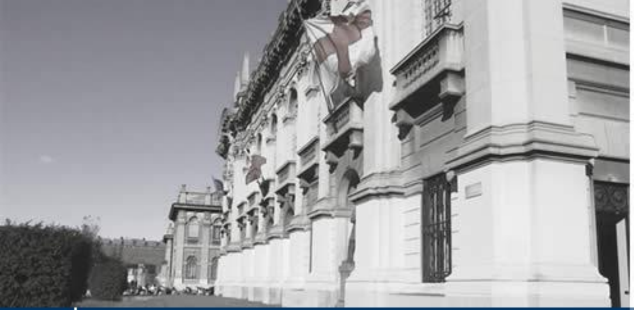


POLITECNICO DI MILANO

THERMODYNAMIC ORC CYCLE DESIGN OPTIMIZATION FOR MEDIUM-LOW TEMPERATURE ENERGY SOURCES

M. Astolfi
M. C. Romano
P. Bombarda
E. Macchi

Purpose

1. Thermodynamic optimization
   - Extended analysis (source, fluid, cycle)
   - General trend in observed variables
   - Global rules in fluid and cycle selection
2. Component efficiency prediction
   - Pump : $f(V, P_{el})$
   - Turbine : $f(V_{out}/V_{in}, Ns, SP, P_{el})$
3. Component cost prediction
   - Heat exchangers (*Aspen HTFS+*, *Thermoflex*)
   - Pump (*in house correlation*)
   - Turbine (*in house correlation*)
4. LCOE economic optimization for a given thermal source

Methodology

- **Matlab**® code + **Nist Refprop** ® database

- **60 Fluids**

Hydrocarbon	17
HFC	13
FC	7
Siloxanes	8
Others	15

6 cycle configurations

Subcritical	superheated	regenerative
		non regenerative
	saturated	regenerative
		non regenerative
Supercritical		regenerative
		non regenerative

- **2 heat sources**

Geothermal Brine	Exhaust Gases
200 kg/s	2 kg/s
4186 kJ/kg	1000 kJ/kg
[100 °C - 200 °C]	[200 °C - 400 °C]
70°C	120°C

Assumptions

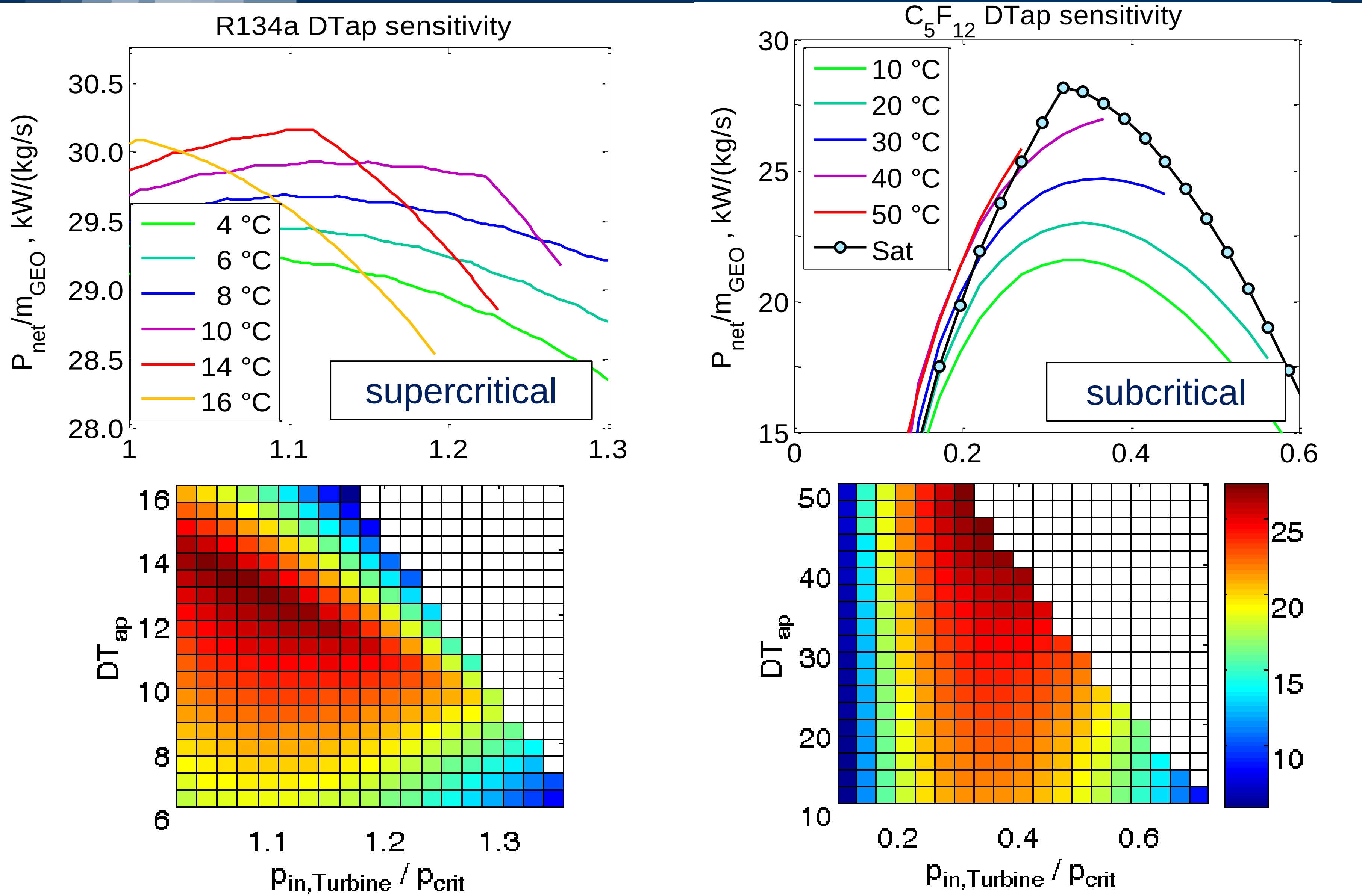
- Pressure drops
  - $\Delta p/p_{in}\%$ vapour phase
  - Δp liquid phase
  - ΔT two phase

