# Heat recovery in low-concentration PV/thermal units using a low-temperature supercritical organic Rankine cycle for improved system performance

by

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- Brief project presentation
- Description of involved technologies
- Supercritical ORC performance
- Control strategy of the combined system
- Productivity increase of the integrated system
- Conclusions and upcoming research work

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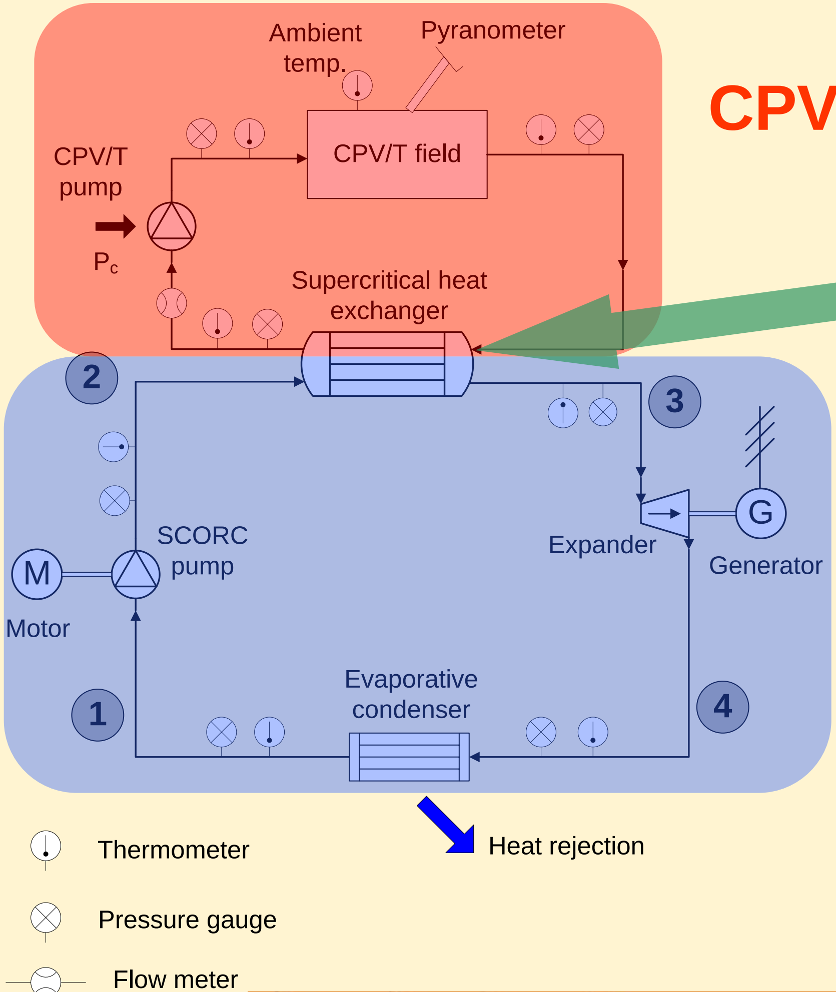
Research project FP7-SME: No. 315049

CPV/Rankine (duration: 2013-2014)




**CPV/T field (100 m$^2$)**

**Supercritical heat exchanger (41 kW$_{th}$)**

**Supercritical ORC (~3 kW)**

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## CPV/T field

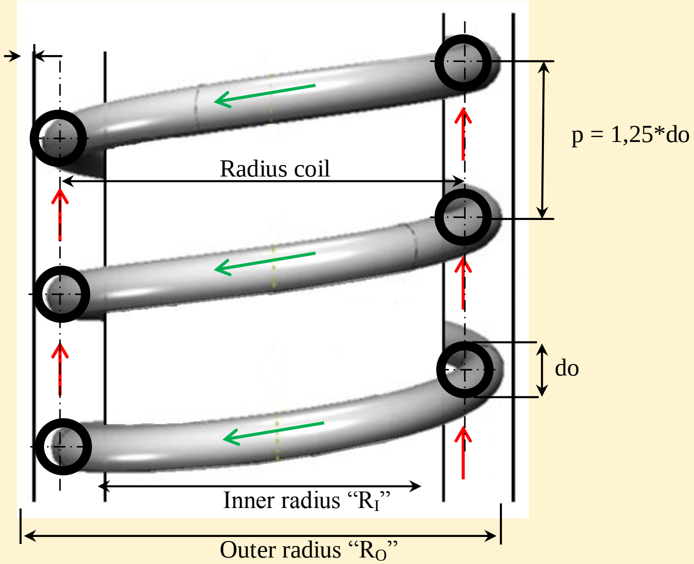
- A solar field of concentrating PV/Thermal (CPV/T) collectors is used with total solar surface 100 m$^2$ (10 collectors of 10 m$^2$ each) with concentration ratio~10x.
- This solar field produces electricity from the PV cells with capacity of 10 kWp, while the produced heat is 41 kW$_{th}$. The operational temperature is below 100 $^o$C and the HTF is water/propylene glycol mixture (30% by vol.).
- An E-W orientation is selected (collectors facing south, 1-axis tracking) and all 10 collectors are installed in parallel, in order to increase the total HTF flow rate (around 1.5 kg/s) and decrease the size of the supercritical heat exchanger.
- The main research aspect deals with the operation at higher temperature than usual (original collector: up to 75 $^o$C), since the produced heat of such collectors is most of the times used for heating purposes (mainly in buildings).

