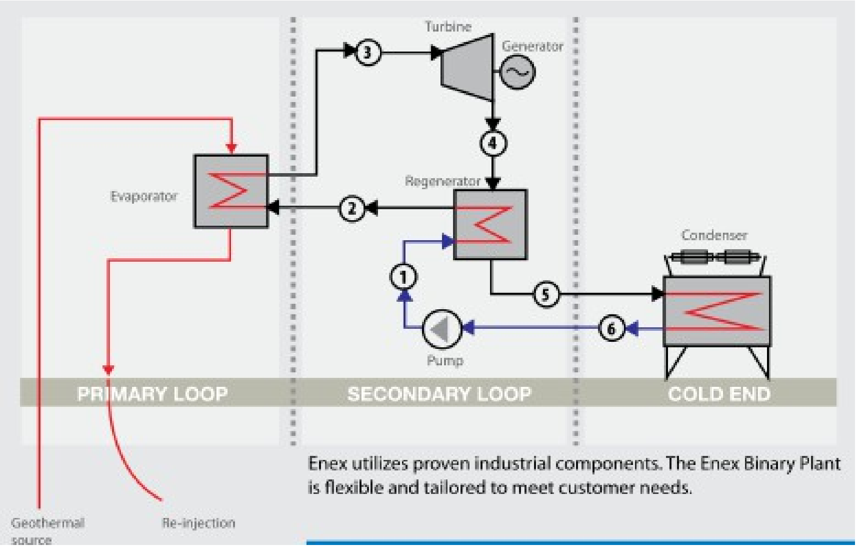
The supercritical option is difficult to implement at low resource temperature conditions, and for small-size plants.

…depending on the shape of the T-s diagram, ORC (binary) power plants may need a recuperator (RHE) at end of expansion



RHE =
Regenerative Heat
Exchanger

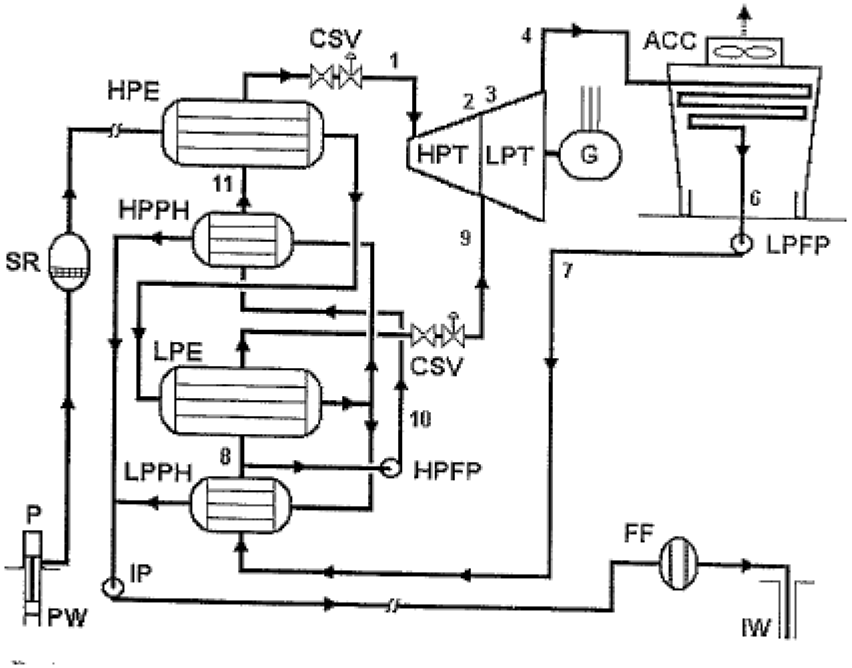


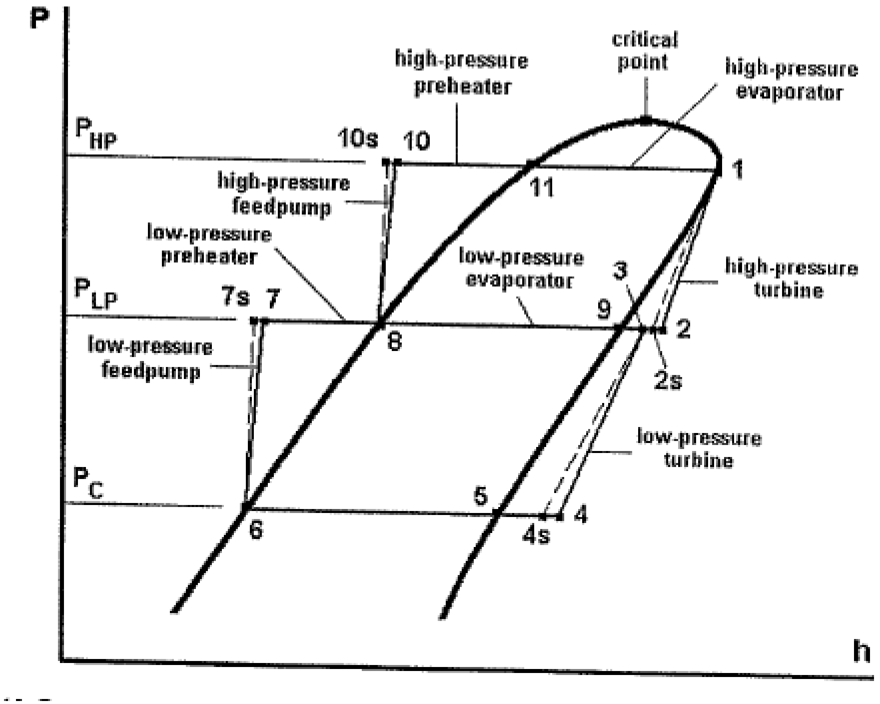


Enex utilizes proven industrial components. The Enex Binary Plant is flexible and tailored to meet customer needs.

ENEX (Iceland) Binary cycle scheme with RHE

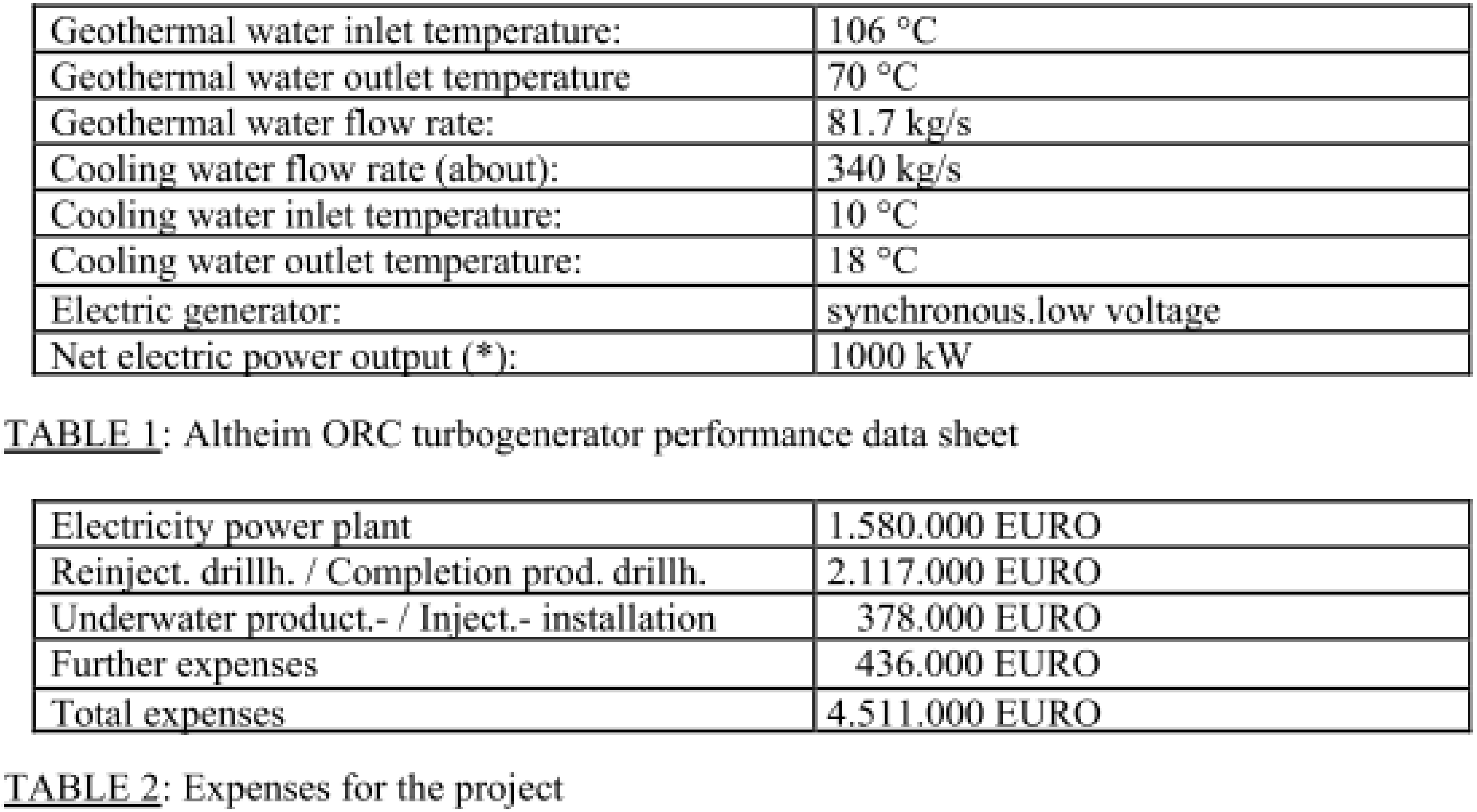
…using **Multple (two) levels of pressure** between geofluid and organic fluid can help to improve correct matching of heat capacities without going to supercritical cycles…





