IV International Seminar on ORC Power Systems

ORC 2017 WELCOME BACK HOME!

POLITECNICO MILANO 1863

Selection Maps For ORC And CO_2 Systems For Low-Medium Temperature Heat Sources

Marco Astolfi, Silvia Lasala, Ennio Macchi

>> INTRODUCTION (1)
A father of two technologies

Professor Angelino was one of the father of both ORC and sCO_2 technologies

In the second half of last century the pioneering studies of Profesor Angelino set the standard for:

- fluid selection criteria and effect on turbomachinery design for ORC field
- Best cycle configurations and optimal design for sCO_2 power systems

The results obtained in those studies are the reference benchmark still today

>> INTRODUCTION (2)
from a clear division…

ORC

- **Low temperature** heat sources like geothermal energy, solar energy with low concentrating ratio and OTEC systems
- **Small available heat** like in civil and domestic cogeneration, small WHR application and biomass

sCO_2

- **High temperature** and **Large available heat** applications like nuclear, solar towers and recently fossil fuels

---

Until recent years ORC and sCO_2 cycles have been studied for two **completely different** application fields as alternative for steam power plants:

>> INTRODUCTION (3)
…to the need of clarity

ORC

- **Low temperature** heat sources like geothermal energy, solar energy with low concentrating ratio and OTEC systems
- **Small available heat** like in civil and domestic cogeneration, small WHR application and biomass

sCO_2

- **High temperature** and **Large available heat** applications like nuclear, solar towers and recently fossil fuels

Nowadays the scenario is **strongly changed**:

- Many organic fluids for ORC applications are going trough a **phase out** process because of their environmental impact (high **GWP**) or safety reasons (flammability and toxicity)
- sCO_2 is experiencing **large investments** mainly driven by CSP field that will bring soon this technology to a **mature technological level**

A new GREY ZONE

ORC VS sCO_2

As result this division will become more and more blurred in future years with ORC and sCO_2 power plants **competing** in a large range of applications

- Large biomass plant
- Large and high temperature WHR (glass, steel, cement industries)
- Medium size CSP plant based mainly based on linear concentrators

As result a NEW GREY ZONE is coming

>> WORK BASIS
Aim of the study and General approach

Our goal:

- Understanding which is the **most suitable** solution among ORC and sCO_2 for different energy sources and applications
- providing **decision maps** for the correct choice of the best plant from a thermodynamic point of view

Our approach:

- We defined the optimal ORC and optimal sCO_2 cycle for a large range of energy sources differing in:
  - **maximum temperature** (250°C – 600°C)
  - **cooling grade** (0% - 100%)

$$\Delta T_{\%} = \frac{(T_{s,max} - T_{s,min})}{(T_{s,max} - T_0)}$$

- Available power is fixed and equal to **30 MW** with reference to medium- large size applications
- Two cases are investigated: **air** and **water** cooled plants with possibility to condensate CO_2

>> MAP RANGE
Heat source characterization

This allows to represent both nearly isothermal heat sources and finite heat capacity heat sources with technical limits in the minimum temperature

a. Heat source maximum temperature,°C

$T_{min,s}$ °C — Heat source cooling grade	200	250	300	350	400	450	500	550	600
0%	200	250	300	350	400	450	500	550	600
20%	163	203	243	283	323	363	403	443	483
40%	126	156	186	216	246	276	306	336	366
60%	89	109	129	149	169	189	209	229	249
80%	52	62	72	82	92	102	112	122	132
100%	15	15	15	15	15	15	15	15	15

Isothermal sources

Solar HTF
(pouring issues)

Flue gases
(acid condenses)

Geothermal brine
(silica deposition)