Responsible partner for the collector adaptation/development is Lumicum (research institute) from Sweden

*Source: www.absolicon.com*

## Supercritical heat exchanger

- This heat exchanger transfers the produced heat from the solar field to the supercritical ORC (capacity: <u>41 kW$_{th}$</u>), operating at pressure ~40 bar.
- Various <u>heat exchanger types</u> have been considered. The final selected is a helical-coil one, which has a simple design and is of low cost.
- The required <u>heat exchanger surface</u> is ~7 m$^2$. Heat transfer coefficients: Mokry et al., Petukhov et al., Garimella (similar values obtained): HTF~400 W/m$^2$/K, R-404a~2200 W/m$^2$/K. Overall heat transfer coefficient: U~250 W/m$^2$/K.



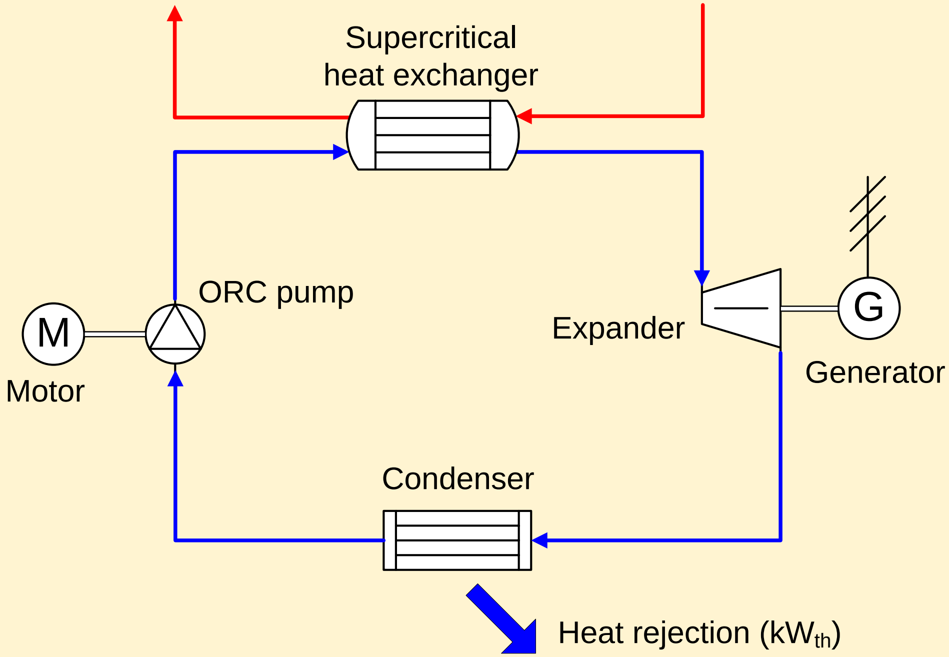

**Boundary conditions (at design conditions):**

- <u>Hot fluid stream</u>: water/glycol mixture with inlet/outlet temperature: 95/90 $^oC$, mass flow rate: 1.5 kg/s
- <u>Cold fluid stream</u>: organic fluid (R-404a) with inlet/outlet temperature: 30/85 $^oC$, mass flow rate: 0.25 kg/s, pressure: 39 bar (~1.04 P/P$_{cr}$)

Responsible partners for this heat exchanger development and construction are University of Ghent and Deconinck NV (SME) from Belgium

## Supercritical ORC

- Selection of appropriate organic fluid: R-404a.
- Heat input is 41 $kW_{th}$, and the supercritical pressure is almost 40 bar.
- The thermal efficiency at design conditions is 6.8% and the net power production is 2.9 kW.
- A standard design (single-stage) is followed.