… the matching of heat capacities can require the application of **Pinch Analysis principles** (a technique well known in process engineering, widely applied in oil refineries…)

…Altheim (Turboden -2003) binary plant specifications and performance (+ 10 MW of district heating)…



Geothermal water inlet temperature:	106 °C
Geothermal water outlet temperature	70 °C
Geothermal water flow rate:	81.7 kg/s
Cooling water flow rate (about):	340 kg/s
Cooling water inlet temperature:	10 °C
Cooling water outlet temperature:	18 °C
Electric generator:	synchronous.low voltage
Net electric power output (*):	1000 kW

TABLE 1: Altheim ORC turbogenerator performance data sheet

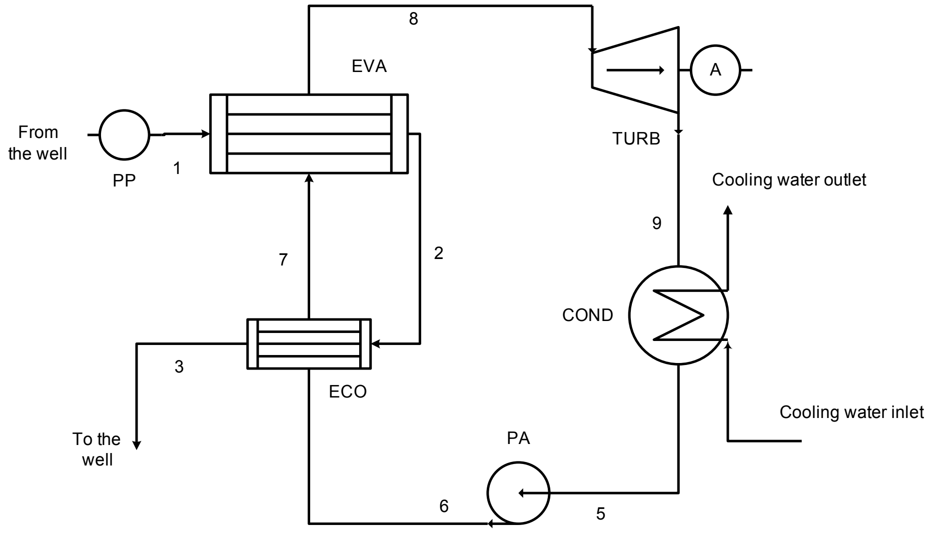
Electricity power plant	1.580.000 EURO
Reinject. drillh. / Completion prod. drillh.	2.117.000 EURO
Underwater product.- / Inject.- installation	378.000 EURO
Further expenses	436.000 EURO
Total expenses	4.511.000 EURO

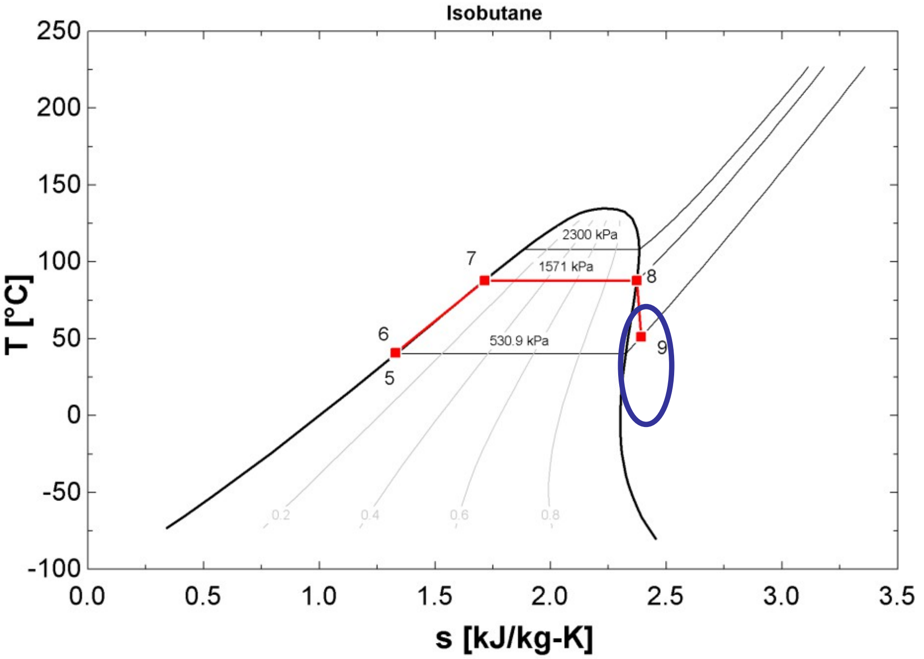
TABLE 2: Expenses for the project

Binary ORC Geothermal plant UniFI EES model

Hydrocarbons

a. m[1]=11.72 kg/s and T[1]=135 °C
b. m[1]=5 kg/s and T[1]=135 °C
c. m[1]=11.72 kg/s and T[1]=90 °C



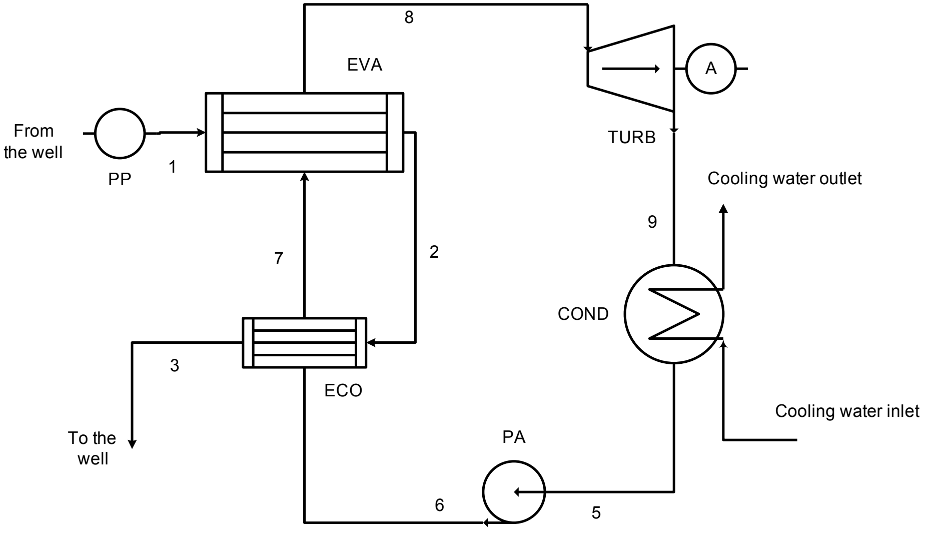


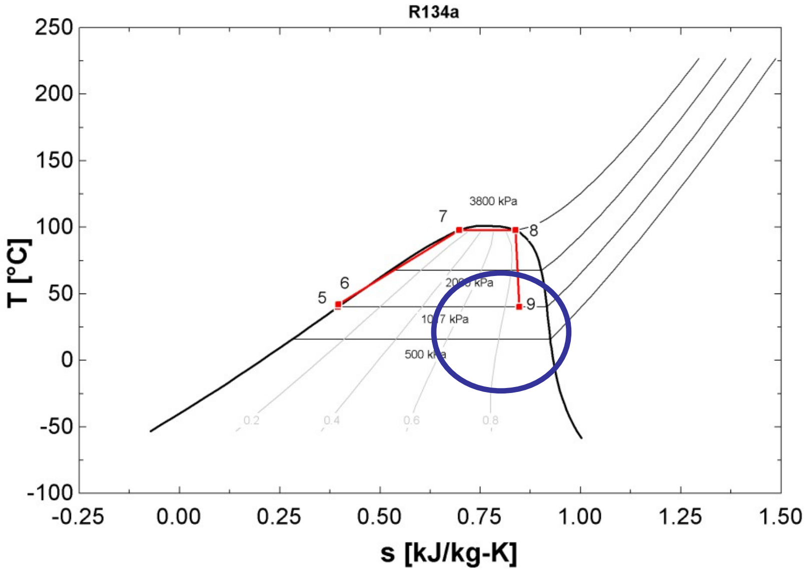
Fluid	Case	p[6]@ max Wnet [kPa]	Wnet [kW]	ηI [%]	x[9] [-]	T[3] [°C]
n-butane	a	1157	268.9	9.25	100	76
	b	1157	114.7	9.25	100	76
	c	659.6	59.34	4.97	100	66
n-pentane	a	415	259.6	9.15	100	78
	b	415	110.7	9.15	100	78
	c	221.9	58.58	4.96	100	66
Isobutane	a	1571	277.9	9.24	100	74
	b	1571	118.6	9.24	100	74
	c	897.5	59.76	4.94	100	65

UniFI EES model

HCFCs

a. m[1]=11.72 kg/s and T[1]=135 °C
b. m[1]=5 kg/s and T[1]=135 °C
c. m[1]=11.72 kg/s and T[1]=90 °C





Fluid	Case	p[6]@ max Wnet [kPa]	Wnet [kW]	ηI [%]	x[9] [-]	T[3] [°C]
R134a	a	3800	407.3	9.28	0.87	46
	b	3800	173.7	9.28	0.87	46
	c	1756	60.52	4.91	0.99	65
R143a	a	2600	152.3	3.39	0.95	44
	b	2600	64.98	3.39	0.95	44
	c	3700	86.74	5.31	0.75	57
R152a	a	3017	284.4	9.72	0.93	76
	b	3017	121.3	9.72	0.93	76
	c	1554	59.24	4.96	0.98	66

Binary ORC UniFI Model (Well-to-electricity)
Exergy analysis

Isobutane

- Exergy efficiency: 28.1 %
- Exergy losses:
  reinjection 39% (T[3]=74°C)
- Exergy destructions:
  evaporator 16%
  condenser 15%
  Turbine 7%