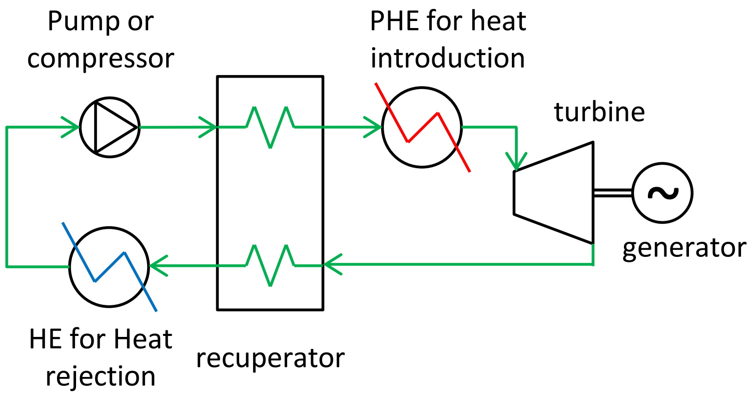
>> DESIGN CRITERIA
Organic Rankine Cycles

- **4 Cycle configurations:**
  saturated and superheated subcritical with or without recuperator
- **47 working fluids:**
  15 alkanes, 8 other HC, 16 halogenated, 8 siloxanes

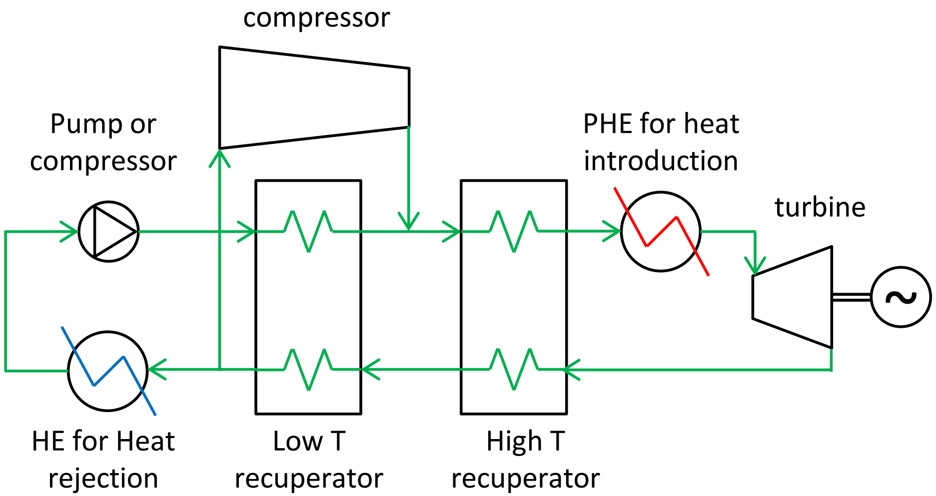
- Large range of **critical temperatures** and **molecular complexity**
- Maximum temperature is set by thermal stability limit or lack of experimental data.
- Minimum pressure is set to 1 bar in order to avoid air leakage

- Optimization variables $\mathbf{T_{eva}}$, $\mathbf{T_{cond}}$, $\mathbf{T_{inTurbine}}$