- Temperature differences
  - ΔTpp PHE
  - ΔTpp Condenser
  - ΔTap Condenser
  - ΔTap Recuperator

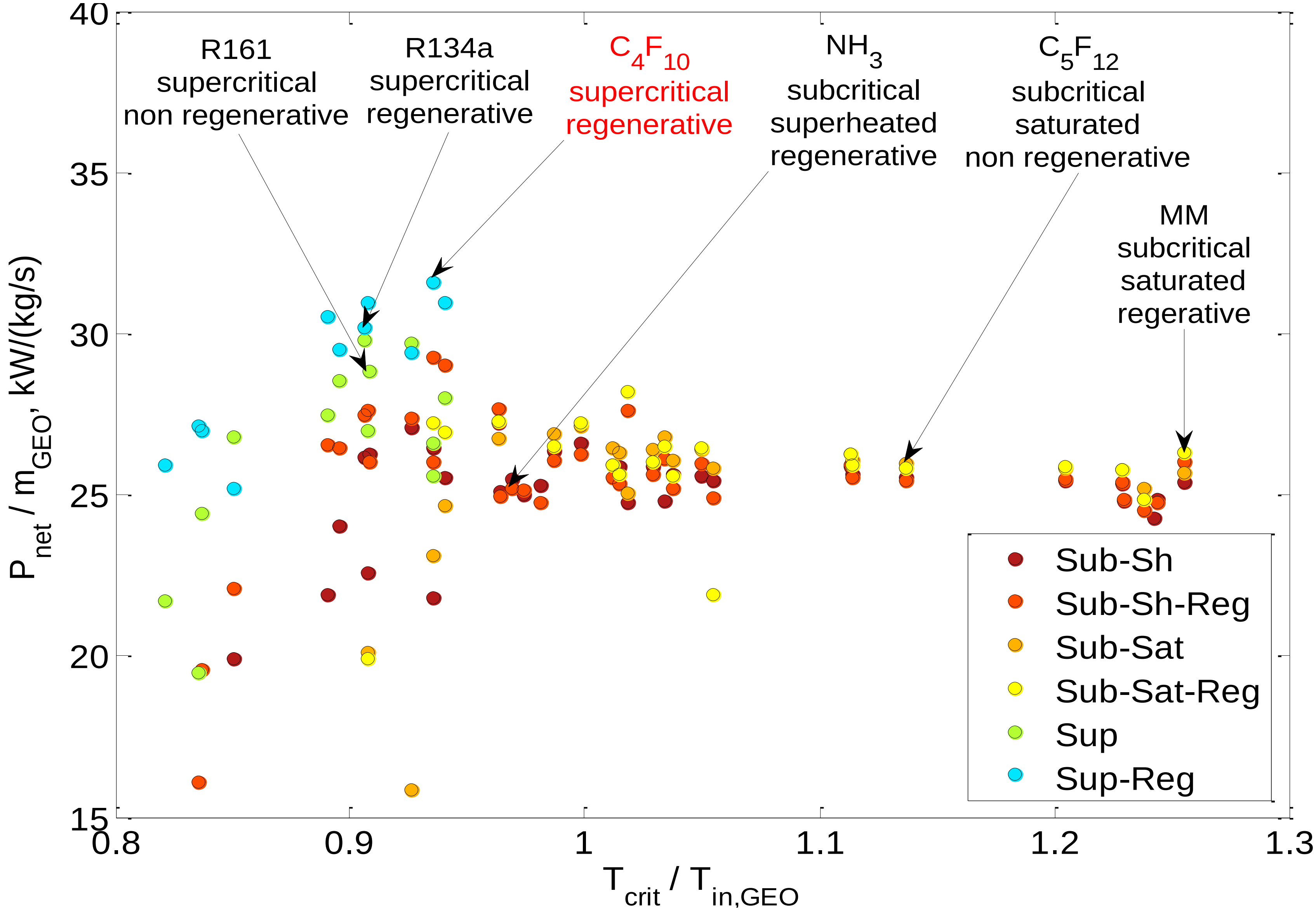
- Efficiencies
  - η_{is} Turbine
  - η_{idr} Pump
  - $\eta_{gen,org,el}$

- Discretization of each heat exchanger: ΔTpp *& US*
- No liquid along the expansion as constrain

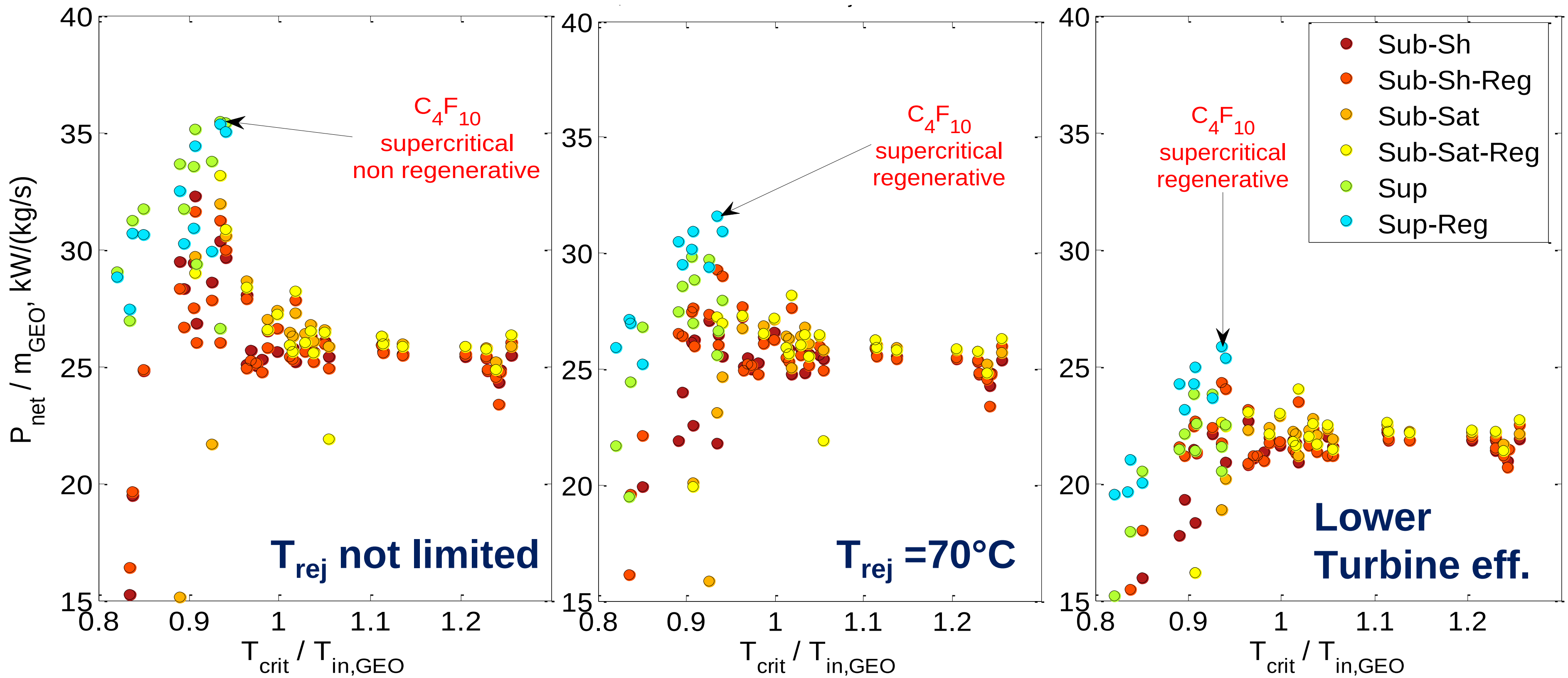
Optimization variables $p_{in,Turbine}$ - ΔT_{ap}