R134a

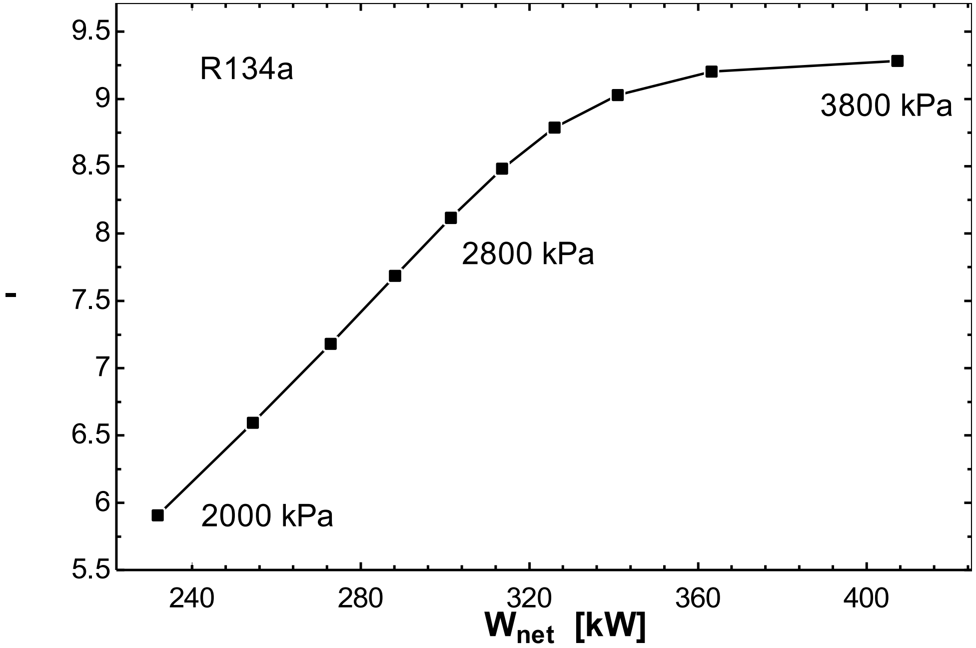
- Exergy efficiency: 41.2 %
- Exergy losses:
  reinjection 28% (T[3]= 46°C…!)
- Exergy destructions:
  evaporator 11%
  condenser 26%
  turbine 14%

Isobutane

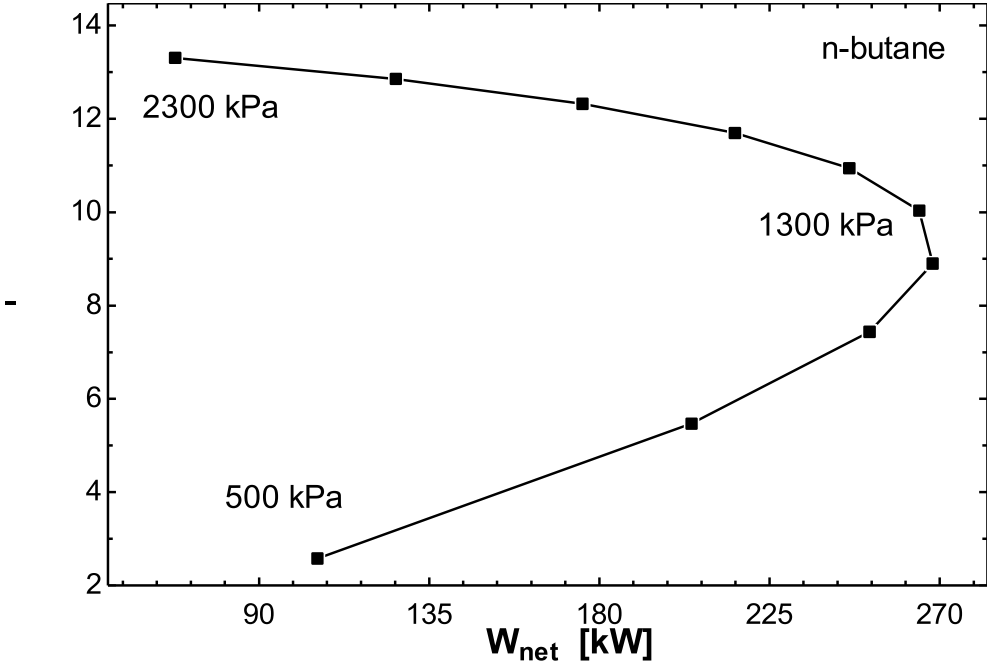
R134a

Binary Cycle (ORC) geothermal power plants

Models show that Organic Fluids or HCFC Refrigerants behave differently in terms of efficiency and power output, with special reference to evaporator pressure level.

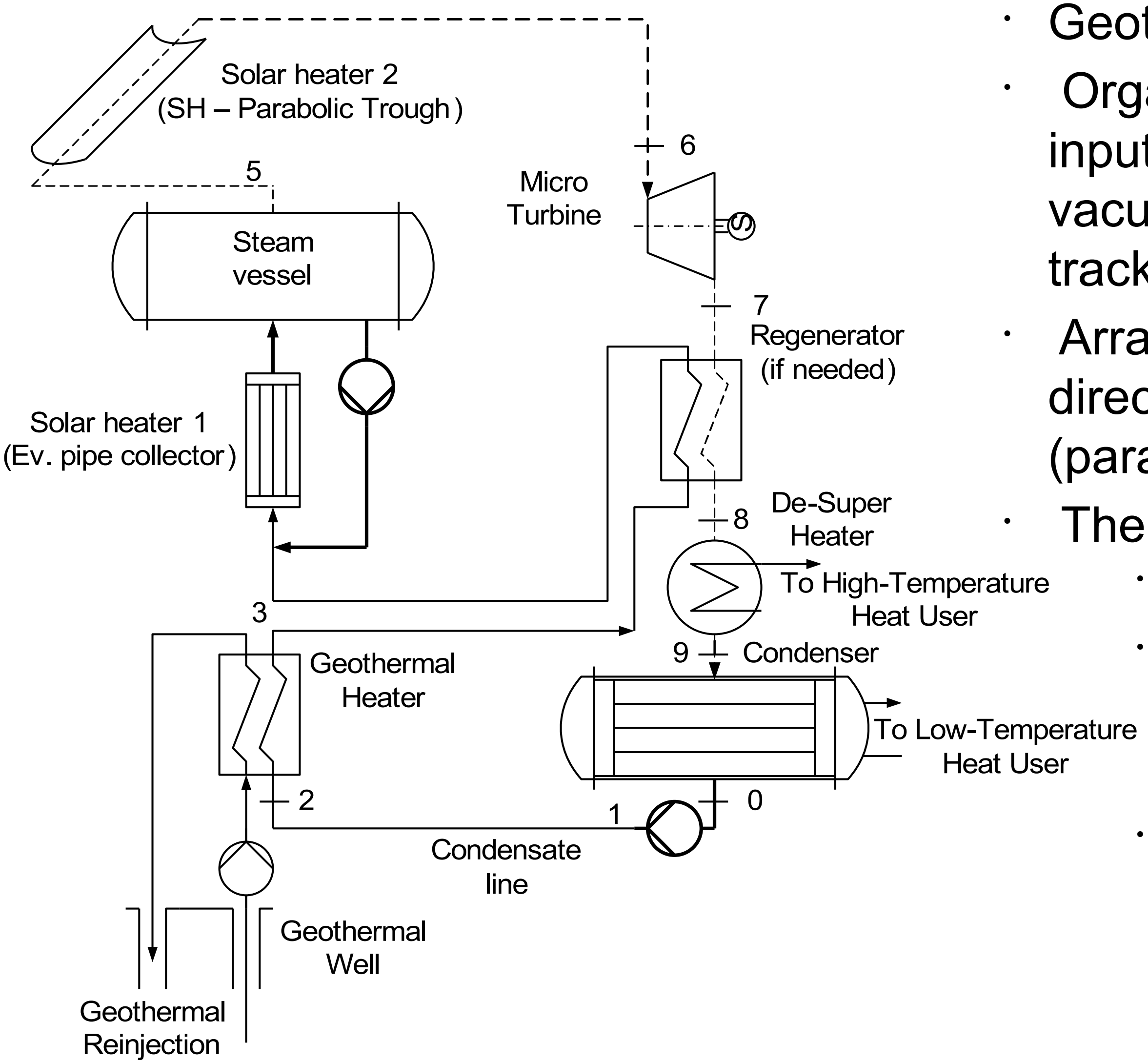


Net work and efficiency with increasing pressure p[6] for **R134a** (trend to supercritical)



Net work and efficiency with increasing pressure p[6] for **n-butane** (optimized at 1300 kPa)

Solar/Geothermal system with ORC microturbine



Circuit description:

- Geothermal heater (e.g. existing well);
- Organic vapour accumulator with thermal input from solar collectors array (typically, vacuum pipe without concentrator or non-tracking concentrator);
- Array of high-temperature solar collectors, direct superheated vapour production (parabolic trough).
- The regenerator is not necessarily needed
  - Micro-turbine;
  - De-Super-Heater connected to high-temperature heat distribution network;
  - Condenser connected to low-temperature heat distribution network.