>> DESIGN CRITERIA
sCO2 cycles



a) *Simple recuperative cycle*



b) *Recompressed recuperative cycle*

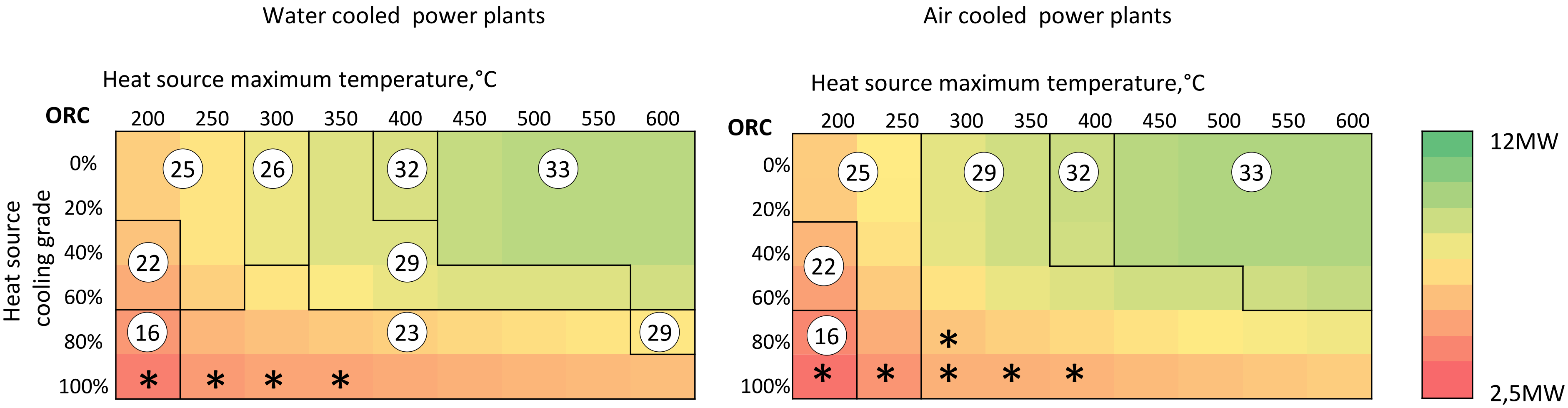
- **Recompressed cycle** allows to limit the temperature differences in the recuperative process
- Water cooled plant allows for **CO_2 condensation** leading to an increase of power output
- Optimization variables **$p_{max\ (UB=300bar)}$, p_{min}, split ratio**

>> DESIGN CRITERIA
Common Assumptions

	CO_2		ORC	
Heat sink temperature	15°C water cooled	25°C air cooled	15°C water cooled	25°C air cooled
Minimum working fluid temperature	25°C	40°C	25°C	40°C
$\Delta T_{ap,PHE}\Delta T_{pp, PHE}\Delta T_{pprec}$	10°C		5°C	
$\Delta T_{subcooling}$	-		5°C	
Δp(or, whether relative, $\Delta p/p_{in}$) PHE	2%		50kPa (ECO), ΔT=1°C (EVA), 2% (SH)	
Δp (or, whether relative, $\Delta p/p_{in}$) REC	2% (hot side), 2% (cold side)		2% (hot side), 50 kPa (cold side)	
Δp(or, whether relative, $\Delta p/p_{in}$) HR	2%		2% (desuperheating), ΔT=0.5°C (condensation)	
Compressor/pump hydraulic efficiency	0.85		0.75	
Generator electrical efficiency	0.97			
Mechanical efficiency	0.97			
Pump electrical motor efficiency	0.97		0.97	
Auxiliaries consumption loss	2%			

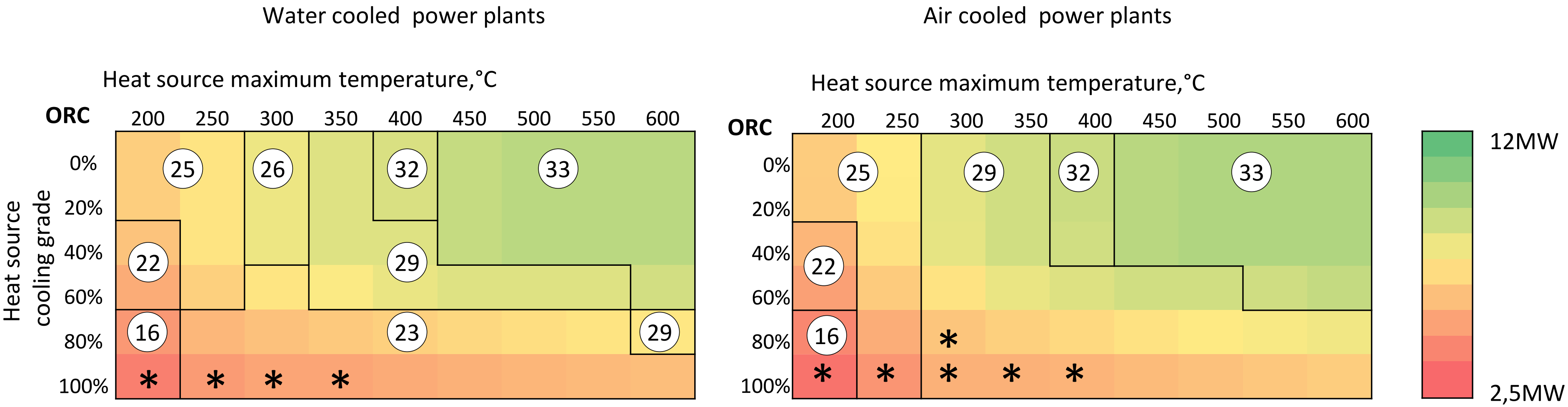
Turbine efficiency is computed as function of SP and Vr

