ORC-PLUS WORKSHOP

May 20th 2016, Casablanca

Solar-based ORC power systems

by

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The Thermodynamics Laboratory
University of Liège

Context

Solar Thermal Power:

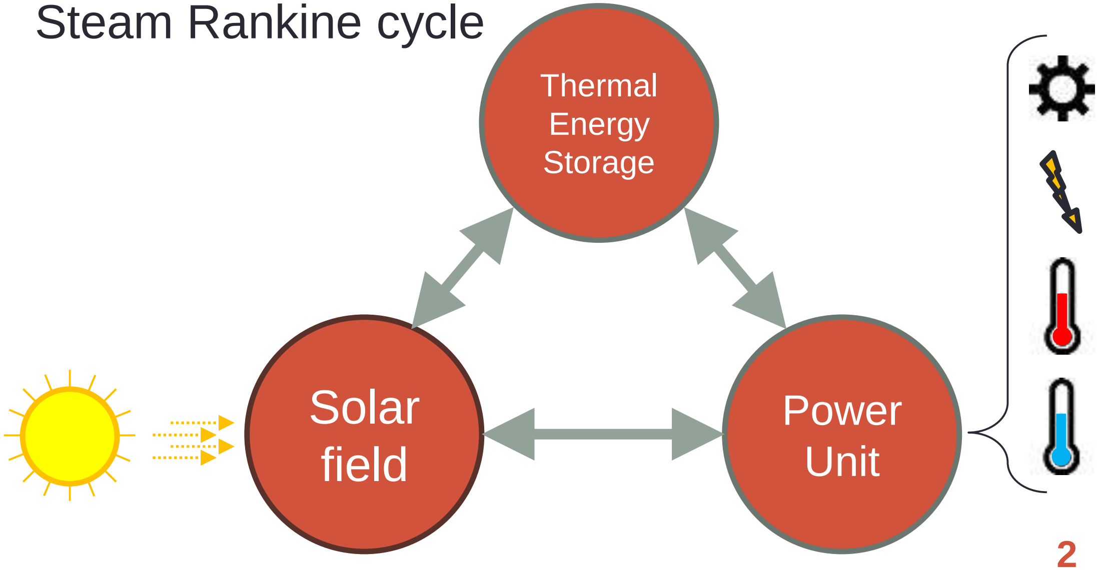
Ivanpah CSP plant (392 MWe)

Organic Rankine cycle

< $1kW_e$ … $1MW_e$ … $10\ MW_e$ … $100\ MW_e$ … $1000\ MW_e$

Steam Rankine cycle

STG CSP plant (3kWe)



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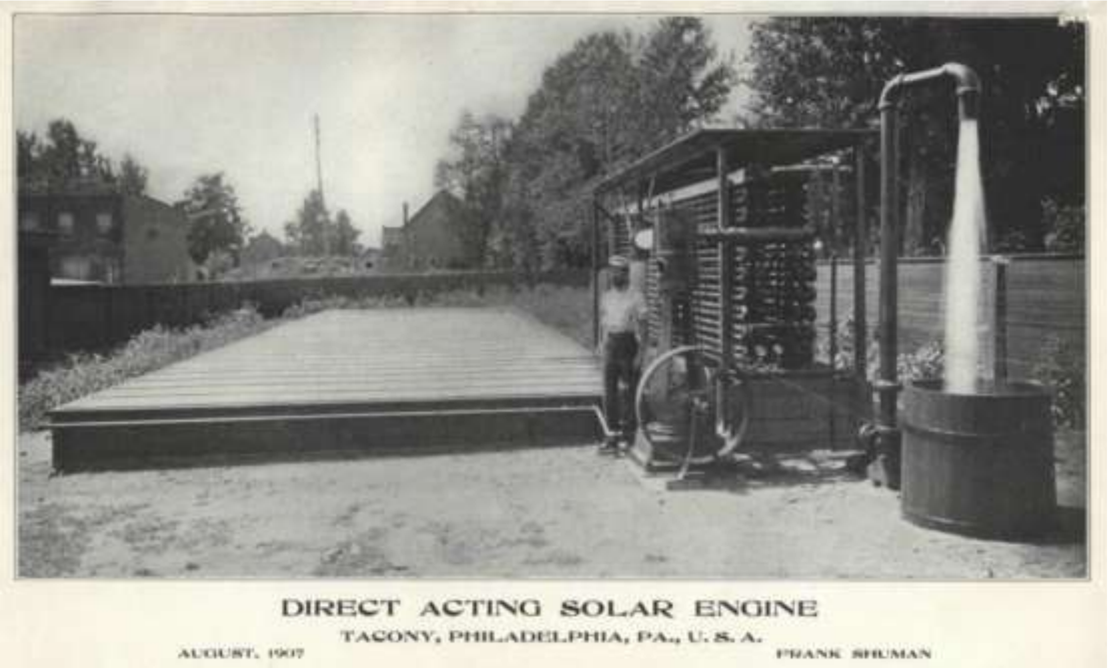
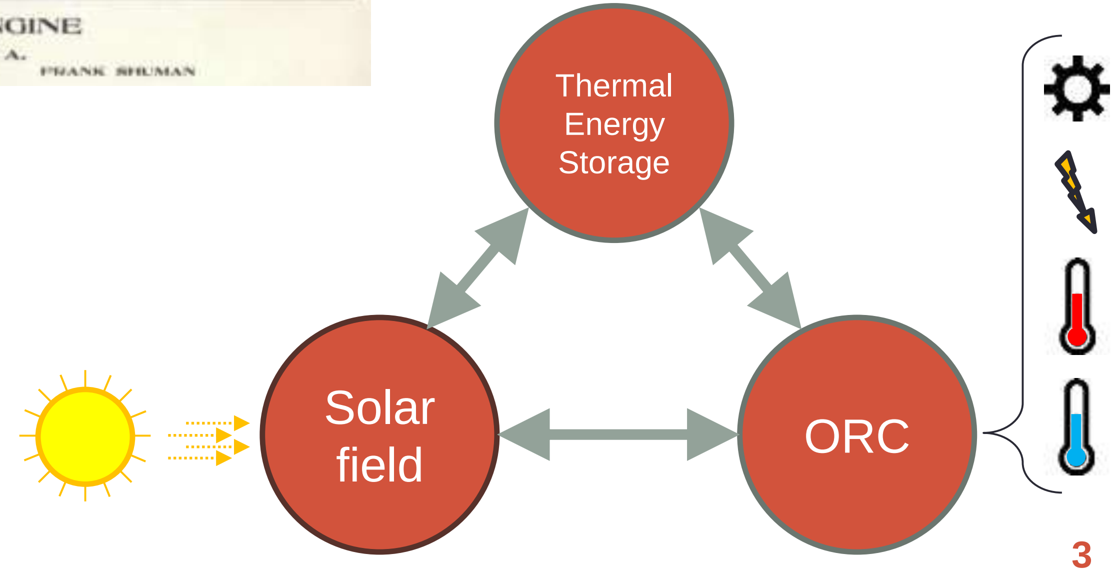
Context



- 1st operational ORC
- Built by Frank Shuman
- Philadelphia (USA), 1907
- “Hot box” collector, 100 m²
- Direct vapor of ether at 115°C
- 2.5 kW ORC
- Irrigation pump

Ref: [1]



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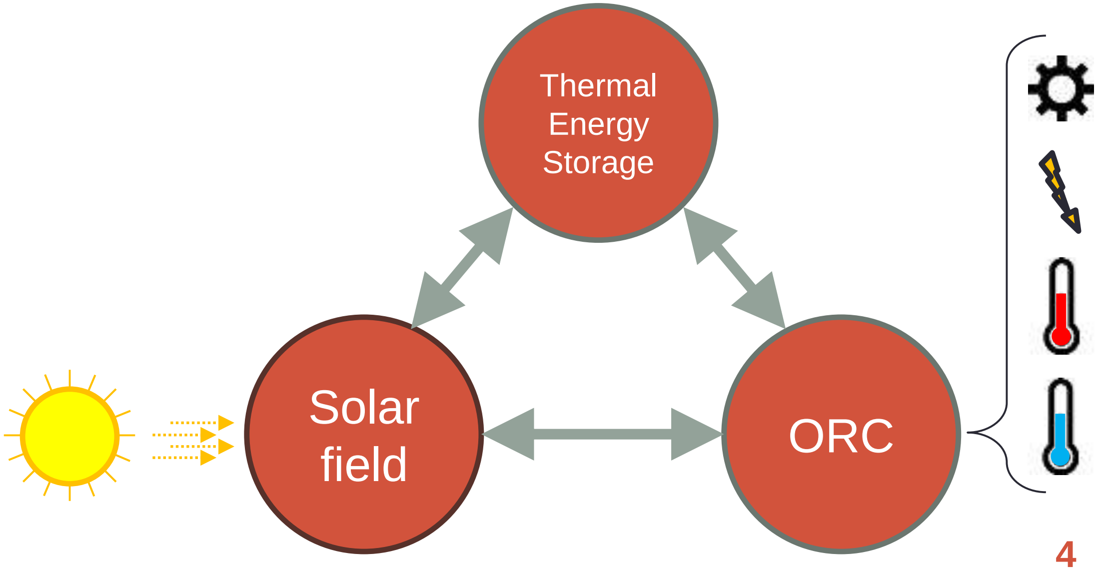
Presentation structure

1. Organic Rankine Cycle
2. Solar field and collectors
3. Thermal energy storage
4. Fields of application
5. Modelling tools



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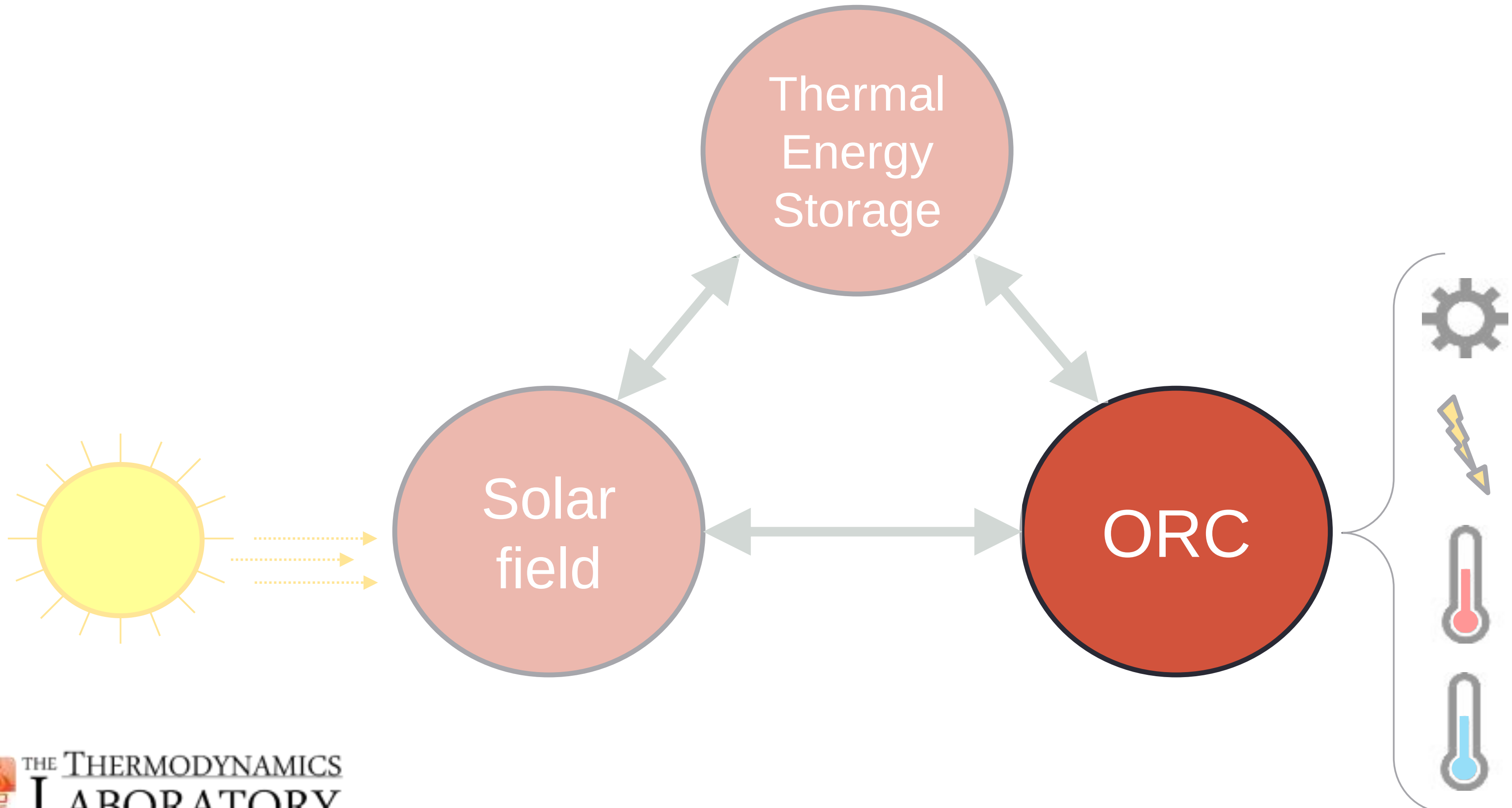
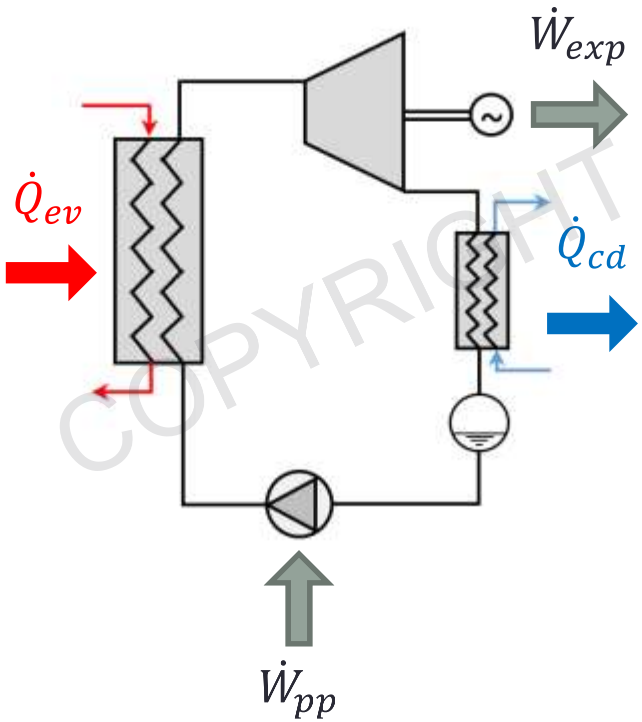
2. Organic Rankine Cycle