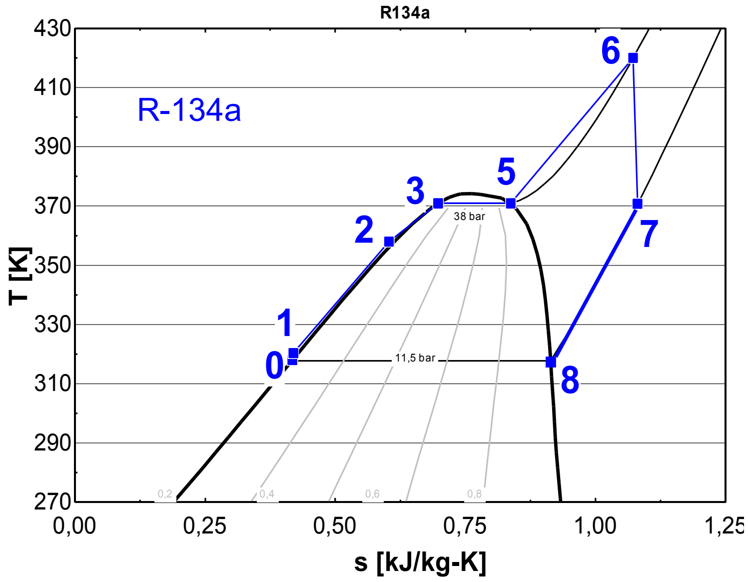
Ottimizzazione del ciclo termodinamico

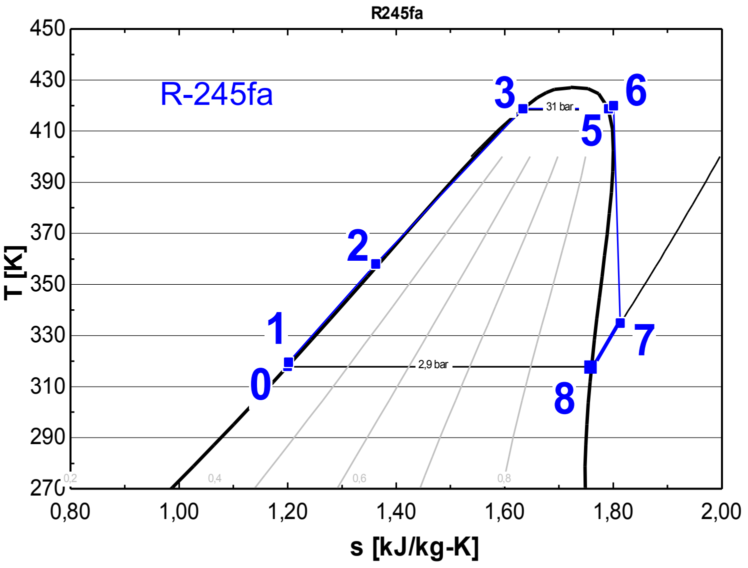
I fluidi frigoriferi utilizzati per i calcoli sono stati scelti in base alle condizioni operative:

- Temperatura della sorgente termica
- Temperatura massima di ciclo
- Pressione al condensatore

ed a criteri prestazionali, di sicurezza e di reperibilità.

Tra i fluidi considerati: R134a, R236fa, R245fa,… CicloEsano





Thermodynamic ORC calculation

Fluid	R134a	CyclHex	N-Pentane	R245fa	R1234yf	R236fa
W [kW]	*50*	*50*	*50*	*50*	*50*	*50*
Rec_Eff	*0*	*0*	*0*	*0*	*0,25*	*0*
T_geoin [K]	*363*	*363*	*363*	*363*	*363*	*363*
T_cond [K]	*318*	*318*	*318*	*318*	*318*	*318*
T_max [K]	*420*	*420*	*420*	*420*	*420*	*420*
p_C [bar]	40,59	40,75	33,6	36,5	33,8	32
T_C [K]	374	554	470	427	368	398
T_DSH [K]	371	358	373	335	369	365
T_geoout [K]	321	321	322	323	333	323
DeltaT_SH [K]	49	1,76	21,8	1,6	56,5	25
p_GV [bar]	38	5	10	31	31	30
p_cond [bar]	11,6	0,298	1,36	2,92	11,5	5
m_f [kg/s]	1,77	0,544	0,67	1,33	2,32	1,83
VFR_7 [m3/s]	0,041	0,6382	0,206	0,088	0,05	0,066
m_geo [kg/s]	0,63	0,2528	0,386	0,43	0,93	0,585
m_solar [kg/s]	1,1	5,73	1,85	3,35	1,234	1,133
A_eff_coll [m2]	338	261	308	252	383	289
[kg/(sm2)]	0,0033	0,0220	0,0060	0,0133	0,0032	0,0039
[kg/(hm2)]	11,72	79,03	21,62	47,86	11,60	14,11

🟧 Negative

🟦 Positive

DSH inlet Temperature

Geoth Well re-injection Temperature

Steam generator Pressure

DSH/Condenser Pressure

Flow rates

Net Absorber surface, solar collectors

Spec. Flow rate Solar Coll.

THD ORC calculation with different working fluids

🟧 Negative

🟦 Positive

Fluid	R134a	CycloHex	N-Pentane	R245fa	R1234yf	R236fa
Eta_sys	9,1	14,6	11,7	13	7,3	9,77
EtaC	10,5	17,2	13,6	15,1	8,5	11,3
Eta_x	13,5	19,4	16,1	18,7	10,7	14,6
FracPump	0,103	0,085	0,024	0,073	0,197	0,17
FracGeo	0,26	0,155	0,188	0,235	0,247	0,265
Q_Geo [kW]	111	44,6	67	72,2	117	97,5
Q_sol [kW]	316	244	288	235	357	270
Q_CHPBT [kW]	280	207	235	236	298	246
Q_CHPAT [kW]	102	31,8	71	24	136	79,7
Q_Rec [kW]	0	0	0	0	45	0
Delta_h_T [kJ/kg]	28,2	91,9	74,5	37,6	21,5	27,3

Efficiencies

← Pump/Turbine Work fractio

← Geothermal Feed Fraction

Heat Rates

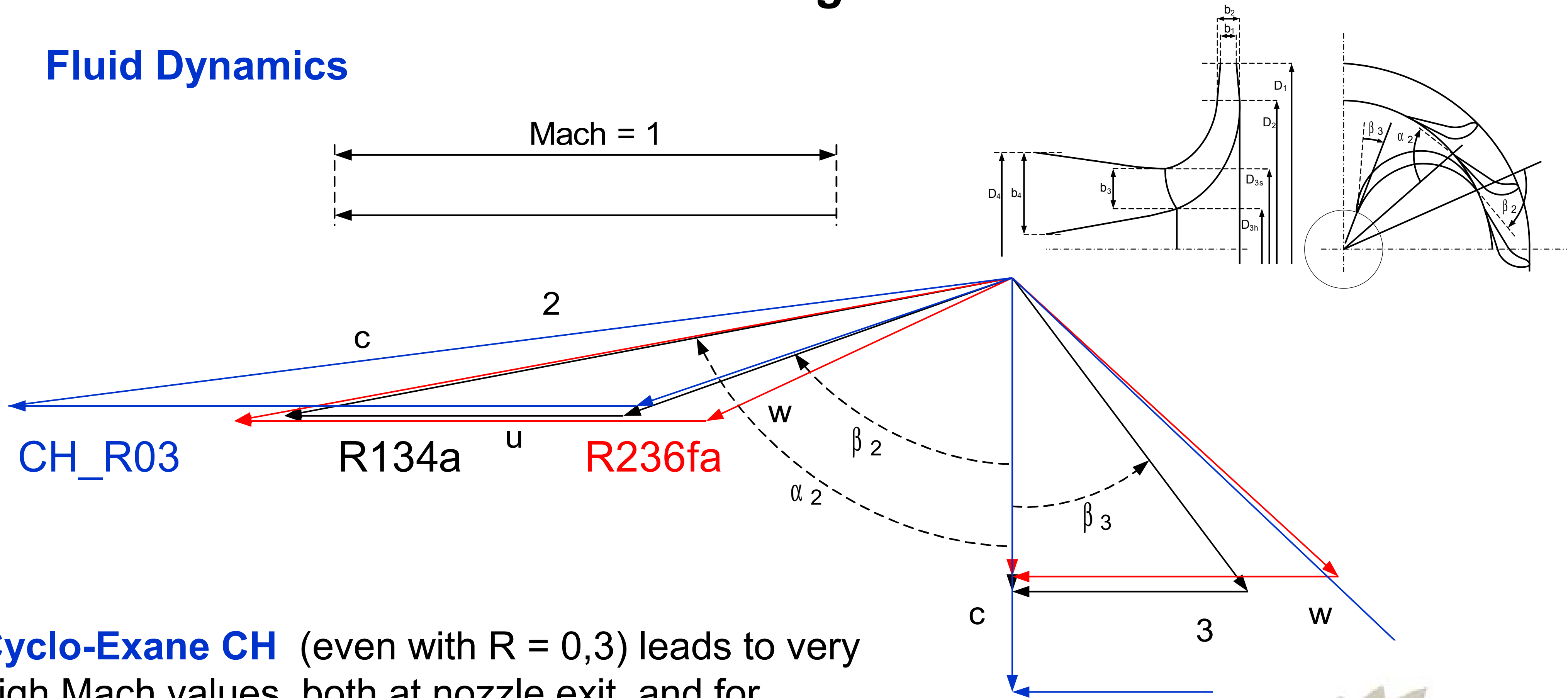
← Turbine Enthalpy drop

(Thermodynamics) Selection of working fluid:

- Best efficiency: Cyclo-Hexane (also, low pressure in steam generator; but vacuum at condenser)
- R236fa maximizes use of geothermal energy (but involves high pump power)
- R245fa, N-Pentane good compromise (moderate pressure in steam generator, slightly pressurized condenser,…)
- The Regenerative Heat Exchanger is necessary only for R1234yf, but its heat duty is small.
- The enthalpy drop is moderate ⇧ single-stage turbines can be proposed