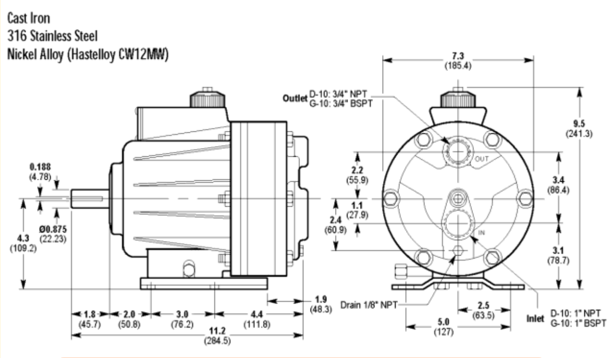



- Maximum temperature~85 °C with a 10 K pinch-point temperature difference (at the outlet side).
- Condensation temperature~30 °C and pressure~15 bar, depending on the condenser's operation.
- The pump and expander are equipped with frequency inverters for controlling their rotational speeds.

## Supercritical ORC

- The <u>scroll expander</u> produces ~3.8 kW. The hermetic scroll compressor (in reverse operation) is manufactured by Copeland (ZP series: ZP137), suitable for high-pressure A/C applications (usually with R-410a). Its max. isentropic efficiency at compressor mode is 75.2% at pressure ratio~2.8.
- The <u>pump consumption</u> is 0.9 kW. The pump selected is a diaphragm pump (20 l/min), having an inlet pressure limit of 17 bar.
- The <u>condenser</u> is an evaporative cooler. Such component has been selected, in order to keep a low condensation pressure → pump issue.

Hermetic scroll compressor (Copeland: ZP137-KCE-TFD)




Diaphragm pump (Wanner: G-10)

Responsible partners for the supercritical ORC development are Agricultural University of Athens and Hellas Energy (SME) from Greece

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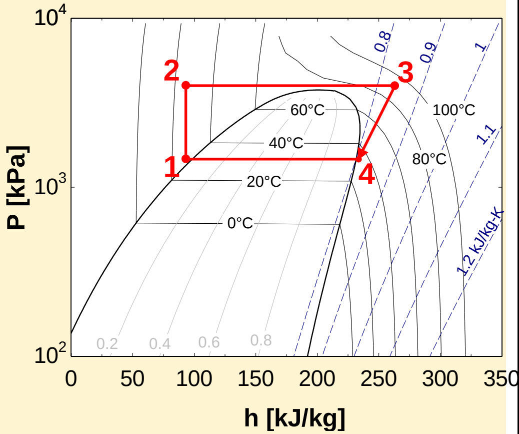
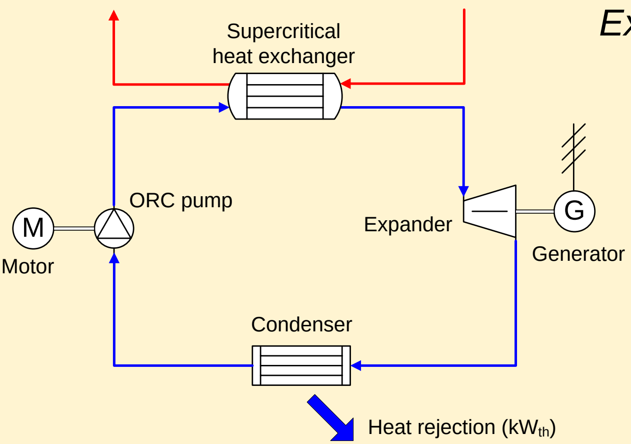
Efficiency values and parameters of the analysis at design conditions (R-404a selected). Commercial software used: Engineering Equation Solver – EES software




| | | |
|---|---|---|
| Expander isentropic efficiency ($n_{ex,is}$) | 85 % | Variable |
| Pump isentropic efficiency ($n_{p,is}$) | 85 % | Constant |
| Expander mechanical efficiency ($n_{ex,m}$) | 85 % | Constant |
| Pump mechanical efficiency ($n_{p,m}$) | 75 % | Constant |
| ORC feed pump efficiency | 64% | Constant |
| Maximum expansion efficiency | 72% | Variable |
| Organic fluid's condensing temperature | 30 °C | Constant |
| Organic fluid's subcooling (pumps' inlet) | 5 K | Constant |