>> RESULTS
Organic Rankine Cycles



- Power production is higher for high temperature heat sources with a low cooling grade,
- Power production is limited for heat sources temperatures higher than 450°C because of the fluid thermal stability limit
- Power production is lower for air cooled plants because of the higher condensation temperature

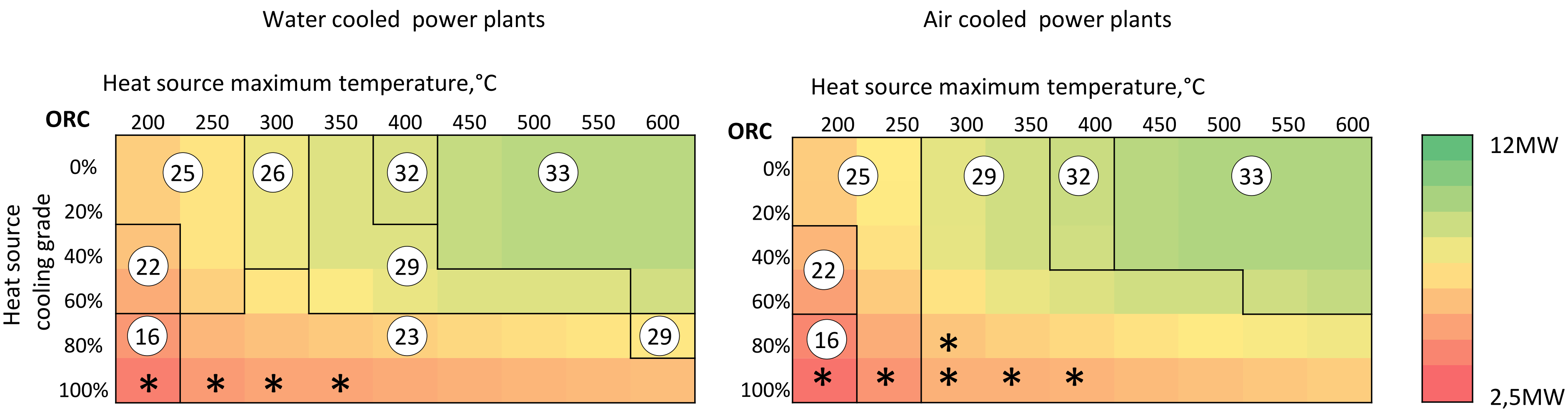
>> RESULTS
Organic Rankine Cycles



- Best fluid critical temperature increases with the heat source temperature and for nearly isothermal heat sources