$T_{in,GEO}$ = 140°C


R161
supercritical
non regenerative
R134a
supercritical
regenerative
C4F10
supercritical
regenerative
NH3
subcritical
superheated
regenerative
C5F12
subcritical
saturated
non regenerative
MM
subcritical
saturated
regerative
Sub-Sh
Sub-Sh-Reg
Sub-Sat
Sub-Sat-Reg
Sup
Sup-Reg
40
35
30
25
20
15
0.8
0.9
1
1.1
1.2
1.3
Pnet / mGEO, kW/(kg/s)
Tcrit / Tin,GEO

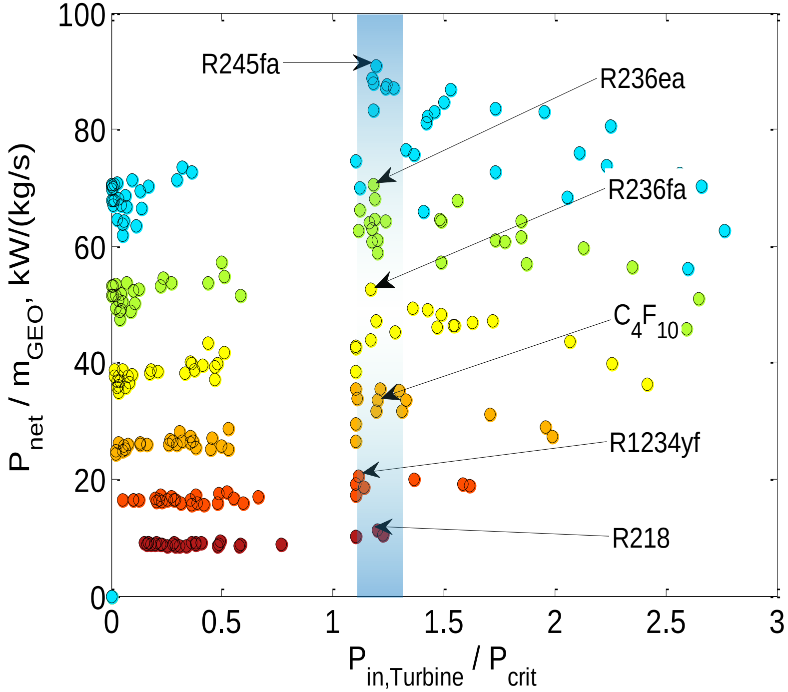
$T_{in,GEO}$ = 140°C limited sensitivity to assumption

