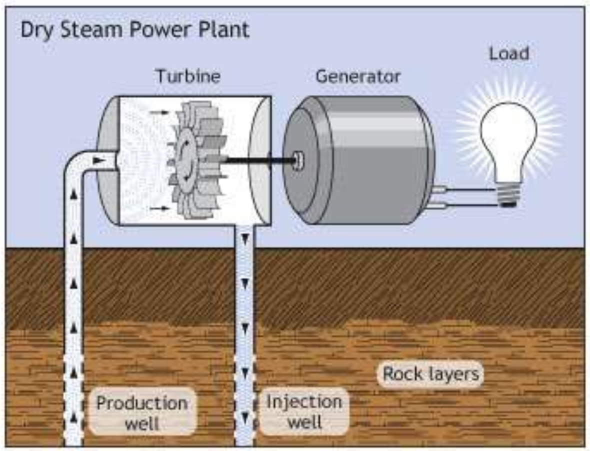
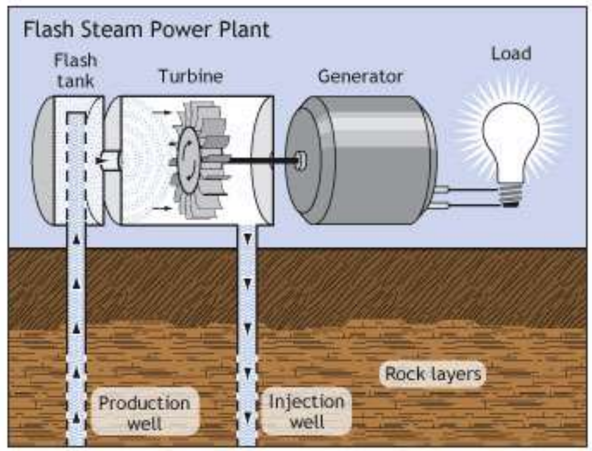
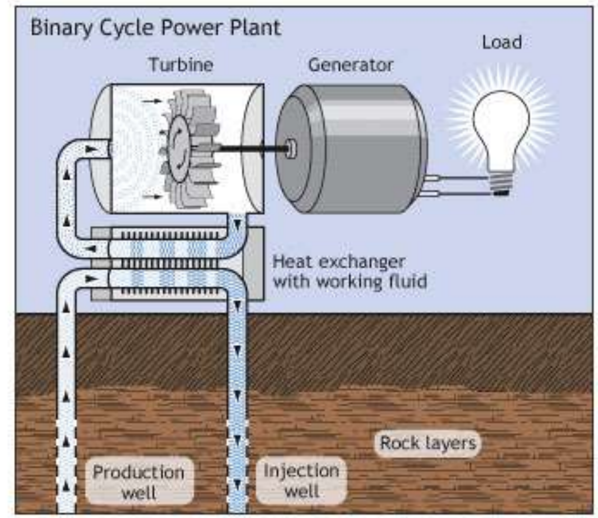
UNIVERSITÀ DEGLI STUDI FIRENZE

DIEF
Dipartimento di Ingegneria Industriale

Geothermal Energy Conversion





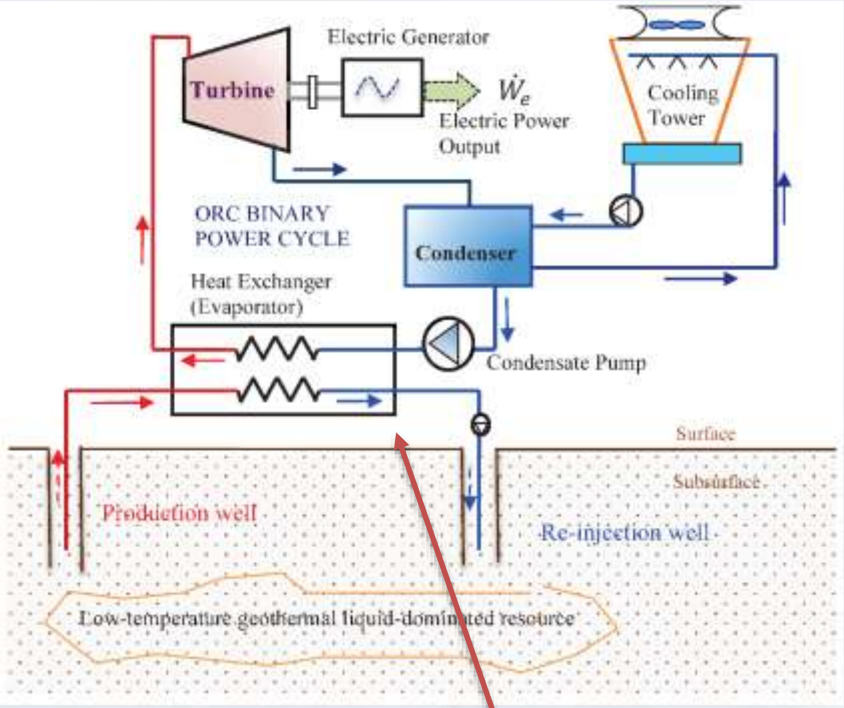


Highlights of Research at DIEF

Daniele Fiaschi, Giampaolo Manfrida, Lorenzo Talluri

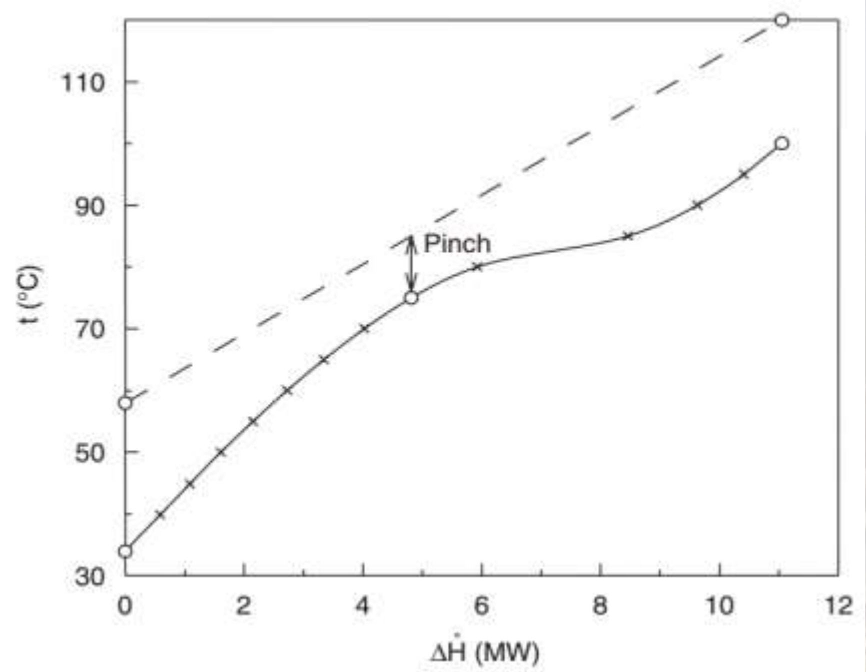
May 26th, 2016

Supercritical ORC for Geothermal Energy Conversion



2016

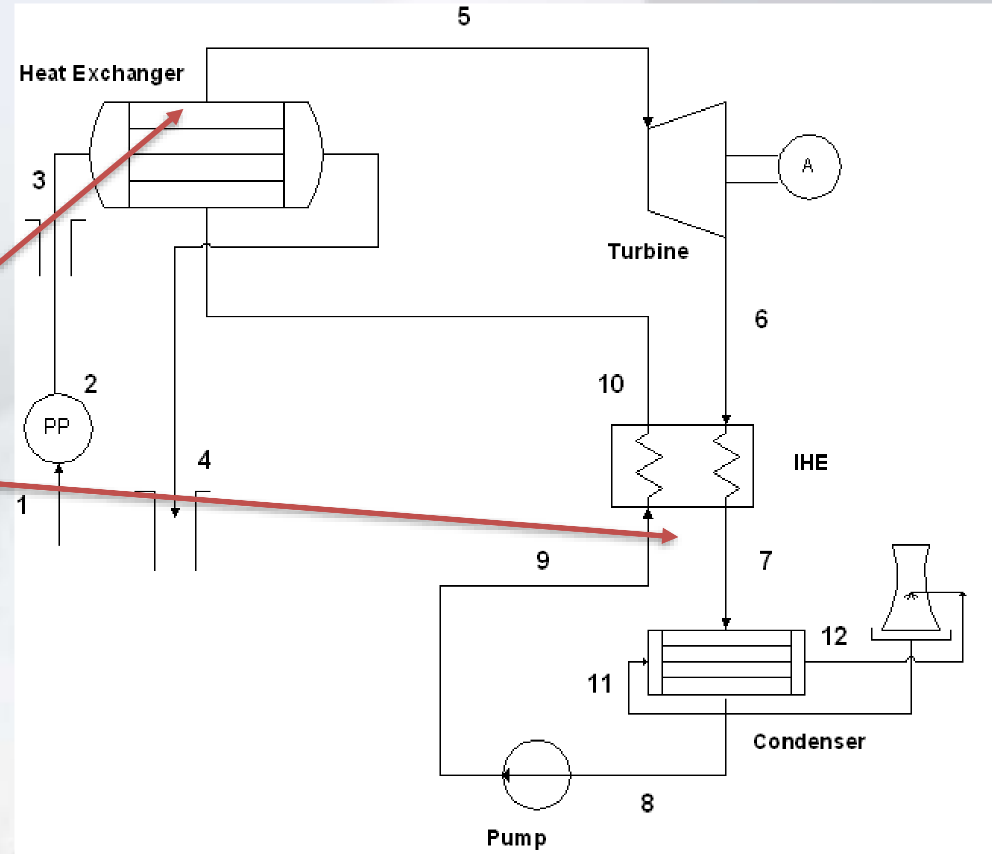
- Completely closed ORC layout
- Heat capacity matching with Geothermal Resource (Well Production Characteristic)
- Close to **Ideal Trapezoidal Cycle**
- **Objectives:**
  - Power production
  - Total reinjection of NCGs – avoiding flash and expensive NCG treatment for contaminants (H2S, Hg, NH3,…); includes reinjection of CO2



Supercritical ORC: Case study

Input data (Monte Amiata Bagnore 3):

- h[1] = 1200 kJ/kg
- p[1] = 60 bar
- m[1] = 122 kg/s
- T[4] = 130 °C
- T[8] = 40 °C
- Depth of BH pump installation = 800 m
- ΔT_HE_approach= variable depending on fluid
- ΔT_IHE_inlet = 5 °C
- P[9]= variable depending on fluid
- Assigned well geometry (ϕ = 0,24 m)

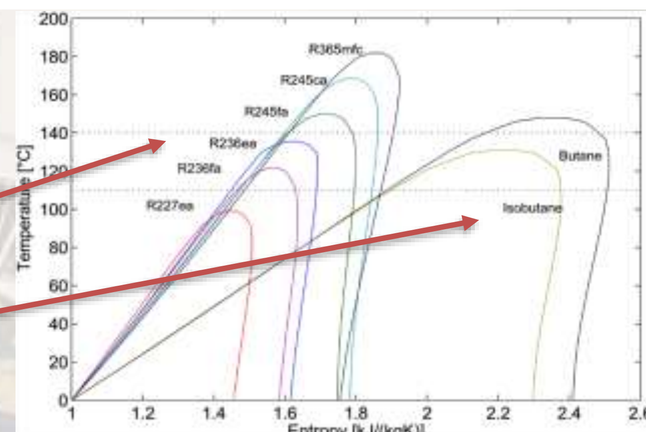


Modeling Approach:

- Thermodynamic and Exergy Analysis
- Exergoeconomic (thermoeconomic) Analysis
- Model includes friction and heat losses in production well
- Optimized temperature profiles in HE e IHE with evaluation of local pinch (variable heat capacities on both sides, brine and working fluid)
- Optimal conditions for THD cycle with different fluids

Working Fluids:

- Refrigerants (R143a, R134a,….)
- Pure Hydrocarbons (n-esane, n-pentane,….)



Model fundamentals:

- **Liquid Phase:** Particle interaction theory
- **Vapor phase:** Accurate Real-fluid EOS

Moles of CO_2 in vapour phase

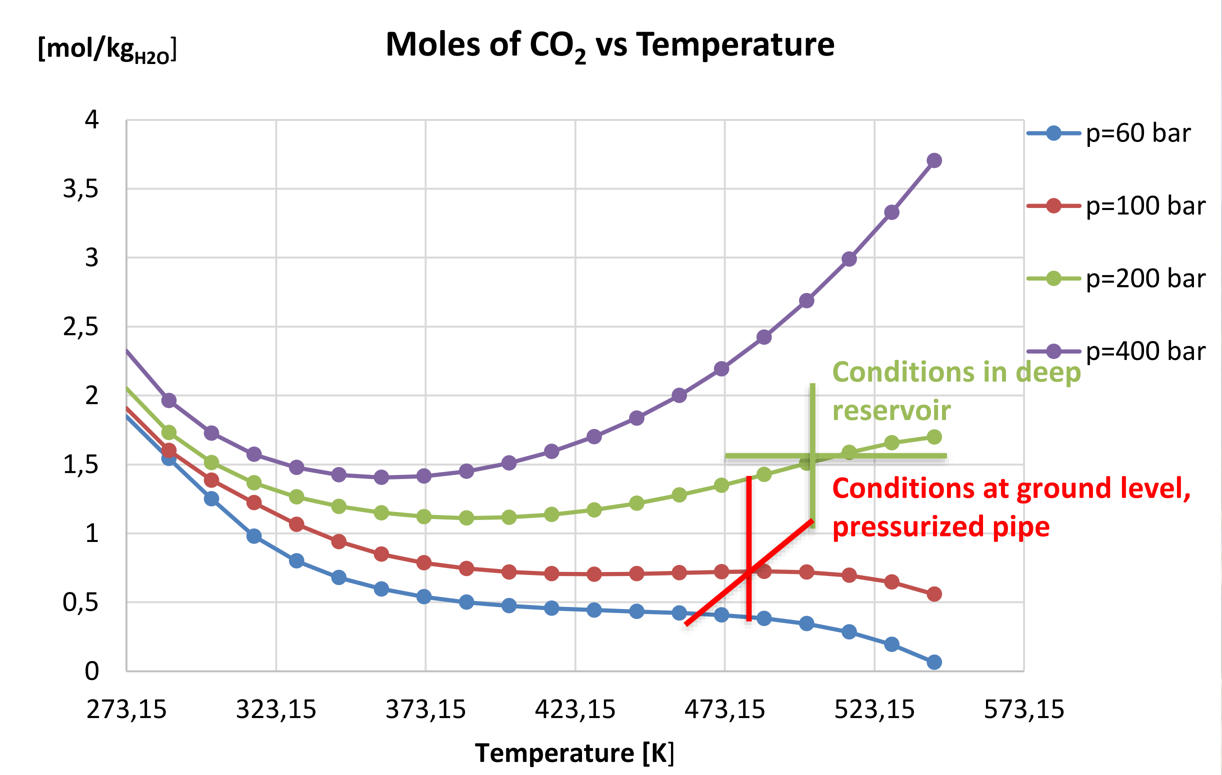
Pressure

Chemical Potential

$$\ln\frac{y_{CO_2}P}{m_{CO_2}} = \frac{\mu^{l(0)}_{CO_2}(T,P) - \mu^{v(0)}_{CO_2}(T)}{RT} - \ln\varphi_{CO_2}(T,P,y) + \ln\gamma_{CO_2}(T,P,m)$$

Fugacity Coefficient (CO2 in Water, EES real fluid)

Activity coefficient (water brine with salts: Na^+,K^+, Ca^+, Mg^{2+}, Cl^- and SO_4^{2-})

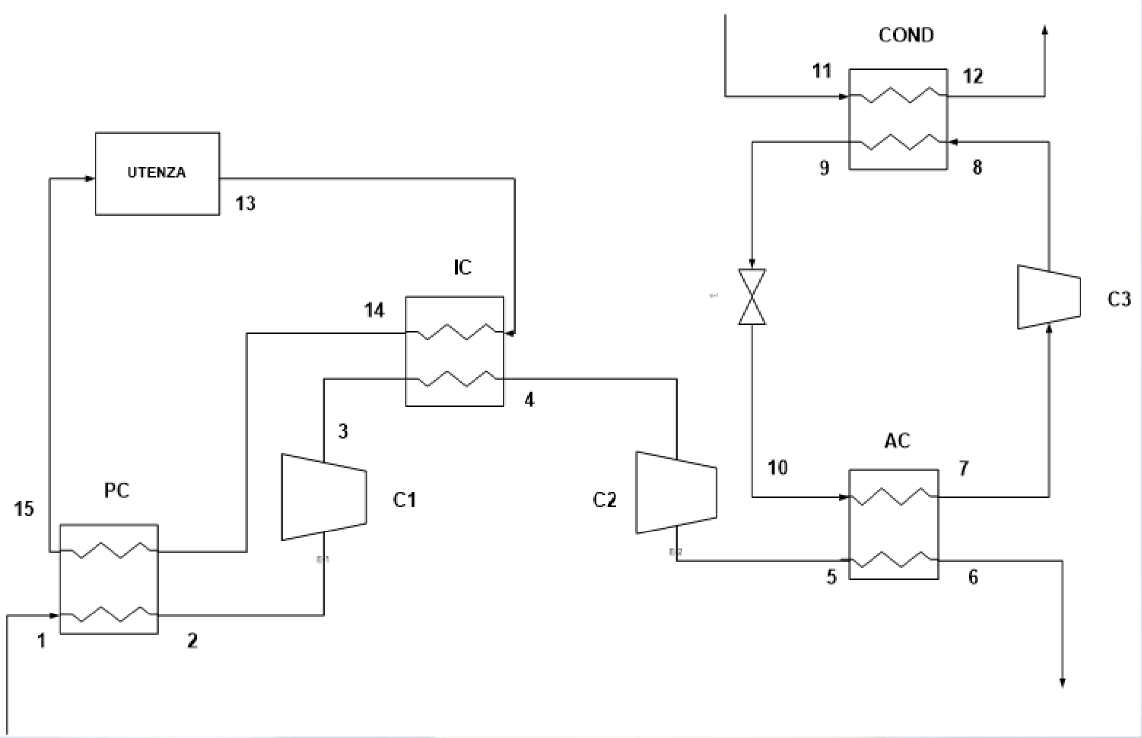


The difference in CO2 solubility determines accumulation of pressurized NCGs in the HE

Management of NCGs (CO_2) for complete reinjection

Objective:

- Obtaining an homogeneous liquid phase for reinjection
- CO_2 droplets of small diameter
- Density: $\rho_{CO2} > \rho_{H2O}$
- Gravity-induced stratification of liquid CO_2