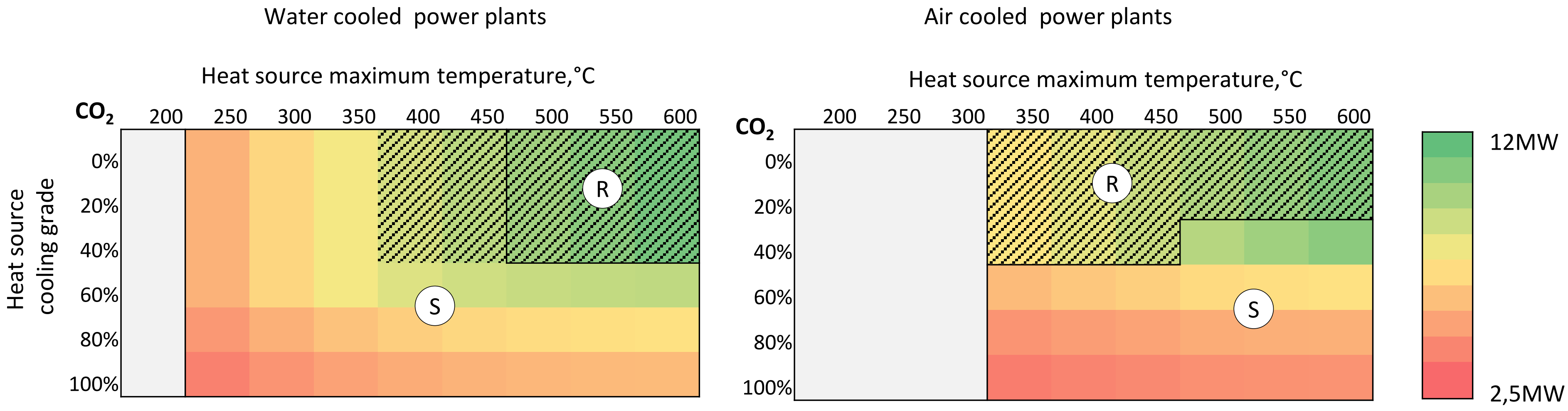
16 – R236ea	139°C	26 – pentane	197°C
22 – neo pentane	161°C	29 – cyclo pentane	239°C
23 – cis butene	163°C	32 – cyclo hexane	280°C
25 – iso pentane	187°C	33 – benzene	289°C

>> RESULTS
Organic Rankine Cycles



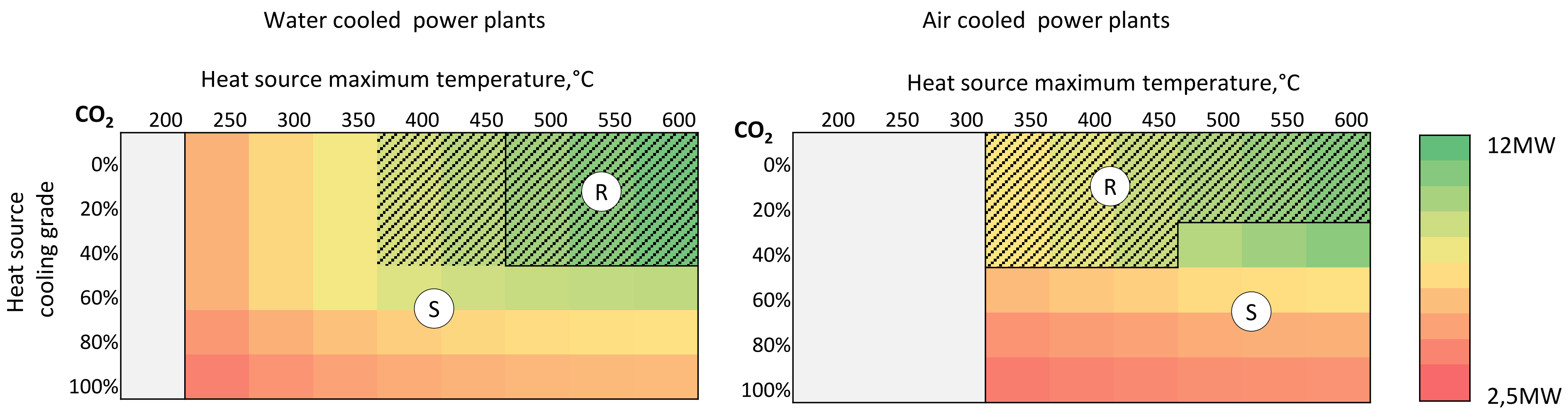
- Superheated recuperative cycle is always convenient however..
  - saturated cycles can be competitive for low temperature sources with small cooling grade
  - Recuperator is not convenient for low-medium temperature heat sources with high cooling grades (marked with *)