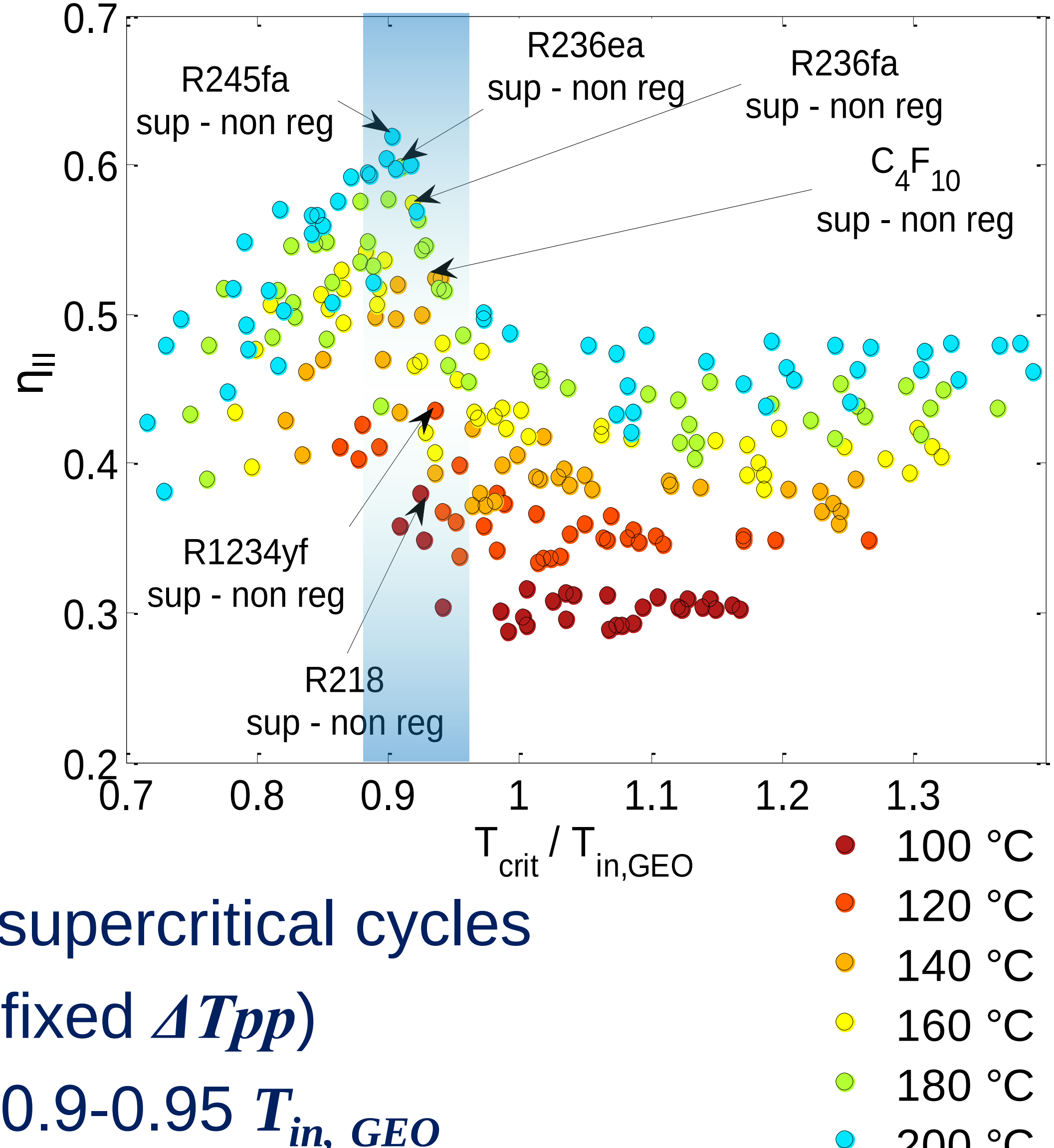


	T_{rej} not limited	Ref Case	Lower eff.	Higher T_{amb}
140	C4F10 [5]	C4F10 [6]	C4F10 [6]	C4F10 [6]
160	R236fa [5]	RC318 [6]	R236fa [6]	RC318 [6]
180	R236ea [5]	R236ea [6]	R236ea [6]	R236ea [6]
200	R245fa [5]	Neopentane [6]	Neopentane [6]	Neopentane [6]

[5] Supercritical non regenerative [6] Supercritical regenerative

Geothermal source - P_{net}/m_{GEO} - η_{II}

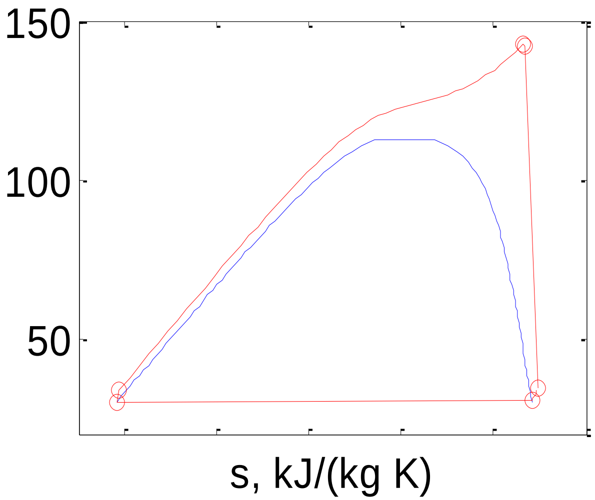




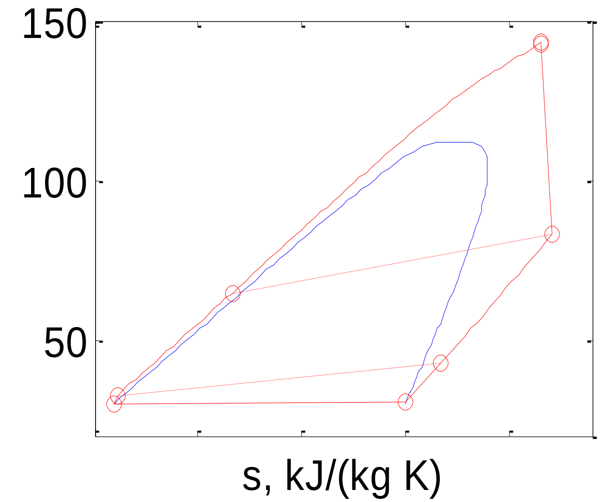
- Maximum P_{net}/m_{GEO} with supercritical cycles
- η_{II} increase with T_{in_GEO} (fixed ΔTpp)
- Optimal fluid has a $T_{crit} \approx$ 0.9-0.95 $T_{in,\ GEO}$