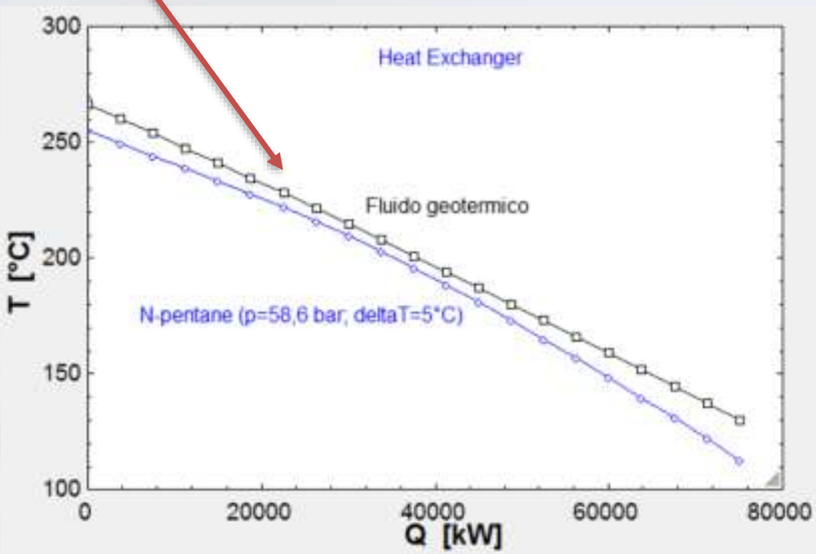
	1%	2%	3%	
W_{tot}	47,51	146,3	241	kW
Q_{PC}	142,5	438,7	722,7	kW
Q_{IC}	125,5	386,5	636,7	kW
Q_{AC}	66,41	204,5	336,9	kW
$Q_{Condenser}$	85,14	262,2	431,9	kW
$Q_{thermal\ user}$	18	54	90	-
$\dot{m}_{CO2}$	0,618	1,903	3,135	kg/s
COP	3,546	3,546	3,546	-

Cycle performance with variable CO2 contents of the brine

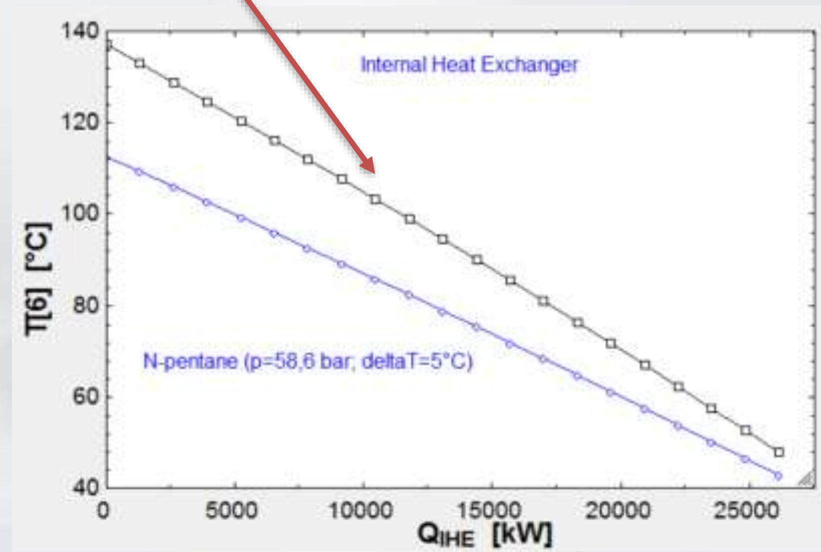
- **T[6] = 15°C**
- **P[6] = 163 bar**
- **T[15] = 80°C**
- **T[13] = 40°C**
- **T cond = 40°C**
- **T eva = -10°C**

ORC: Brine modeled as pure Water

HE Temperature profile

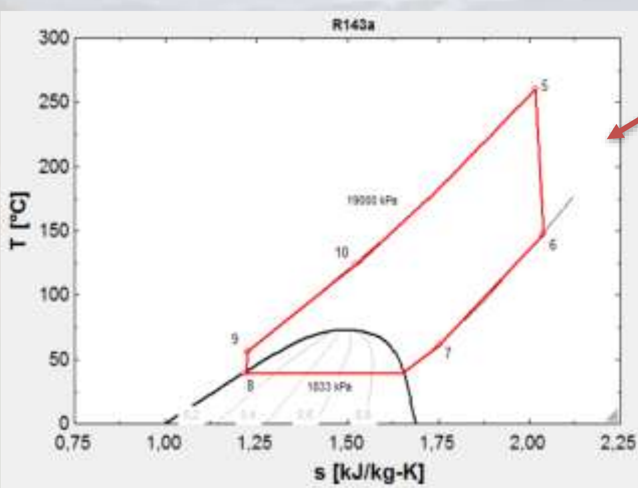


IHE Temperature profile

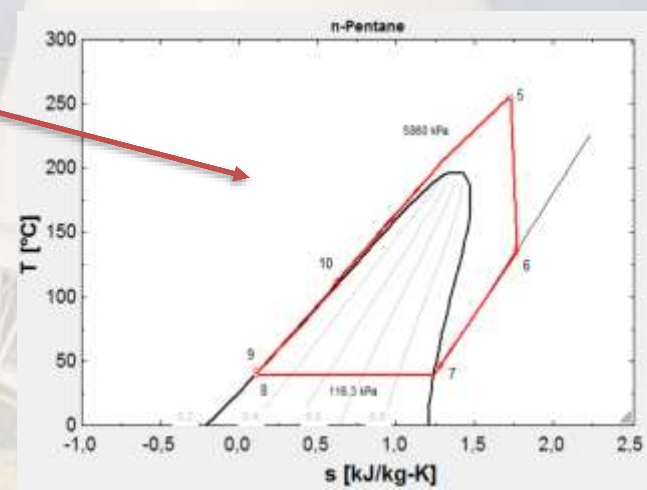


ORC cycle diagram:

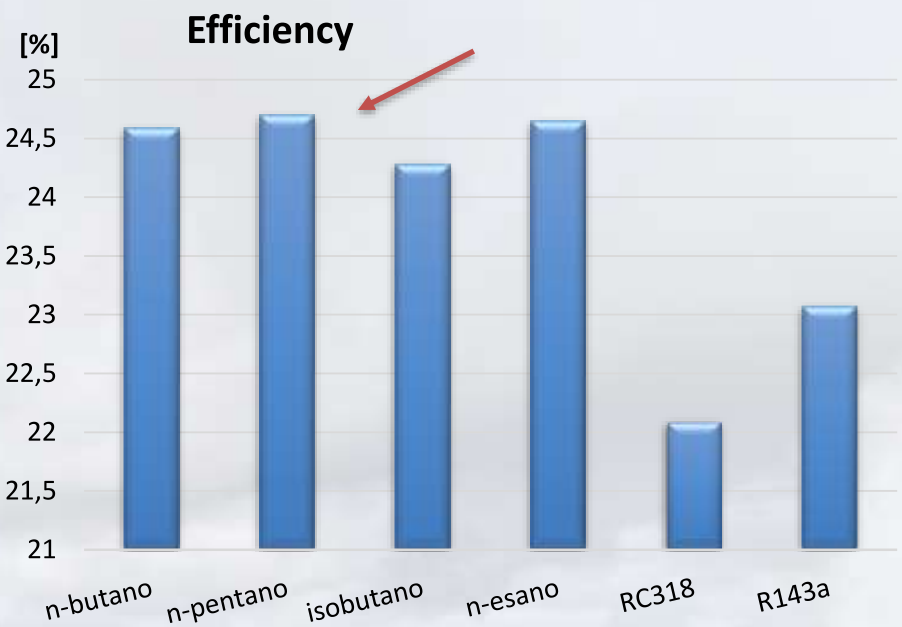
R143a

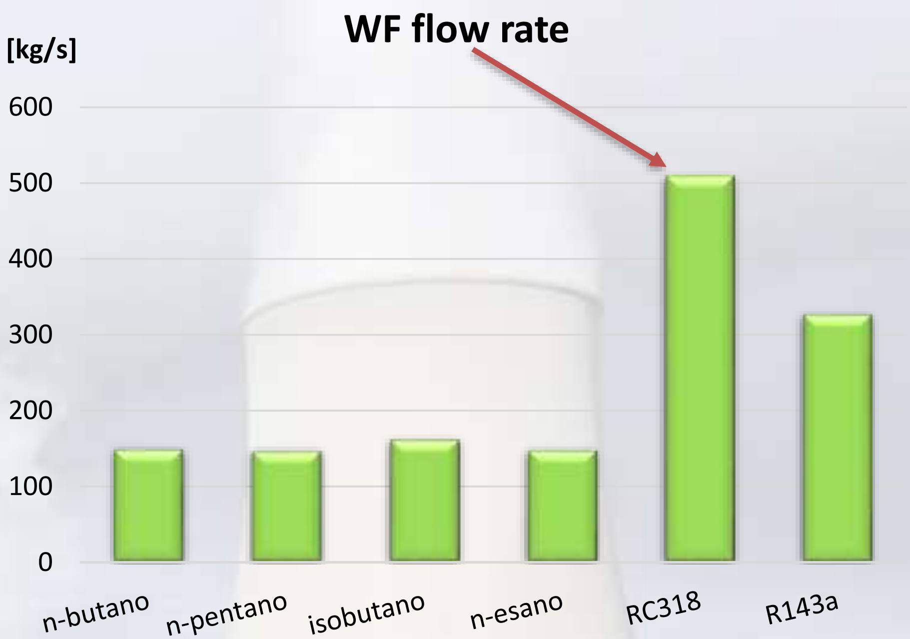


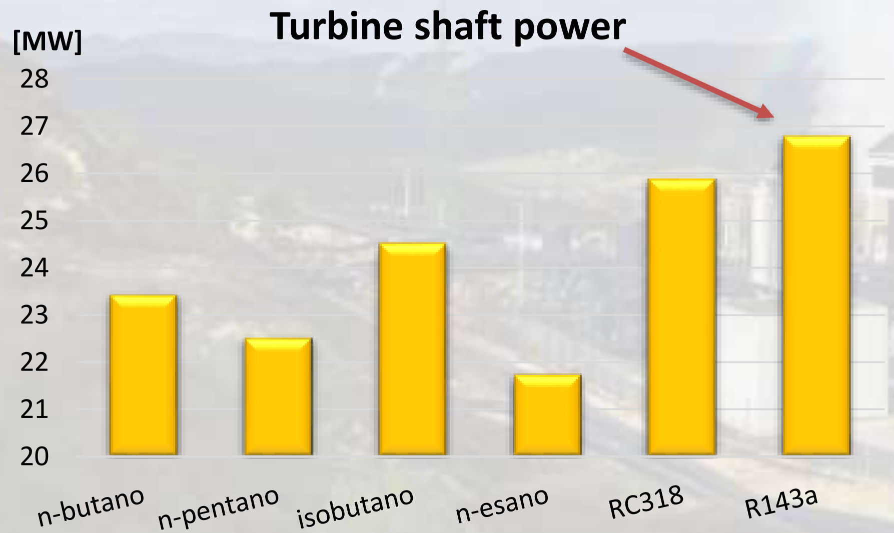
N-pentane

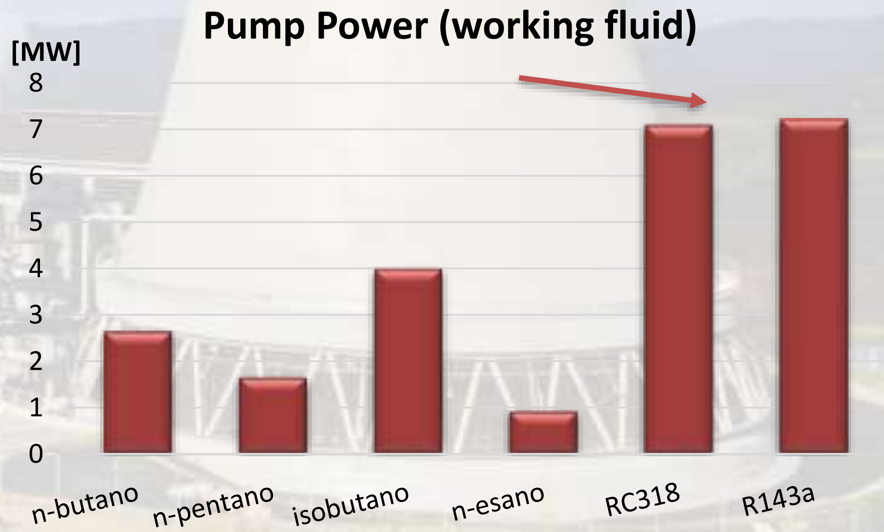


ORC: Performance (Brine = Water)









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ORC: Analysis with real brine properties (water and CO_2)

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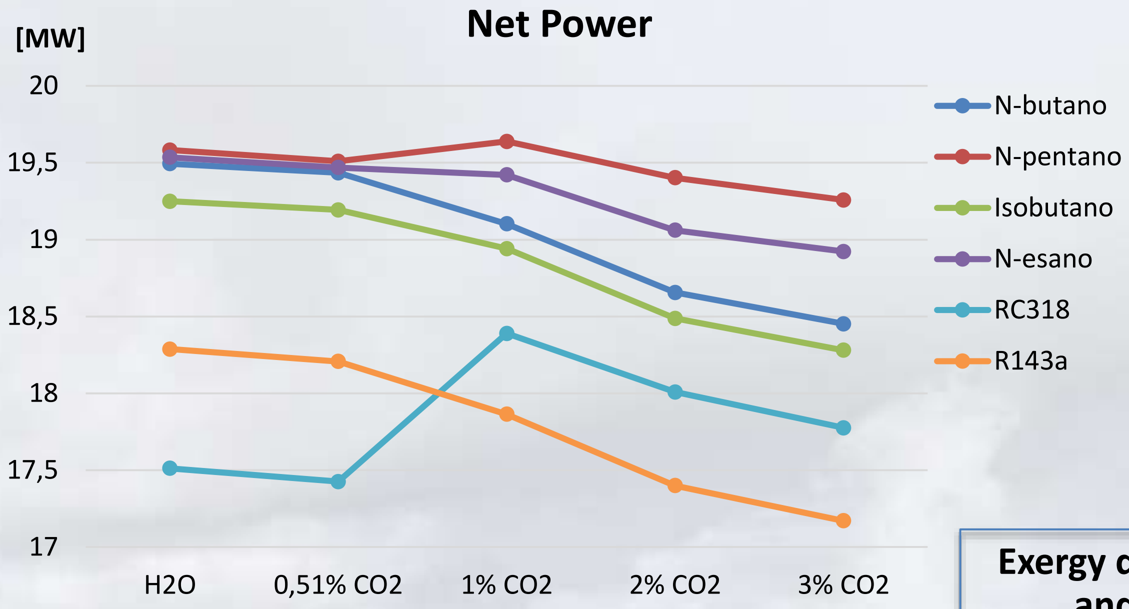
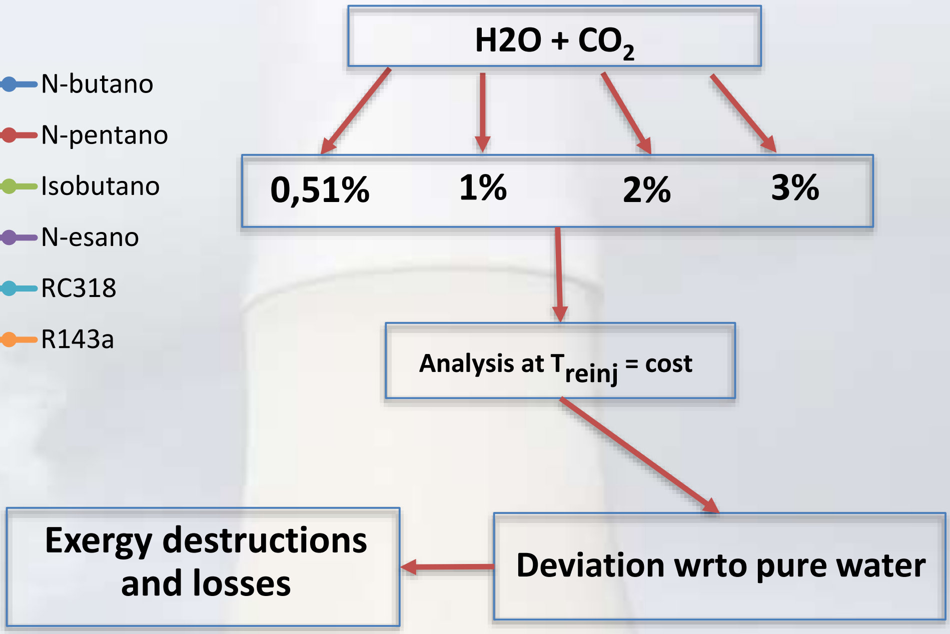
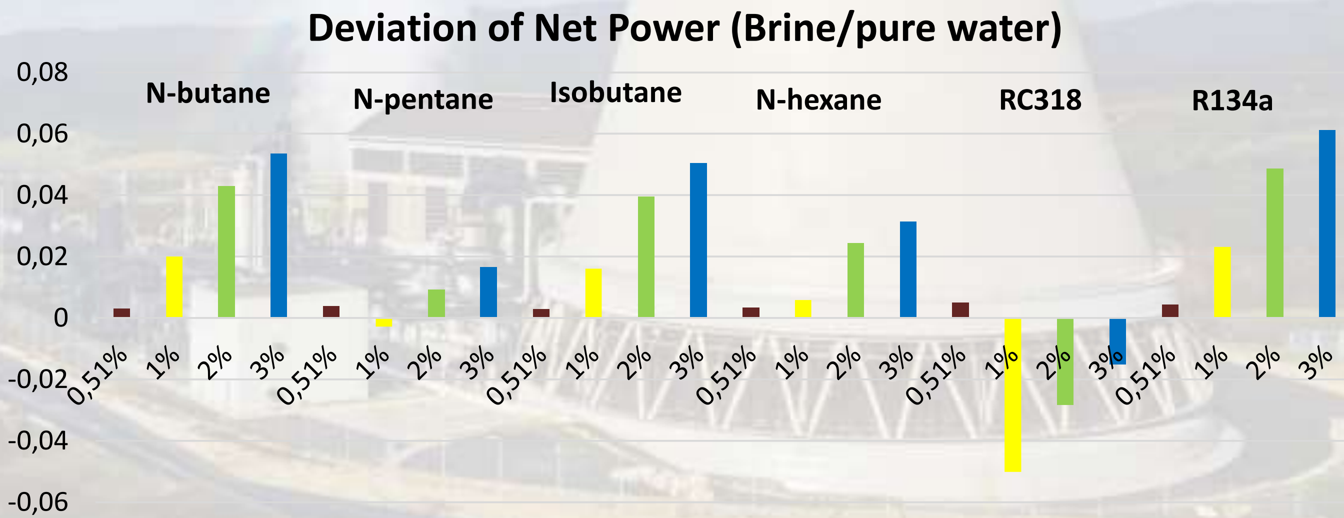