Rotor inlet/exit Mach triangles for different fluids

Fluid Dynamics



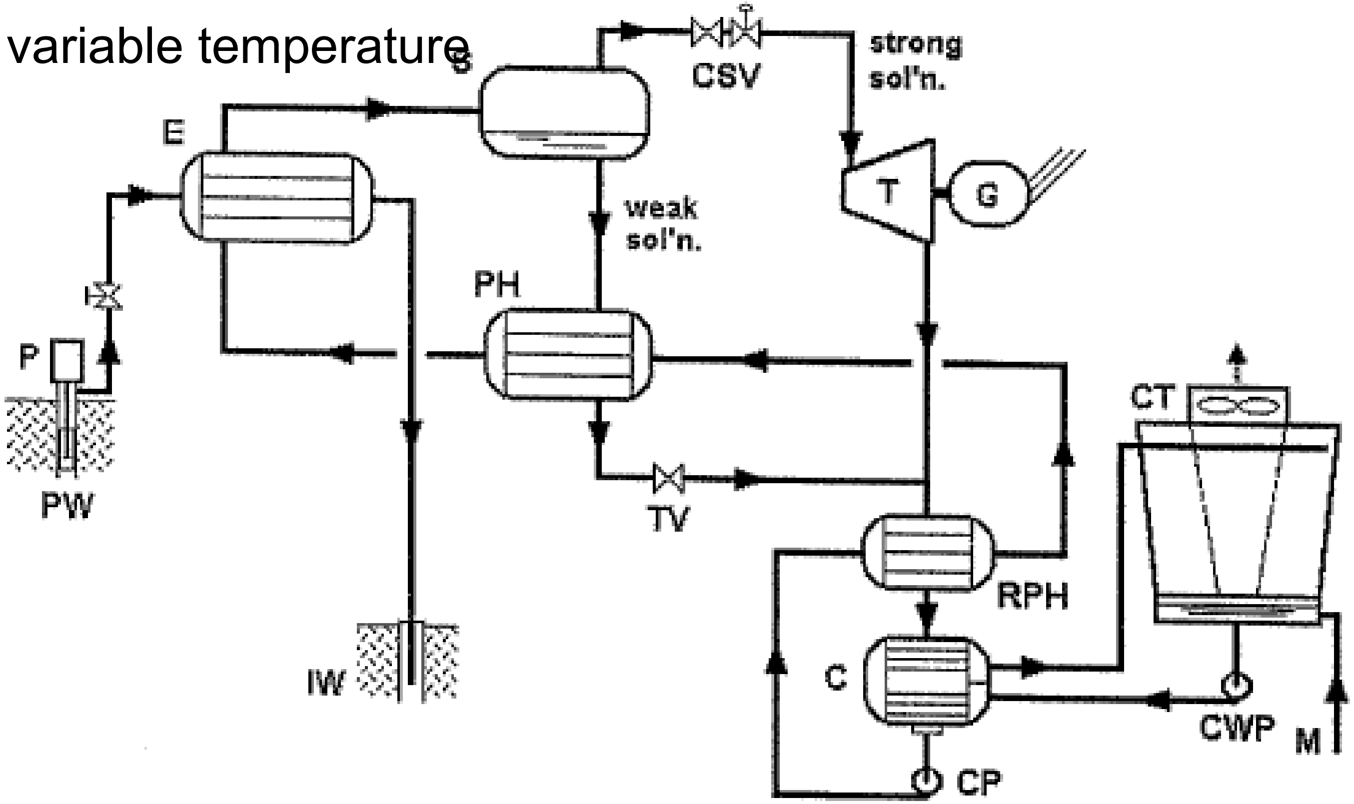
Cyclo-Exane CH (even with R = 0,3) leads to very high Mach values, both at nozzle exit, and for peripheral and meridional Mach number (a good diffuser is needed at rotor discharge)

R236fa is a promising fluid for fluid dynamics performance, similar to **R134a** and with a moderate increase of specific volume after

Kalina Cycle – Variable- composition Ammonia/Water mixture working fluid.

Different approach to the problem of matching heat capacities
(getothermal resource/working fluid)

Evaporation/condensation at variable temperature
(Zeotropic Mixture)



The Kalina cycle concept allows variable temperatures during phase-change processes

(…"Zeotropic mixture"….)…

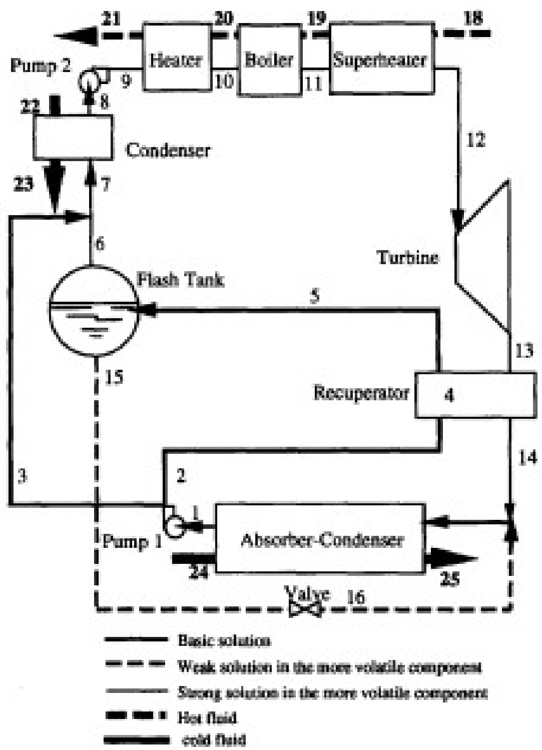
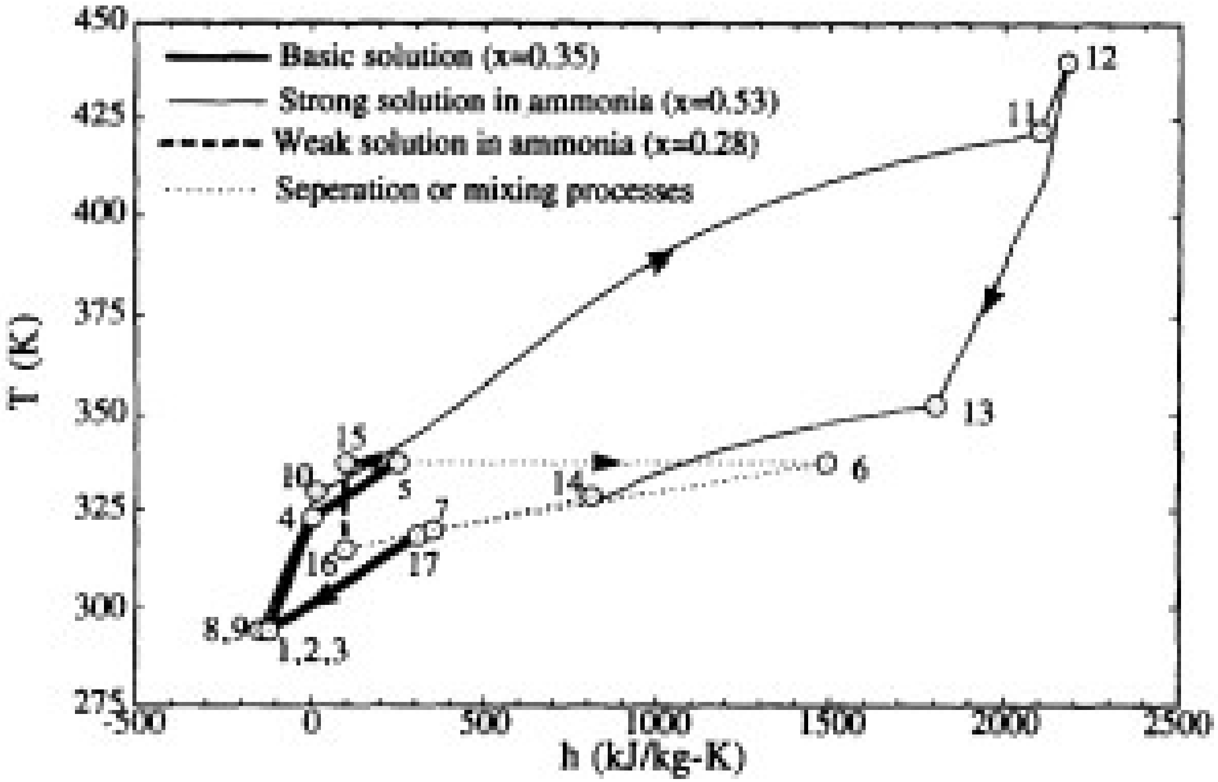


Fig. 4. The Kalina cycle.[2]