Rankine cycle – the basics

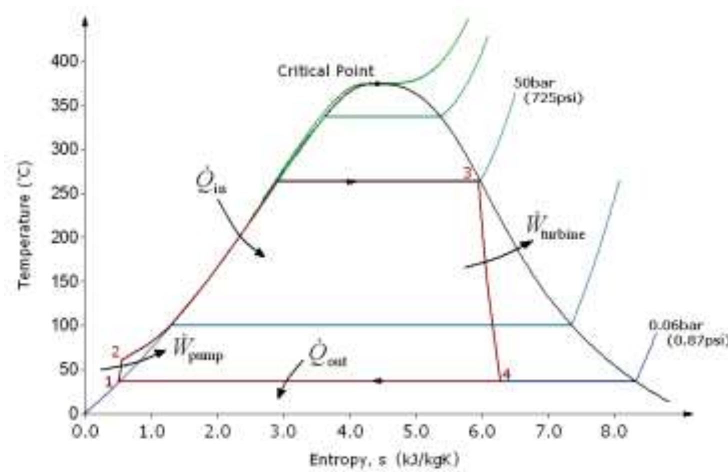


Thermodynamic cycle in 4 steps:

- 1-2 : liquid compression (P_{low} → P_{high})
- 2-3 : evaporation (Liquid → Vapor)
- 3-4 : vapor expansion (P_{high} → P_{low})
- 4-1 : condensation (Vapor→Liquid)

Result : $\dot{W}_{net} = \dot{W}_{exp} - \dot{W}_{pp} > 0$

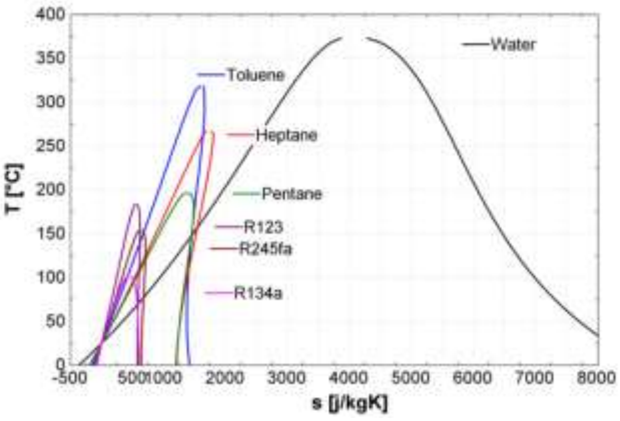
Working medium: water … or organic fluid



Why going organic?

+ Dry expansion → no need for superheating
+ Lower boiling point → permit to apply Rankine cycle with low temperature heat source
+ Lower evaporating pressure → safer and less complex
+ Simpler boiler architecture → no need of steam drum +recirculation (single HEX ok)
+ Higher density at same condensing temperature→ smaller components size
+ Supatmospheric condensing pressure → no infiltration

- Higher relative pump consumption (Back Work Ratio)
- Fluid characteristics (cost, availability, safety properties)
- Lower thermal efficiency



→ ORC suitable for low temperature OR/AND small capacity systems

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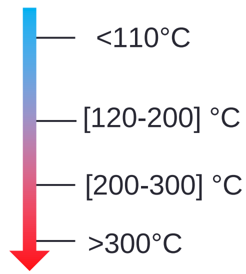
Organic fluids

- Organic fluid = contains Carbon → very large variety (CFC, HFC, HCFC, HC,…)
- Proper fluid selection is among the most important design parameter
- Common working fluid in experimental facilities:
  - R134a
  - R245fa
  - SES36
  - n-pentane
  - Toluene



- Characteristics to account for:
  - Thermodynamic performance
  - High vapor density (component size)
  - Acceptable evaporating pressure (safety)
  - Condensing pressure > 1 atm (infiltration)
  - Temperature stability
  - Melting point (vs. T_{amb})
  - Toxicity/Flammability
  - ODP/GWP
  - Cost, availability
  - **Integration with components**

Expansion devices

Positive-displacement expander

Scroll
[0.1-10 kW]

Screw
[5-100 kW]

Piston
[1-20kW]

+ Low rotational speed
+ Wet expansion
+ Availability (e.g. HVAC)
+ Cost

- Fixed built-in r_v
- Limitation in supply conditions (T/P)

→ Low capacity ORC (<50 kWe)

Turbomachinery

Axial

Radial

[1kW -1MW]

+ Compactness/weight
+ High efficiency
+ Off-design performance

- High rotational speed
- Design complexity
- Dry expansion only

→ High (... and low) capacity ORC

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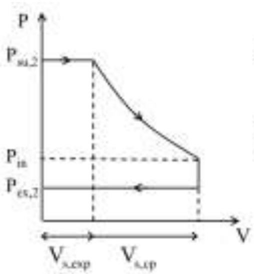

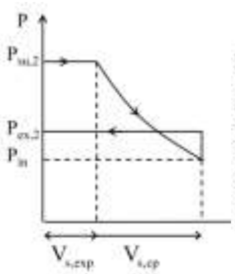

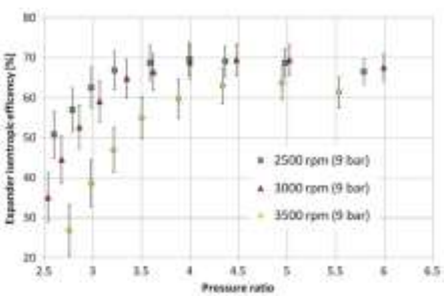

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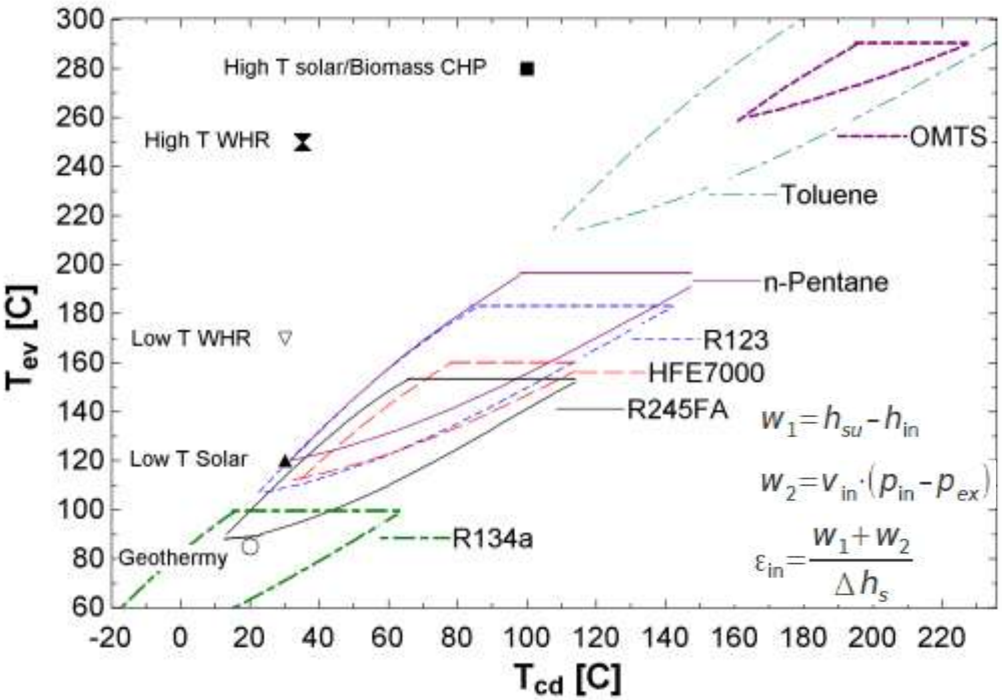
Operating conditions

Screw expander (n-pentane)



Boundary limits:

1. $T_{ev} < T_{cd}$

   Pressure ration >1

2. $T_{ev} > T_c$

   Subcritical ORC

3. $\varepsilon_{in} < 0.9$

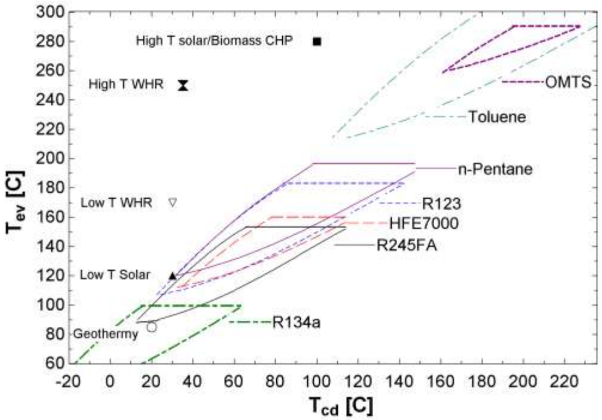
   Limited under/over expansion losses

4. VC > 0.5

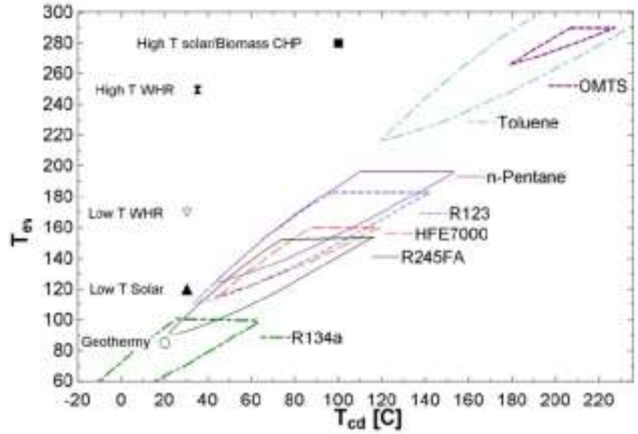
See Ref [2] for further information

Operating conditions

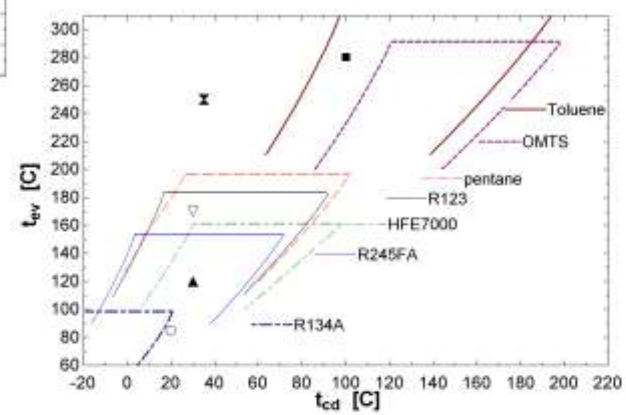
Screw expander



Scroll expander



Turbine



See Ref [2] for further information

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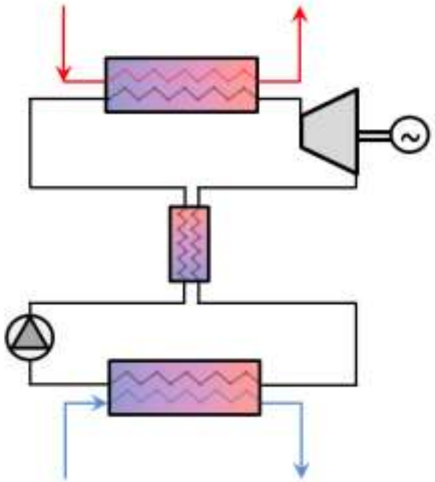
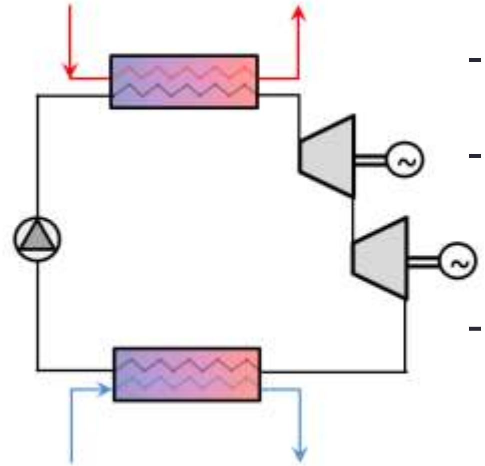
System architecture

Recuperative ORC



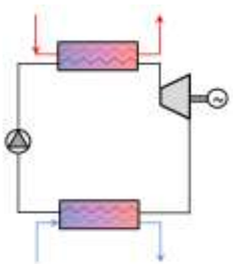
- $\nearrow \varepsilon_{ORC}$
- $\searrow \eta_{SF}$
- ? ε_{net}

Cascaded expansion

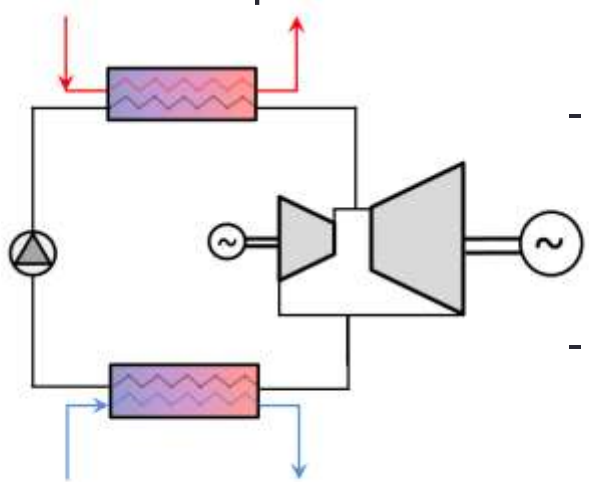


- $Rv_{tot} = rv_1 * rv_2$
- Lower expansion losses
- Careful with design!