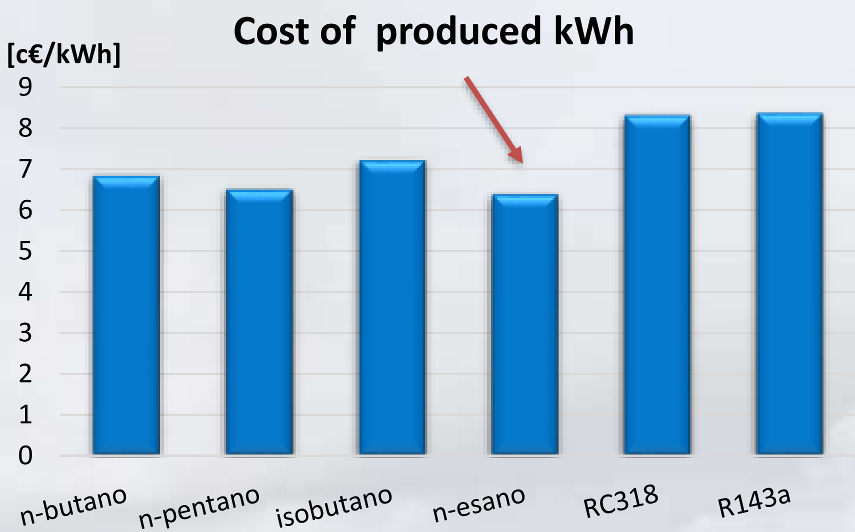


Non-dimensional performance assessment:

- Efficiency
- Exergy Efficiency
- **Power** →
- Working fluid flow rate
- Turbine Power
- Pump power
- HE effectiveness
- IHE effectiveness



ORC: Exergoeconomics (Thermoeconomics)

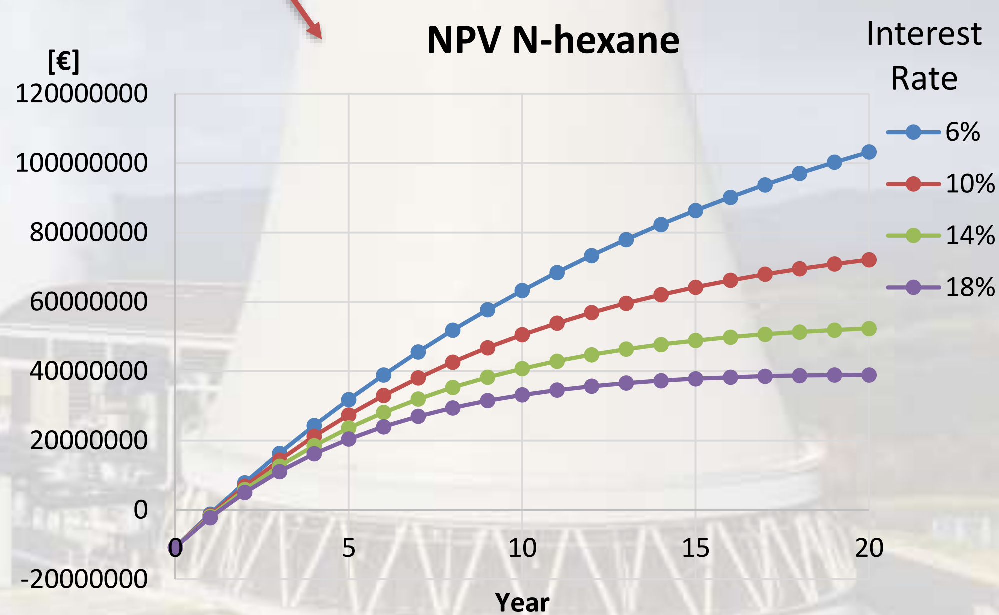


Evaluation process

- Cost of Exergy Destruction
- Exergy Efficiency
- Exergoeconomic Factor

NPV Analysis → 1% Inflation rate

ORC-N-esane	T_MAX=245,1°C – T_CO=40°C	
Thermal input	79267	[kWt]
Output net power	19532	[kW]
Hours per year	7446	[ore/anno]
Cost of kWh ORC	**0.06384**	**[€/kWh]**
Interest rate	10%	
Selling price electricity	0,0722	[€/kWh]
kWh per year	145435272	[kWh/anno]
Yearly cash flow	10500426,6	[€/year]
Total Capital Investment	**10780000**	**[€]**
Time span	20	[years]
O&M + insurance	323400	[€/ear]
NPV	**72148051,3**	**[€]**



ORC: check of borehole pump feasibility

Non-dimensional coefficient method for pump design (Anderson, Stepanoff,…)

Input data:

- p[1] = 60 bar
- m[1] = 122 kg/s
- h[1] = 1200 kJ/kg
- p[2] = 128,64 bar
- D[2] = 200 mm

Pump geometry → Velocity triangles and metal angles → Evaluation of losses

		Units
η	0,84	[-]
N_s	4800	[-]
N_{Stages}	34	[-]
Z	6	[-]
RPM	2910	[RPM]
Q	0,002605	[m^3/s]
H_{Stage}	27	[m]

Mixture of water and CO_2

CO2%	0,51%	1%	2%	3%	Units
W_{pump}	1,34	1,51	1,76	2,04	[MW]

Supercritical CO_2 Solutions

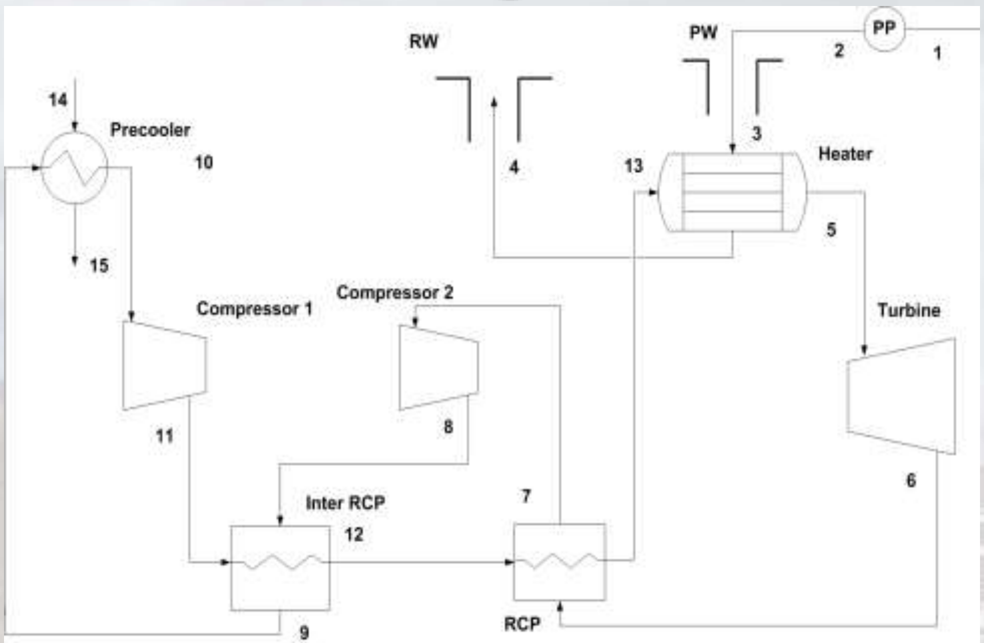
CO_2 Cycle

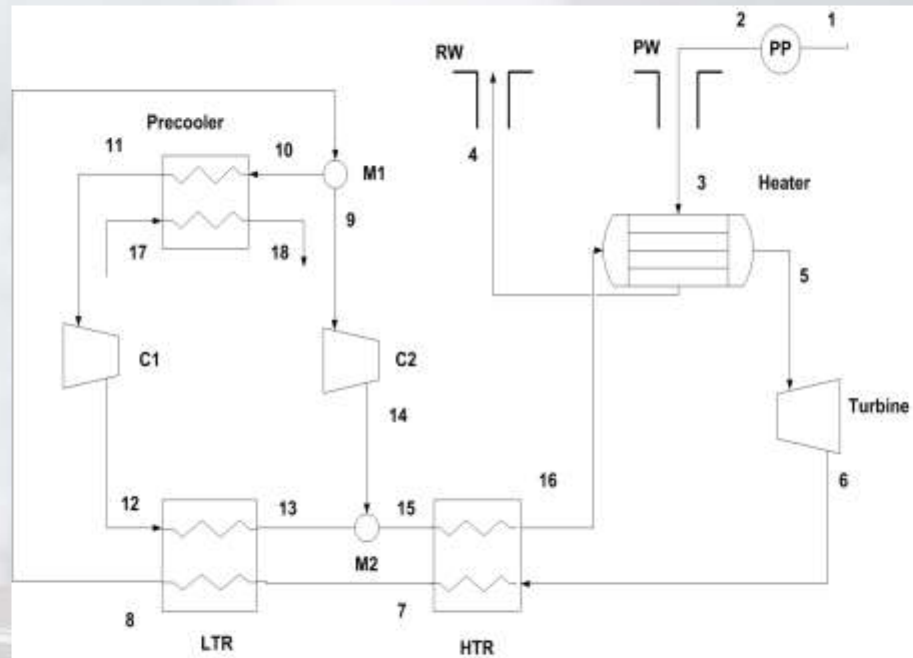
Regenerative

Same layout as for Supercritical ORC

Pre-compression

Recompression





Thermodynamic, Exergy and Thermoeconomic Analysis

Constant T reinjection

Variable T reinjection

Variable T condenser

Comparison of ORC and supercritical CO2 solutions

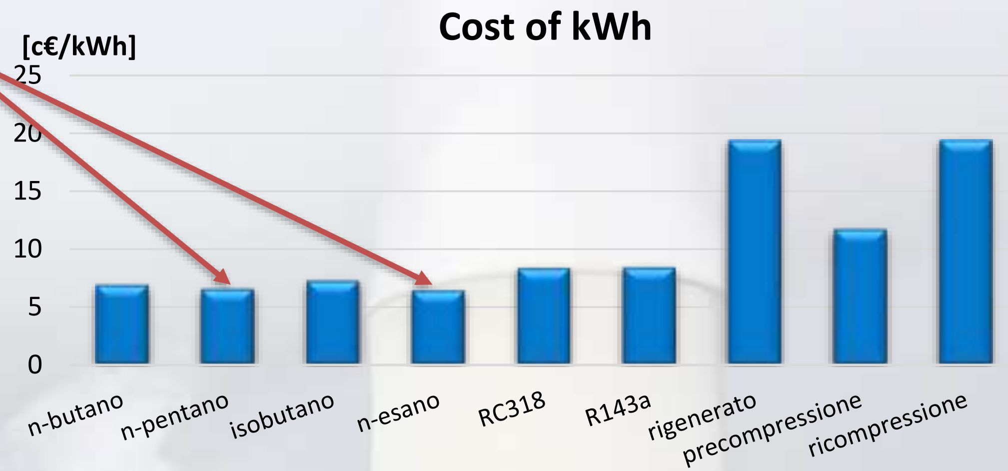
Analysis

Thermoeconomics

Thermodynamics

Hydrocarbons

Refrigerants



Effects of real brine composition
(MAX Deviation35%)

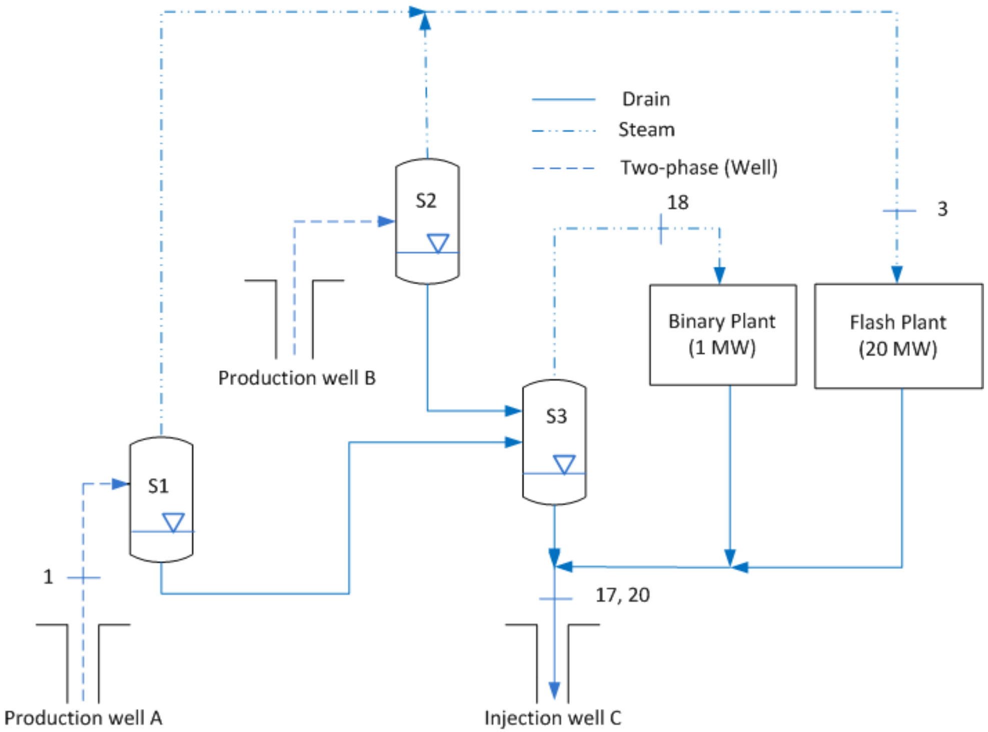
THD variables (pressure, temperature, flow rate, …)

Size of components

Cost of components

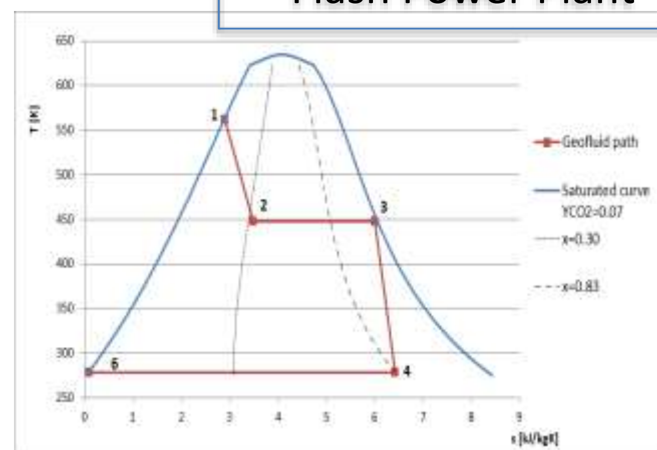
Case study: Bagnore 3 Hybridization

2015

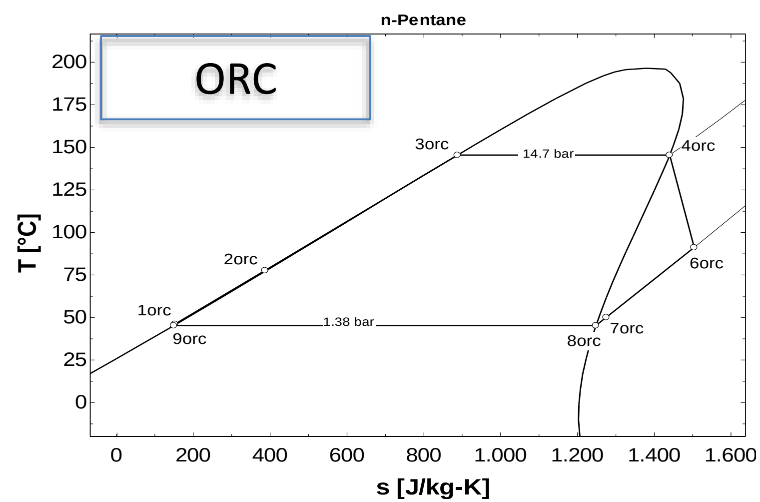


Present Plant Layout

Flash Power Plant

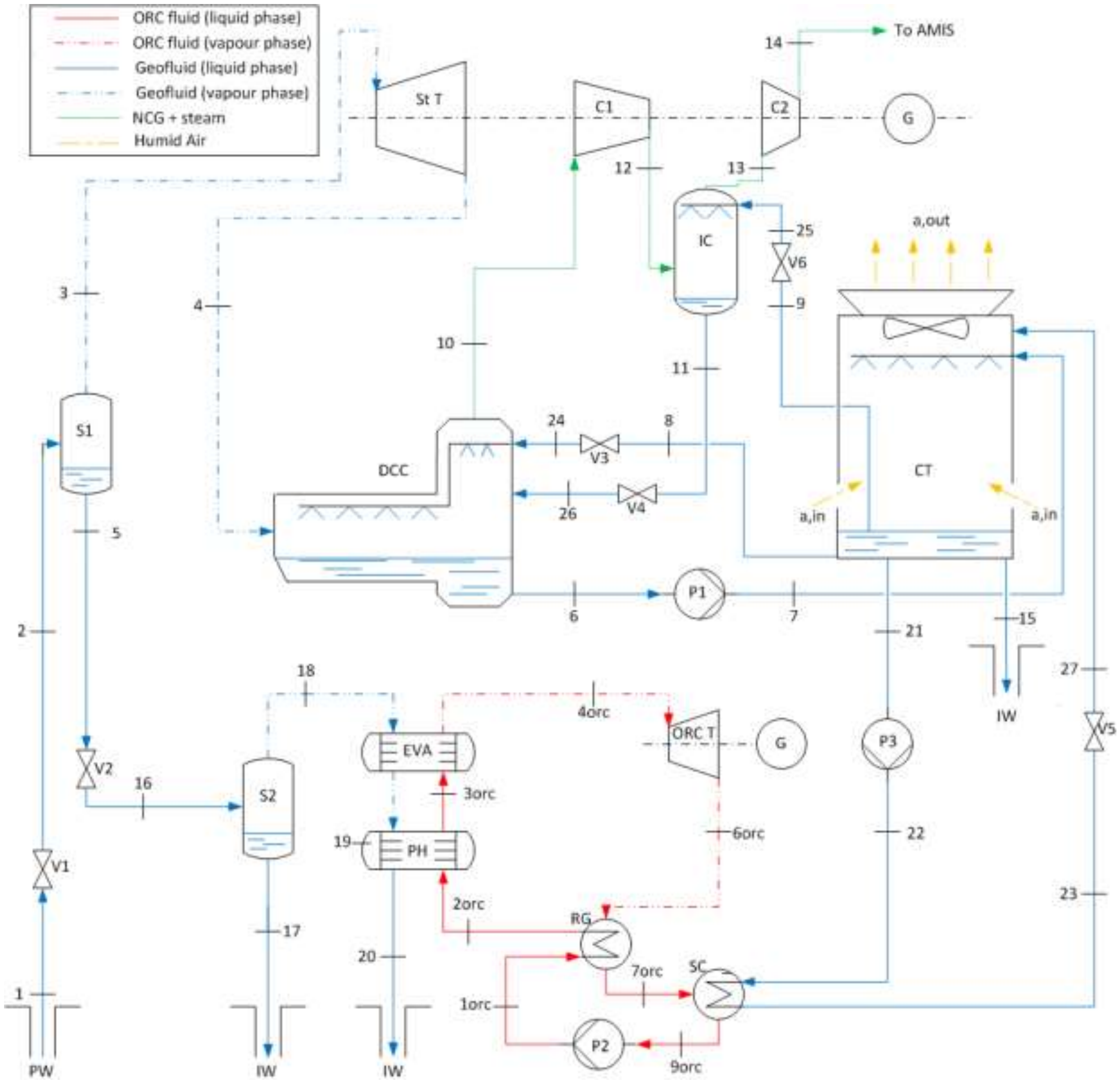


ORC



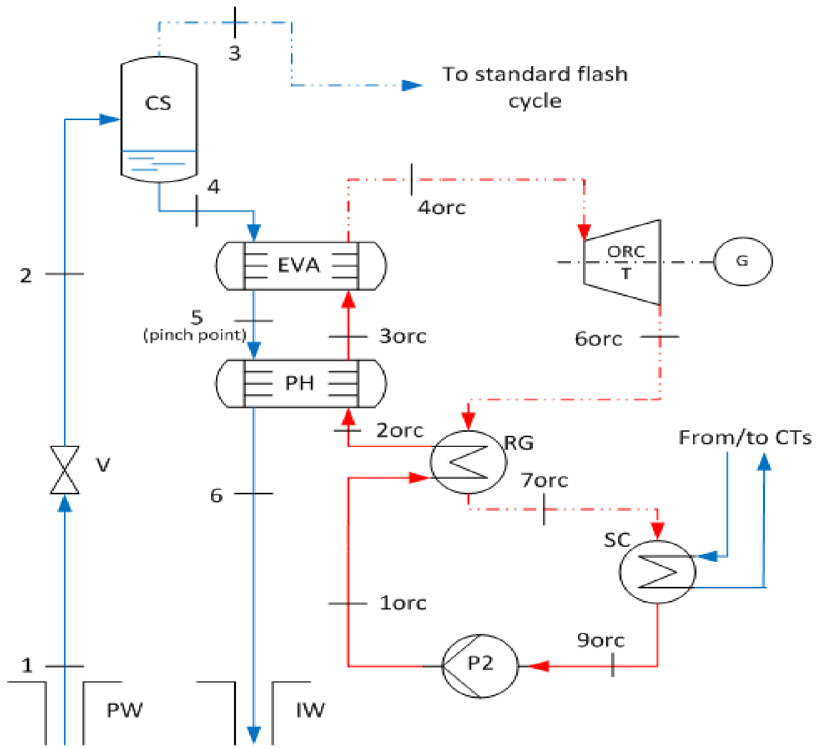
Sustainability **2015**, *7*, 15262-15283; doi:10.3390/su71115262