>> RESULTS
sCO_2 cycles



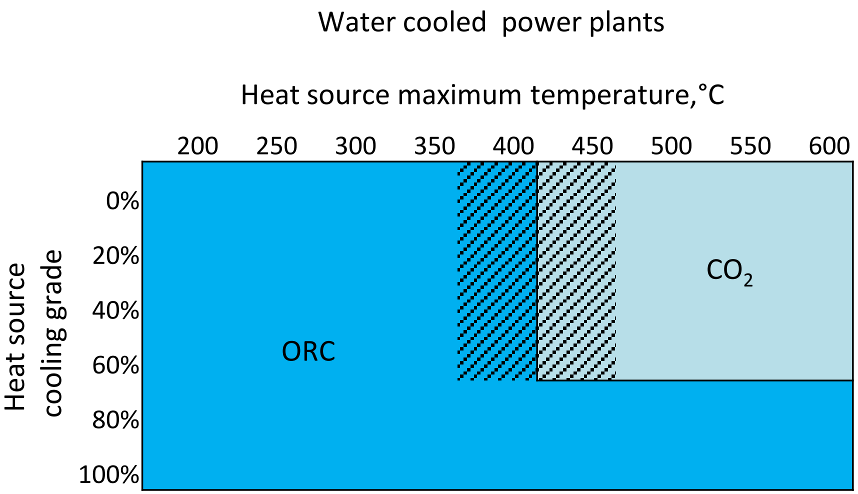
- Power production always increases reaching thanks to CO_2 stability at high temperatures
- Power production strongly penalized for air cooled plants because condensation is not possible. Positive net power is obtained for heat sources temperatures higher than 300°C

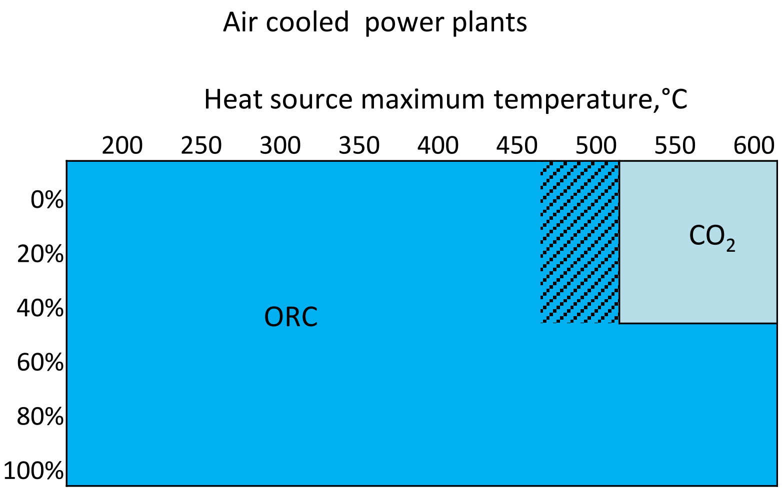
>> RESULTS
sCO_2 cycles



- Recompressed cycle (R) performs better than simple recuperative cycle (S) for high temperatures and nearly isothermal heat sources
- The advantages in adopting a more complex configuration are limited and the two cycles have similar power outputs (2% difference) in the shaded area