Basic ORC



Parallel expansion



- 3 modes :
  - Big expander
  - Small expander
  - both
- Better compliance of expanders performance in part-load conditions

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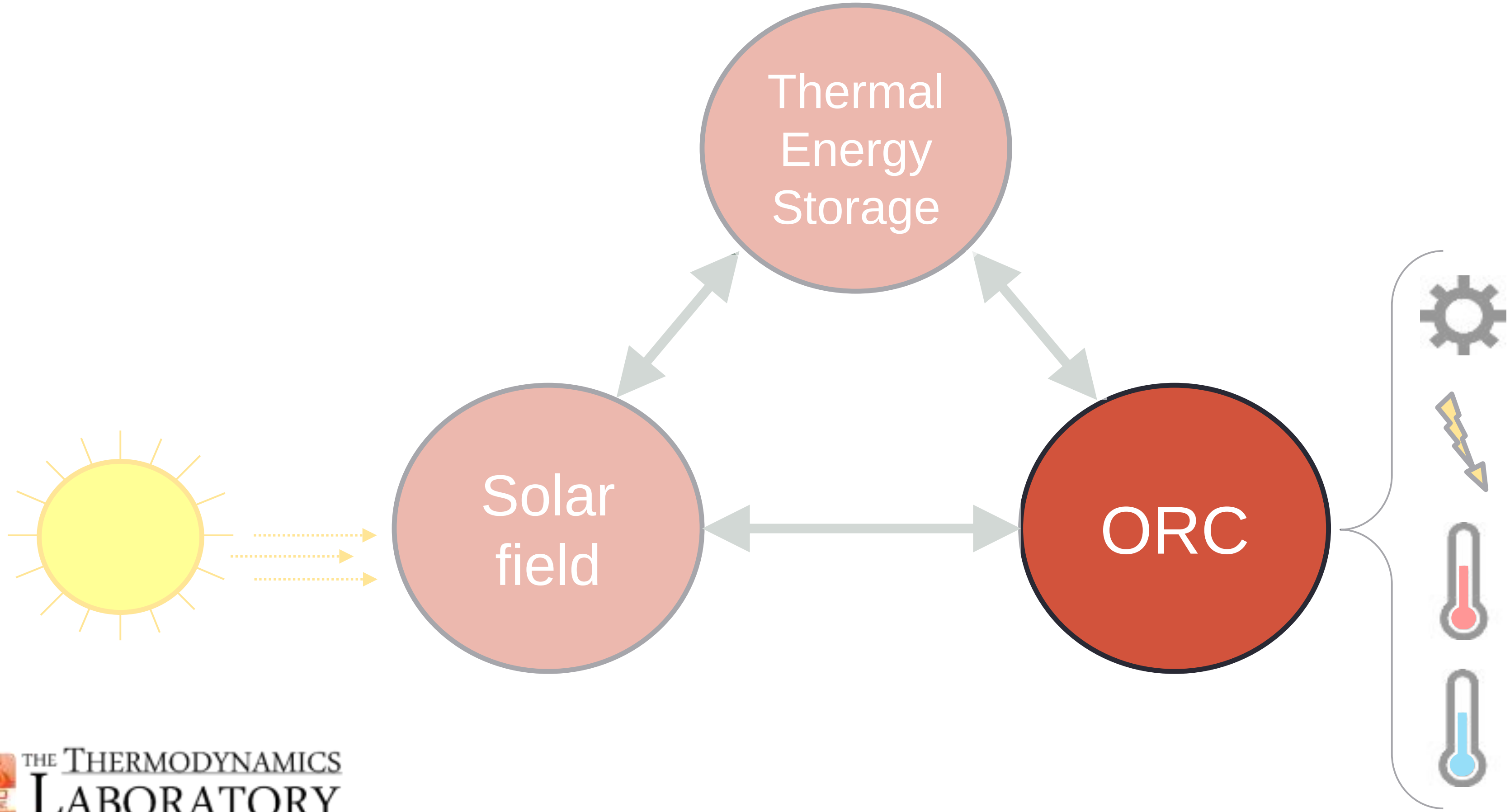

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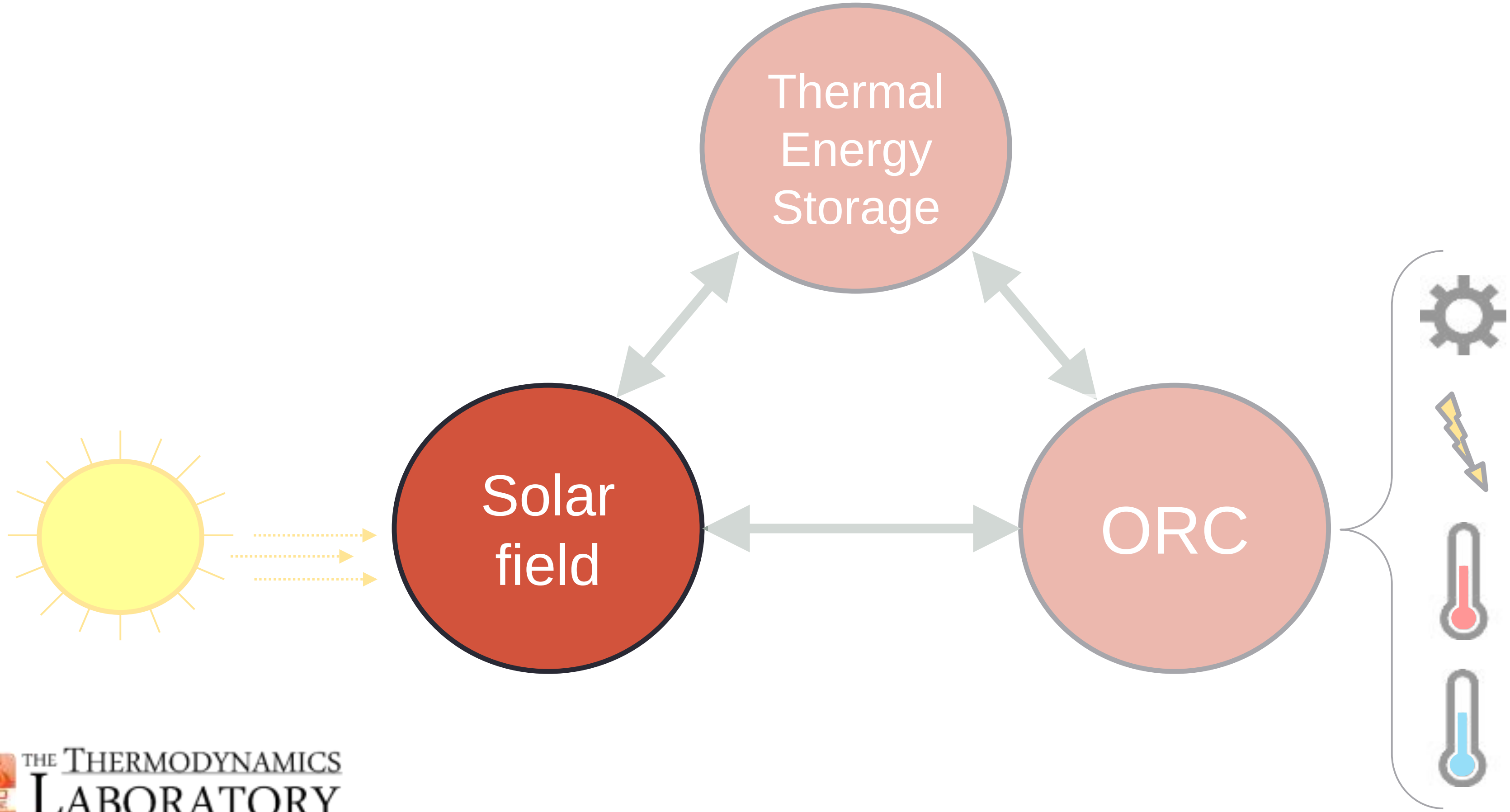
4. Solar field and collectors



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Solar collectors

- Non-concentrating collectors
  - Flat Plate Collectors (FPC)
  - Evacuated Tube Collectors (ETC)
  - Salt-Gradient Solar Pond (SGSP)

- Concentrating collectors
  - Compound Parabolic Collector (CPS)
  - Linear Fresnel Collector (LFC)
  - Parabolic Trough Collector (PTC)
  - Parabolic Dish Reflector (PDR)
  - Solar Central Tower (SCT)

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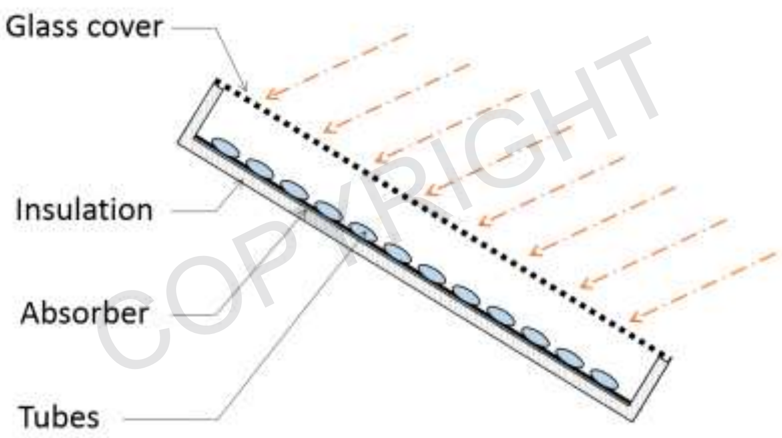

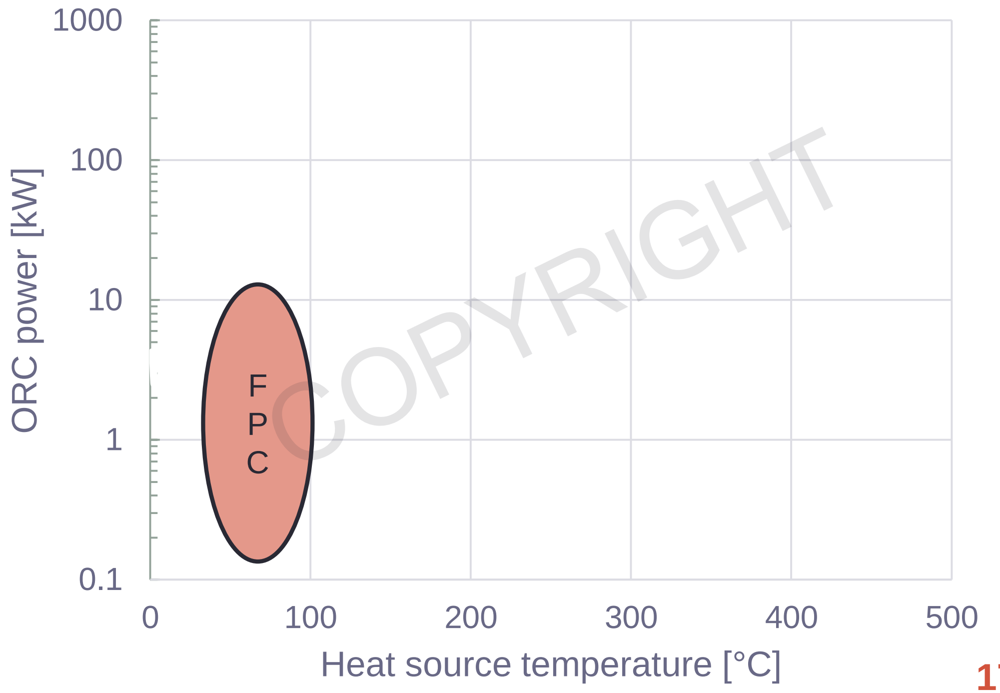

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Power plant example

- Borj Cedria , Tunisia (1982)
- 760 m² of FPCs
- Water at 98 °C
- 16 kWe ORC unit (Turboden)
- Single stage turbine
- WF : C_2Cl_4

Ref: [3]

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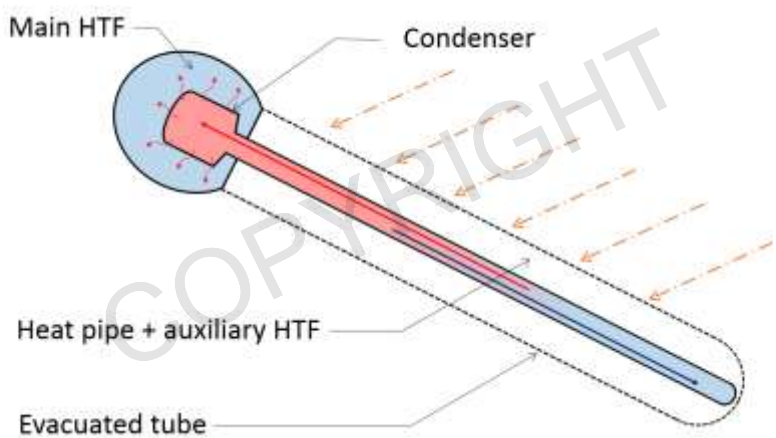

