Potential and cost effectiveness of a reversible high-temperature heat pump/ORC unit for the exploitation of industrial waste heat

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Introduction and objectives

The cost effectiveness of low-temperature (100 °C) waste heat recovery solutions is not secured, especially in small/medium sized industries, although there are available technological solutions for such applications:

- ORC units for electricity production.
- High-temperature heat pumps for producing process heat.

These two components can be combined within a single unit, by reversing the heat pump cycle for operation as a heat-to-power unit, resulting to an ORC. The resulting **reversible high-temperature heat pump/ORC** can then exploit the low-temperature industrial waste heat and produce either **electricity** (ORC operation) or **upgraded heat** (heat pump operation), according to the availability of waste heat, the real-time needs for process heating, and the economic benefits derived from each mode.

Main objectives:

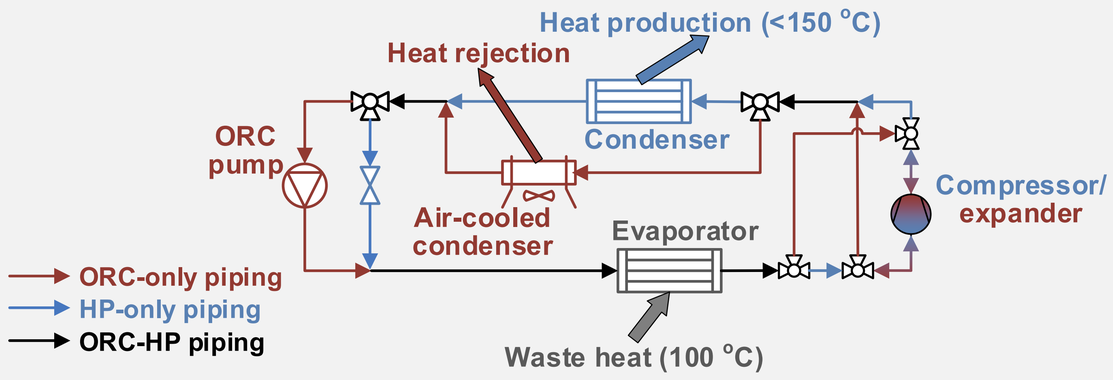
Investigate the **energy production potential** of this reversible concept at industrial settings, for exploiting **low-temperature waste heat at 100 °C**. Focus is given on small/medium sized industries, limiting the heat pump capacity up to 1000 kW, defining accordingly the maximum ORC capacity. Various scenarios are examined that lead to different operational hours of each mode, according to the temporal profile of the heating load and the heat pump capacity.

Implement a **cost analysis**, to quantify the benefits of the reversible concept in financial terms, using average EU energy prices for gas and electricity.

Reversible configuration

At heat pump mode, electricity is used to upgrade this heat to a temperature up to 150 °C. At ORC mode, the waste heat is converted to electricity. The reversible cycle is shown in the next Figure. Additional components due to ORC mode:

- ORC pump placed in a parallel circuit to the expansion valve (with a 3-way valve).
- air-cooled condenser for heat rejection.
- three-way valves actuated according to the operating mode.



Design/operating conditions

- Organic fluid: R1234ze(Z), an HFO with ultra-low GWP.
- Heat source temperature at either HP or ORC mode: 100 °C.
- Heat production at HP mode: 150 °C.
- Volume ratio at compressor/expander: 4.29 / 6.67
- Pressure ratio at compressor/expander: 2.97 / 6.15
- Performance values: COP=3.5 / ORC efficiency=4.5%

Cost figures

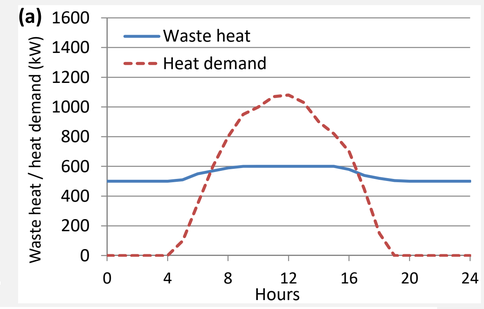
- HP specific cost: 200-800 €/kW_{th} (average: 500 €/kW_{th}).
- Additional cost: Function of pump capacity (20+5% of an ORC-only of 3000 €/kW_e)
- Running cost (O&M), excluding the electricity cost: 1% of the capital cost.
- Capacity factor: 90%.
- EU average energy prices: 0.036 / 0.07 €/kWh for gas and electricity respectively.
- Discount rate: 3%

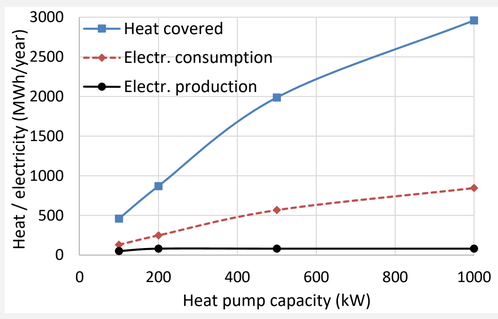
The **discounted payback period (PBP)** is calculated, according to capital/running costs, the discount rate and the annual (net) energy savings for gas and electricity.