*Expansion and pump efficiencies include isentropic and mechanical efficiency*

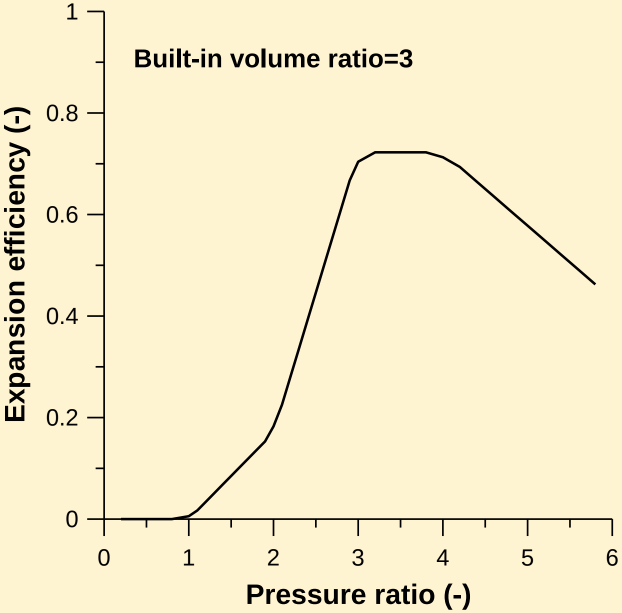


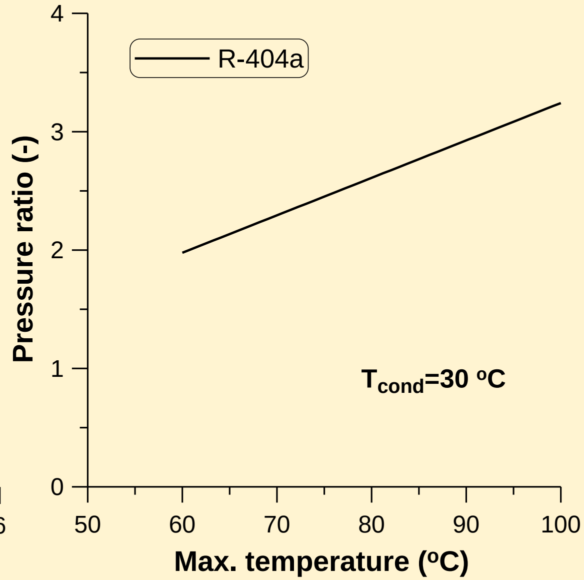

Main aspects investigated, affecting the performance:

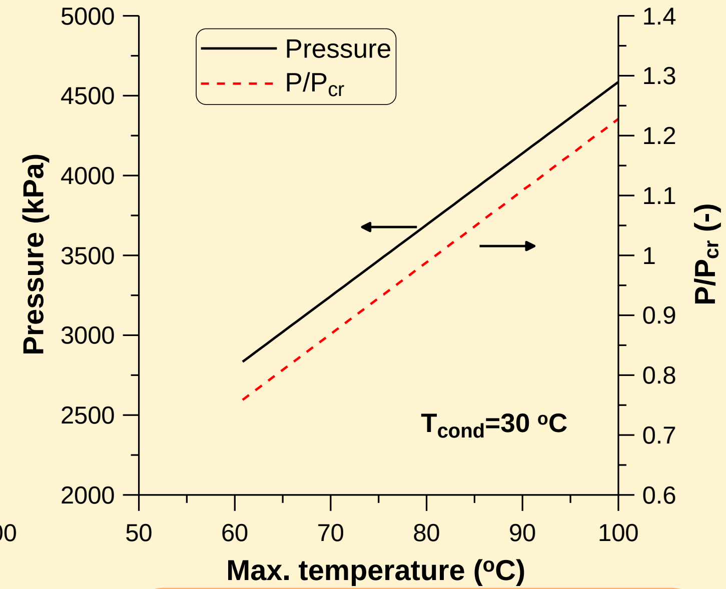
- Max. ORC temperature
- Expansion parameters
- Pump operation

# Supercritical ORC performance

Effect of expansion parameters and max. temperature on ORC properties (heat input: 41 $kW_{th}$)