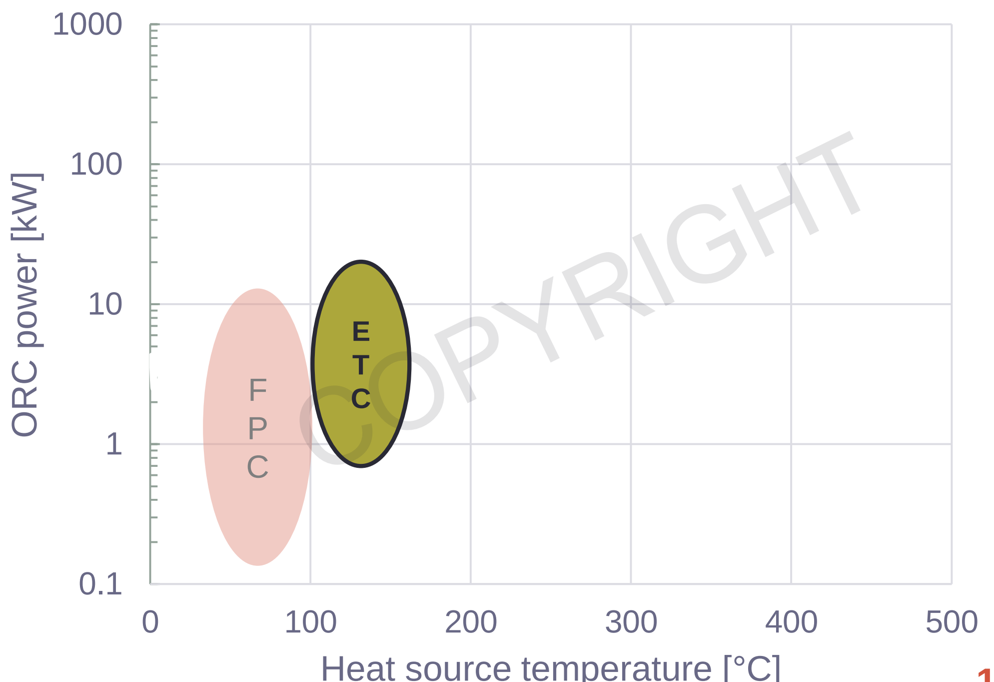

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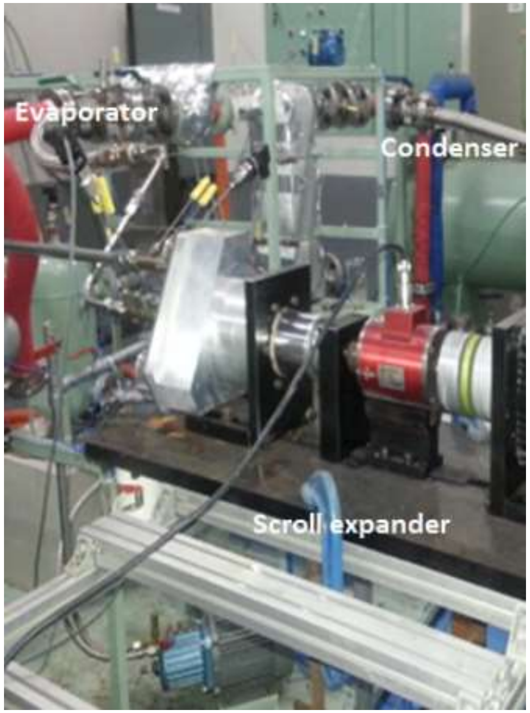
Power plant example

- Busan, Korea (2015)
- 33 m² of ETCs
- Water at 120 °C
- 1.5 kWe ORC unit (R&D)
- R245fa
- Scroll expander

Ref: [4]



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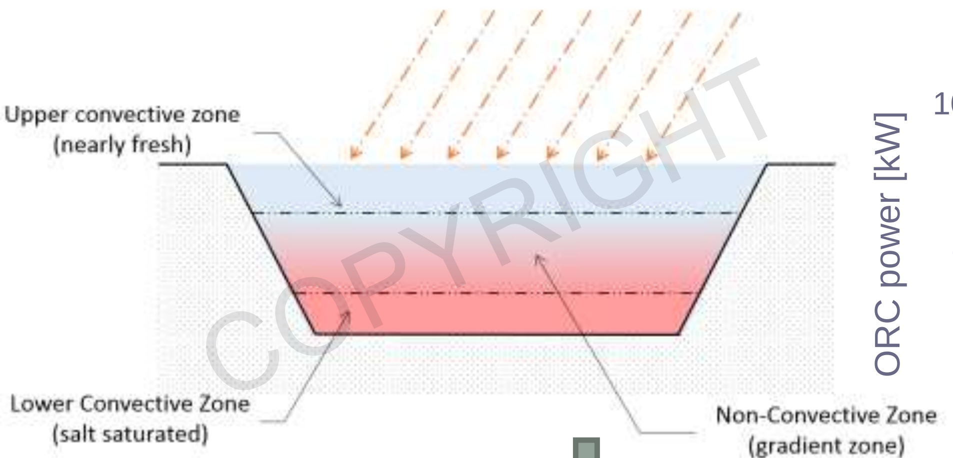

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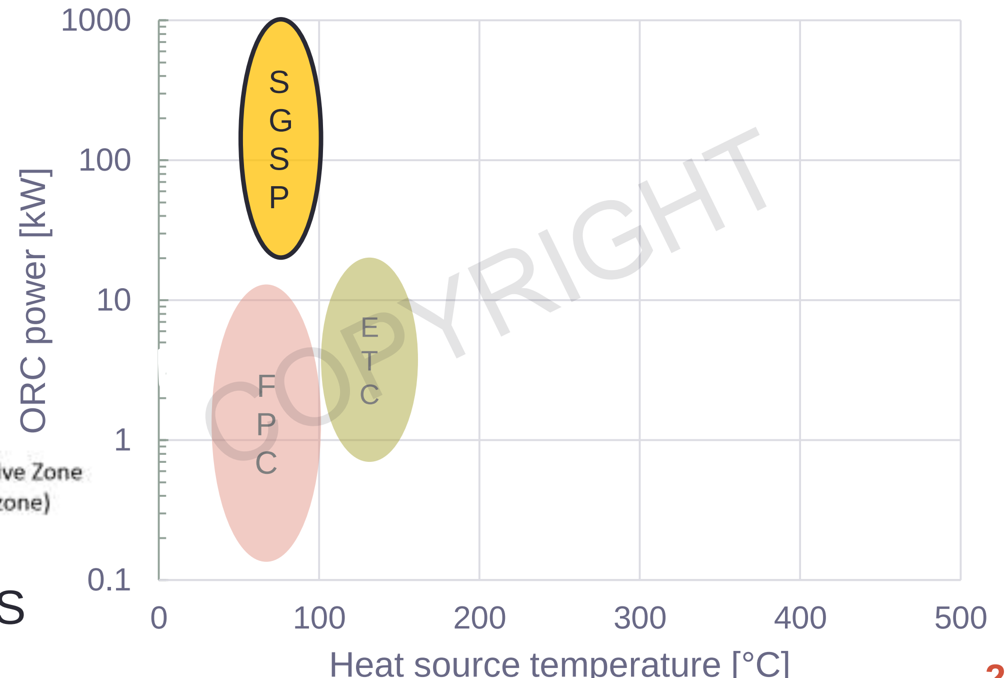

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Power plant example

- El Paso (Texas), USA (1986)
- 3300 m² solar pond (3.2m depth)
- Brine at 90°C
- 100 kWe ORC unit (Ormat)

Ref: [5]

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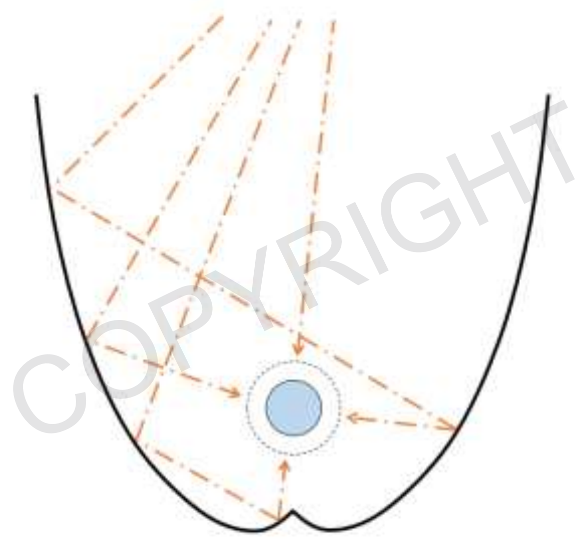

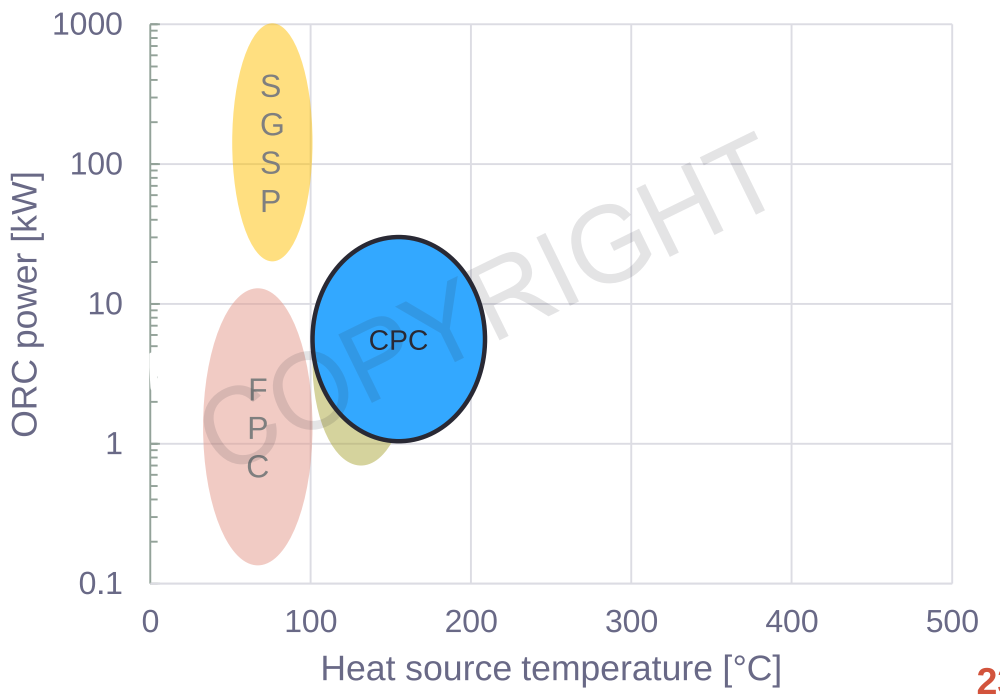

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Power plant example

- Miyagi, Japan (2005)
- 5.75 m² CPC
- Water at 140 °C
- 0.5 kWe ORC unit (R&D)
- R113 (despite of high ODP..)
- Scroll expander

Ref: [6]

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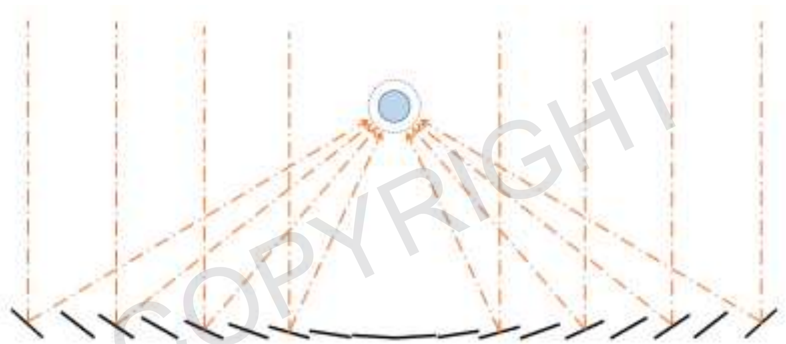

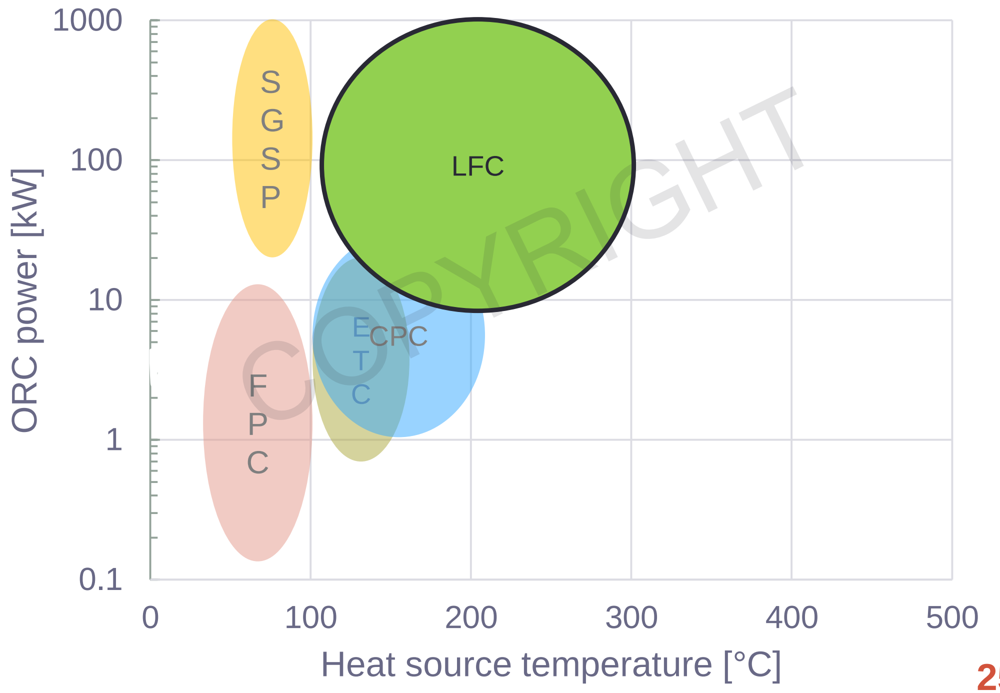

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Power plant example

- Ottana (Sardinia), Italy (2015)
- 8400 m² Frena LFC
- Diathermic oil at 260 °C
- 600 kWe ORC unit (Turboden 6HR)

Ref: [7]

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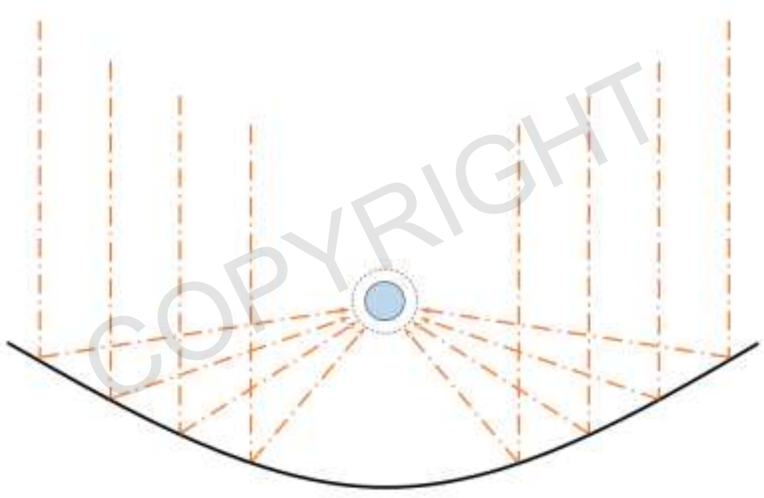