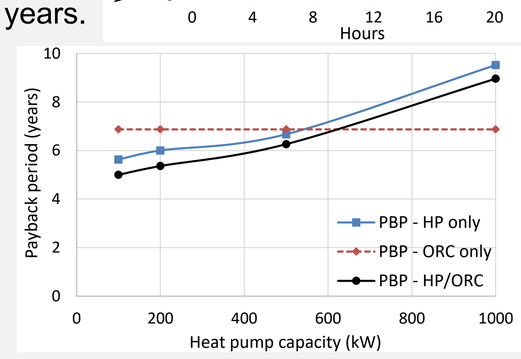
Results

A small/medium industrial site is examined with its energy demand profile deciding the relative operation of the heat pump and ORC.

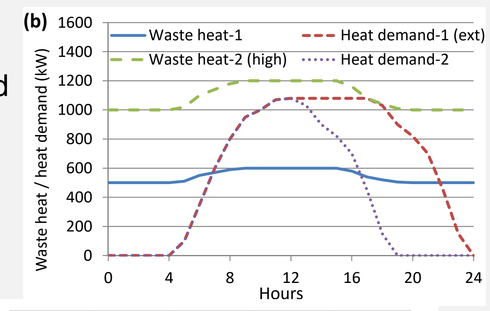
A **reference** waste heat/heat demand profile has been initially considered. The reversible concept requires that heating demand needed for less time than the waste heat availability. The PBP of the reversible unit is improved for HP capacity below 500 kW_{th}, reaching even 4.5 years.

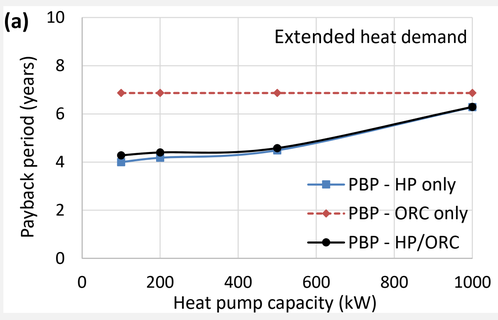


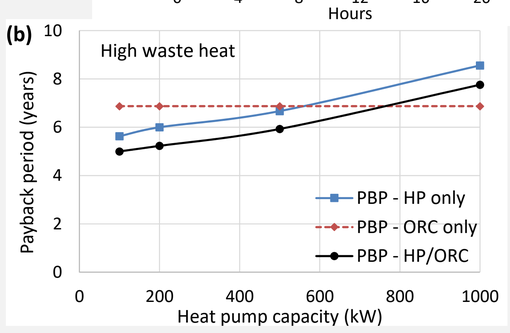




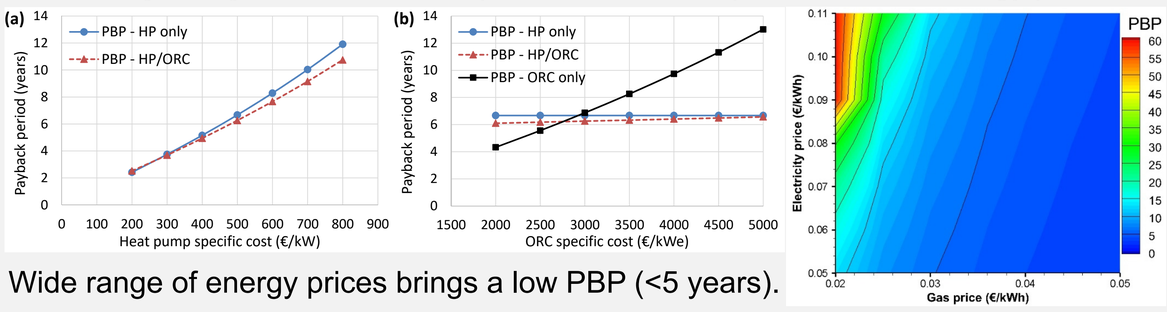
Alternative profiles examined with either an extended heat demand (larger period needed) and another one with higher waste heat profile. The PBP of the reversible unit is improved, especially for high HP capacity. For an extended heat demand, the PBP can reach even 4 years.







Sensitivity analysis: Variation of specific HP/ORC capital costs and energy prices.



Wide range of energy prices brings a low PBP (<5 years).

The effect of the ORC specific cost on the reversible unit PBP is negligible.

The HP specific cost is important, making it possible to reach a PBP of shorter than 4-5 years with reasonable costs.

Conclusions and future work

The application of a reversible high-temperature heat pump/ORC in industrial settings is examined for various load profiles. The payback period of the reversible unit is improved compared to the heat pump-only or ORC-only solutions, in most of the cases (up to a specific capacity), making **waste heat recovery solutions more cost-effective** in small/medium sized industries, in which the use of either a heat pump or ORC is not favored. The payback period can be shortened up to 2-3 years, with the energy prices for industrial consumers having the dominant role on this (the ORC cost has a negligible effect). Therefore, the reversibility option except from introducing superior flexibility on operation, it also enhances the cost-effectiveness.

The **future work** will include site-specific load profiles to identify the exact potential of an industry (based on the local energy prices), as well as a detailed cycle simulations for introducing part-load operation and compressor/expander performance. This activity will lead to a more detailed estimation of system costs and the PBP.

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http://www2.ipta.demokritos.gr/themlab/THEMLab_HeatPumps.html