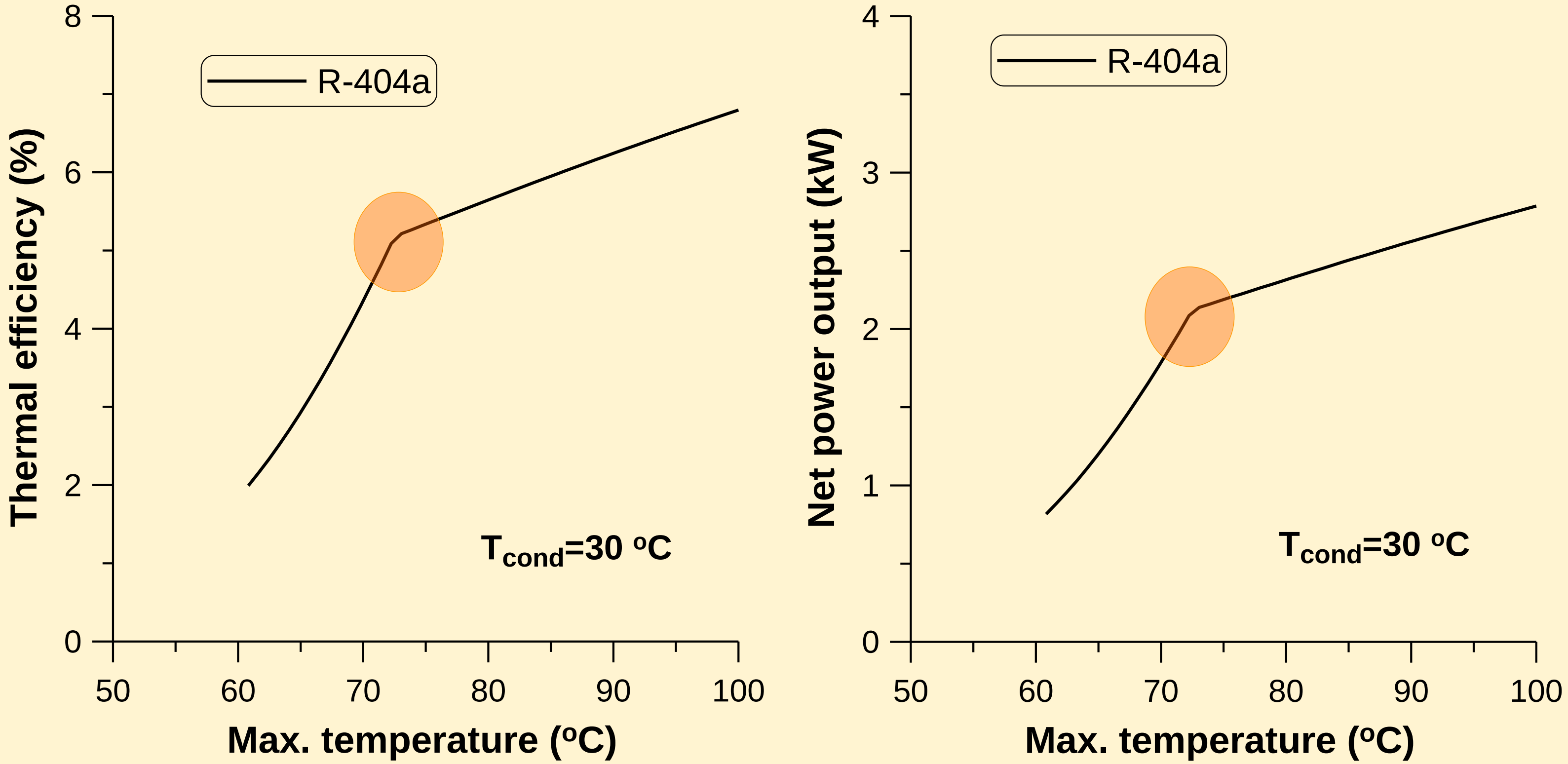

- Empirical expansion efficiency profile
- Max. efficiency at pressure ratio~3-4 (72%)
- For pressure ratio=2, the expansion efficiency is ~20%

- Expander pressure ratio as a function of temperature (optimized conditions)
- Un-acceptable pressure ratio for low temperature (→low cycle efficiency)

- For temperature over 80 °C a supercritical cycle shows higher efficiency
- The max. pressure is lower than 40-45 bar, making it possible to use conventional HVAC components