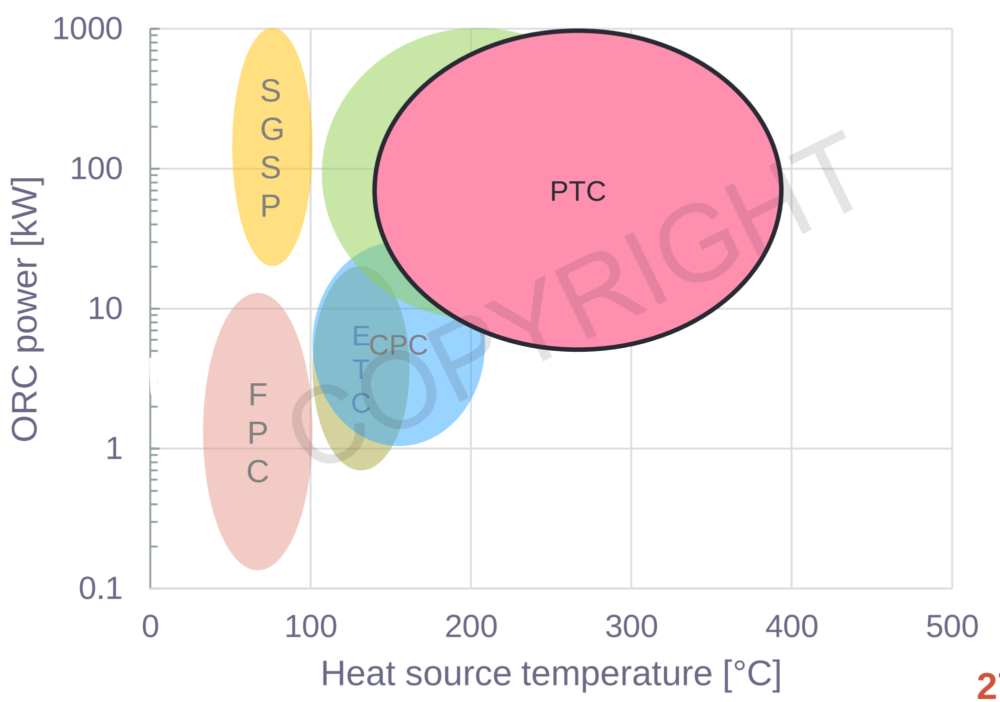

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Power plant example : Sun2Power

- University of Liège, Belgium (2016)
- 70 m² PTC (T13 from STG International)
- Thermal oil at 175°C (2bar)
- 3 kWe ORC unit (R&D from ULg)
  - R245fa
  - Scroll Expander
  - Air-cooled condenser
  - CPHEX, recuperative ORC

Ref: [8] + www.sun2power.eu

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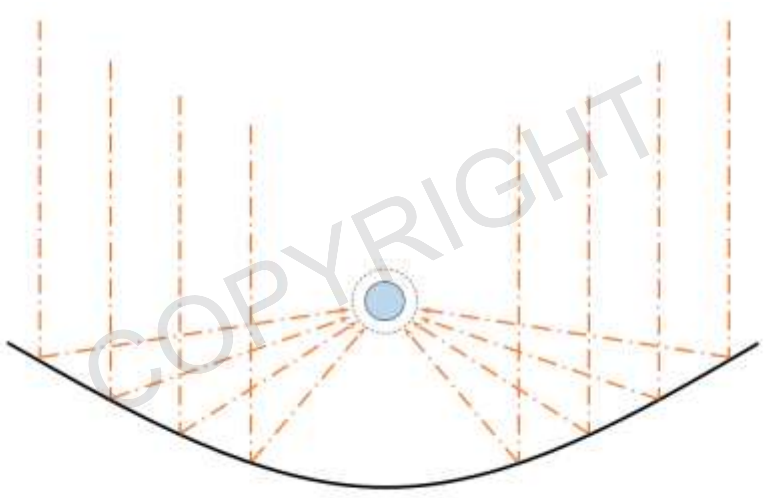

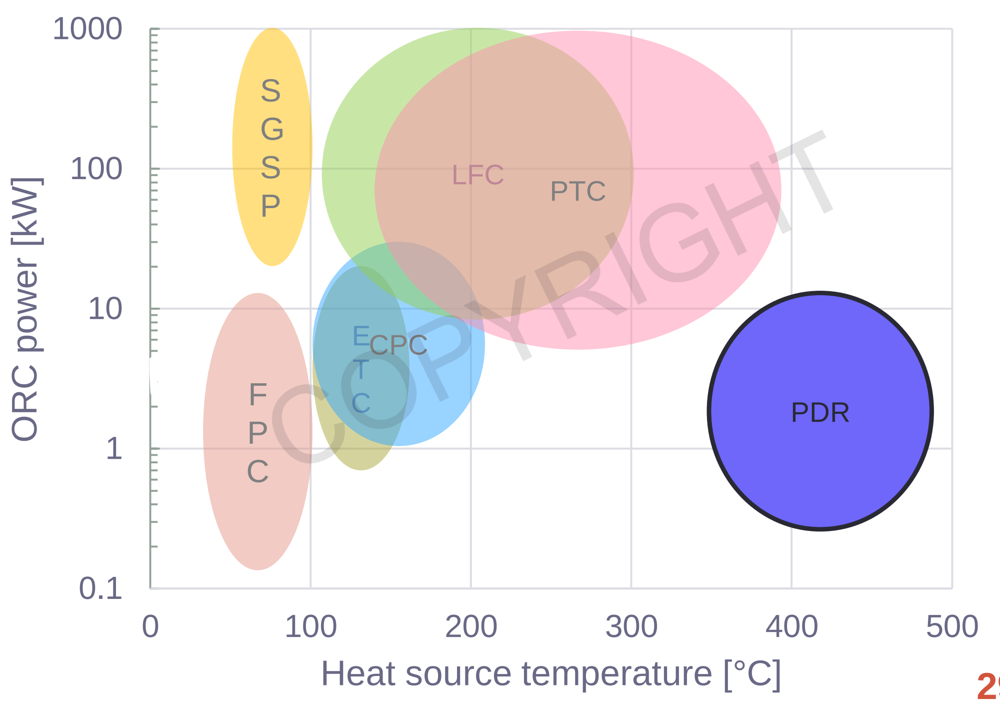

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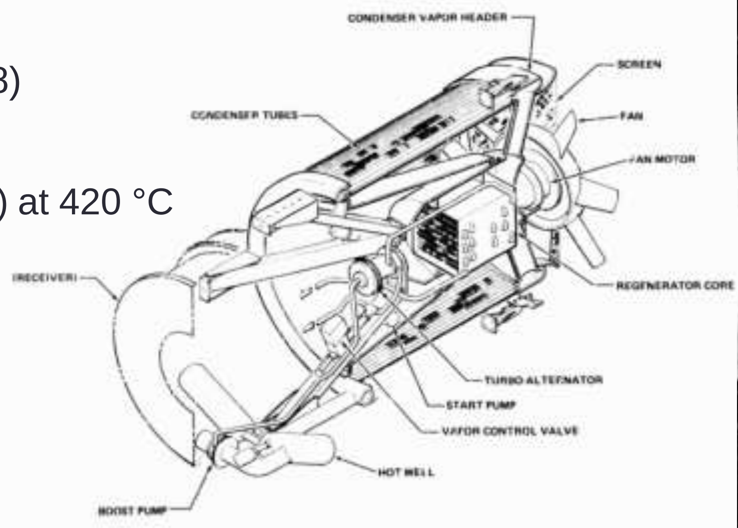
Power plant example

- Pasadena (California), USA (1978)
- 117 m² of PDR
- Direct steam generation (Toluene) at 420 °C
- 30 kWe ORC unit (R&D)

Ref: [9]



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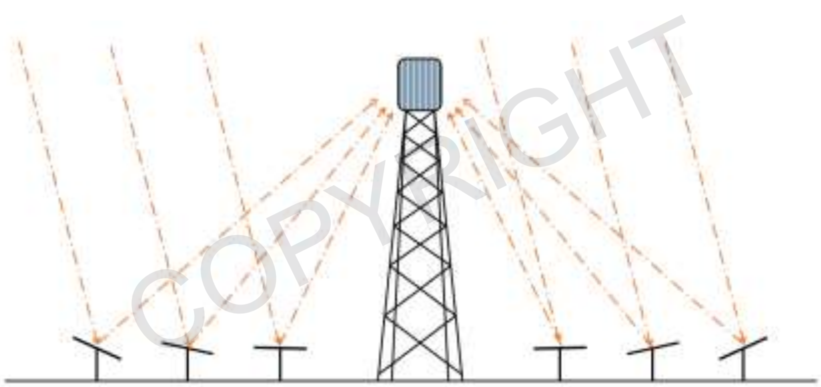
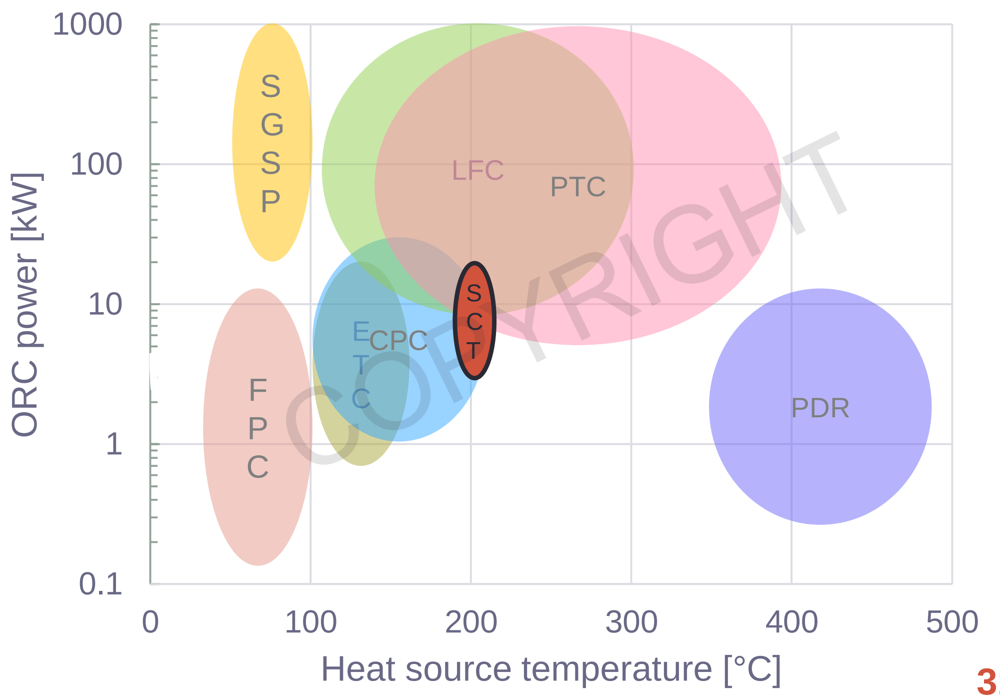
  - Salt-Gradient Solar Pond (SGSP)

- Concentrating collectors
  - Compound Parabolic Collector (CPC)
  - Linear Fresnel Collector (LFC)
  - Parabolic Trough Collector (PTC)
  - Parabolic Dish Reflector (PDR)
  - **Solar Central Tower (SCT)**





Solar collectors

- Non-concentrating collectors
  - Flat Plate Collectors (FPC)
  - Evacuated Tube Collectors (ETC)
  - Salt-Gradient Solar Pond (SGSP)

- Concentrating collectors
  - Compound Parabolic Collector (CPC)
  - Linear Fresnel Collector (LFC)
  - Parabolic Trough Collector (PTC)
  - Parabolic Dish Reflector (PDR)
  - **Solar Central Tower (SCT)**

Power plant example

- Kamboinsé, Burkina Faso (2016)
- 180 m^2 of heliostats
- Vegetable oil at 200 °C
- 10 kWe ORC unit (Infinity Turbine)

Ref: [10]

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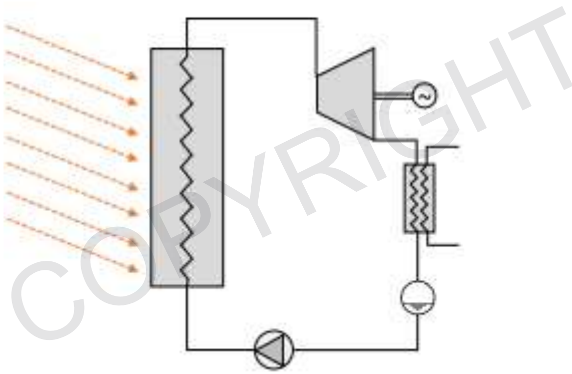
Solar field architecture

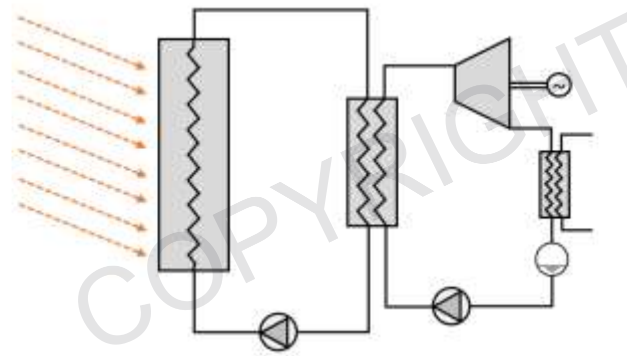
Direct Vapor Generation



- \+ Avoid one heat delivery HEX
- \+ No parasitic pump losses
- \+ Simple architecture
- \- High-pressure in solar receiver
- \- Larger volume of costly/unsafe WF

↳
- Small-scale (domestic) systems
- Parabolic dish / Flat plate collector

Intermediate Heat Transfer Fluid



- \+ Low-pressure in solar receivers
- \+ Higher safety and control
- \- Additional HEX
- \- Parasitic pump consumption

↳
- Medium- and large scale systems
- Linear collectors (CPC/PTC/LFC)
- **<u>Proper selection of HTF</u>**