Hybrid 1 – Base Case



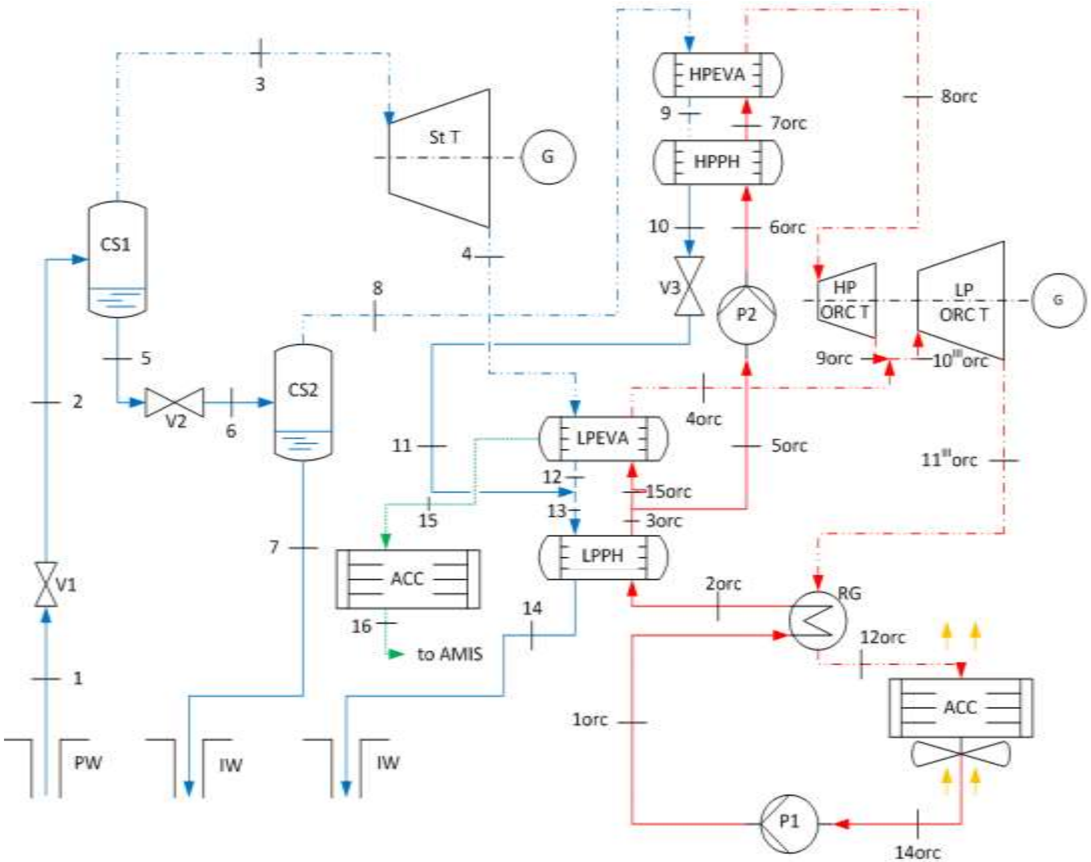
ORC coupled to secondary flash S2 (double-flash)

Hybrid 2 – LB/ORC



ORC coupled to Liquid Brine heat recovery (single-flash)

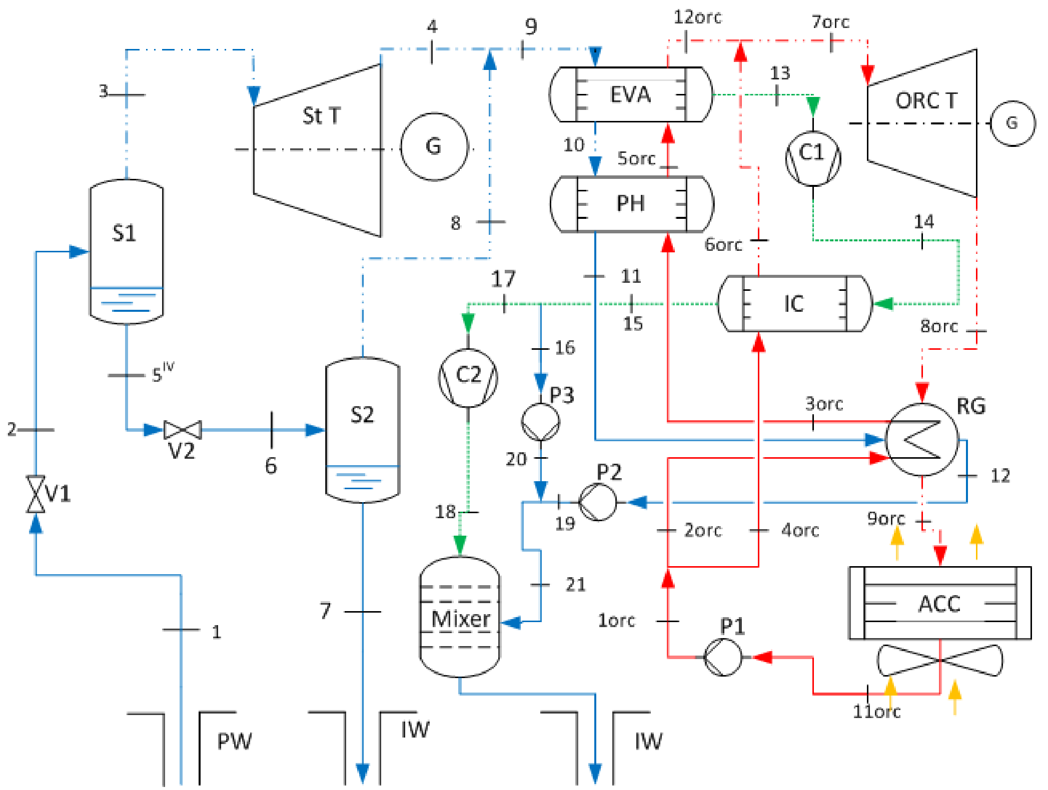
Hybrid 3 – 2P-ORC/BPS



2-pressure level ORC coupled to backpressure steam turbine; double-flash.

With air-cooled condenser ACC.

Hybrid 4 –ORC/BPS/TR



1-pressure level ORC coupled to backpressure steam turbine; double-flash; with total reinjection of NCGs.

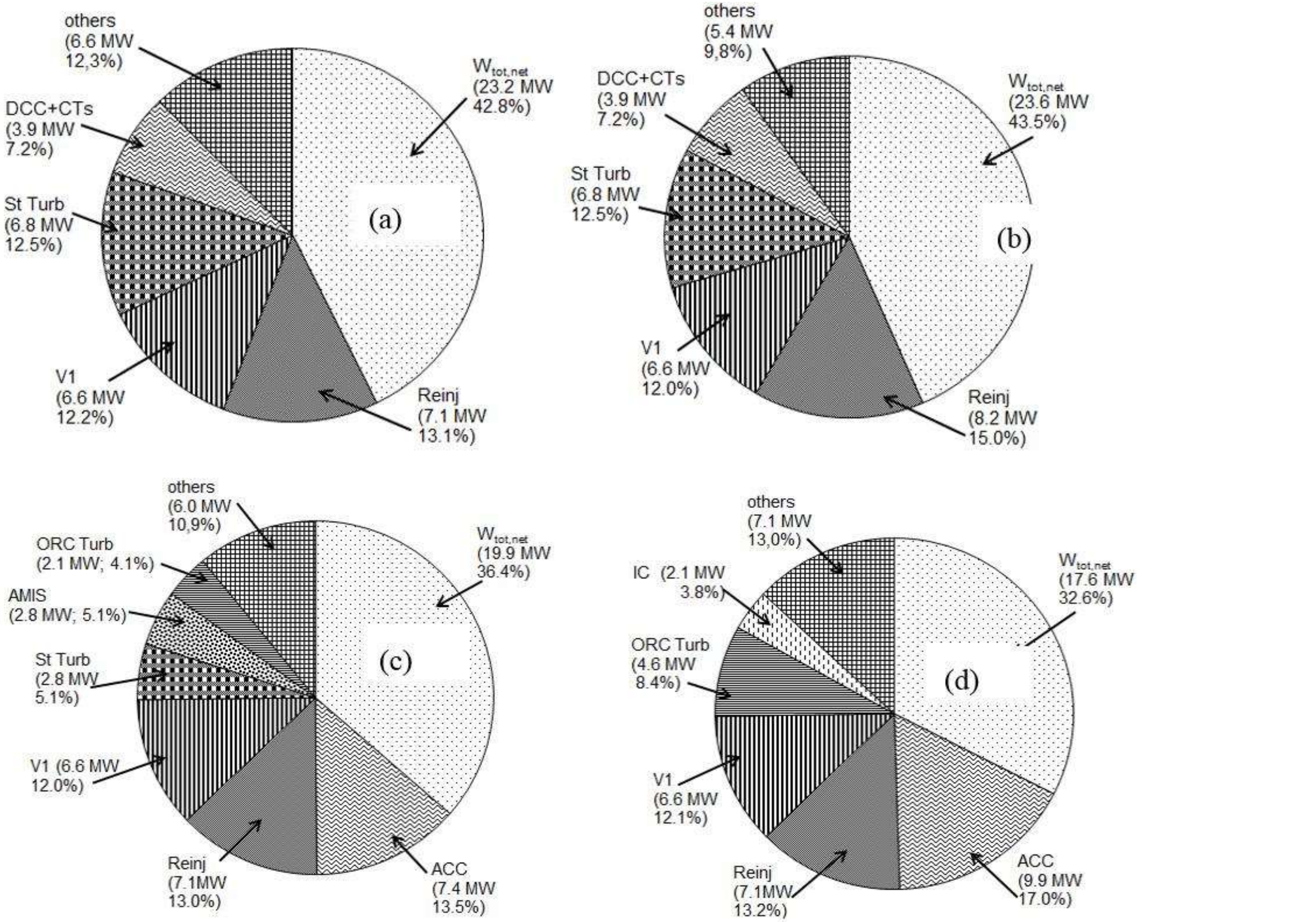
With air-cooled condenser ACC.

Bagnore 3 Hybridization – Performance Comparison

Table 2. Comparison of power and heat rates in key power plant components.

Powers/Heat Rate (MW)	Baseline	LB-ORC	2PORC/BPS	ORC/BPS/TR
$\dot{W}_{st,T,gross}$	21.2	21.2	11.77	6.21
$\dot{W}_{HPorc,T}$	-	-	1.62	-
$\dot{W}_{LPorc,T}$	-	-	7.93	-
$\dot{W}_{orc,T,gross}$	4.04	4.36	9.55	17.0
$\dot{W}_{tot,gross}$	25.23	25.56	21.31	23.22
$\dot{W}_{p1}$	0.47	0.47	0.09	0.36
$\dot{W}_{p2}$	0.19	0.13	0.06	0.33
$\dot{W}_{p3}$	0.15	0.06	-	0.08
$\dot{W}_{fans}$	0.18	0.18	1.24	2.21
$\dot{W}_{C1}$	0.62	0.62	-	2.14
$\dot{W}_{C2}$	0.47	0.47	-	0.50
$\dot{W}_{tot,par}$	2.08	1.94	1.39	5.58
$\dot{W}_{tot,net}$	23.16	23.64	19.92	17.63
$\dot{Q}_{EVA}$	13.62	10.05	-	53.76
$\dot{Q}_{PH}$	11.36	11.28	-	20.01
$\dot{Q}_{LPEVA}$	-	-	45.71	-
$\dot{Q}_{LPPH}$	-	-	14.02	-
$\dot{Q}_{HPEVA}$	-	-	16.16	-
$\dot{Q}_{HPPH}$	-	-	7.51	-
$\dot{Q}_{RG}$	4.63	6.15	12.02	31.1
$\dot{Q}_{IC}$	-	-	-	25.87
$\dot{Q}_{WCC}$	21.14	17.56	-	-
$\dot{Q}_{ACCs}$	-	-	86.0	91.06

Bagnore 3 Hybridization – Exergy Balances



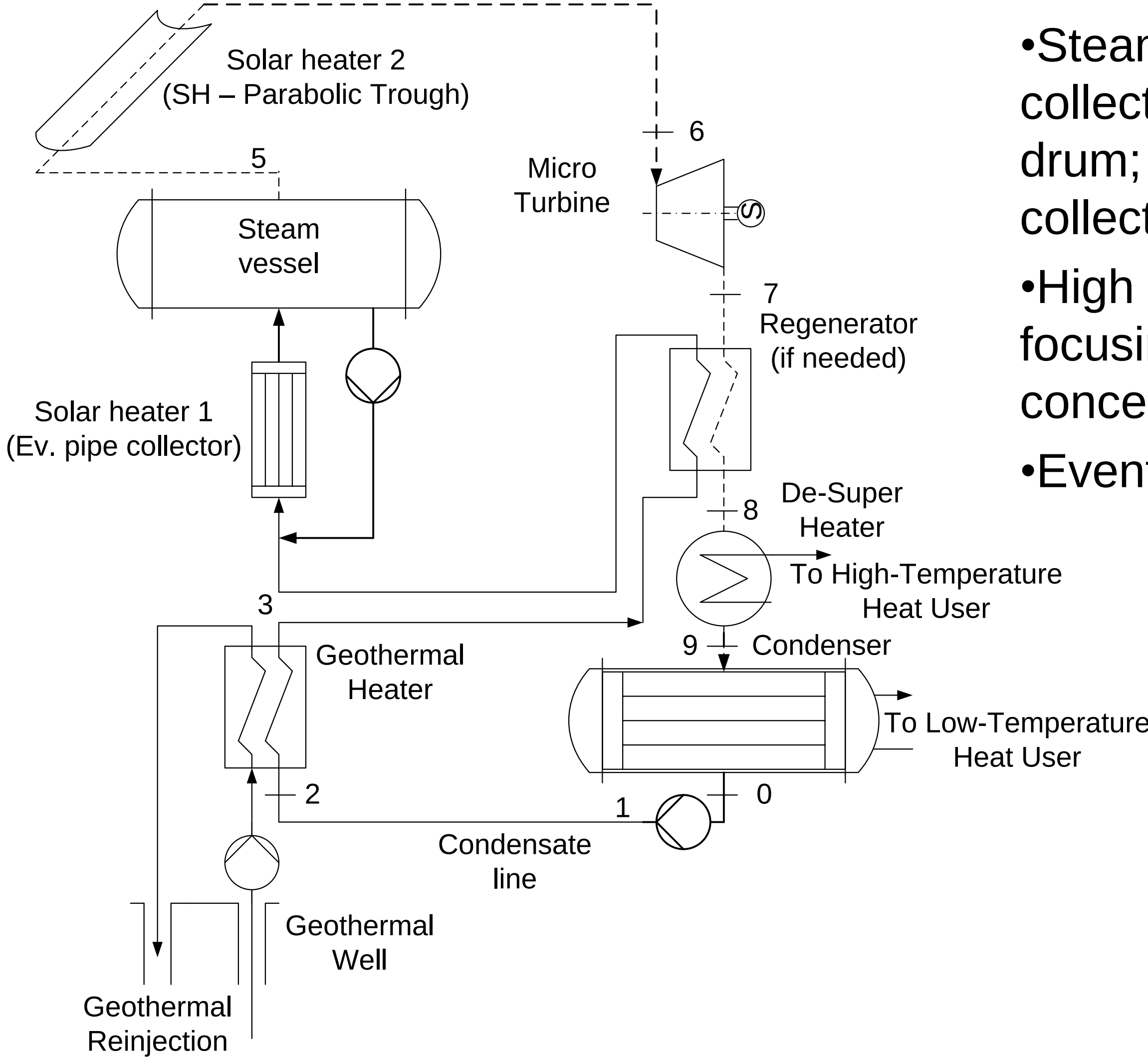
Exergy balances: destructions, losses and power output. (**a**) = Baseline; (**b**) = 2P-ORC/BPS; (**c**) = *ORC/BPS/TR*; (**d**) = ORC/BPS/TR.

Bagnore 3 Hybridization – Environmental Performance

Table 3. Overall performance of the four power plant options.