$T_{in,GEO}$ = 160°C fluid molecular complexity

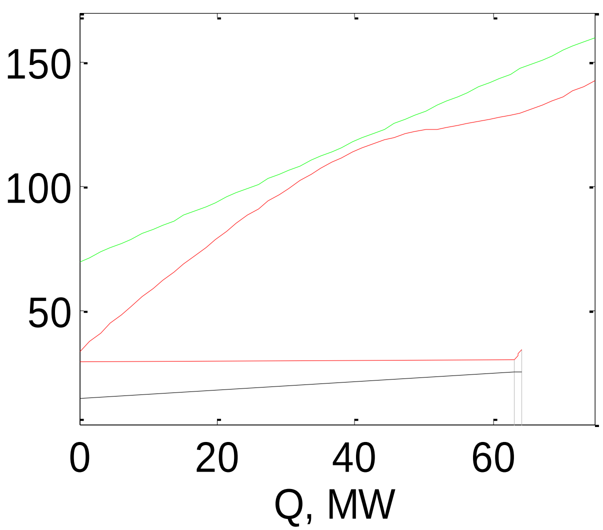
R152a



Perfluorobutane



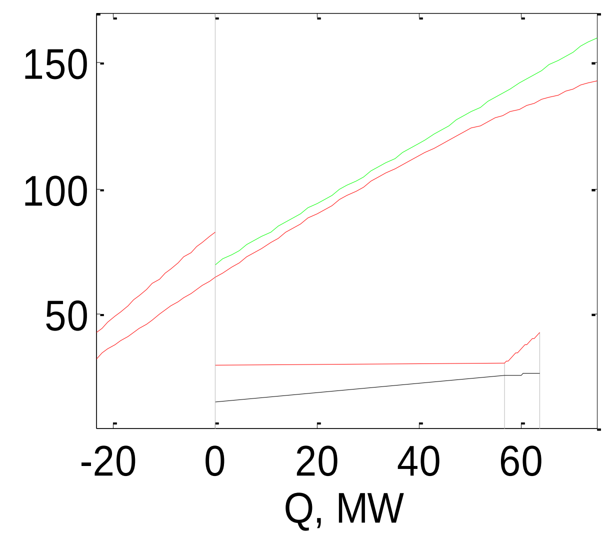
	CHF_2CH_3	C_4F_{10}
T_{crit} °C	113.26	113.28
P_{net}/(kg/s)	44.5	45.7
$P_{pump}/P_{turbine}$	16.50%	19.10%
η_{cycle}	11.93%	12.25%
η_{rec}	100%	100%
η_{plant}	11.93%	12.25%
US_{TOT}/P_{net}	1.645	2.39
ΔTmln	9.86	5.66