…. With interesting performance figures…

…(Water-ammonia cycles)….
Tamm and Goswami, 2004

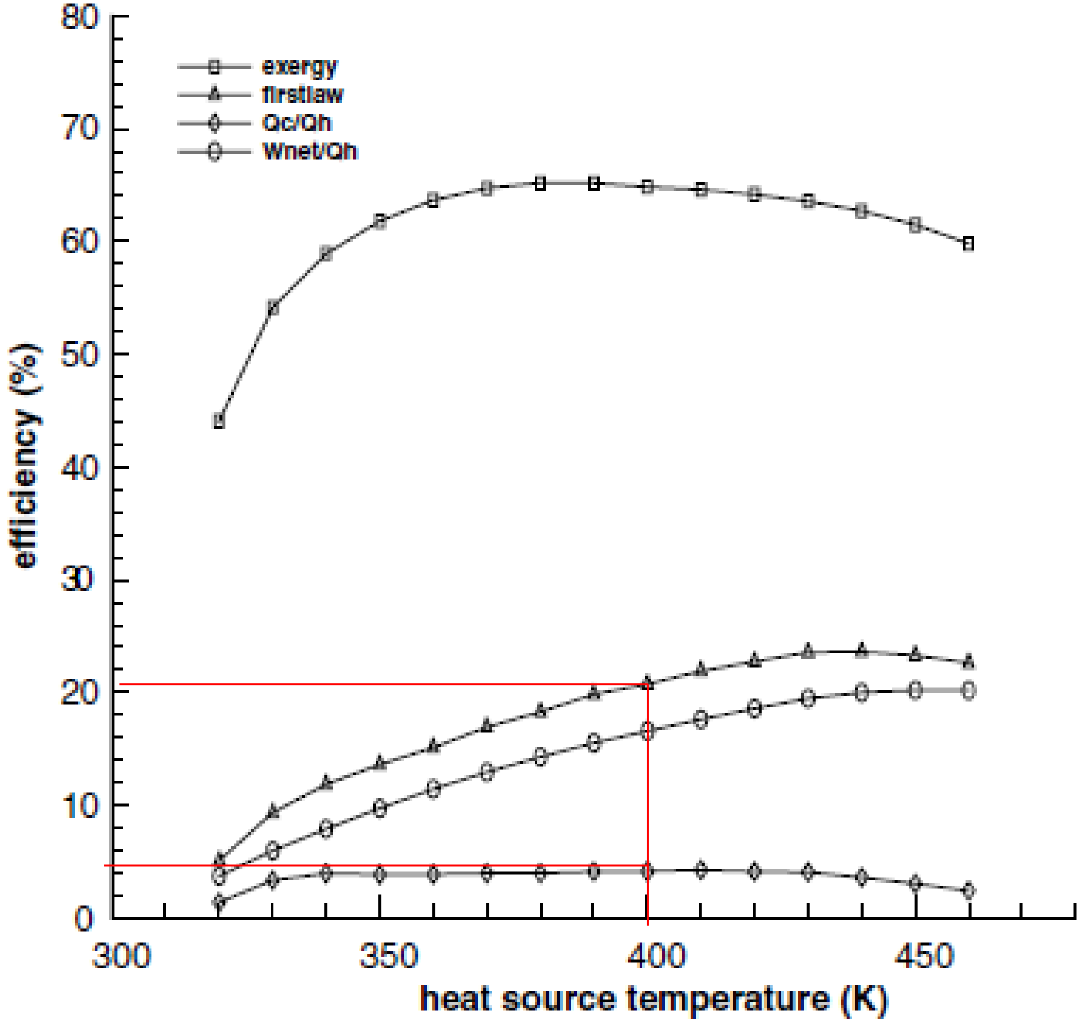


Fig. 4. Efficiencies of the optimized cycle at various heat source temperatures, optimized for second law efficiency.

A flow sheet for the Kalina saturated cycle is shown in Figure 20.

The fluid is not boiled entirely in the vaporizer, and the vapour- liquid mixture is separated afterwards.

The geothermal fluid enters the well at the source inlet temperature, station *s1.*

The geofluid is liquid water (or hot geothermal brine).

If the pressure is kept sufficiently high, no non-condensable gases will be separated from the liquid, and a gas extraction system is not necessary.

The geofluid is then cooled down in the vaporizer, and sent to re-injection at *station s2.*

Kalina cycle

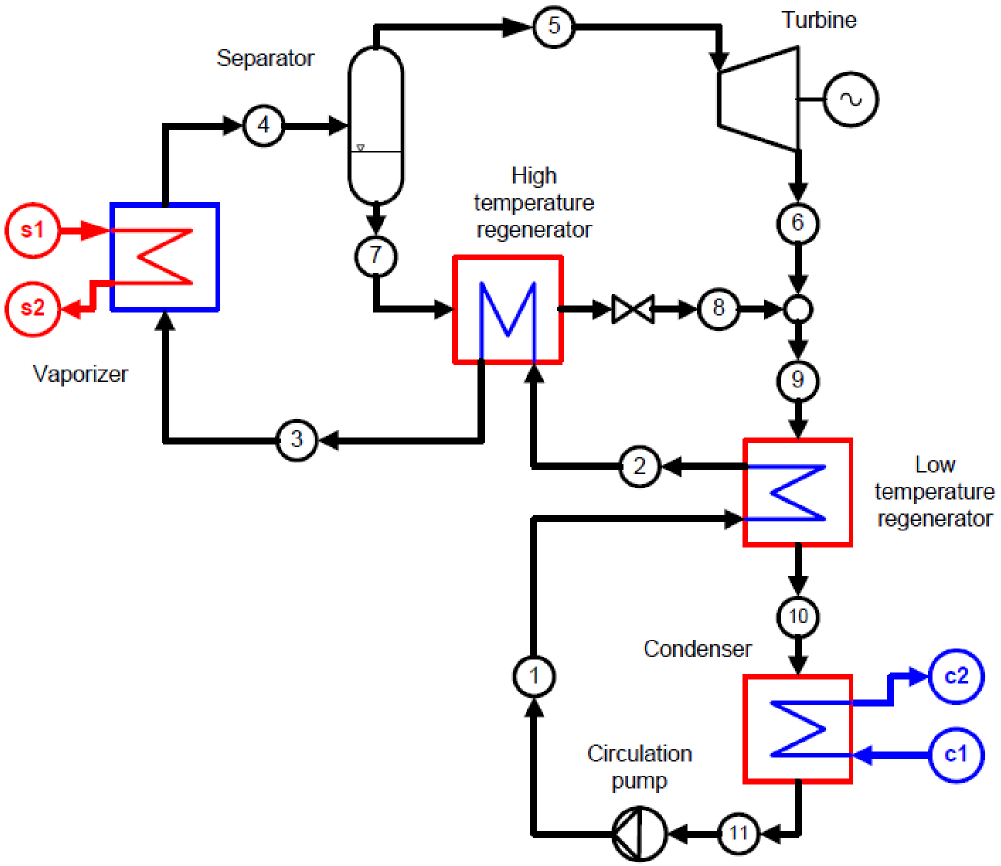


FIGURE 20: Flow diagram of a saturated Kalina cycle

Kalina cycle

A mixture of ammonia and water boils changing the chemical composition. The vapour is ammonia – rich, whereas the liquid is leaner.

This results in a variable temperature during the heat transfer process both in the vaporizer and the condenser. Figure 21 is a heat exchanger diagram for a vaporizer, where typical curves have been drawn both for isopentane and 80% ammonia – water mixture.

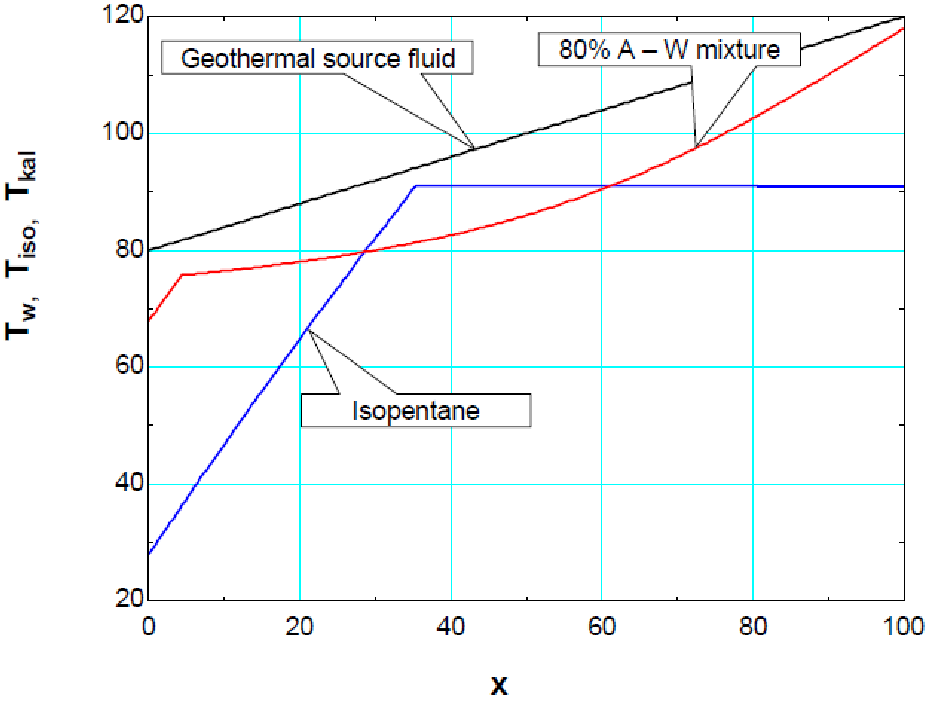


FIGURE 21: Heat exchanger diagram for a vaporizer in a binary power plant
x=100 is at geothermal fluid entry, and x=0 at the outlet

The temperature difference between the primary and the secondary fluid in the Kalina vaporizer is small compared for the isopentane vaporizer, for similar pinch temperature difference.
Entropy is generated whenever heat is transferred over a finite temperature difference, thus the entropy generation in the Kalina vaporizer is lower, as is the destruction of exergy.

A similar situation occurs in the **condenser**.

Ammonia rich vapour is absorbed and condensed, with the associated changes in chemical composition of both liquid and vapour.

Figure 22 is a heat transfer diagram for isopentane and ammonia – water mixture in a water-cooled condenser.

Both fluids have the pinch point internally in the condenser.

The isopentane will obviously have the pinch at the liquid vapour point, but pinch conditions for the ammonia – water mixture must be determined by a complete, step-by-step variable-heat-capacity model.