Parameter	u.m.	Baseline	LB-ORC	2PORC/BPS	ORC/BPS/TR
	-	13.2	13.5	11.32	10.02
	-	42.8	43.5	36.38	32.55
USFR	(kg/s)/kWh	19.08	18.72	22.03	24.91
EF_{CO2}	g/kWh	396	388	454	0
EF_{H2S}	g/kWh	1.21	1.18	0.28	0
EF_{Hg}	mg/kWh	1.3	1.27	0.42	0

2009-2012



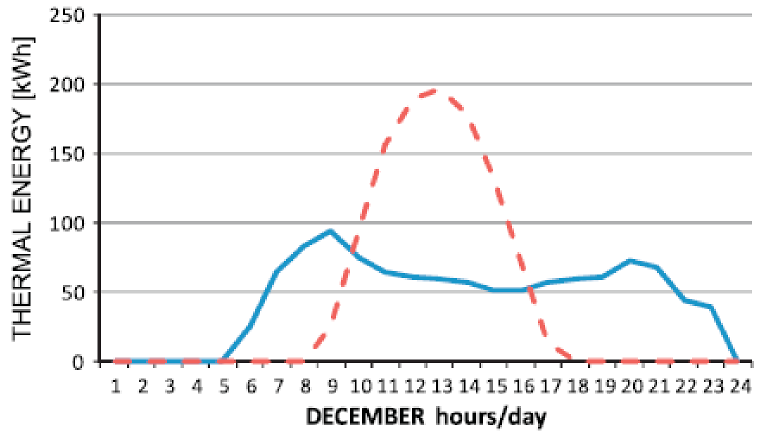
Circuit Layout:

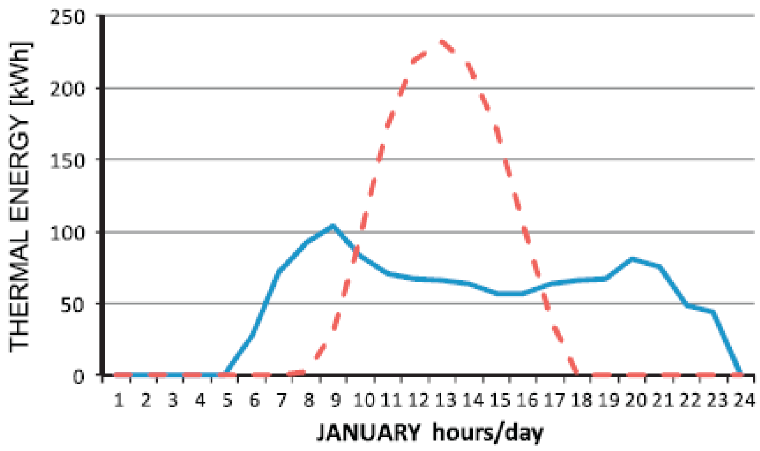
- Geothermal Heat Exchanger;
- Steam vessel fed by solar thermal collectors (preheaters/evaporators with drum; typically evacuated pipe collectors without concentration);
- High temperature solar field with focusing collectors (low optical concentration).
- Eventual reheater/RHE (regenerator)

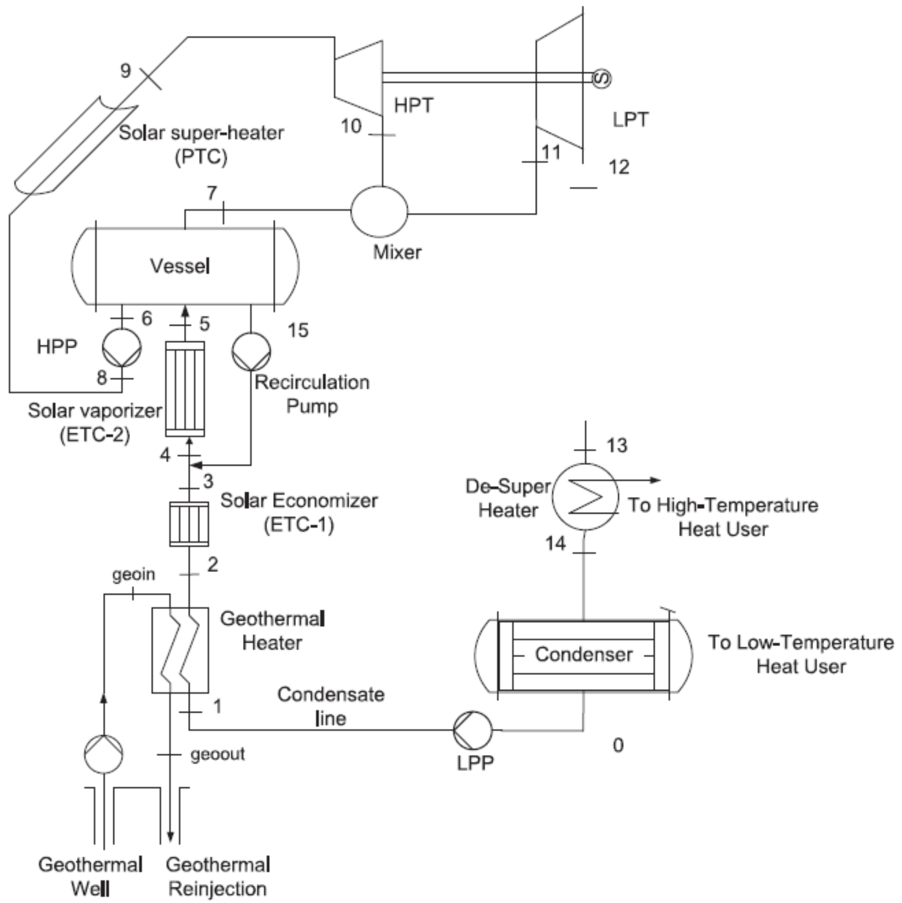
- Microturbine expander;
- High-temperature heat user (desuperheater)
- Low-temperature heat user (condenser)

Small Solar/Geothermal Power Units

Micro CHP: geothermal + solar superheating from low enthalpy resources







Dynamic analysis of system including off-design behavior of main components (HXs, expander)

Small Solar/Geothermal Power Units

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

Well Reinjection Temperature

Steam Generator Pressure

DSH/Condenser Pressure

Flow rates

Net area collectors field

Collectors field specific flow rates

Small Solar/Geothermal Power Units

Results of simulation with different working fluids

Negative
Positive

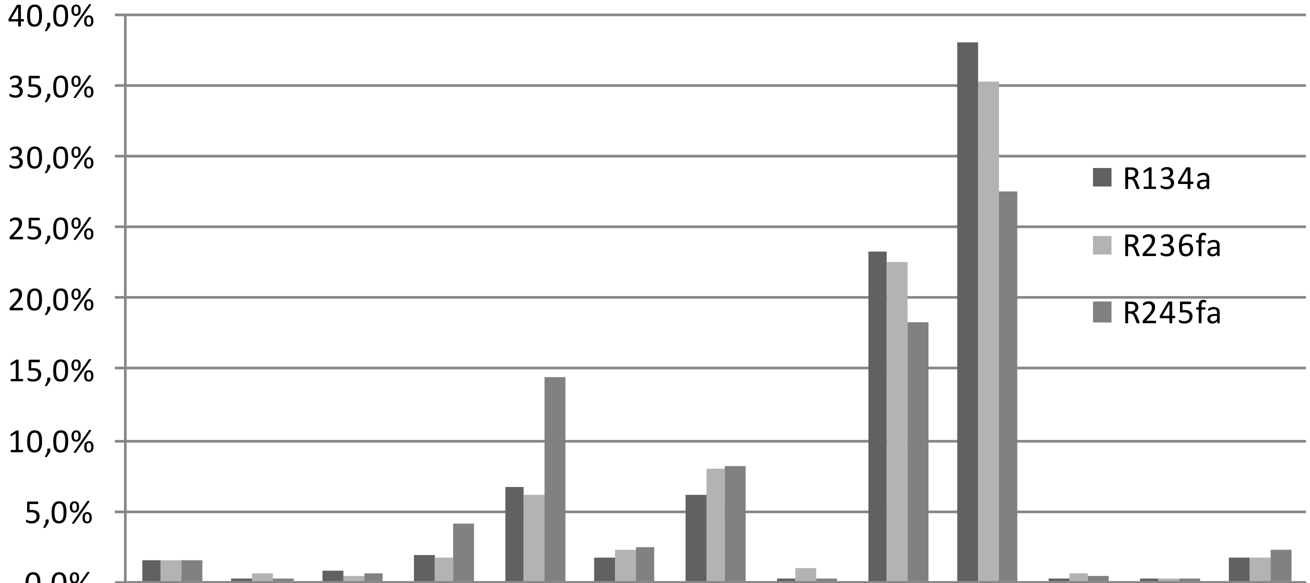
Fluid	R134a	CycloHex	N-Pentane	R245fa	R1234yf	R236fa
Eta_sys	9,1	14,6	11,7	13	7,3	9,77
EtaC	10,5	17,2	13,6	15,1	8,5	11,3
Eta_x	13,5	19,4	16,1	18,7	10,7	14,6
FracPump	0,103	0,085	0,024	0,073	0,197	0,17
FracGeo	0,26	0,155	0,188	0,235	0,247	0,265
Q_Geo [kW]	111	44,6	67	72,2	117	97,5
Q_sol [kW]	316	244	288	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

Efficiency (Eta_sys, EtaC, Eta_x)
Work fraction Pump/Turbine (FracPump)
Geothermal fraction (FracGeo)
Heat balance (Q_Geo, Q_sol, Q_CHPBT, Q_CHPAT, Q_Rec)
Turbine Enthalpy drop (Delta_h_T)

Choice of Working Fluid:

- Cyclohexane best for power output (Low pressurization)
- R236fa best for geothermal fraction (but large pump power)
- R245fa and N-Pentane good compromise (Low Pressurization)
- Regenerator necessary for R1234yf (not large)
- Moderate enthalpy drop, possible simple one-stage axial expanders

Exergy balance, different working fluids

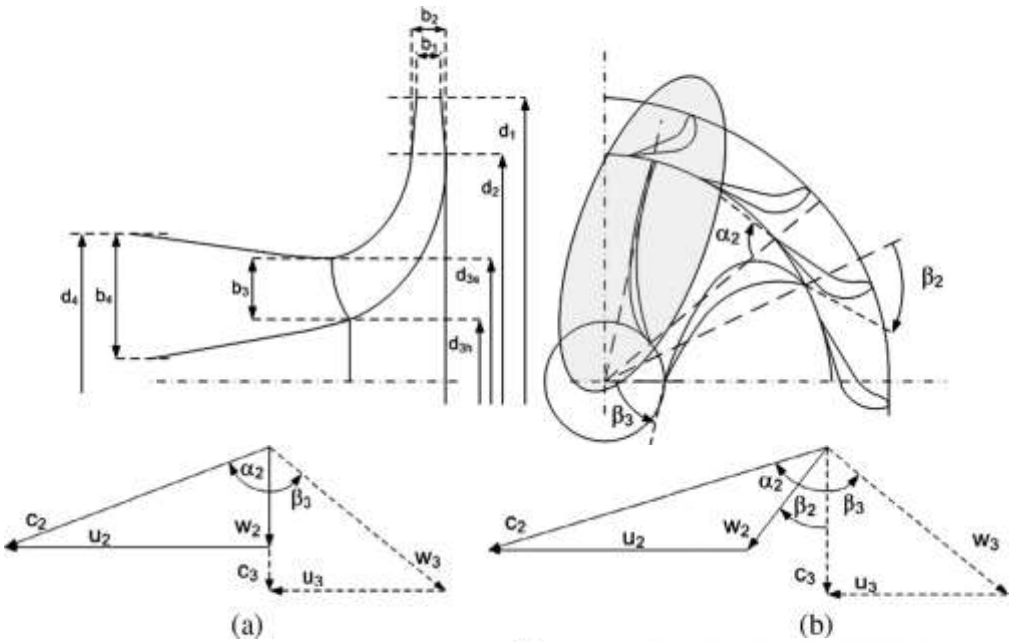


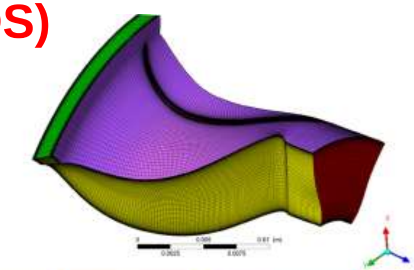
	DSH+CON D	LPP	GEO HX	Etc-1 EXL	Etc-1 EXD	Etc-2 EXL	Etc-2 EXD	HPP	PTC EXL	PTC EXD	HPT	Mixe r	LPT
R134a	1,6%	0,2%	0,7%	1,8%	6,7%	1,7%	6,2%	0,0%	23,2%	38,1%	0,2%	0,3%	1,8%
R236fa	1,5%	0,6%	0,3%	1,7%	6,1%	2,2%	8,0%	0,9%	22,5%	35,4%	0,5%	0,1%	1,6%
R245fa	1,5%	0,1%	0,5%	4,1%	14,5%	2,4%	8,2%	0,1%	18,3%	27,5%	0,5%	0,0%	2,3%

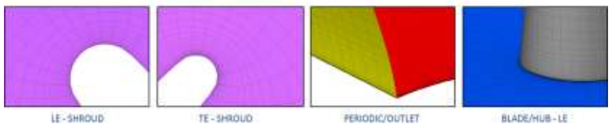
Mini and micro Expanders for ORCs
Radial turboexpanders

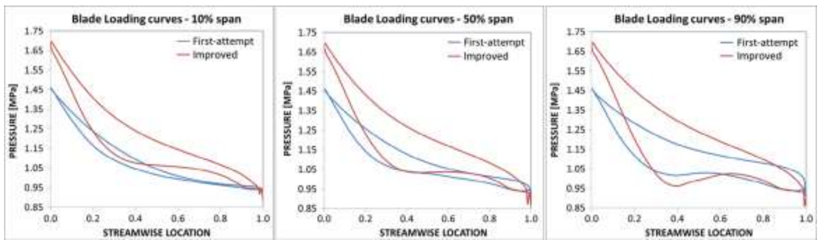
From accurate 0D design (real EOS with evaluation of losses) …

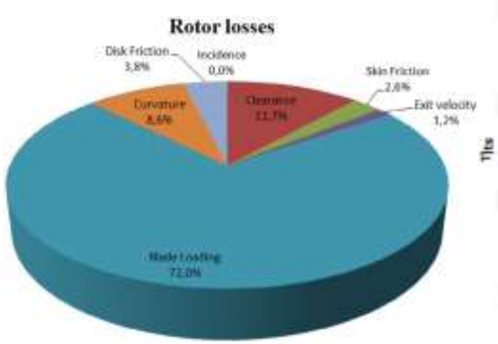
… to refined 3D design (real PR EOS)

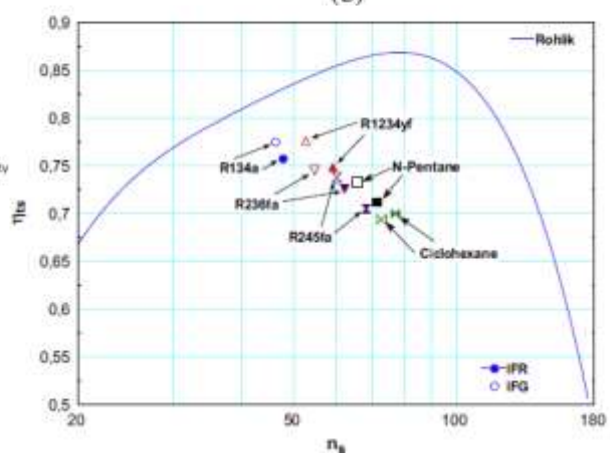


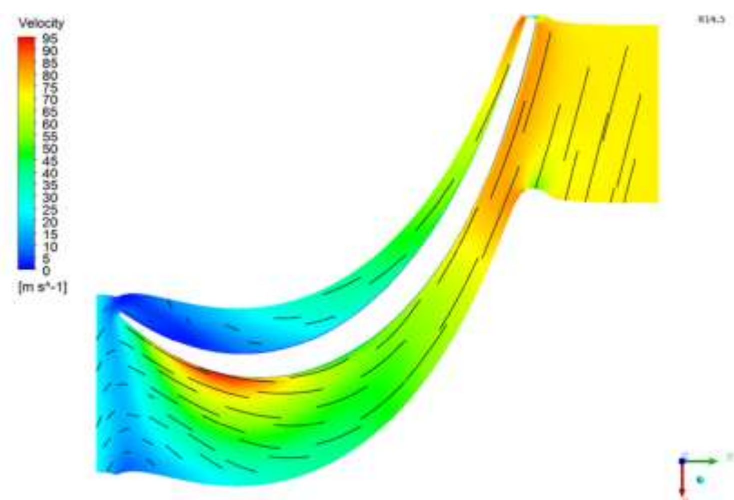








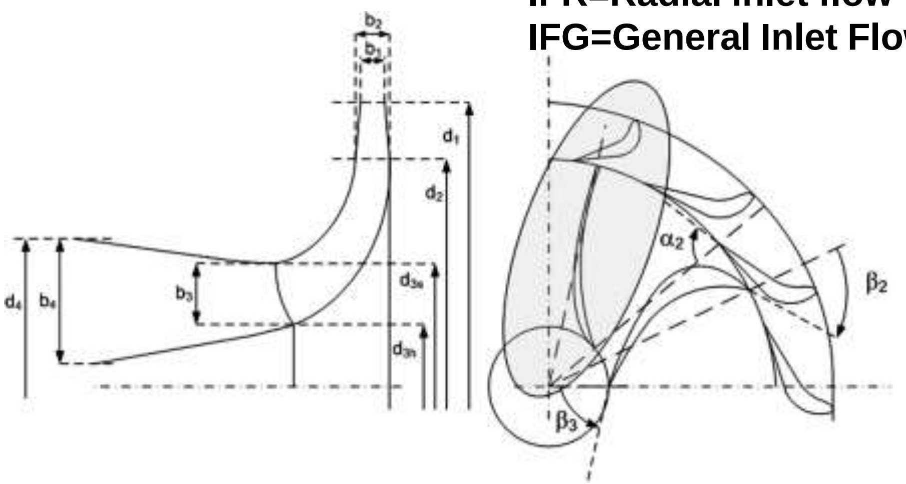




Mini and micro Expanders for ORCs
Radial turboexpanders

Accurate 0D design for different fluids (real EOS with evaluation of losses)

IFR=Radial inlet flow
IFG=General Inlet Flow



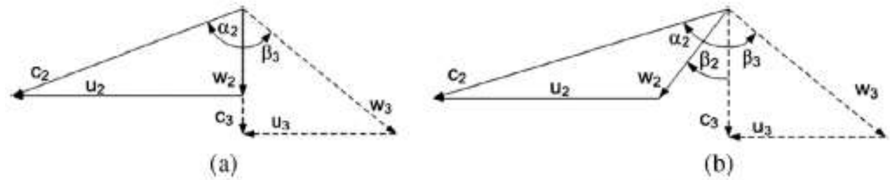


Fig. 2. Velocity triangles – nominal conditions; (a) 90° IFR and (b) IFG.