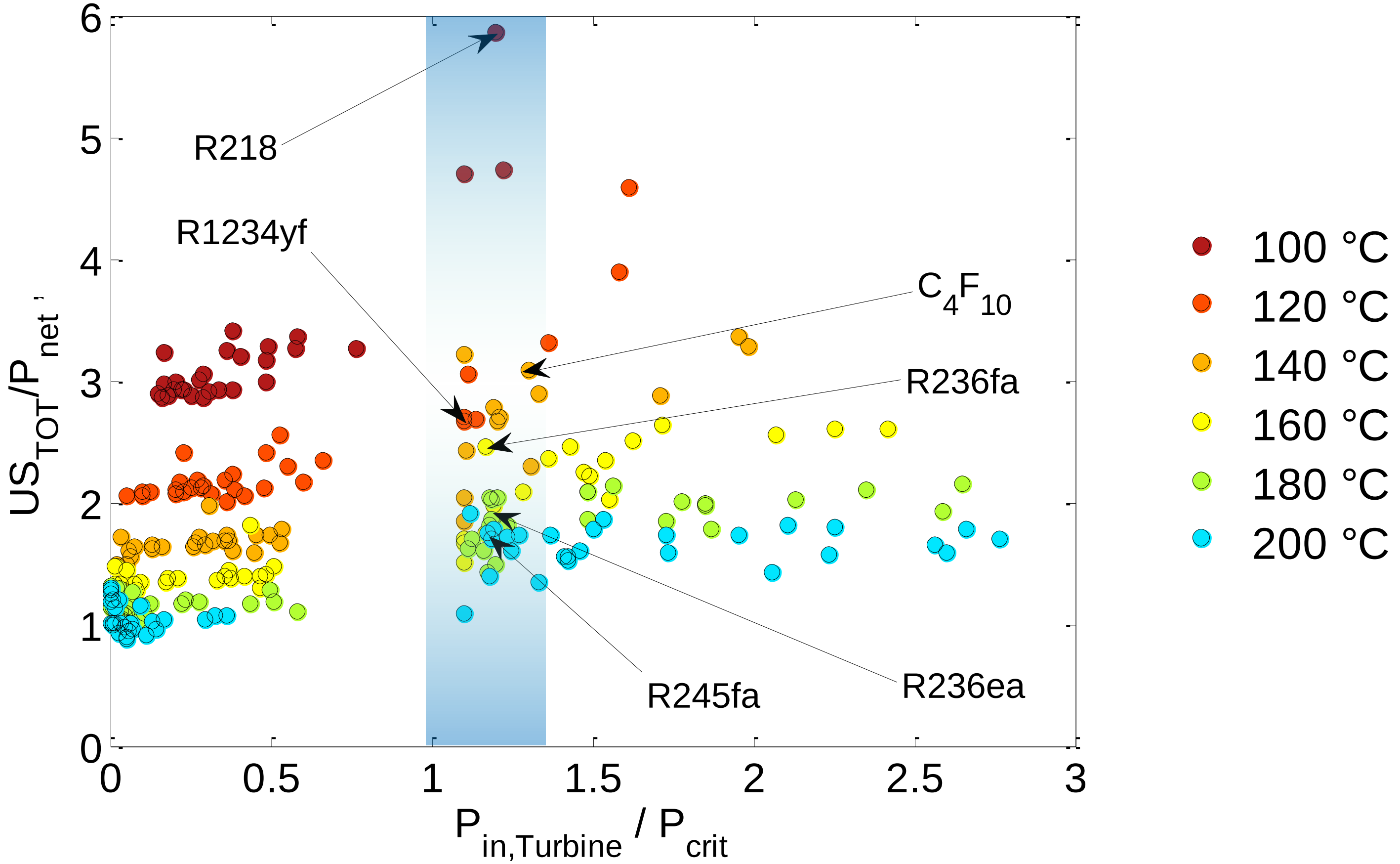
$$cp_{liq} \approx cp_{vap}$$

Overhanging saturation line

Possibility to adopt regenerator

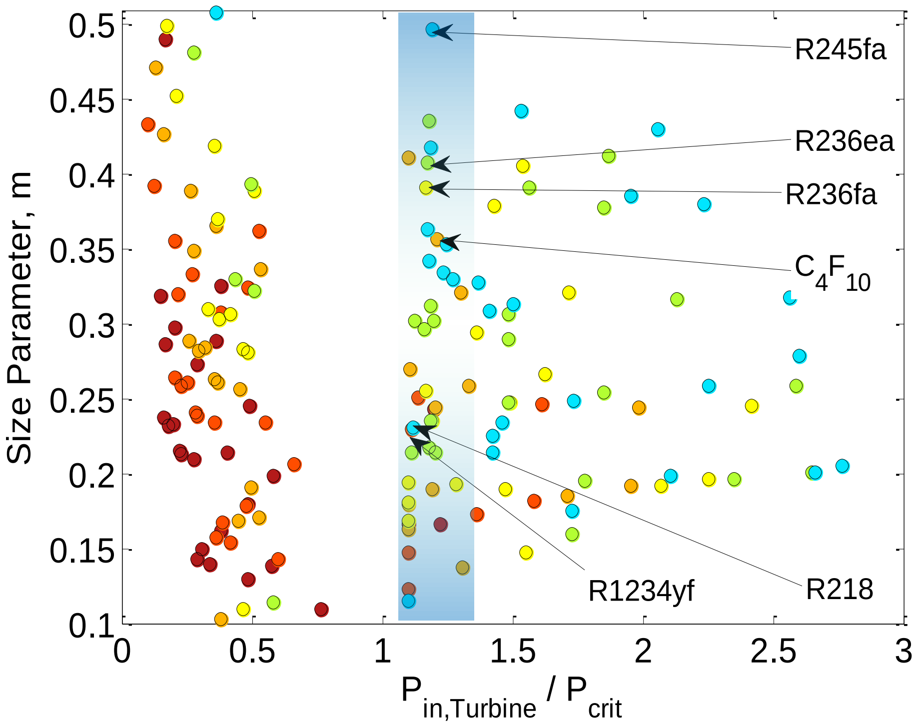


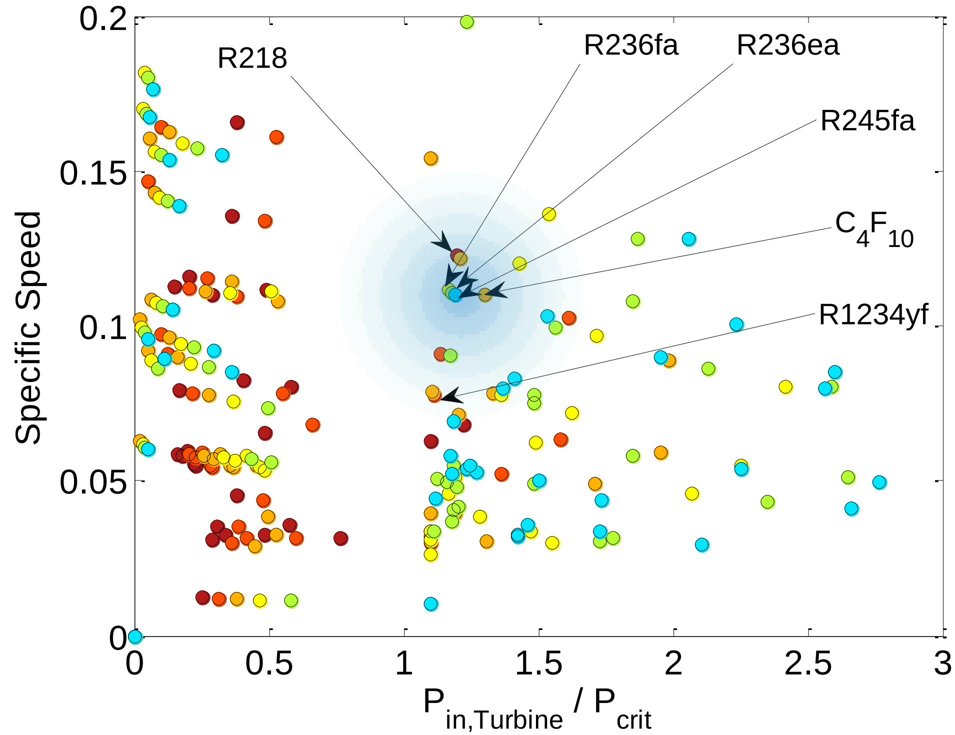
Geothermal source - US_{TOT}/P_{net}



- US_{TOT}/P_{net} decrease for higher T_{in_GEO}
- Lower investment cost *vs* lower power production: Economic optimization is necessary