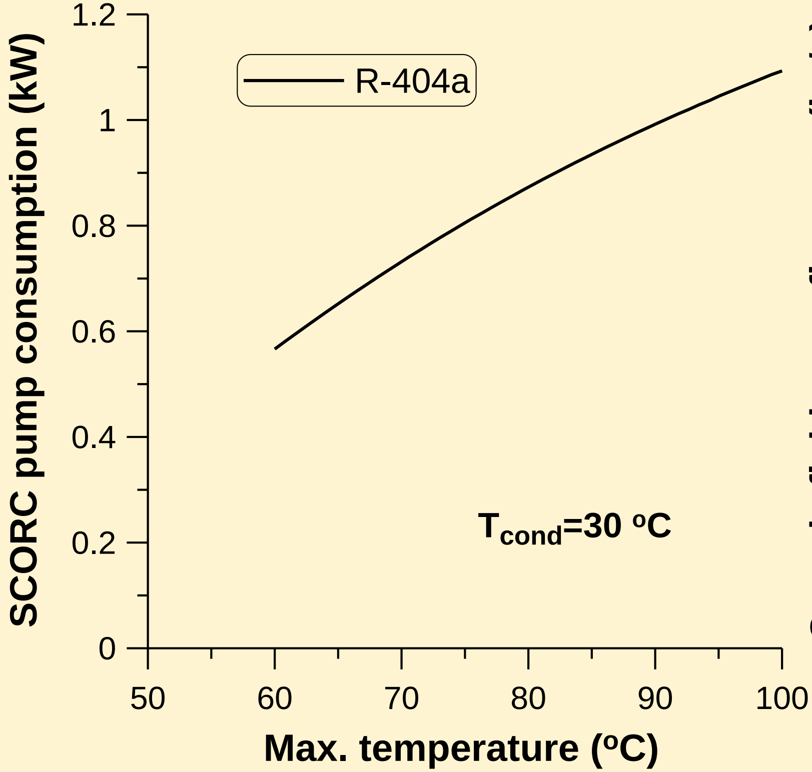
# Supercritical ORC performance

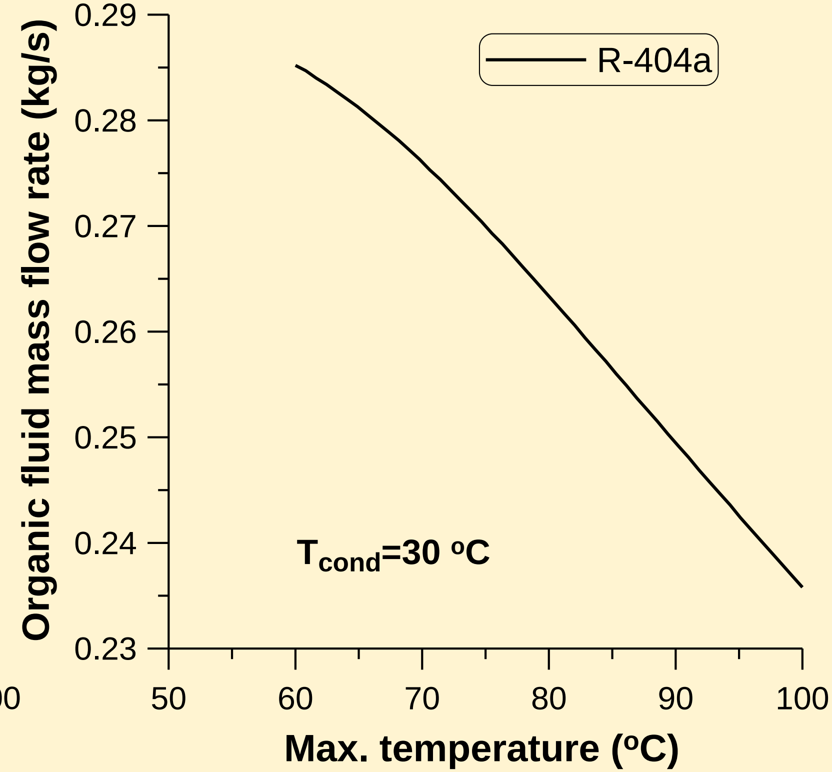
Effect of max. temperature on ORC performance (heat input: 41 $kW_{th}$)




- Thermal efficiency is increased for higher temperature, reaching even 7%.
- The max. net power production is almost 3 kW when the heat input is 41 $kW_{th}$.
- For temperature higher than ~72 °C the expander's pressure ratio is increased to acceptable level, significantly increasing the supercritical cycle performance.

Effect of pump operation (heat input: 41 $kW_{th}$)




- For operation at higher pressure, the pump consumption is increased, while the organic fluid mass flow rate is slightly decreased.
- The pump consumption is around 25% of the expander power, due to the high-pressure operation (compensated by the increased thermal efficiency).

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## Control of the solar circuit

- The main target is to adjust the solar field outlet temperature, by regulating the pump (with an inverter) within the acceptable flow rate range. The outlet temperature is decided to be equal to 95 $^oC$. Such temperature can be reached for incident direct solar radiation higher than 200 $W/m^2$.
- For decreased irradiation, the collectors' temperature glide is low (even 1-2 K).
- At design conditions, the pinch point temperature difference is 10 K at the supercritical heat exchanger. This difference is significantly decreased at low incident irradiation, even up to 2-3 K, since more heat exchanging surface is available than required (very beneficiary for the ORC thermal efficiency).

## Control of the supercritical ORC

- The ORC pump operation is adjusted with a frequency inverter, regulating the organic fluid mass flow rate and closely following the fluctuations of the solar field pump and heat input.
- The expander speed is also adjusted (with a frequency inverter), in order to keep the desired pressure, which maximizes the thermal efficiency. This regulation is minor (±few bar), since the max. temperature varies within a small range.