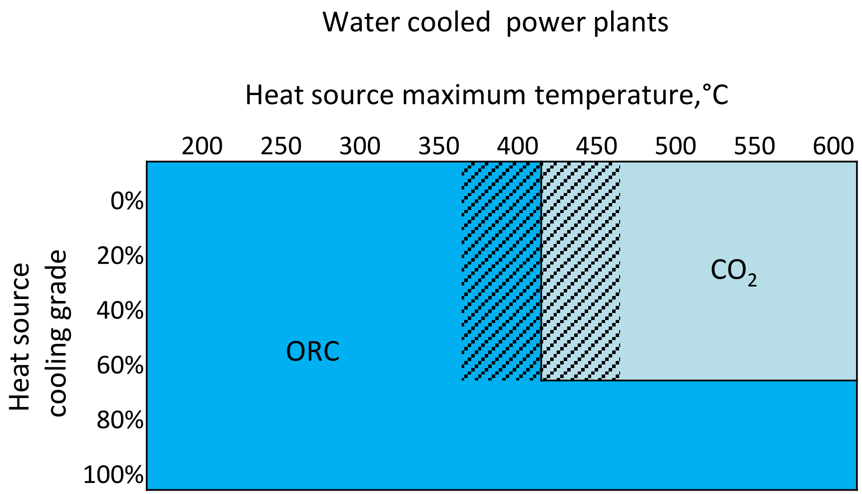
>> RESULTS
ORC vs sCO2

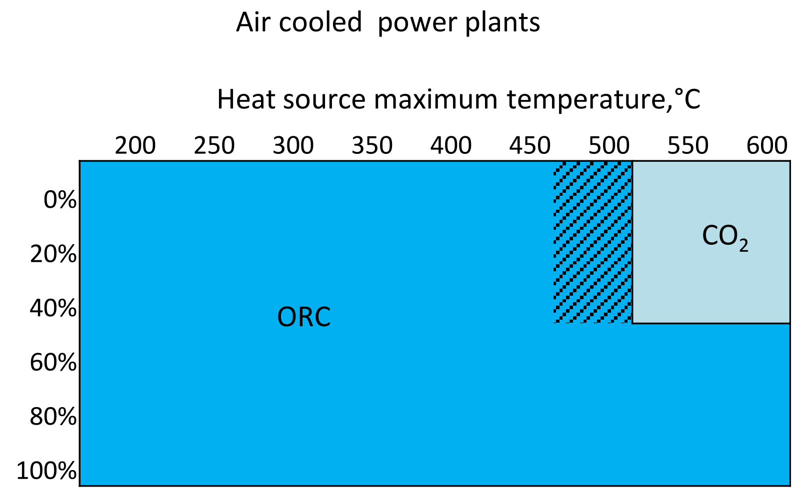




- For water condensed cycles ORC are recommended for :
  - heat sources temperatures below 350°C
  - for hotter heat sources having high cooling grades thanks to their ability to recover heat at low temperatures

>> RESULTS
ORC vs sCO_2





- sCO_2 cycles are more efficient for high temperatures thanks to the increase of turbine power output respect to the compressor consumption
- Air cooling strongly penalizes sCO_2 that becomes convenient only for a very limited number of applications

>> CONCLUSIONS
based on preliminary results

- sCO_2 cycles are certainly a reliable option for high temperature large power plants while they must compete with ORC in other applications
- Performances attainable by sCO_2 also at lower temperatures and for medium size application can be attractive especially in presence of particular constraints related to safety.
- Excluding flammable and toxic fluids CO_2 prevails also at low temperature (350°C)and high cooling grades

- Analysis should be extended to other sCO_2 plant configurations
- Analysis should be extended to economic analysis in order to catch the reduction of power plant capital cost allowable with compact CO_2 cycles

IV International Seminar on ORC Power Systems

THANKS FOR THE ATTENTION

Marco Astolfi, Silvia Lasala, Ennio Macchi