Geothermal source - *SP* - *Ns*



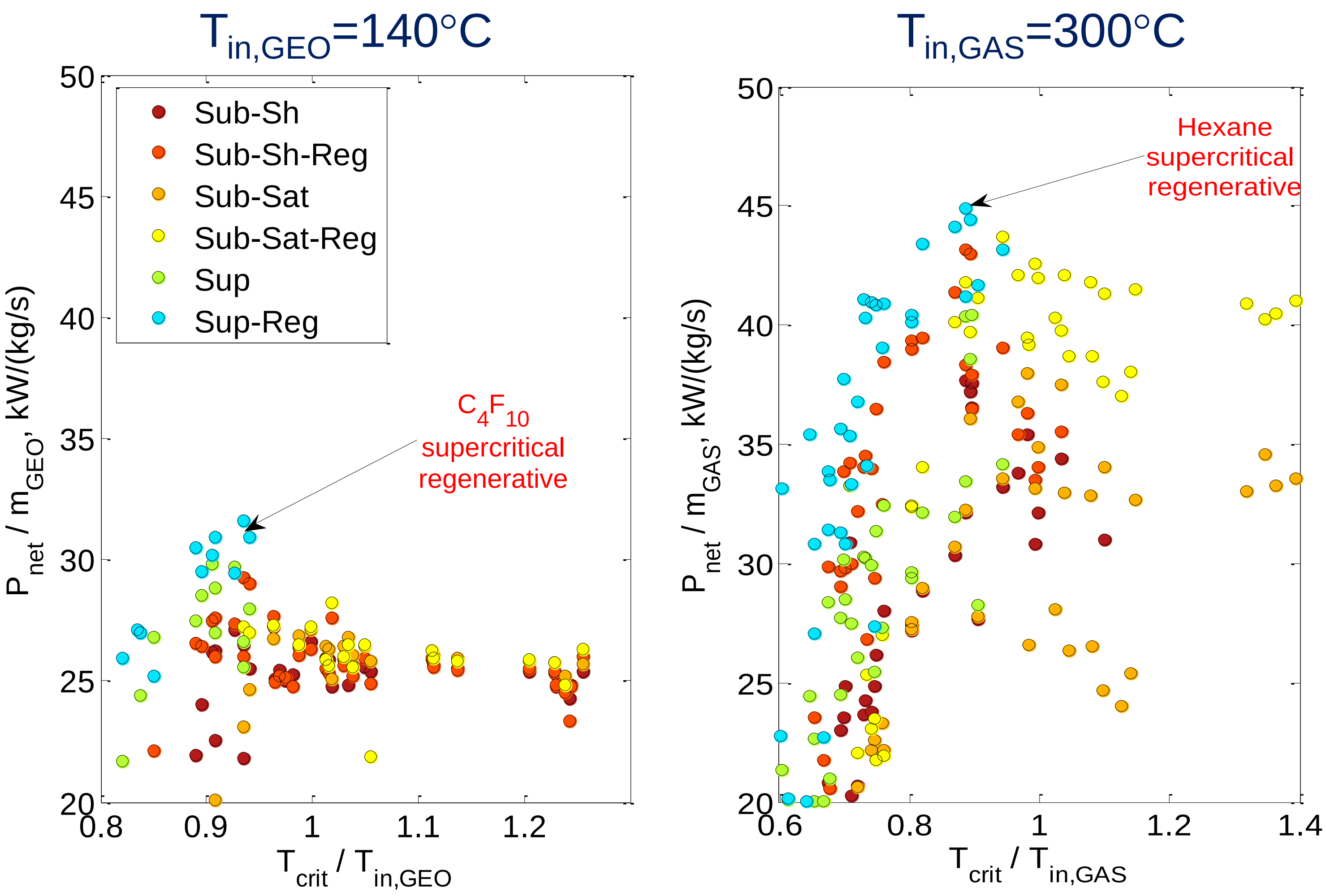


- Well designed turbines for all the optimized cycles
- Good values of ***SP***
- ***Ns*** values near to optimum (0.1)

$$SP = \frac{\sqrt{\dot{V}_{out}}}{\sqrt{\Delta h}} \qquad Ns = N\frac{\sqrt{\dot{V}_{out}}}{\Delta h^{3/4}}$$