Water / Thermal oil

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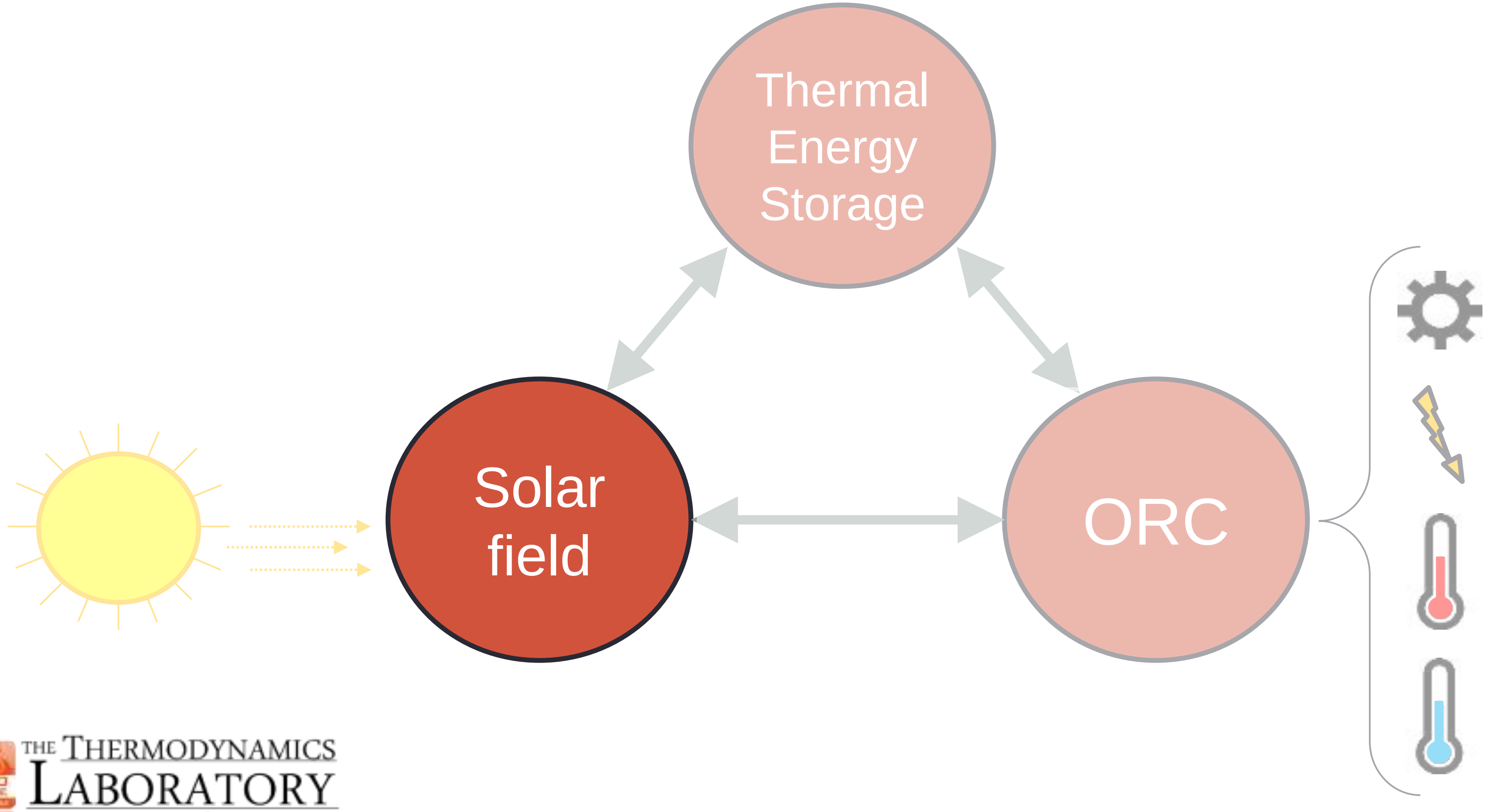

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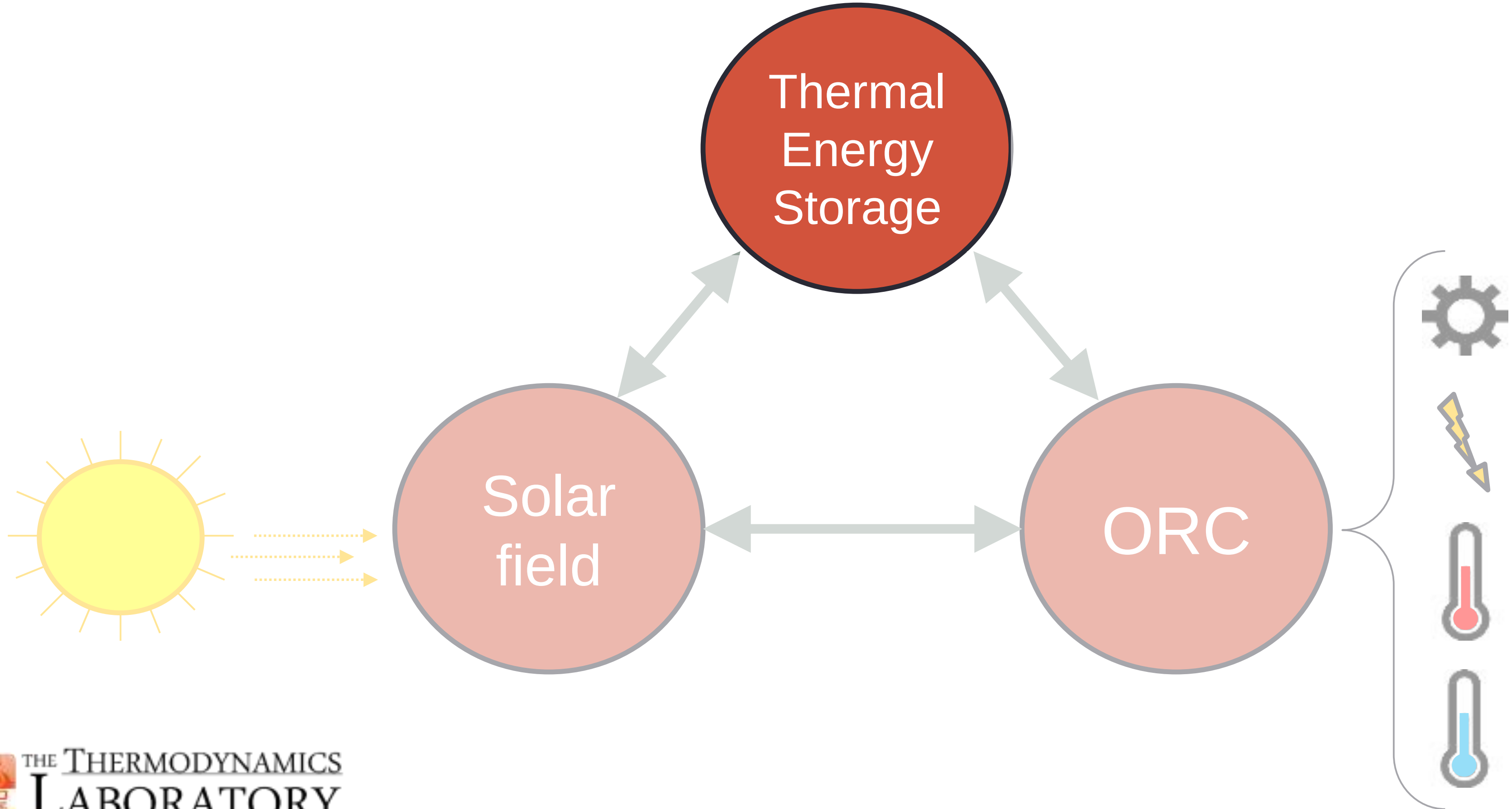
4. Thermal Energy Storage



Thermal Energy Storage

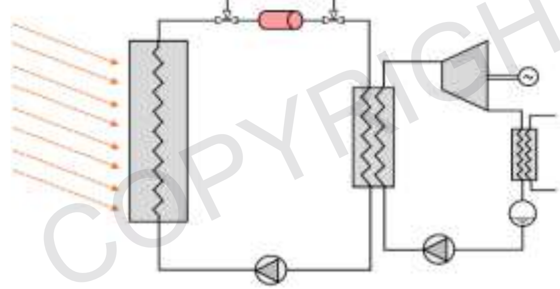
- Sensible TES
- Latent TES
- Thermochemical TES

Thermal Energy Storage

- **Sensible TES**
- Latent TES
- Thermochemical TES

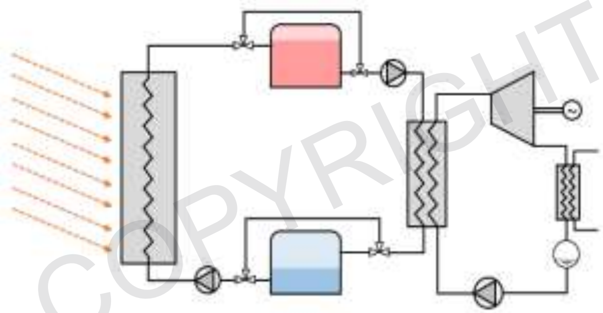
Sensible thermal energy storage

Single buffer:

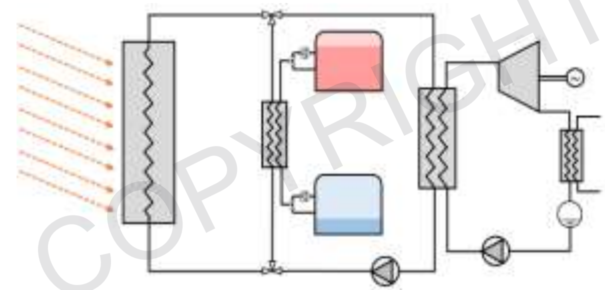


- ρ_{TES} ~ kJ/m³
- Possibility of filler material

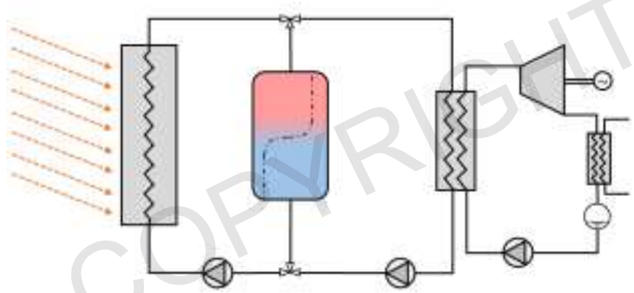
Two-tank direct



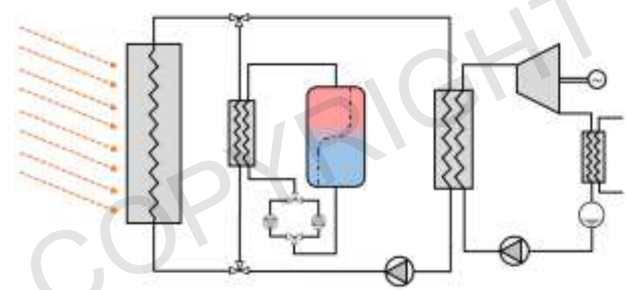
Two-tank indirect



Thermocline direct



Thermocline indirect



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Thermal Energy Storage

- Sensible TES
- **Latent TES**
- Thermochemical TES

Latent thermal energy storage

exothermic

$$A_{phase,1} \leftrightarrow A_{phase,2}$$

endothermic

- Mostly solid-liquid phase-change
- Often with encapsulation (avoid mixing with HTF)
- Higher energy density (ρ_{TES} ~ MJ/m^3)
- Quasi-isothermal process
- Change in thermal conductivity (dis/charging time)
- Storage media:
  - Organic: paraffins/ fatty acids
  - Inorganic : salt hydrates
  - Eutectic mixtures

Thermal Energy Storage

- Sensible TES
- Latent TES
- **Thermochemical TES**

Thermochemical thermal energy storage

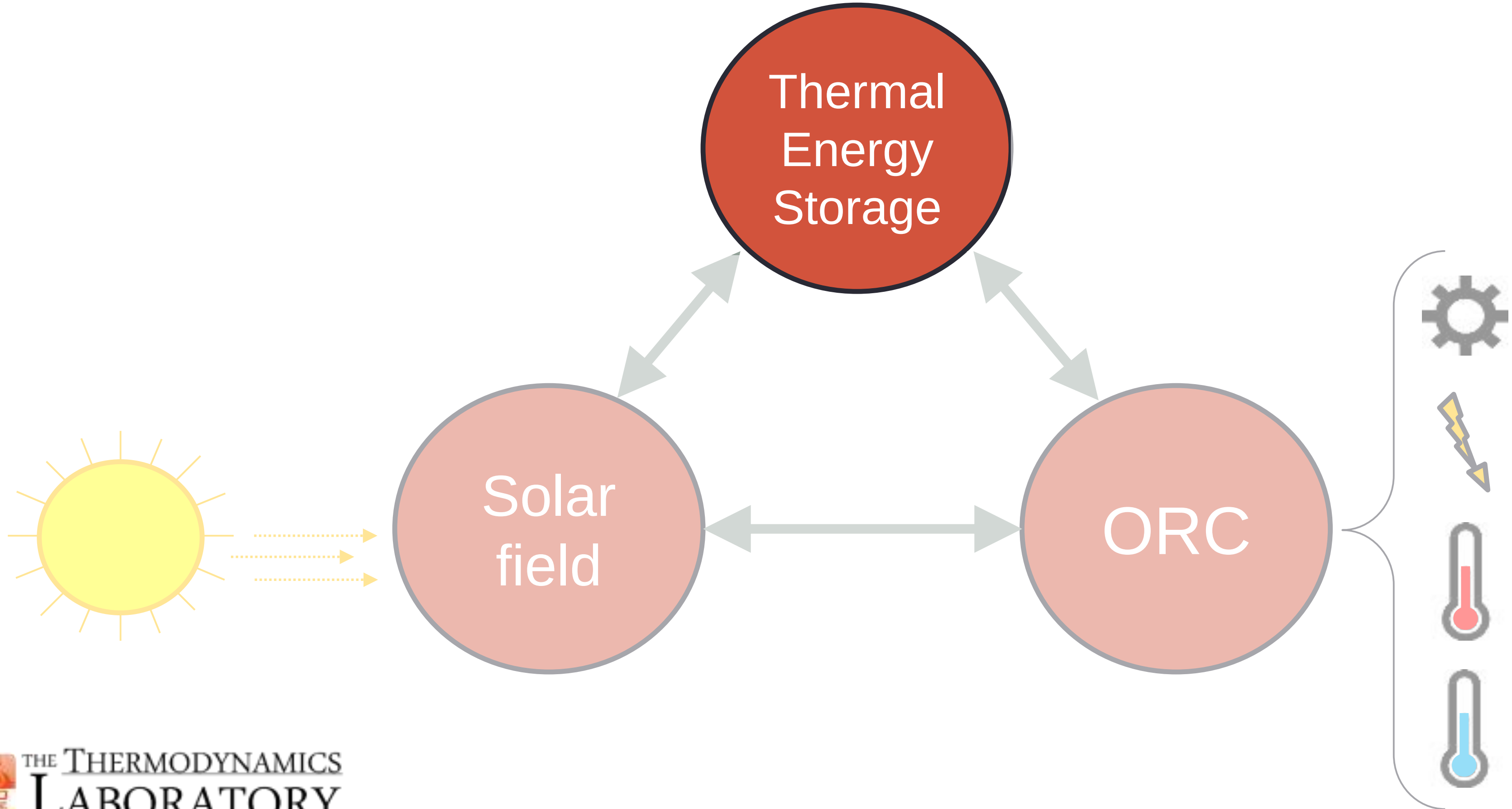
exothermic

$$AB \leftrightarrow A + B$$

endothermic

- Highest energy density (ρ_{TES} ~ GJ/m³)
- Quasi-isothermal process
- Storage at ambient temperature → lossless
- Large temperature range of application
- Examples:

Chemical reaction	Temperature range	Energy density
$FeCO_3 \leftrightarrow FeO + CO_2$	180 °C-200°C	2.6 GJ/m³
$CH_3OH \leftrightarrow CO + 2H_2$	200°C - 250°C	-
$Ca(OH)_2 \leftrightarrow CaO + H_2O$	400 °C-600°C	3 GJ/m³
$CaCO_3 \leftrightarrow CaO + CO_2$	800°C -900 °C	4.4 GJ/m³
$6\,Mn_2O_3 \leftrightarrow 4\,Mn_3O_4 + O_2$	900°C-1000°C	1 GJ/m³



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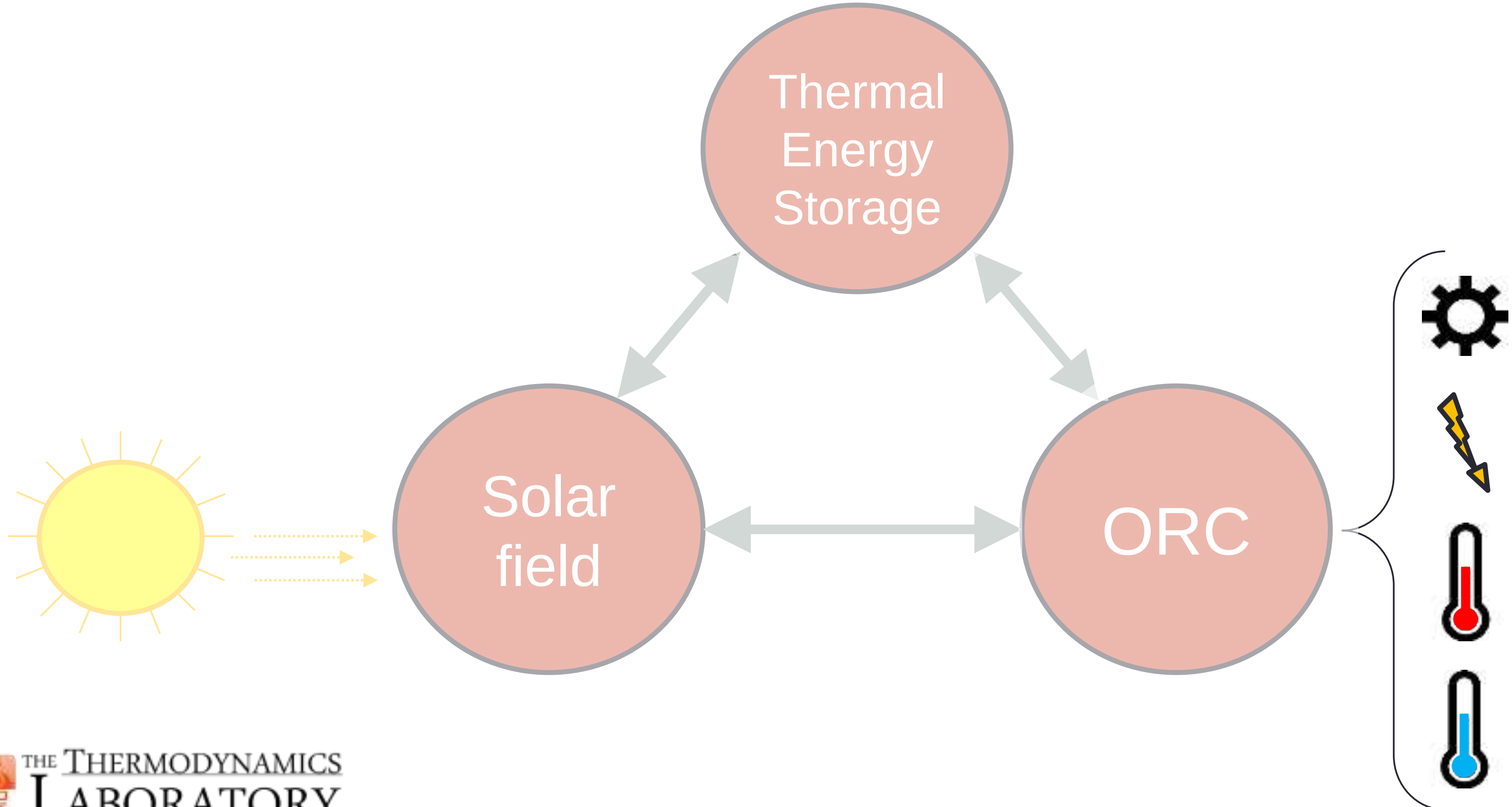
5. Fields of application



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Application – Power Generation

Grid-connected power generation:

- Small-scale solar ORCs are unlikely to be developed for grid-connected generation
- CSP for grid-scale application is more attractive with high capacity and high temperature systems (steam, Brayton or sCO_2)
- Two examples :
  - Beith Ha'Arava (Dead Sea), Israel
  - 1985-1986 (continuously) – stop in 1989
  - 250 000 m² solar pond (brine water at 95°C)
  - 5 MWe ORC unit (Ormat)
  - Ref: [11]

- Saguaro (Arizona), USA
- 2006-Now
- 10300 m² of PTC (thermal oil at 300 °C)
- 1 MWe ORC unit (Ormat)
- n-pentane
- Ref: [12]

Application – Power Generation

Distributed power generation:

- Small solar ORCs much more competitive :
  - Robustness and ease of local development/exploitation
  - Mass manufactured component from HVAC industry
  - Polygeneration (mechanical power, electricity, hot, cold)
  - Storage + control → good dispatchability
  - Hybridizing with local biomass or genset WHR
- Example of one STG International*power system:
  - Matjotjo Village, Lesotho
  - 70 m² PTC field + 3 kWe ORC unit (MEG at 150°C)
  - Single buffer TES
  - R245fa with scroll expander
  - Health clinic with 50-80 partients
  - 24 kWh_e and 380 m³ hot water per day
  - Ref: [13]

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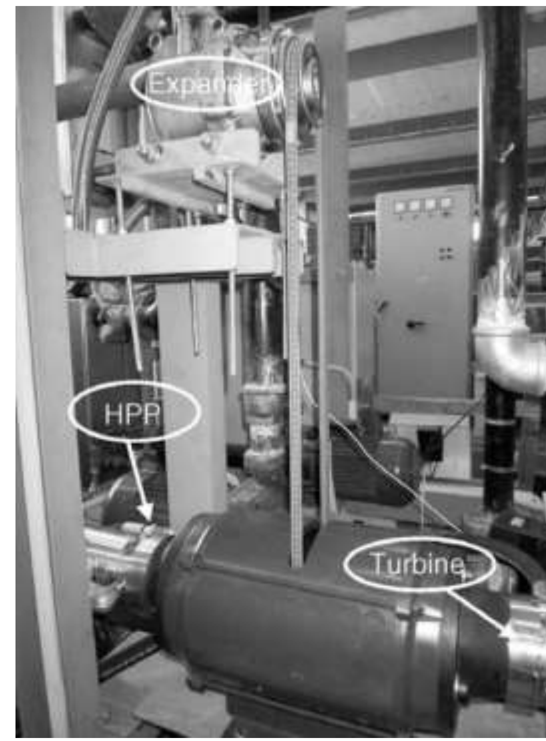
* http://www.stginternational.org

Fields of application - Desalination

Desalination (or water purification)

- ORC + Reverse Osmosis (RO) system

- Example
  - Marathon, Greece
  - 216 m² of ETC (water at 78°C)
  - 2.5 kW ORC with R134a
  - Single scroll expander
  - RO unit 0.3 m³/h of fresh water (15% recovery)
  - Ref : [14]



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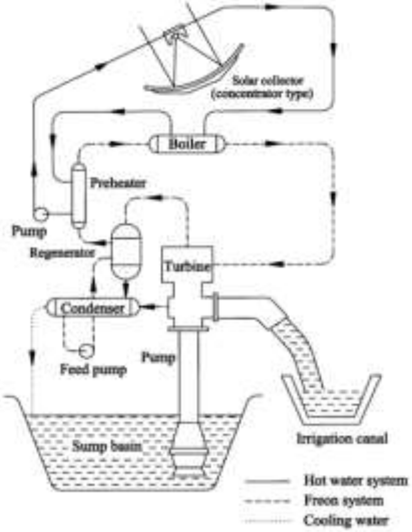
Fields of application - Irrigation

- ORC + irrigation water pump
- Good match between solar resource and irrigation requirements
- Examples

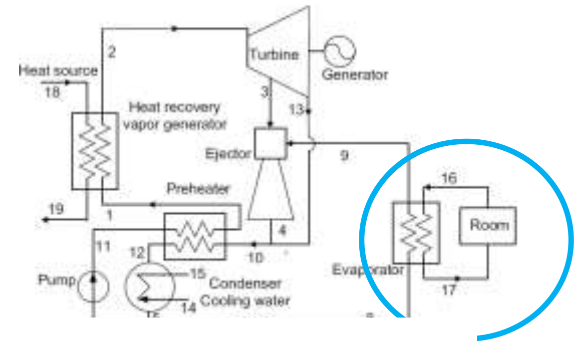
- Coolidge, Arizona (USA)
- 1972-1982
- 2140 m² PTC (thermal oil at 288°C)
- 200 kWe ORC unit
- Toluene, turbine, 20% net
- Ref: [15]

- Gila Bend, Arizona (USA)
- 1977
- 537m² PTC (water at 155°C)
- 37 kW_m ORC unit
- R113, turbine
- Ref: [16]

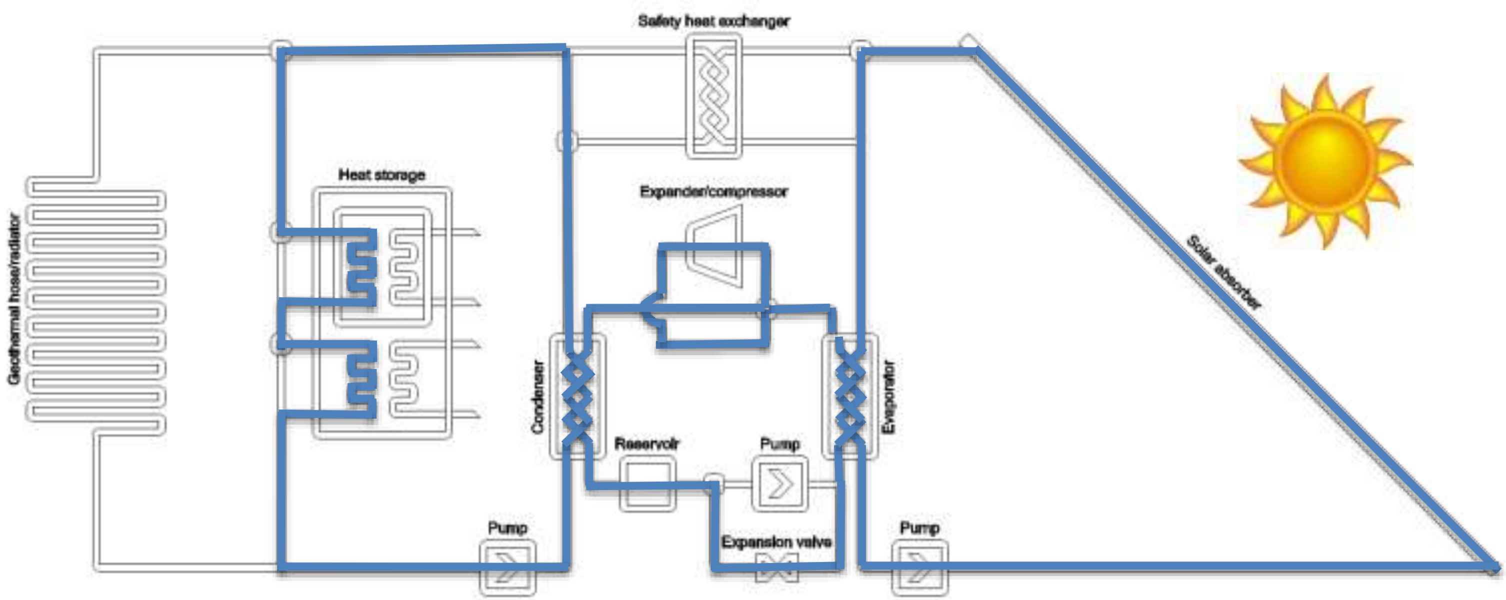


Fields of application – Hot / Cold generation

- Hot generation : solar collectors / condenser heat recovery
- Cold generation : ORC + ejector
- Hybrid CHP systems: ORC/HP/direct heating



Direct heating
mode



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Ref: [17]

Fields of application – Hybridizing

Industrial WHR-solar ORC

Example:

- Aït Baha, Marocco
- 6200m² PTC (air at 600°C)
- 2 MWe (Turboden 18HR)
- Fluid : HMDS
- Air-cooled condenser
- TES : Sensible (12hours)

- Ref: [18]