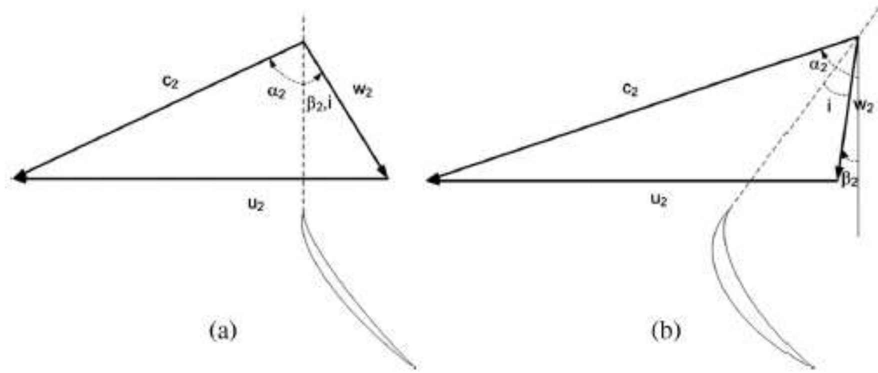
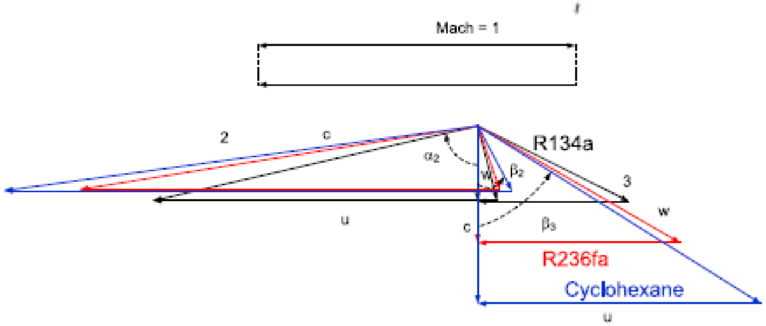
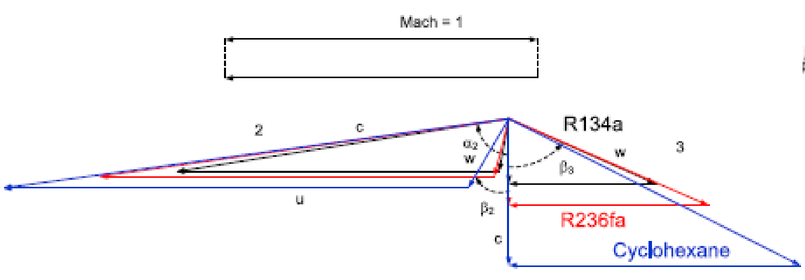


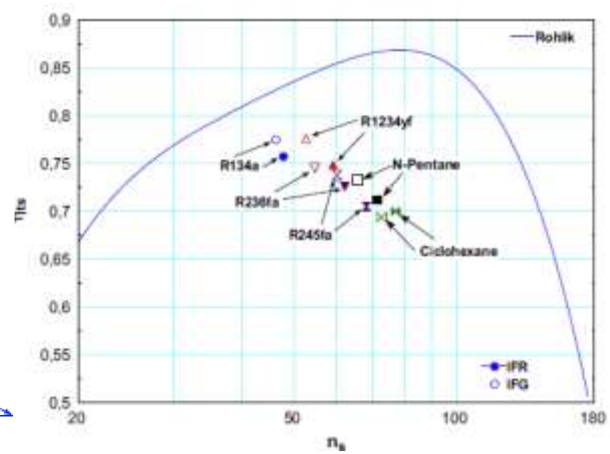
Fig. 3. Velocity triangles – optimal incidence conditions; (a) 90° IFR and (b) IFG.

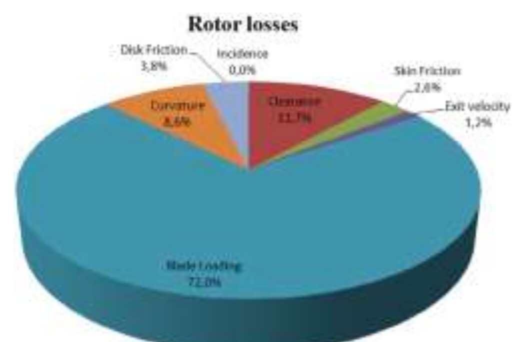


(a) IFR



(b) IFG

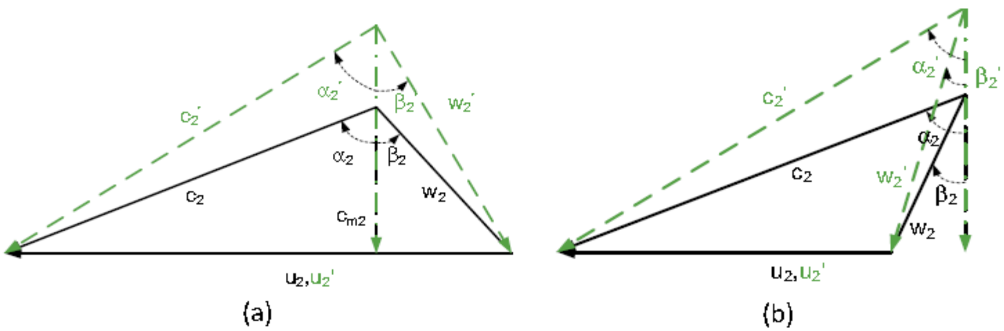




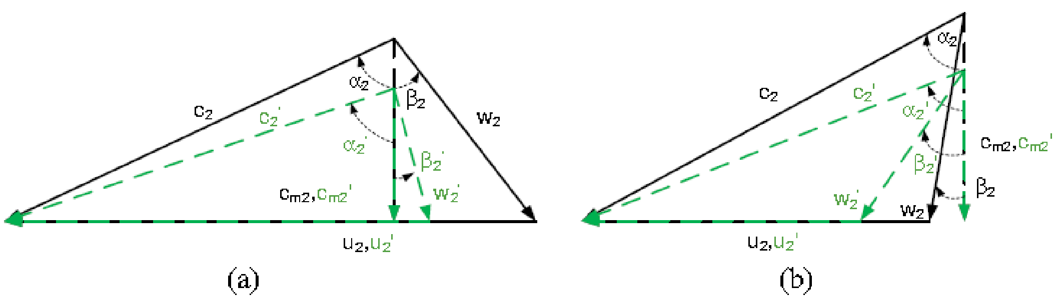
Mini and micro Expanders for ORCs
Radial turboexpanders

Accurate 0D design: influnce of the main parameters on the geometry:

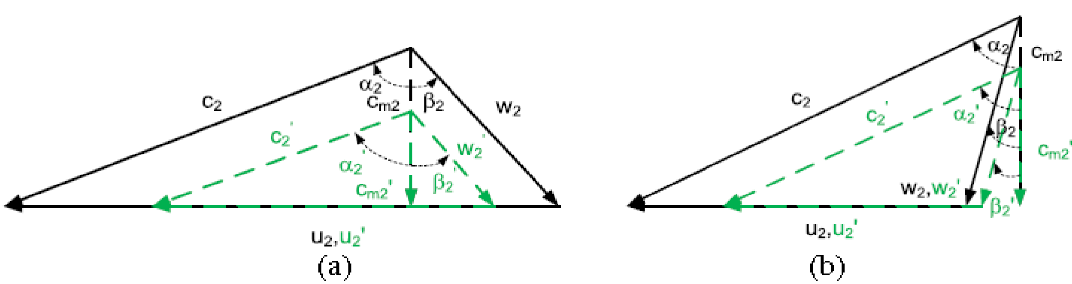
flow coefficient ϕ , load coefficient ψ isentropic degree of reaction **Rs**



Variation of velocity triangles with increasing flow coefficient ϕ (from **solid black** to **dashed green**, (a) **IFR** and (b) **IFG**)

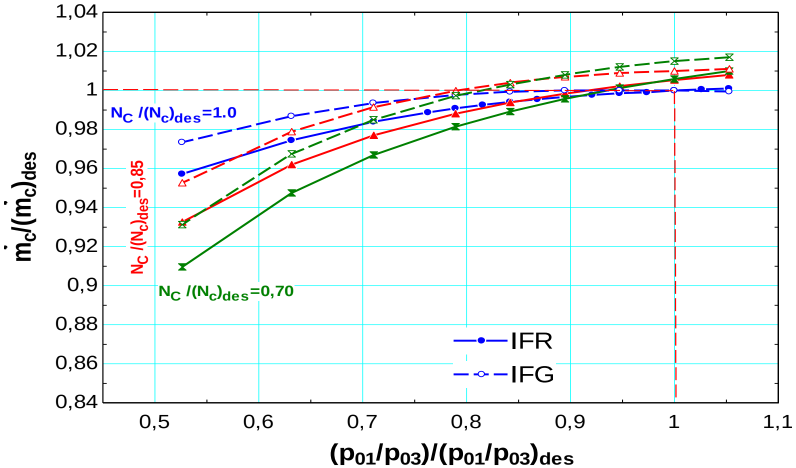


Variation of velocity triangles at rotor inlet with increasing load coefficient ψ (from **solid black** to **dashed green**, (a) **IFR** and (b) **IFG**)

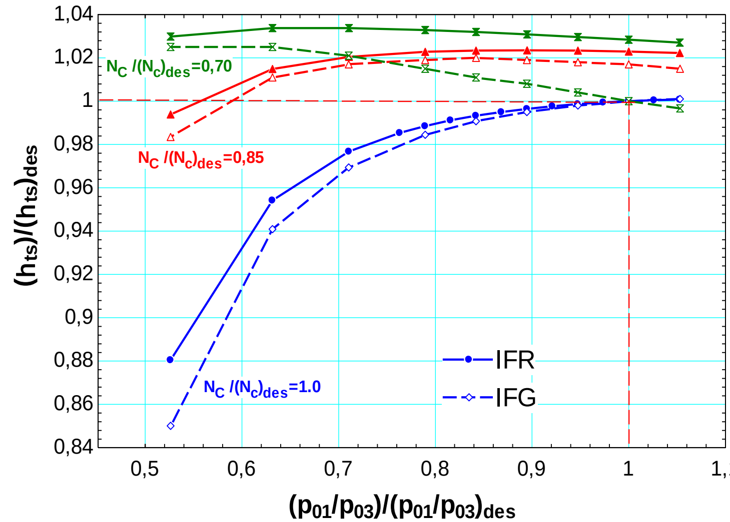


Variation of velocity triangles with increasing isentropic degree of reaction **Rs** (from **solid black** to **dashed green**, (a) **IFR** and (b) **IFG**)

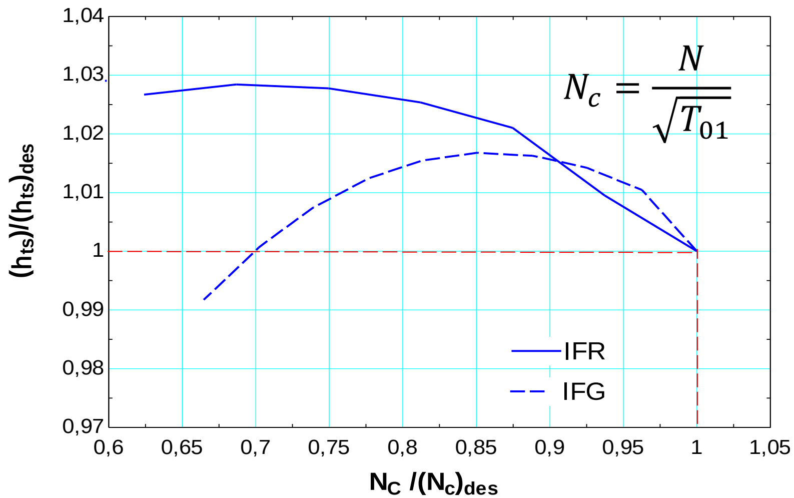
Accurate 0D model: off design analysis and characteristic curves (des = design value)



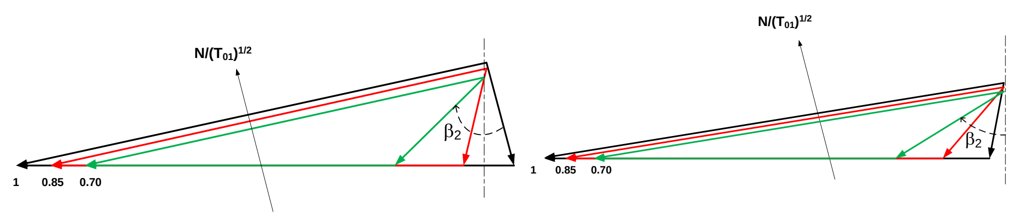
Mass flowrate m_c vs. pressure ratio p_{01}/p_{03}



Isentropic efficiency η_c vs. pressure ratio p_{01}/p_{03}



Isentropic efficiency η_c vs. corrected speed N_c



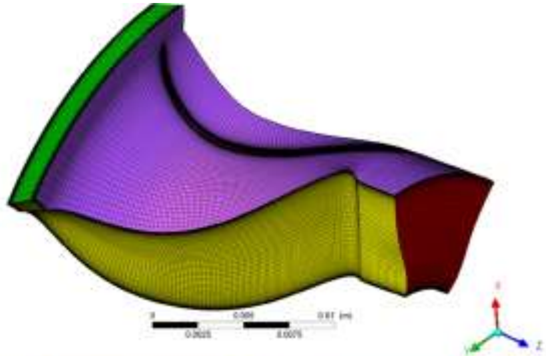
Velocity triangles at rotor inlet at variable corrected speed
a) Radial blades b) Backswept blades

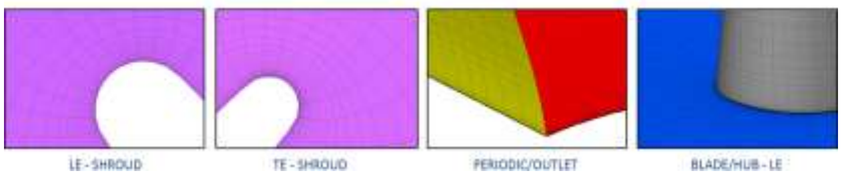
Mini and micro Expanders for ORCs
Radial turboexpanders

From the preliminary 0D to the Refined 3D design (real PR EOS, R134a)

Downscaled size from 50 kW of the basic 0D design **to 5 kW**

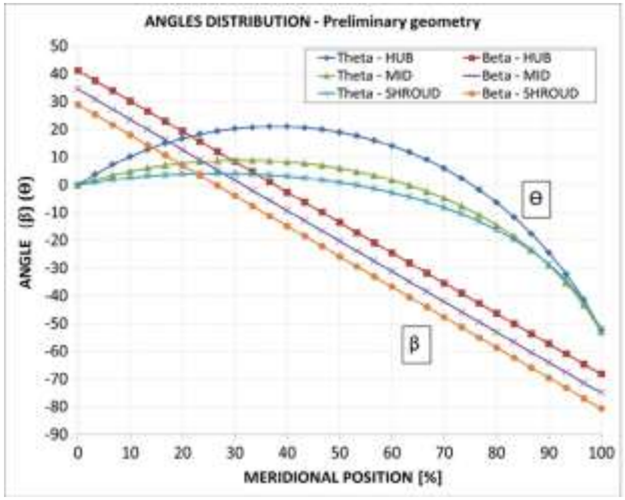
Meshing

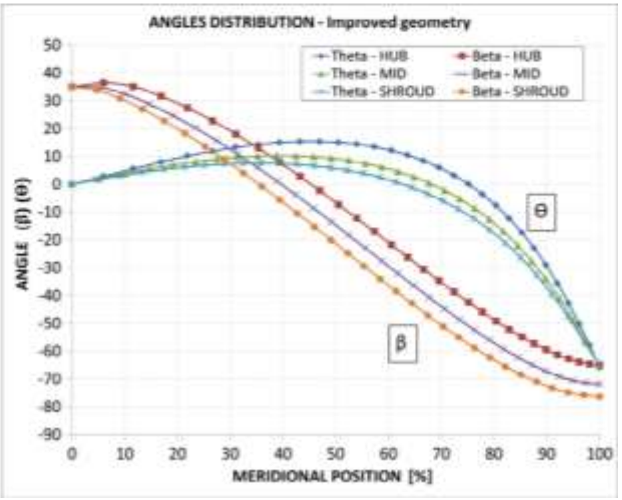


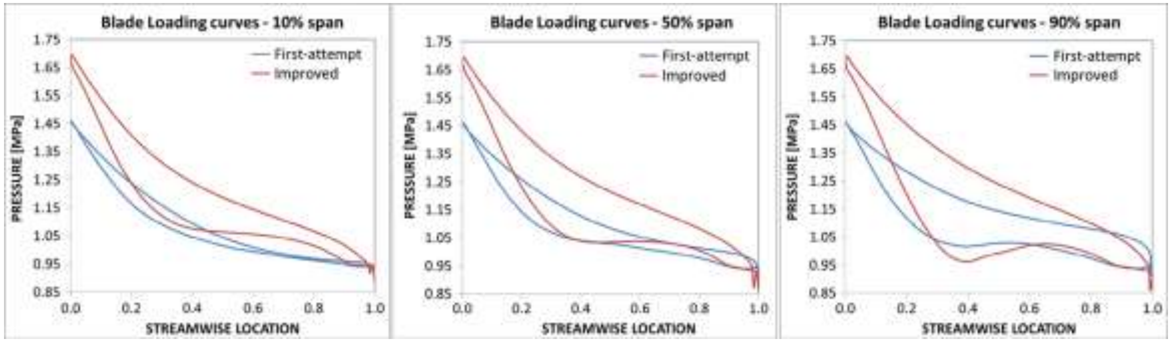


2 steps:
1) first attempt design;
2 refined design

3D design important to assess the **convenient number** of **blades**



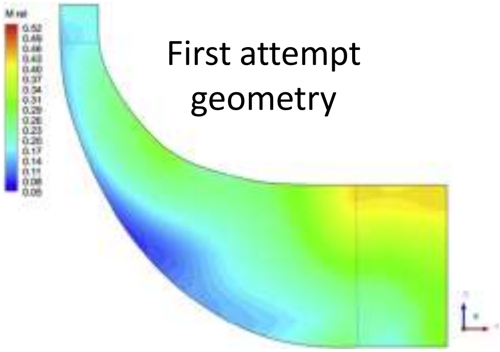


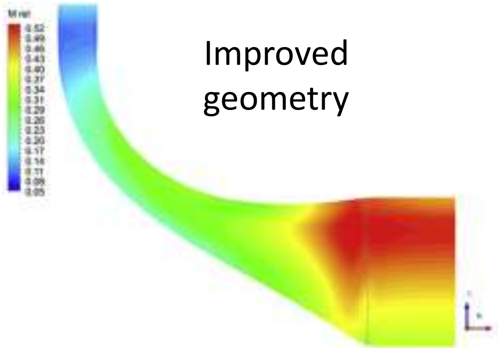


Mini and micro Expanders for ORCs
Radial turboexpanders

From the preliminary 0D to the Refined 3D design (real PR EOS, R134a)

Relative Mach Number distribution on meridional surface





CFD design main results – improved geometry.

Variable	CFD design	Unit
$\dot{m}$	0.2013	[kg/s]
η_{ts}	71.76	[%]
P	5,162	[W]
Z_B	10	
p_2	1.67	[MPa]
p_{02}	2.87	[MPa]
p_3	0.94	[MPa]
p_{03}	0.95	[MPa]
T_{02}	399.4	[K]
T_{03}	362.2	[K]
h_{02}	342,990	[J/kg]
h_{03}	317,348	[J/kg]

Distribution of relative velocity (Midspan layer, Improved geometry).