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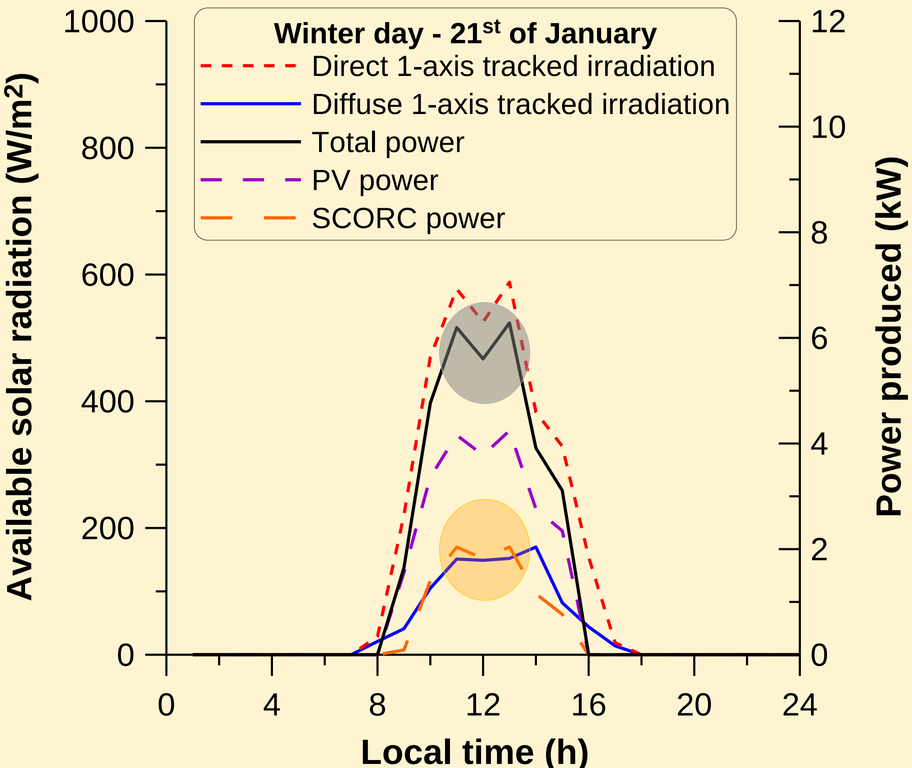
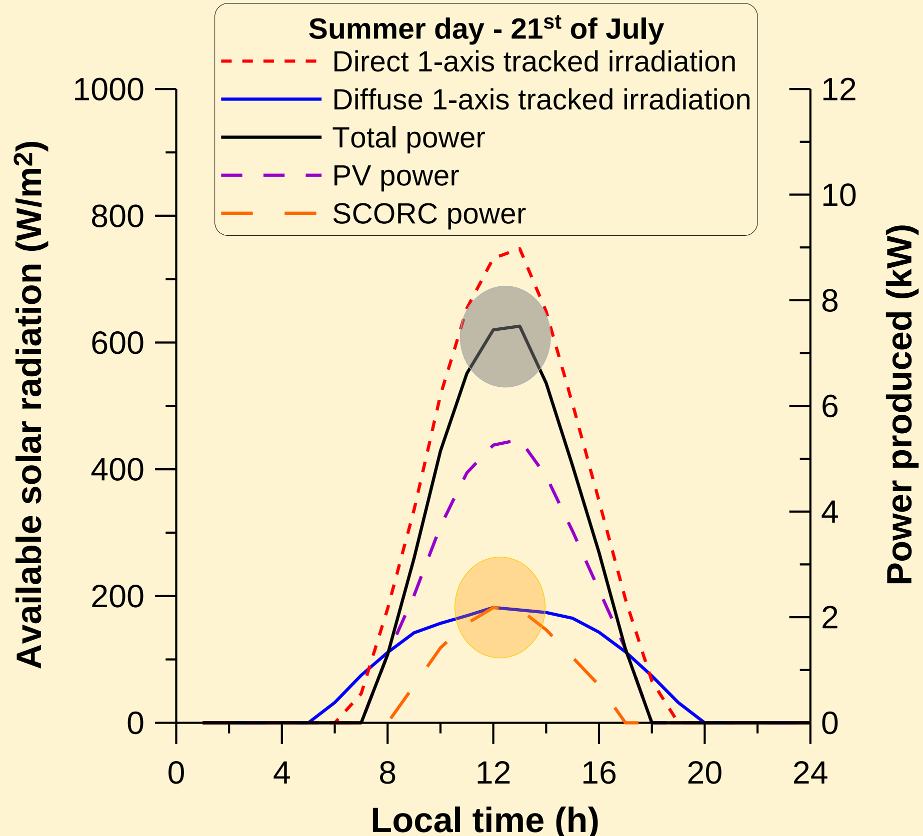
## Investigation of the performance of the integrated system

- Two representative days have been selected (winter/summer day), using the local weather data of Athens, Greece.
- The independent variables are: direct/diffuse incident solar radiation, incident angle, and ambient temperature.
- The system operation is simulated during the two days, using an hourly time-step (unsteady operation).
- During each time-step, an optimization procedure is implemented, adjusting the operation of the pumps and the expander (regulating the mean temperature of the collectors and the ORC max. temperature/pressure), within their pre-defined range, with the aim to maximize the total electricity produced (from both the PV cells and the supercritical ORC engine).