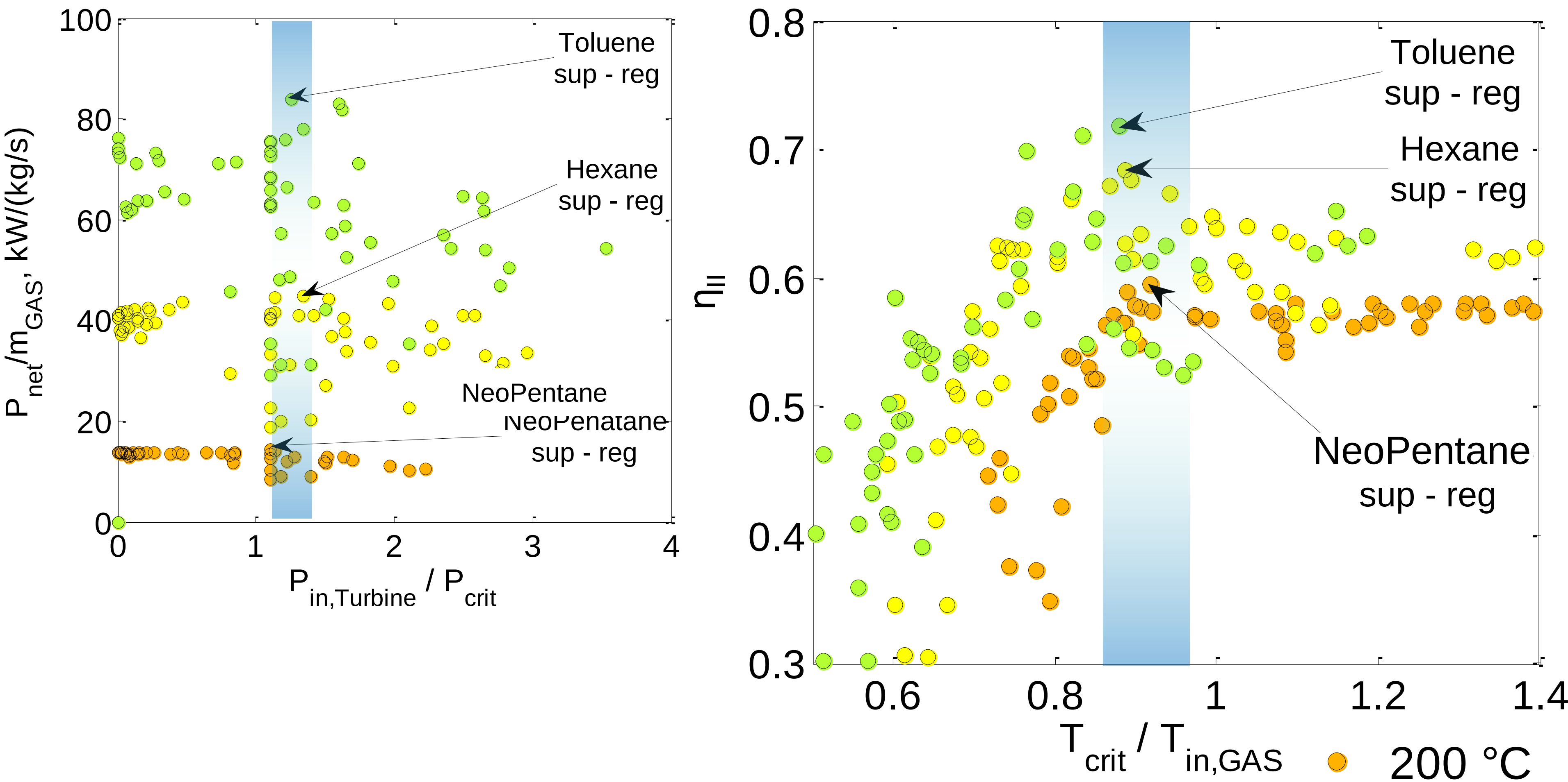
$$N = 50Hz$$

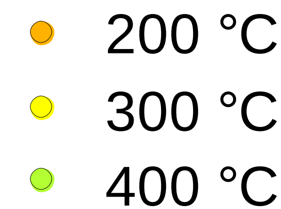
Geothermal brine vs exhaust gases



- Similar trends
- Competitive efficiency for saturated cycle at higher T_{in}

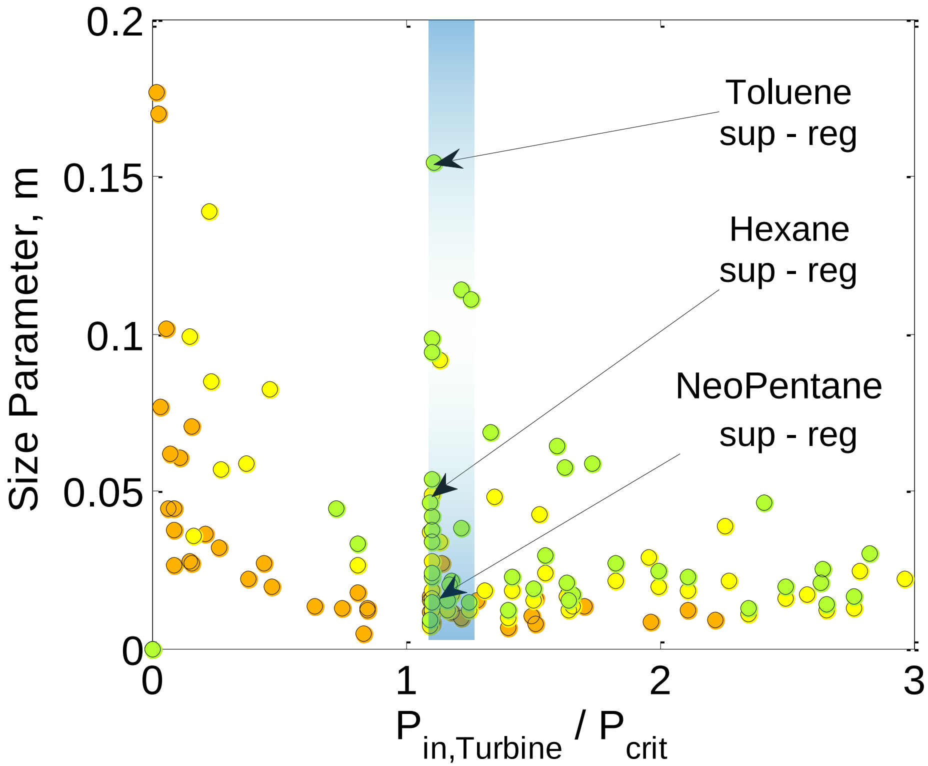
Exhaust gas - P_{net}/m_{GEO} - η_{II}

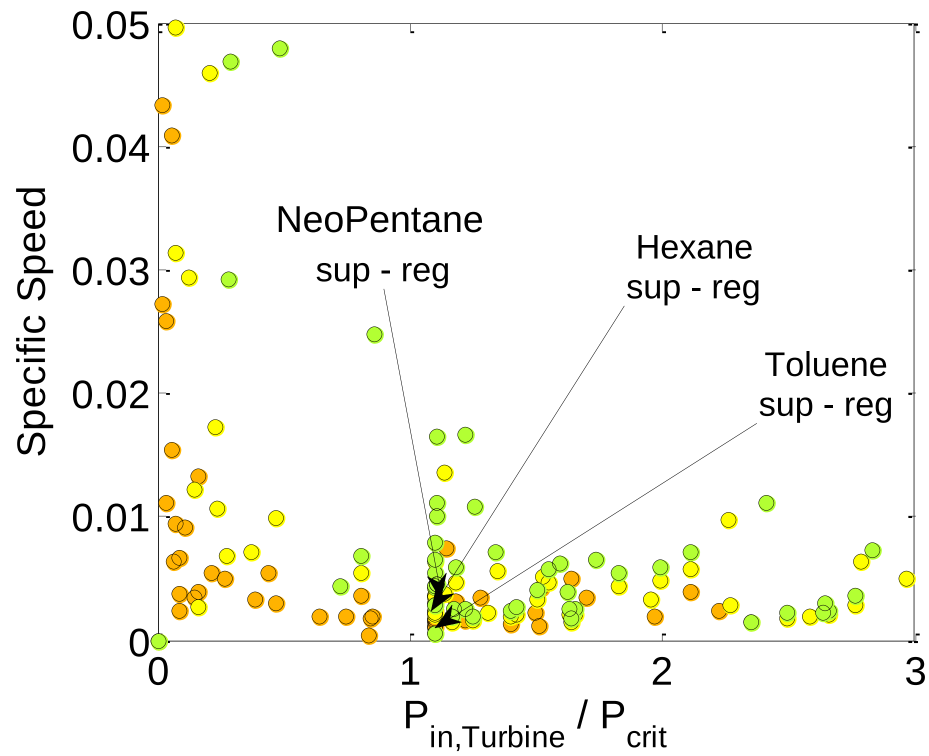




- With high temperature sources the same global trends are obtained

Exhaust gas - *SP* - *Ns*





- With 3000 rpm non feasible design of turbine is obtained
- Low ***SP*** and ***Ns*** below the optimal value
- High speed turbines have to be adopted

- 200 °C
- 300 °C
- 400 °C

Conclusion

1. For thermodynamic optimization at least 2 parameters have to be considered: $p_{in,Turbine} - \Delta T_{ap}$
2. Global considerations:
   - In reduced variables all the analysis give similar results
   - Optimal fluid has a $T_{crit} \approx$ 0.9-0.95 T_{in}
   - Higher efficiency using complex fluids are obtained
   - Optimal cycle are Supercritic with $P_{rid} \approx$ 1-1.1
   - US_{TOT}/P_{net} decrease with T_{in} thanks to the higher η_{II}
3. Other considerations:
   - T_{amb} and T_{rej} have little influence on fluid choice
   - Feasibility of turbine design and actual efficiency could influence fluid and cycle selection and should be carefully considered together with heat transfer coefficients and fluid cost

Thank you
for your attention