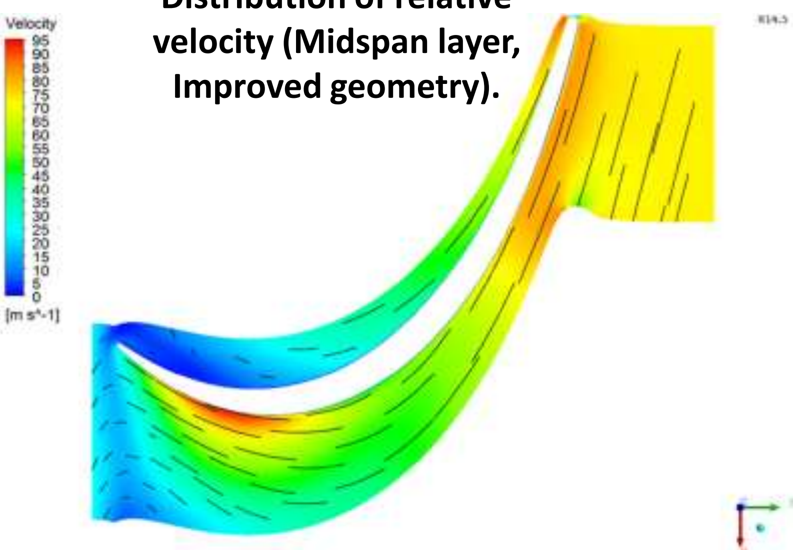


Table 7
Comparison between 0D design and 3D CFD design for improved geometry.

Variable	Unit	0D design	3D CFD improved design	0D–3D relative error [%]
c_2	[m/s]	162.3	166.0	2.2
c_3	[m/s]	21.7	26.8	19.0
η_{ts}	[%]	72.78	71.76	–1.42
P	[W]	5422	5162	–4.8

Good agreement between preliminary 0D and 3D refined design

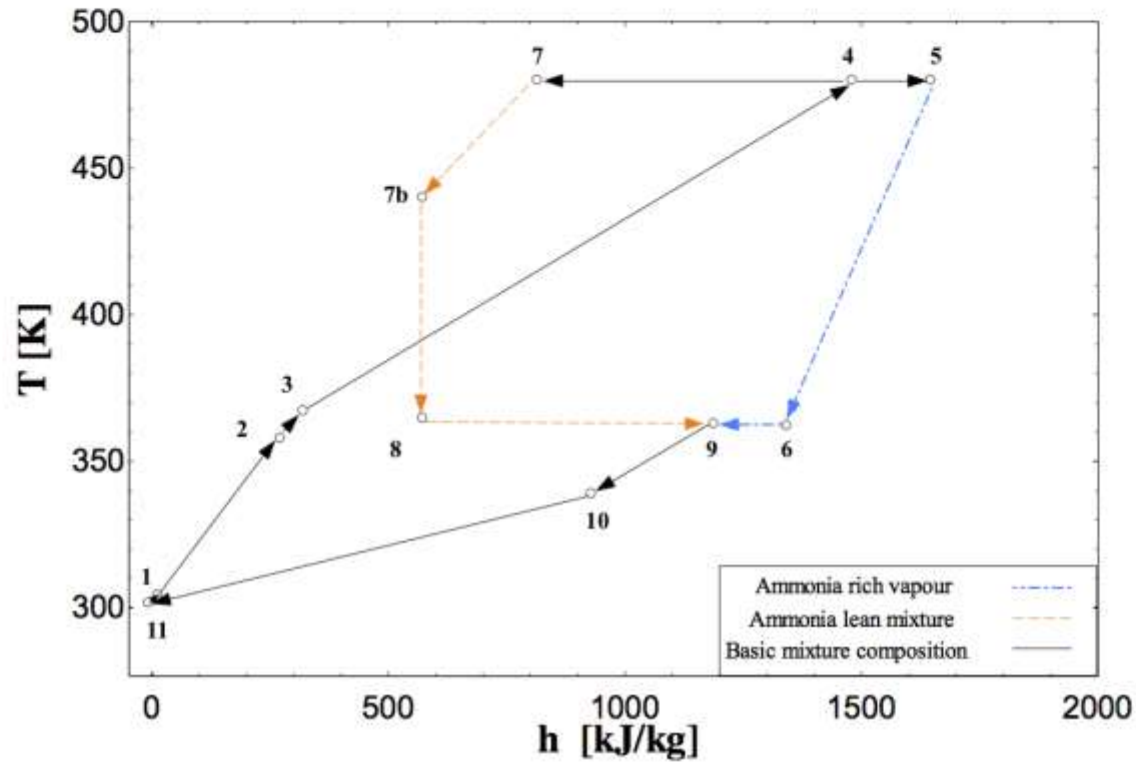
⇒ Reliable combined tool:

0D: defines the basic geometry;

3D: refines the channels shape and the number of blades

Kalina 2015

- Kalina cycles: may be **preferred to ORCs** when the **geothermal fluid** has **temperature < 150 °C**
- **NH3-H2O mixture** has a **range of evaporation curves** depending on the composition and temperature ⇒ possibility of **working** with **low well temperature** is **considerably extended**

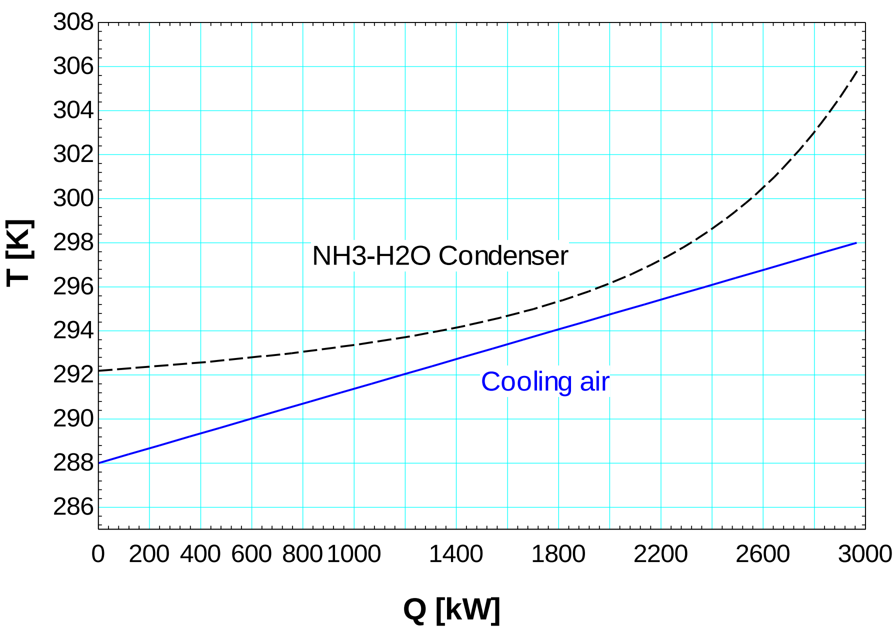


ASME Power Energy **2015**

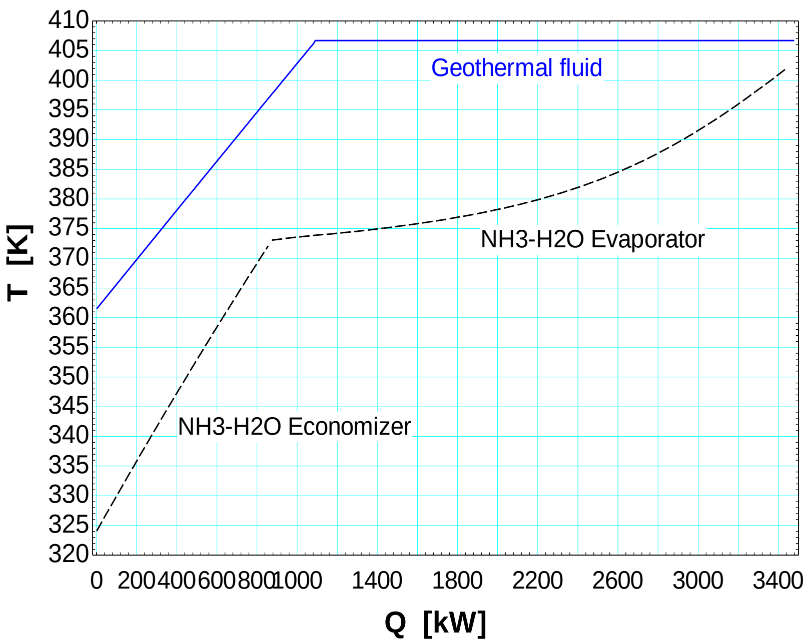
MATCHING THE CONDENSER AND EVAPORATOR CURVES

The **matching level of the curves is attractive** due to the variable evaporation and condensing temperatures.

⇒ reduction of the irreversibilities related to heat transfer.



***Condenser** temperature/heat transfer diagram*



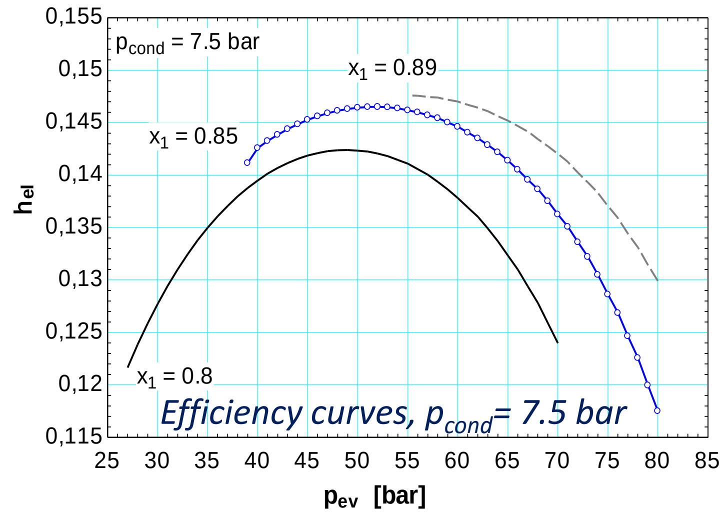
***Evaporator** temperature/heat transfer diagram*

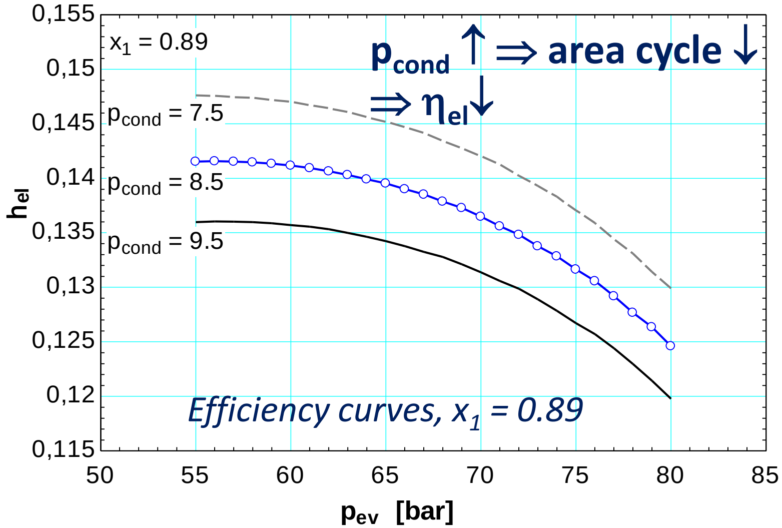
PARAMETRIC ANALYSIS AND OPTIMIZATION OF THE POWER CYCLE

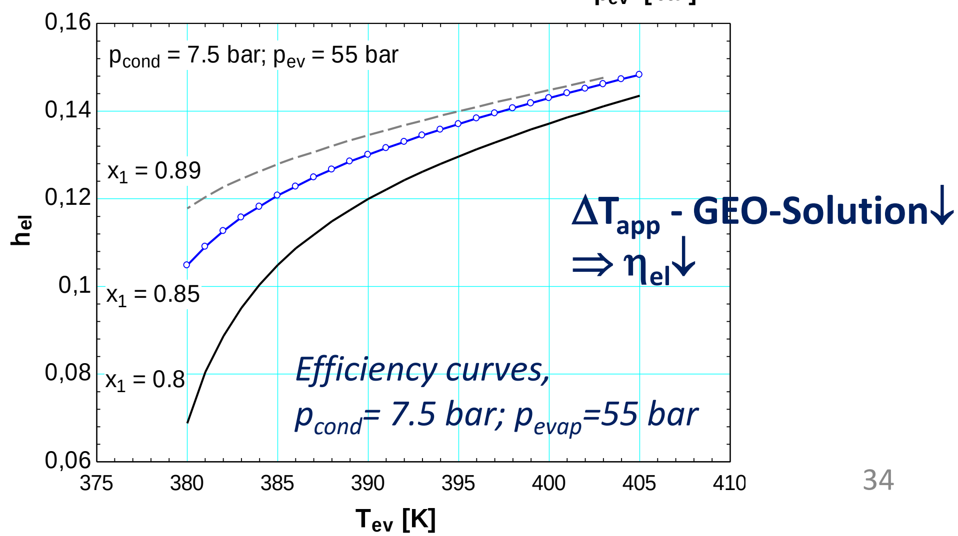
$Q\downarrow \quad W_P\uparrow \quad x_1\downarrow \Rightarrow W_T\downarrow$

A **sensitivity analysis** was performed analyzing the power cycle performance (**efficiency η_{el}**) in function of the following main parameters:

1) NH3-H2O composition (3 values)
2) Condenser pressure
3) Evaporator pressure (**optimizing** range 45-55 bar)
4) Evaporator temperature

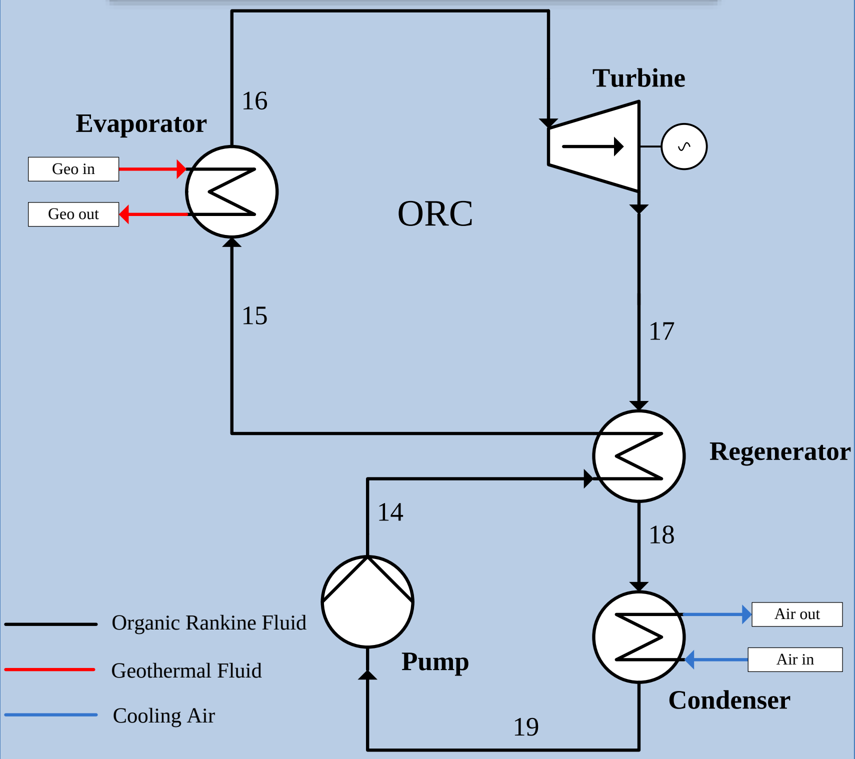


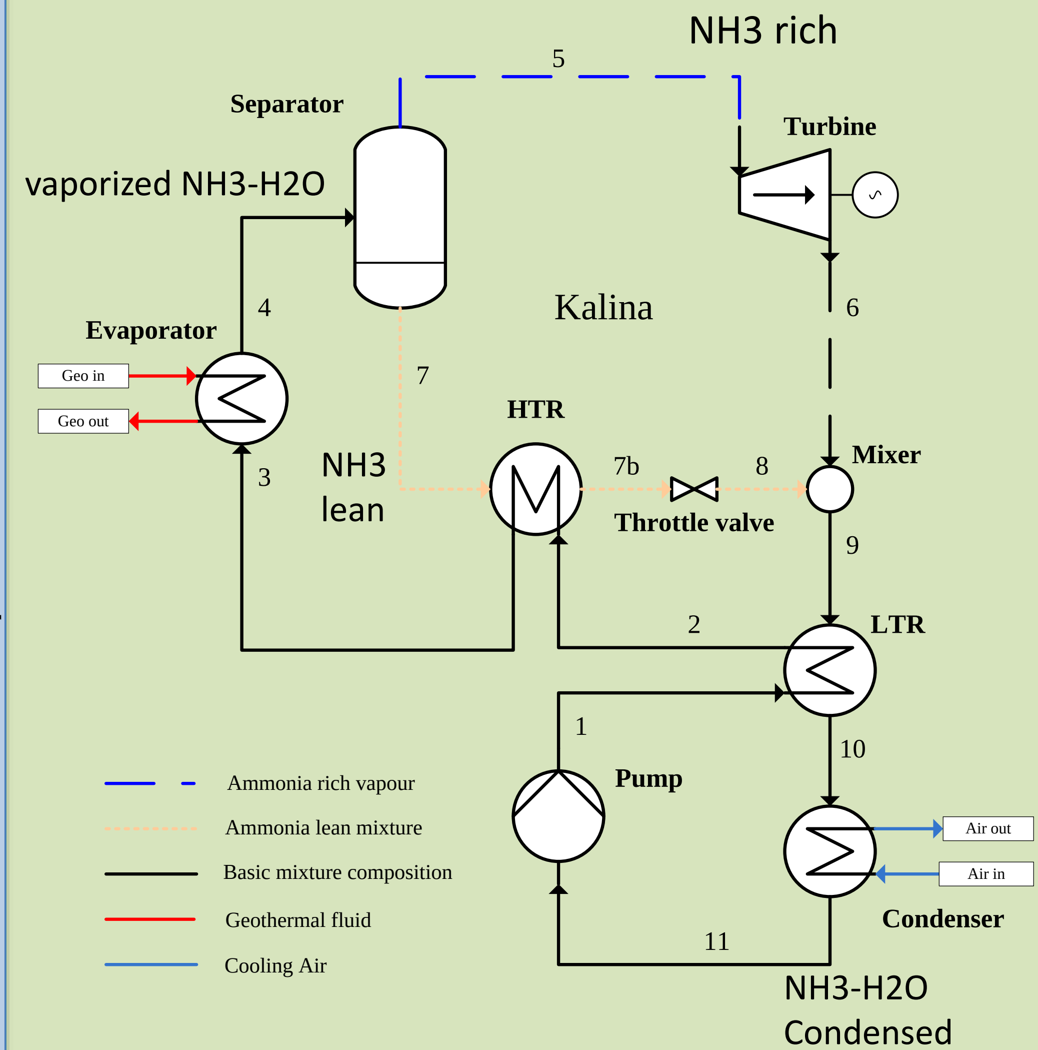




Kalina 2016

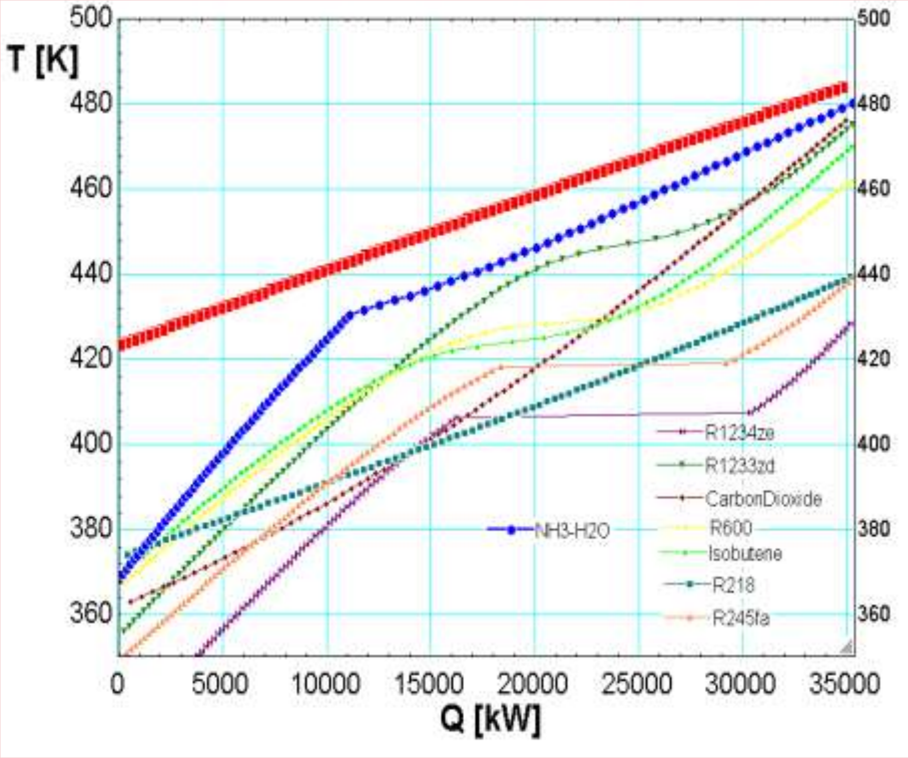
- R245fa
- Isobutene
- R600
- R218
- Carbon Dioxide
- R1234ze
- R1233zd