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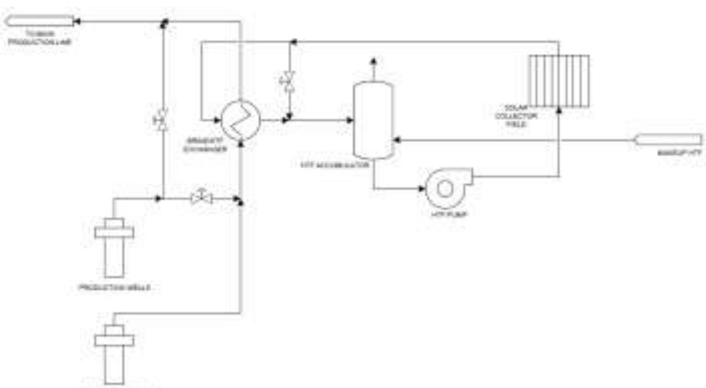
Fields of application – Hybridizing

Geothermal-solar ORC

Example:

- Stillwater hybrid geothermal-solar power plant
- Fallon, Nevada (USA)
- 2 MWe CSP + 33 MWe geoth. + 26 MWe PV
- 660 m² of PTC (water at 155°C)
- WF : Isobutane
- Air-cooled / 4 turbines



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Ref: [19]

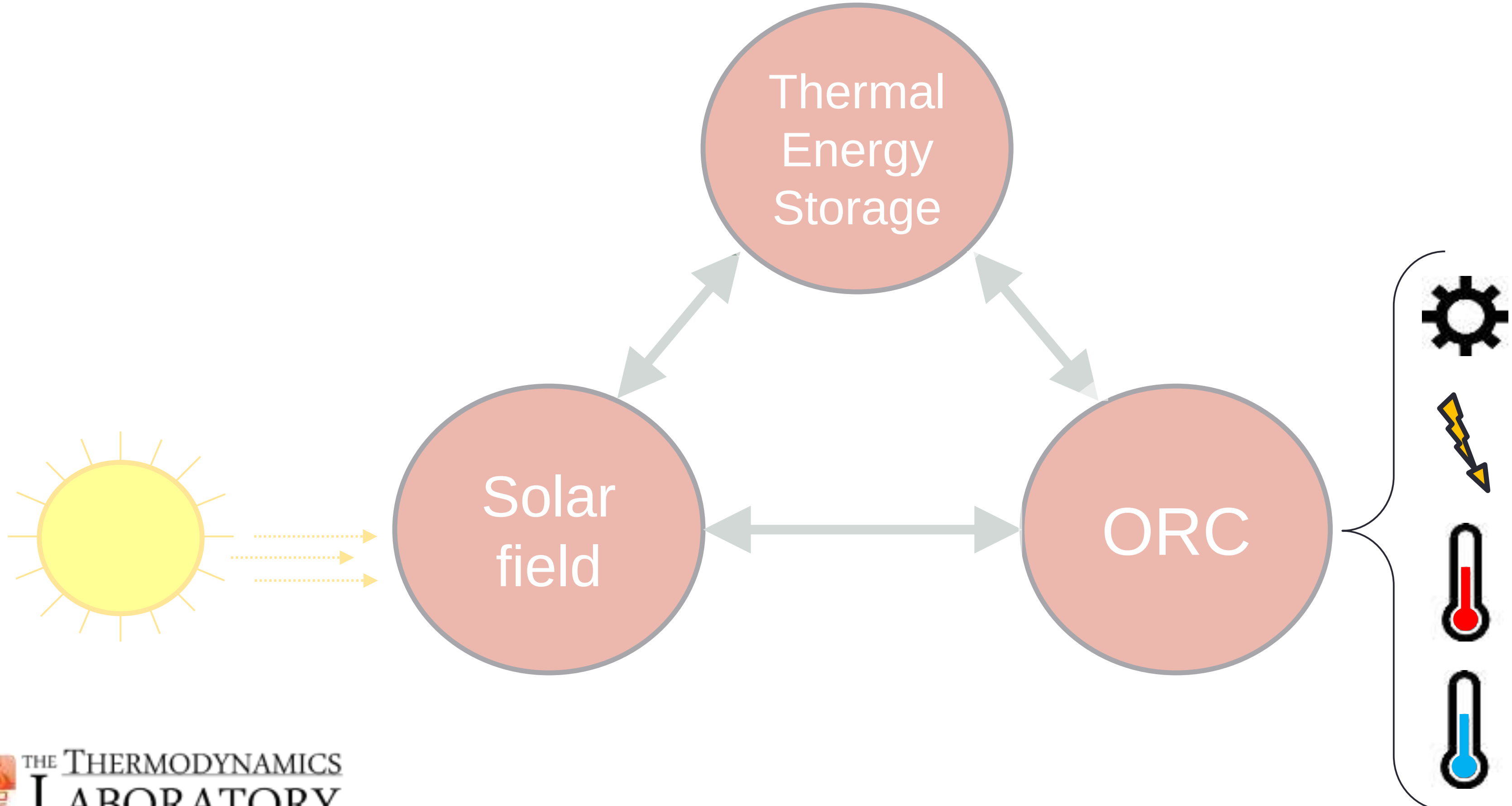
Fields of application – Hybridizing

Biomass-solar ORC

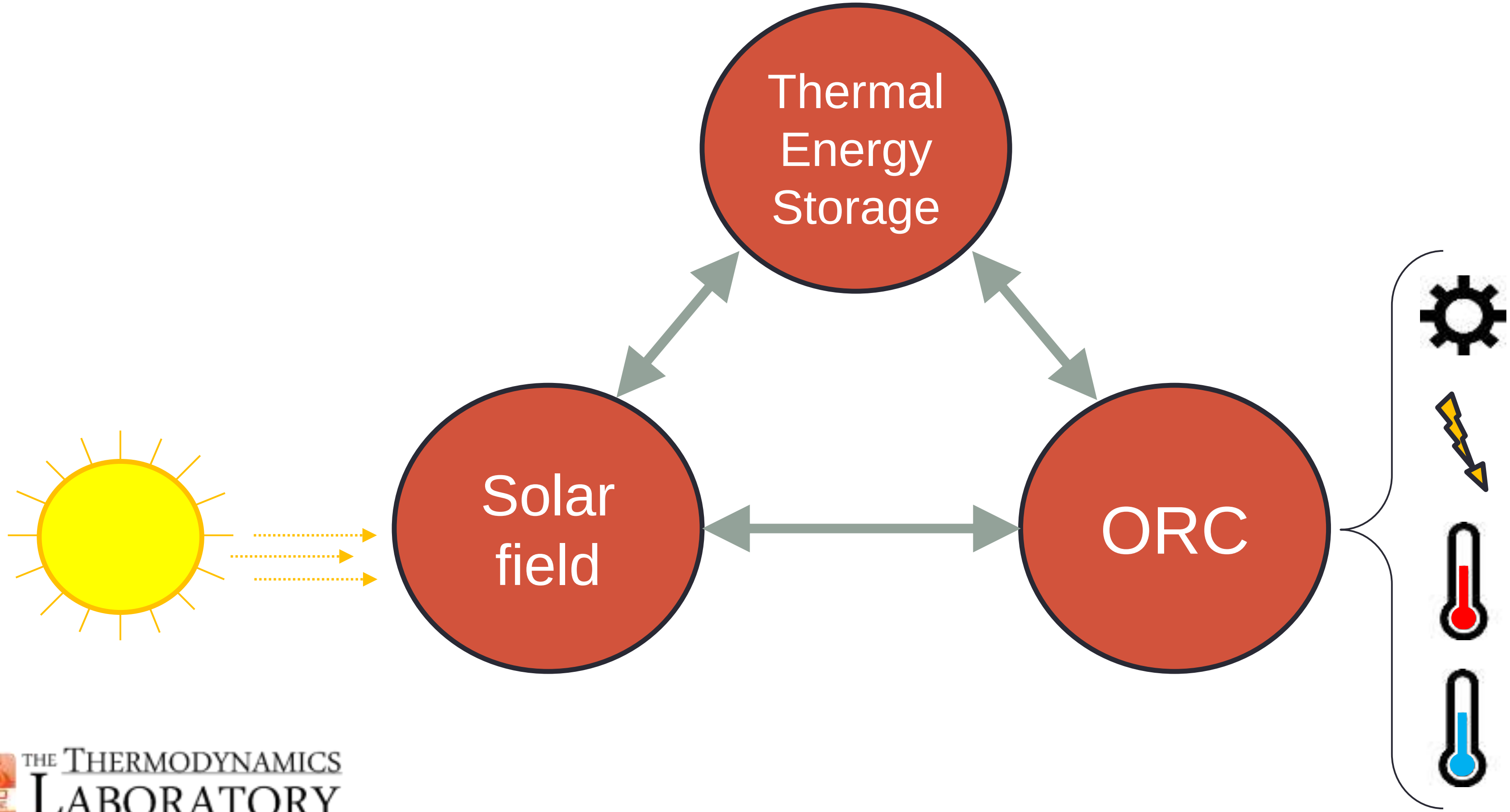
Example:

- Rende CSP-biomass power plant (Italy)
- Retrofit of existing 14 MWe biomass ORC with CSP (total 15 MWe)
- 9800 m² of LFC (thermal oil at 280°C)
- No information on the ORC (?)
- No TES

- Ref: [20]


Thermal
Energy
Storage
Solar
field
ORC

6. Modelling tools

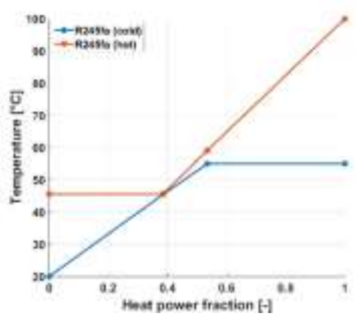


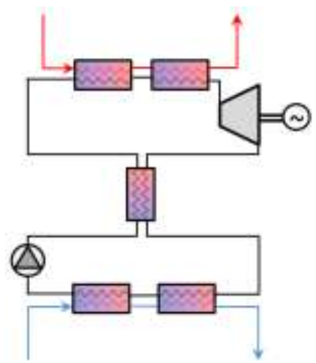
Modelling tools

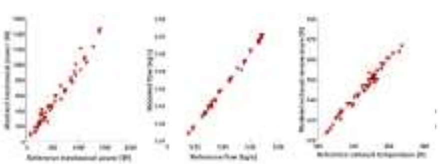
- Modelling crucial in
  - Thermo-economic studies
  - System design and sizing optimization
  - Off-design performance assessment
  - Control definition
- Major distinction between
  - Steady-state modelling: equilibrium conditions
  - Dynamic modelling : accounts for mass and energy accumulation in transients operation
- Time consuming process for model development but open-access libraries exist

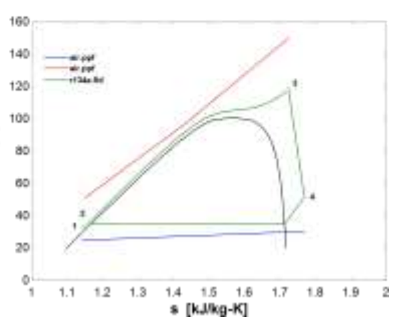
Modelling tools – Steady-state modelling

‘ORCmKit’ modelling library









- ✓ Open-source modelling library dedicated to ORCs
- ✓ Initiated by ULg and UGhent but aimed for entire community
- ✓ 3 modelling platform: EES/Python/Matlab
- ✓ Models for HEX, expander, pump, pipelines, ORC,…
- ✓ Calibration and graphical tools
- ✓ Reference:
  - https://github.com/orcmkit/ORCmKit
  - http://kcorc.org/en/open-source-software/
  - Dickes et al., 2016 . ORCmKit : an open-source library for organic Rankine cycle modelling and analysis, in: Proceedings of ECOS 2016, Portoroz (Solvenia), 2016. (ref: [21])

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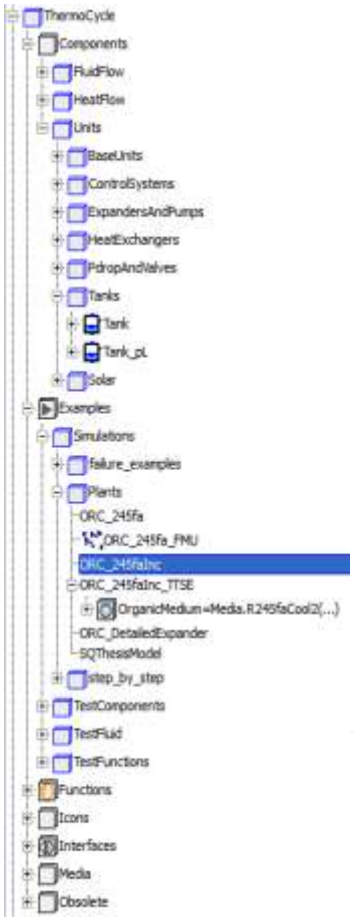
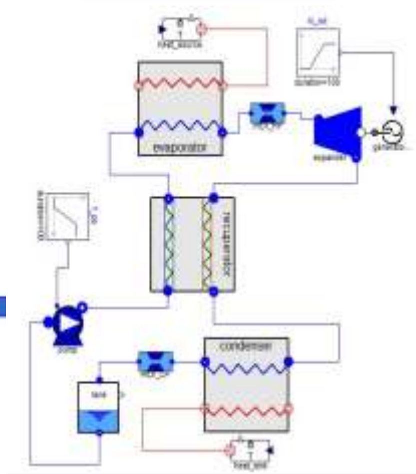
Modelling tools – Dynamic modelling

‘ThermoCycle’ Modelica library



Thermo Cycle THE MODELICA LIBRARY



CoolProp

- ✓Open-source Library for the modelling of thermal systems (including SORCs)
- ✓Software : Dymola (Modelica language)
- ✓Special focus on thermodynamic cycles
- ✓Component and cycle models available
- ✓Cross-Platform
- ✓Computational efficiency and robustness
- ✓Websites:
  thermocycle.net
  modelica.org/libraries

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Thanks for your attention

Any questions?

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References

This presentation is mainly inspired by the following chapter co-written by the author:

Matthew Orosz, Rémi Dickes. *Chapter 17 – Solar thermal powered ORCs* in *Organic Rankine Cycle (ORC) Power Systems: Technologies and Applications.* Elsevier. Not published yet – expected in 2017.

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