Kalina cycle

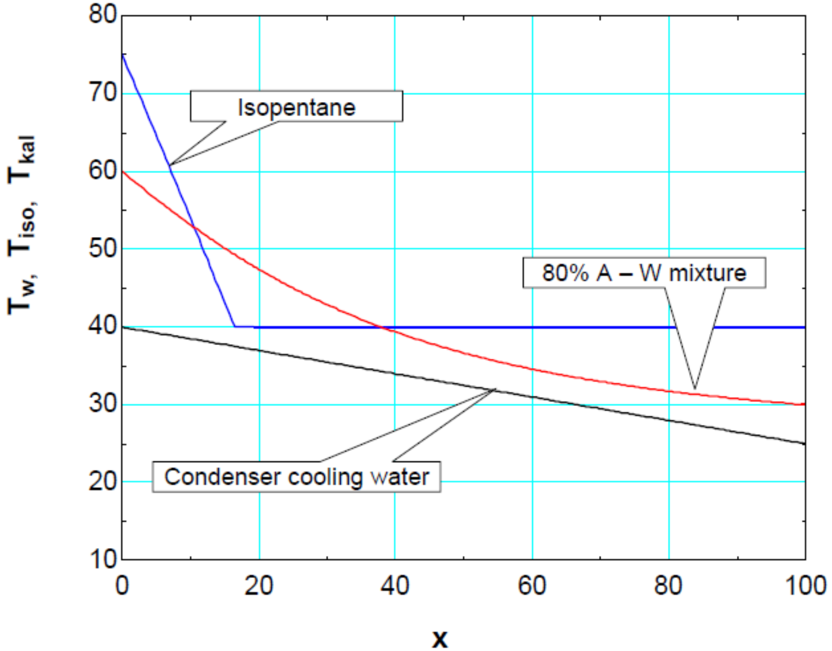


FIGURE 22: Heat exchanger diagram for a condenser in a binary power plant x=100 is at cooling water entry, and x=0 at the outlet

Water-ammonia cycles can be extended to other configurations, including dual-purpose plants (electricity+ refrigeration).
They can be adapted to many cases of low-temperature energy sources…..

Tamm and Goswami, 2004

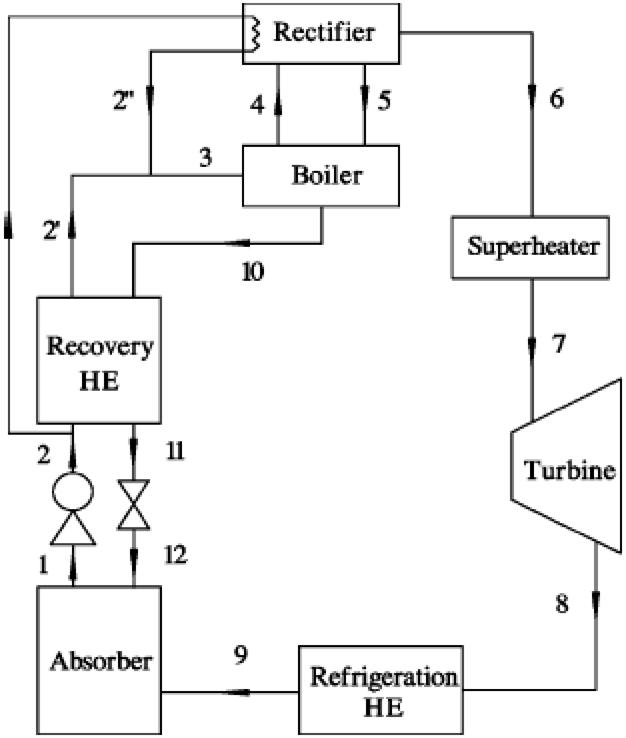


Fig. 1. Schematic of the power and cooling cycle, as used in the theoretical studies.

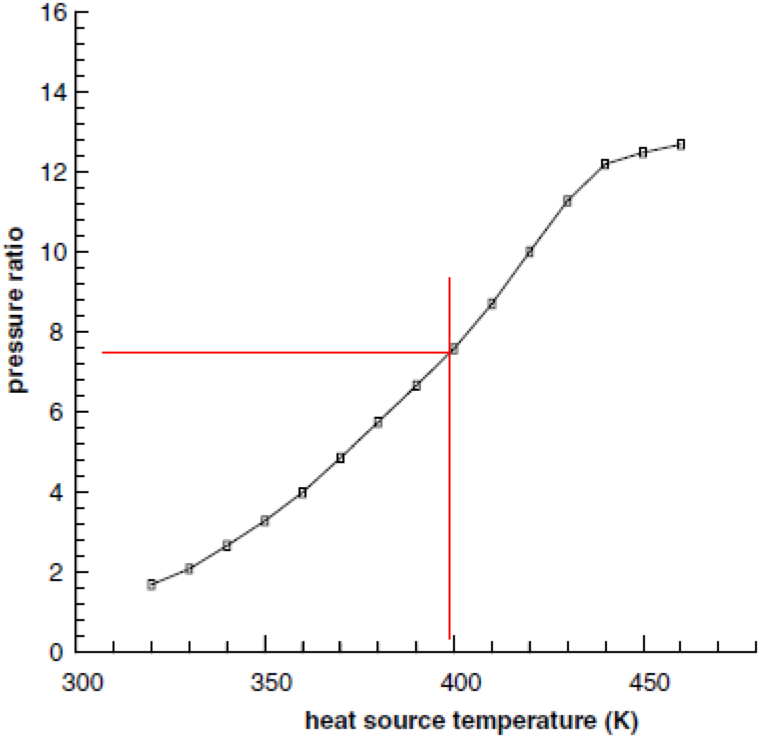
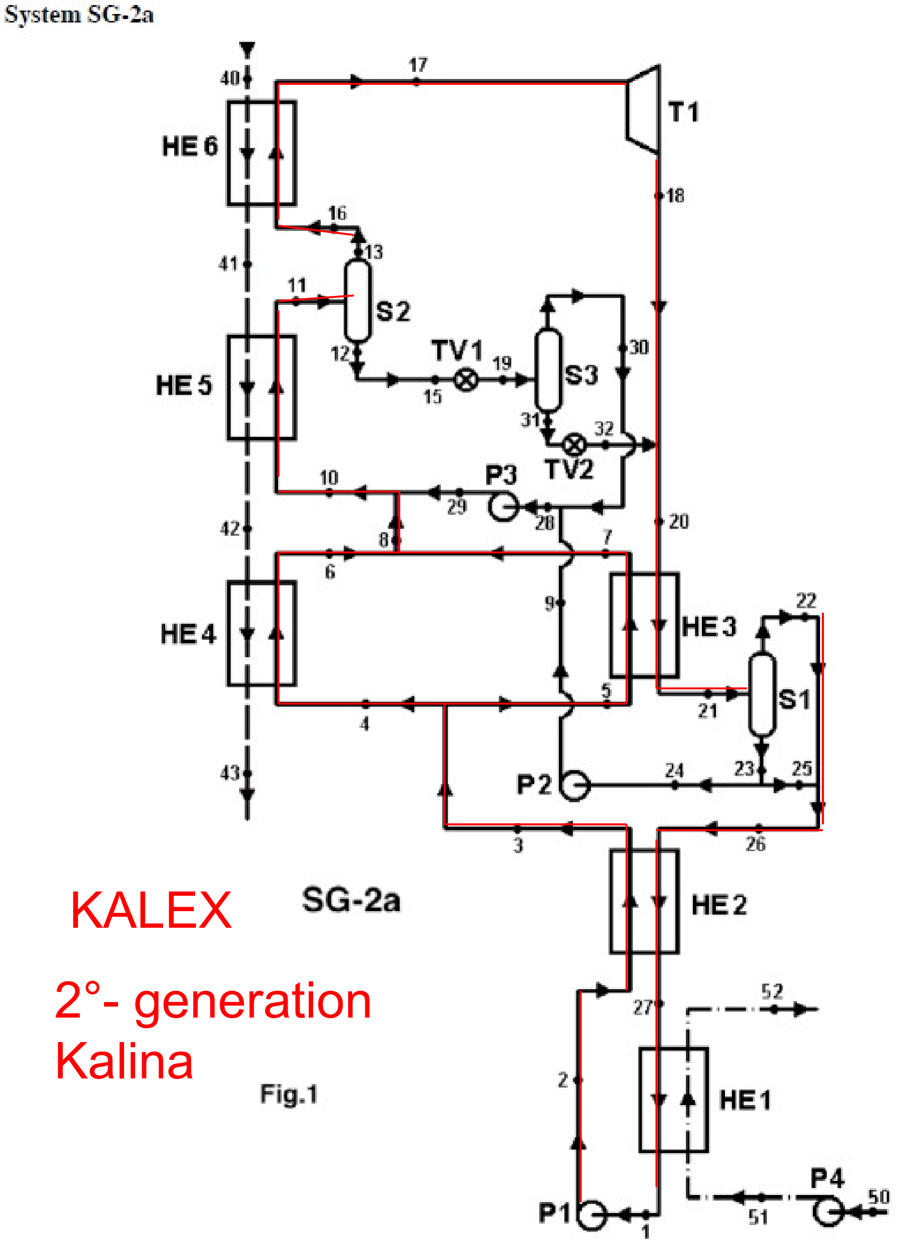


Fig. 5. Pressure ratio of the optimized cycle at various heat source temperatures, optimized for second law efficiency.

I nuovi sistemi Kalina (KALEX) adottano una circuitazione molto più complessa, adatta per impianti di una certa taglia (> 5 MWe) e destinati alla sola produzione di energia elettrica.

Lo scopo del circuito più complesso è di migliorare ancora sia il recupero della risorsa geotermica (scaricando il geofluido raffreddato a temperatura più basse), sia il rendimento del ciclo termodinamico.

Kalex ha ceduto la licenza internazionale a diversi soggetti industriali.