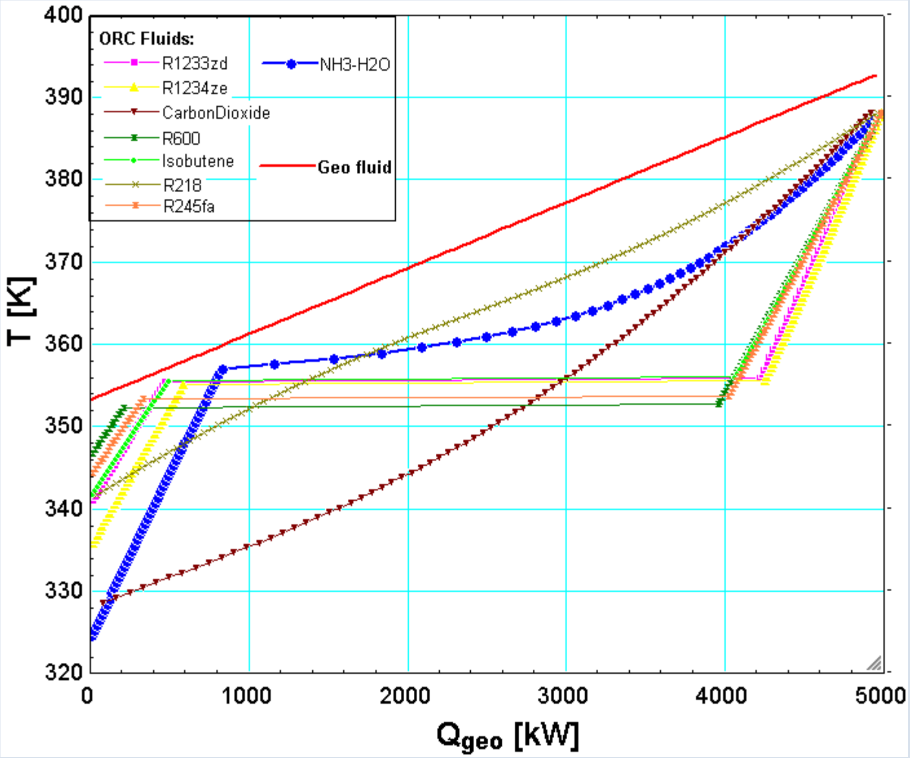
Mt. Amiata case study

T_{well} = 212°C

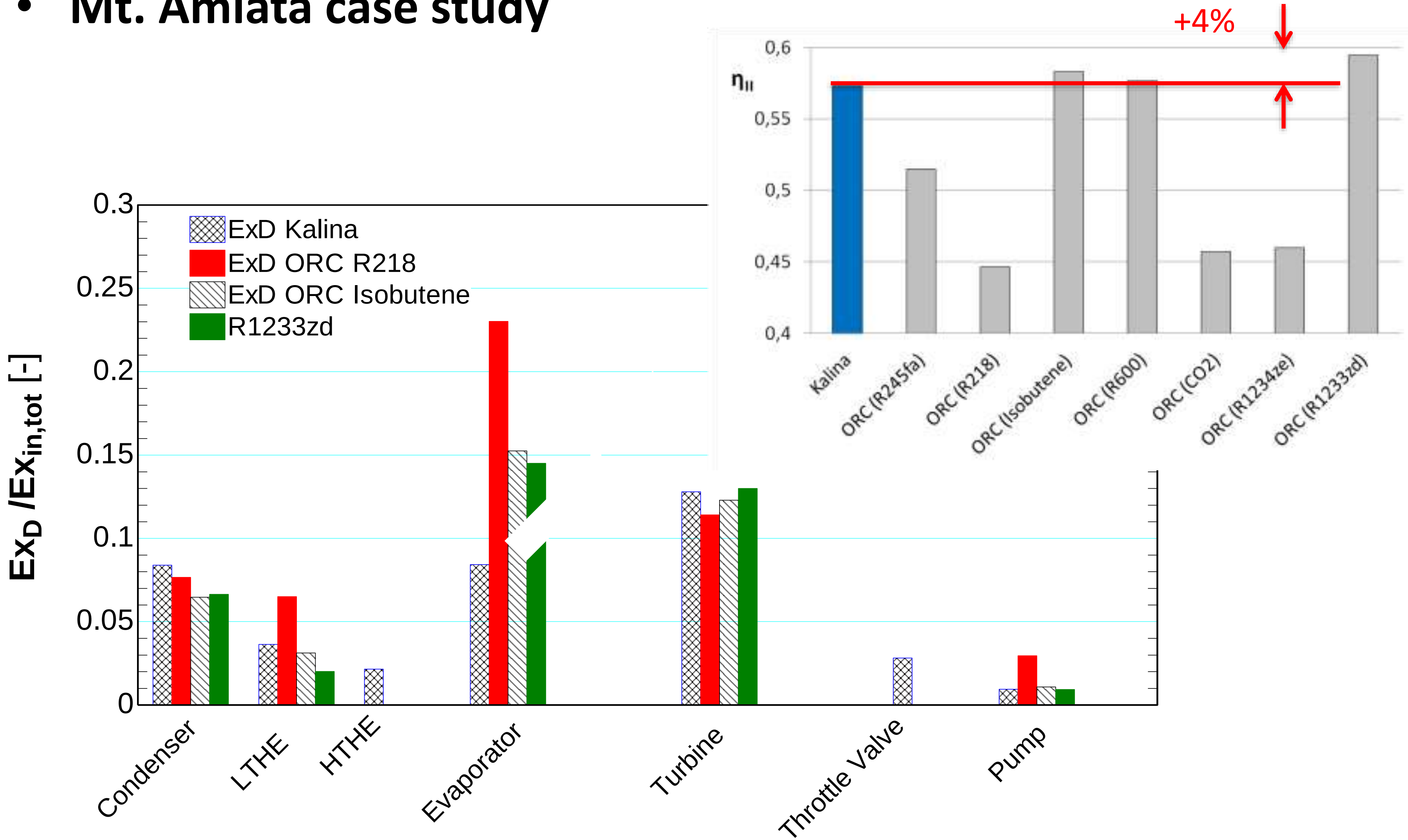


Pomarance case study

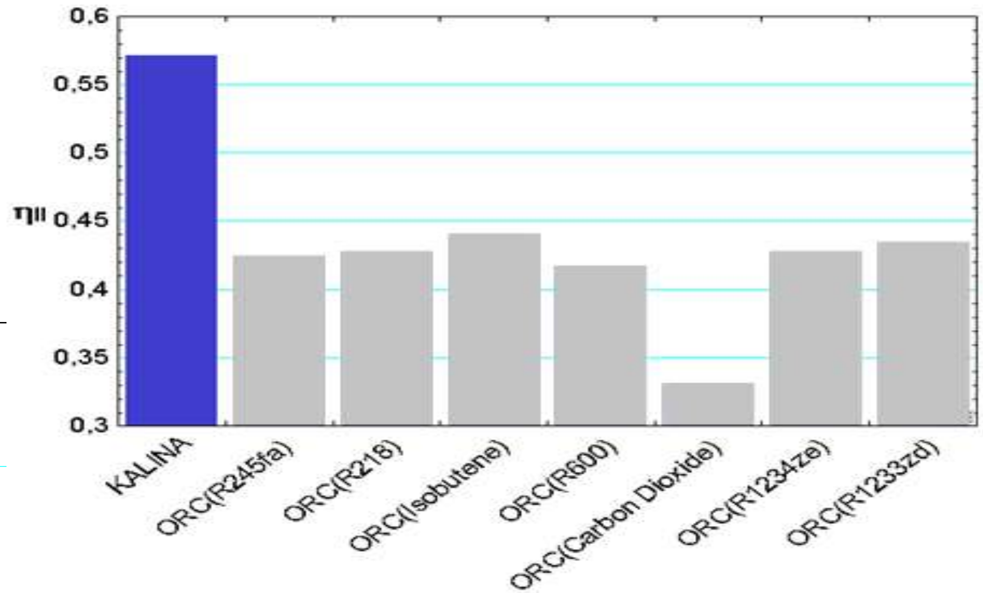
$T_{resource}$ = 120°C

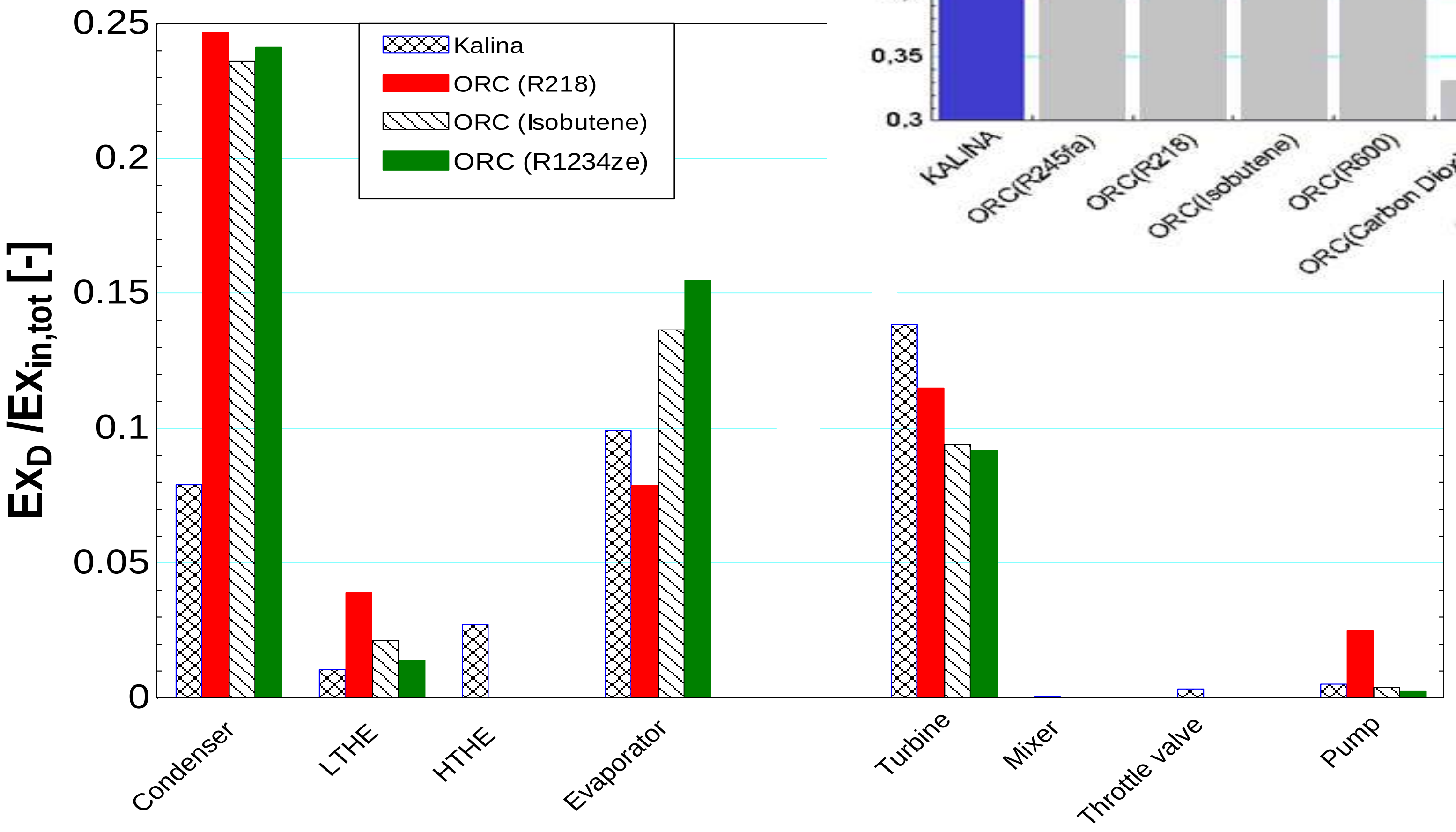


- **Mt. Amiata case study**



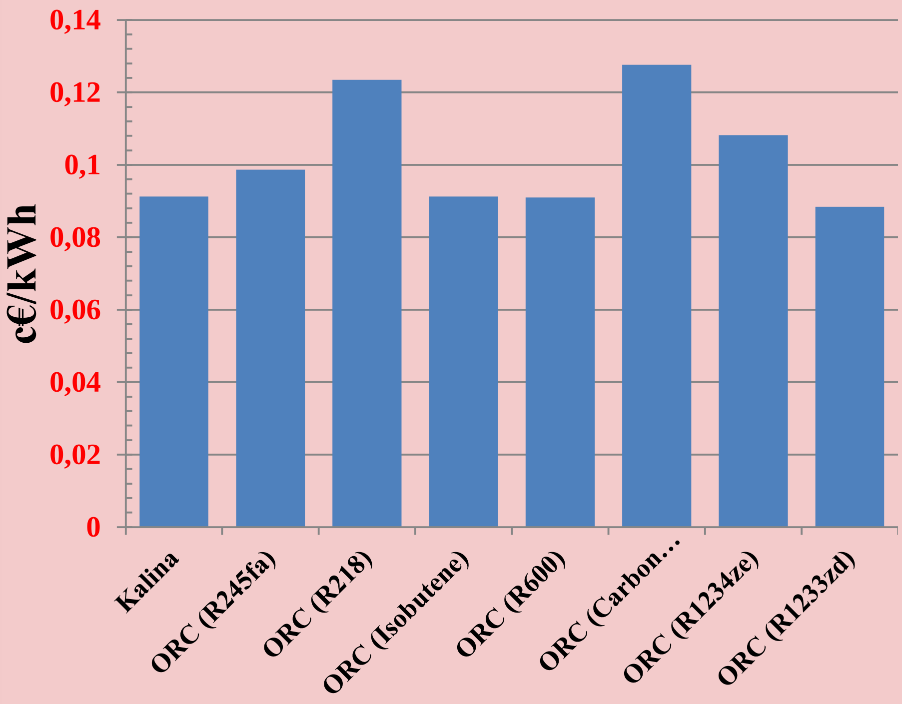
- **Pomarance case study**





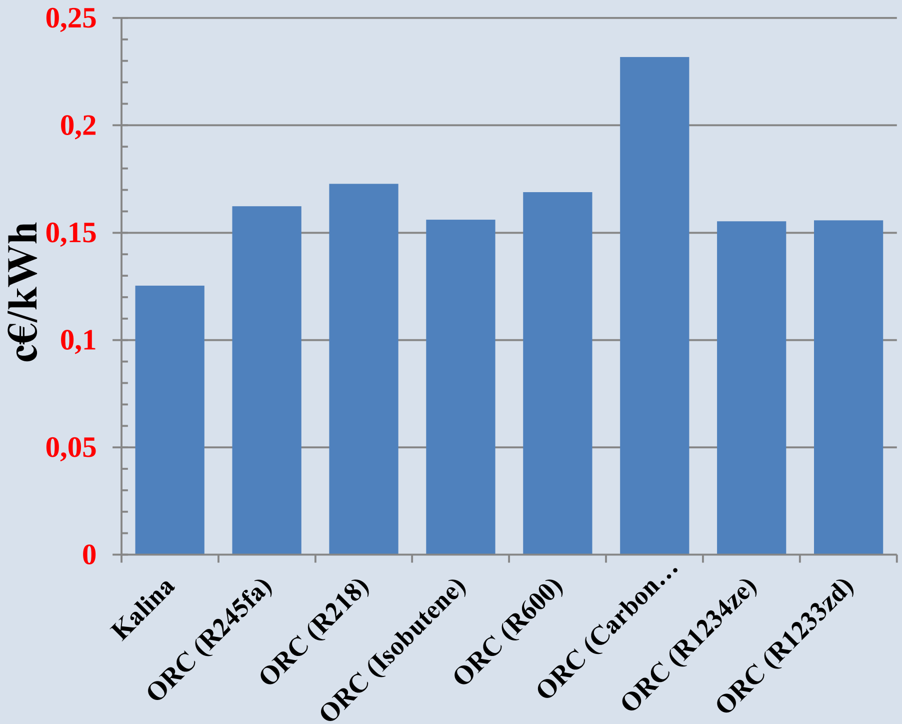
Mt. Amiata case study

T_{well} = 212°C



Pomarance case study

$T_{resource}$ = 120°C



Thermoeconomic analysis and comparison – ORC and Kalina cycles at low and medium-high resource temperature

	Mt. Amiata case study (212°C)		TLR Pomarance case study (120°C)	
	Kalina	ORC (R1233zd(E))	Kalina	ORC (R1234ze)
Power [kW]	5982	6237	645	483
First law efficiency	0.1684	0.1755	0.1289	0.0966
Second law efficiency	0.5731	0.5943	0.5709	0.4276
Critical component	Turbine	Turbine	Turbine	Condenser; Evaporator
TCI [k€]	8663	8483	2244	1852
Electricity cost	9.125	8.845	12.53	15.53