# Productivity increase of the integrated system

## Daily simulations for Athens, Greece




- During both days the integrated system can produce 6-8 kW of electric power.
- The power production duration is much higher during the summer day, with smoother power profile.
- The SCORC net power is comparable during both days, since the ambient temperature is lower during the winter day (lower condensation temperature).

## Cumulative results during a summer-winter day in Athens, Greece

| | Summer day | | Winter day | |
|---|---|---|---|---|
| | Integrated system | CPV/T system | Integrated system | CPV/T system |
| Total incident radiation (kWh) | 767.8 | | 501.0 | |
| Direct incident radiation (kWh) | 542.9 | | 357.6 | |
| Diffuse incident radiation (kWh) | 224.9 | | 143.4 | |
| Thermal energy produced (kWh) | 206.9 | 216.2 | 116.1 | 129.9 |
| Electrical energy produced by PV cells (kWh) | 35.0 | 40.7 | 22.2 | 27.0 |
| Electrical energy produced by SCORC engine (kWh) | 12.0 | - | 9.3 | - |
| Total electric energy produced (kWh) | 47.0 | 40.7 | 31.5 | 27.0 |
| Overall solar to power conversion efficiency (%) | 6.1 | 5.3 | 6.3 | 5.4 |

- The performance of a conventional CPV/T system is also shown (operating at lower temperature~75 °C).
- The proposed system produces around 16% more electricity.
- 25-30% of electric energy is produced from the SCORC engine (mean winter/ summer thermal efficiency: 8 / 6%).
- The overall solar to power efficiency is increased during the winter day, due to lower ambient temperature.

# Productivity increase of the integrated system

## Cumulative simulation results during a whole year in Athens, Greece

| | Integrated system | CPV/T system |
|---|---|---|
| Total incident radiation (MWh) | 184.99 | |
| Direct incident radiation (MWh) | 120.96 | |
| Diffuse incident radiation (MWh) | 64.03 | |
| Thermal energy produced (MWh) | 42.1 | 45.5 |
| Electrical energy produced by PV cells (MWh) | 7.6 | 9.0 |
| Electrical energy produced by SCORC engine (MWh) | 2.8 | - |
| Total electric energy produced (MWh) | 10.4 | 9.0 |
| Overall solar to heat conversion efficiency (%) | 22.8 | 24.6 |
| Overall solar to power conversion efficiency (%) | 5.6 | 4.9 |

- With similar methodology, the annual system simulation is also conducted.
- Around 7.6 MWh of electric energy are produced from the PV cells and another 2.8 MWh from the SCORC engine, 10.4 MWh in total (mean thermal efficiency~6.7%).
- The system productivity is increased by 16% fully justifying the concept of the integrated system.

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## Main conclusions from the investigation of the integrated system

- The capability of the solar collectors to produce heat of constant temperature for a large range of incident irradiation, makes it possible to operate the supercritical ORC with good efficiency all year-round (showing even higher efficiency at low loads/winter days).
- The integrated system produces around 16% more electricity than a similar conventional CPV/T system for the weather data of Athens, Greece. Such combined concept is suitable for the coupling of CPV/T units, especially in cases when there is not a thermal consumer available, increasing the system electric energy generation.
- For such low-temperature application, the thermal efficiency of the supercritical ORC unit is higher than a similar subcritical configuration by around 15%. This aspect increases the performance of the integrated system.
- The operational pressure of the supercritical cycle is not very high (around 40 bar) and standard equipment from HVAC applications can be used for its implementation (e.g. pump and scroll expander).

## Upcoming work of the CPV/Rankine project

- The adapted CPV/T unit prototype (receiver and collector), operating at higher temperature, has been designed, manufactured and successfully tested. It will be then reproduced (10 collectors in total will be used), in order to be included in the final installation on the university building roof in Athens (Greece).
- The supercritical ORC is under construction, with most of its components adapted (such as the hermetic scroll expander) and mounted on the main frame, including the supercritical heat exchanger (already manufactured). It will be then extensively tested in the laboratory (under controlled heat input from an electric heater) and evaluated.
- The combined system will be installed on the rooftop and tested for a long-term (during 2014), in order to have rigid conclusions about its performance over a wide period and operating conditions.

# Thank you for your attention

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