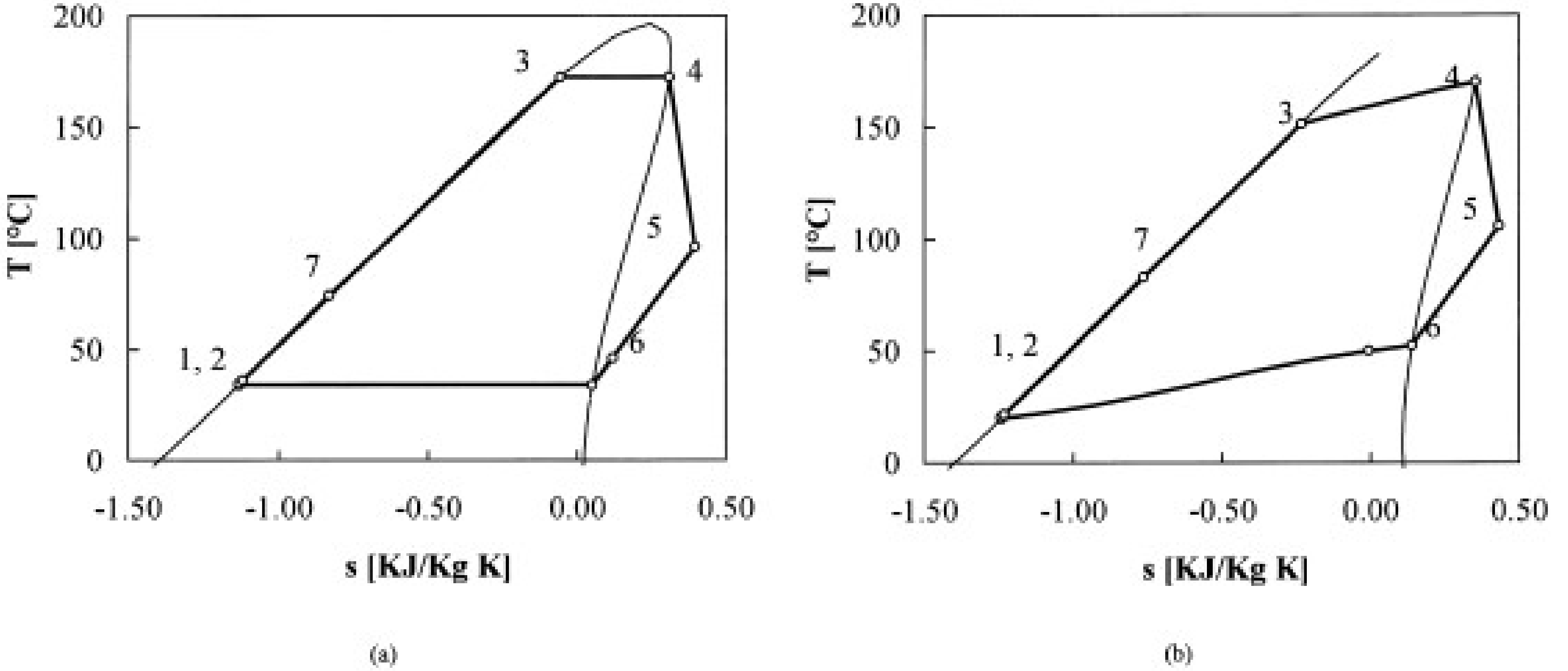


KALEX

2°- generation Kalina

…. The future of low-temperature resources will see the combination of Organic Fluid Cycle technology with use of **zeotropic mixtures of hydrocarbons** (Kalina-concept), allowing imroved matching of heat capacities without necessarily going to supercritical …

G. Angelino, P. Colonna di Paliano, 1997

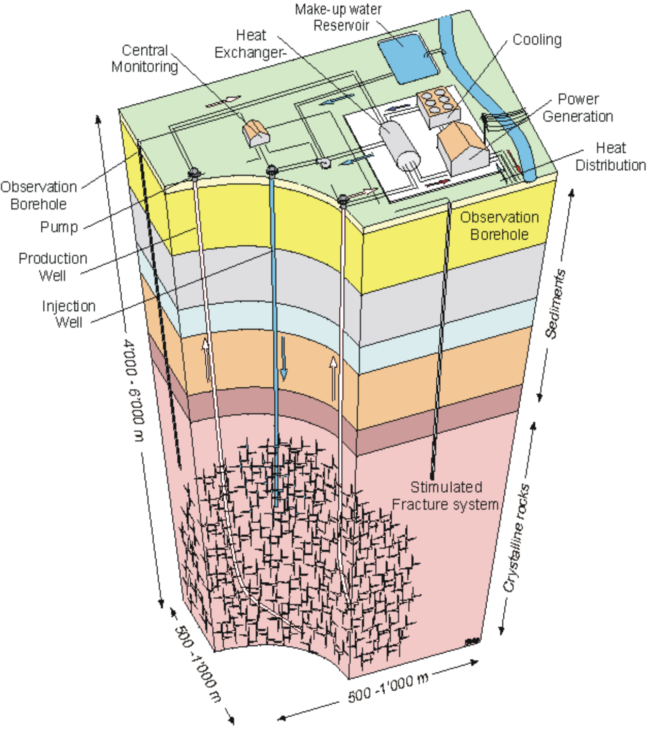


(a)

(b)

Fig. 12. Comparison between an n-pentane regenerative cycle (a) and an equimolar n-butane/n-hexane cycle (b) in the T-s plane. Fluid parameters are selected so that $T_{eq,min}$ and $T_{eq,max}$ are the same for both cycles.

Nuove frontiere: EGS (Sistemi geotermici ingegnerizzati)

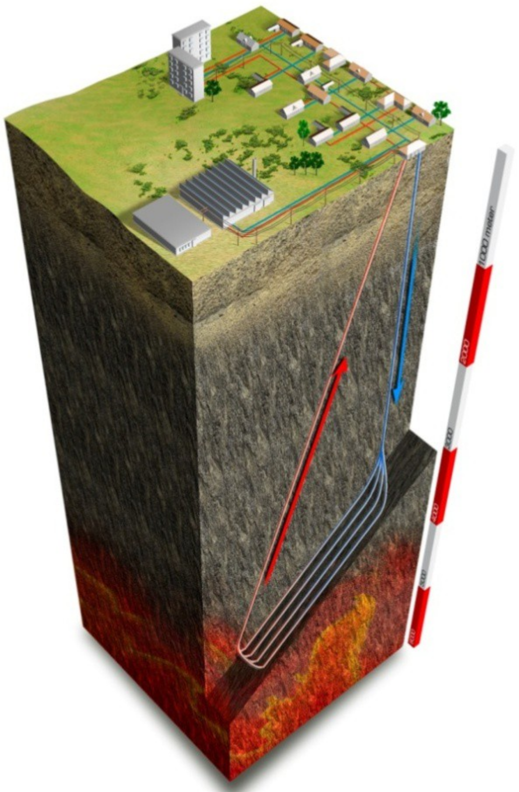


Concept of the Deep Heat Mining System

© Häring Geo-Project

Ci sono vari progetti di Ricerca e Sviluppo in corso:

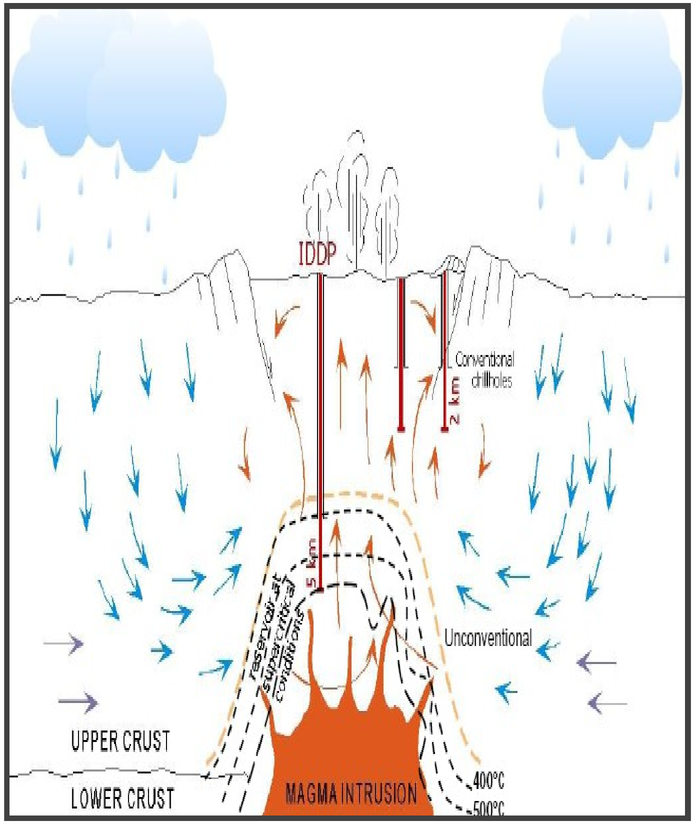
- Il progetto europeo "EGS Pilot Plant" a Soultz-sous-Forêts (Francia), attivo dal 1985. Attualmente è presente un impianto di generazione elettrica (1.5 MWe) che utilizza la risorsa geotermica a 200°C.
- Altri progetti realizzati in Europa (Austria, Germania)
- Australia: attività di larga scala è attualmente in corso
- USA _ DOE sta finanziando vari progetti



Norvegia _ studio di fattibilità per impianto a ciclo chiuso da 5 MW

Gli Enhanced Geothermal Systems, nonostante siano ancora a livello sperimentale, rappresentano una grande opportunità di sviluppo per la geotermia nel medio- lungo periodo

Nuove frontiere: Fluidi supercritici e sistemi magmatici



L’acqua raggiunge lo stato supercritico quando la sua pressione e la sua temperatura superano rispettivamente 218.3 atm e 374.1°C..

	Pozzi geotermici convenzionali	Pozzi supercritici
Temperatura	235 °C	430-550 °C
Pressione	30 bar	230-260 bar
Flusso volumetrico	0.67 m3/s	0.67 m3/s
Potenza elettrica	Circa 5 MWe	Circa 50 MWe

In Islanda è stato avviato un progetto pilota per verificare la fattibilità di reperire ed utilizzare fluidi supercritici (Iceland Deep Drilling Project).

…Credits/List of references

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