POTENTIAL AND COST EFFECTIVENESS OF A REVERSIBLE HIGH-TEMPERATURE HEAT PUMP/ORC UNIT FOR THE EXPLOITATION OF INDUSTRIAL WASTE HEAT

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ABSTRACT

ORC units have demonstrated their potential for the exploitation of waste heat sources in industry, with many applications even at low-temperatures of 100 ^{o}C. At the same time, high-temperature heat pumps have been developed for various industrial sectors to exploit the waste heat thus producing useful heat, and subsequently recycling the heat quantities instead of rejecting them to the ambient.
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. This is achieved with few modifications, such as the addition of a pump for ORC mode and minor auxiliaries. 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: (1) the real-time needs for process heating and electricity, and (2) the economic benefits derived from each operating mode, which depend on the local energy prices and fluctuations.
The current work investigates the potential of this reversible concept at industrial settings. Focus is given on the exploitation of low-temperature waste heat of 100 ^{o}C, in order for the heat pump to produce useful heat with a temperature lift of up to 50 K, which is close to its upper temperature limit, while at ORC mode the thermal efficiency is 4.5%. The maximum heat pump capacity is 1000 kW, defining accordingly the maximum ORC capacity, representing the actual sizes in small/medium-scale industries, and considering a variable operating load. 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. The results of this analysis show the energy production of each mode, as well as of the whole reversible unit.
To quantify the benefits of this reversible unit, a cost analysis is implemented, using average energy prices for electricity and gas of medium-sized EU industries, subjected to a sensitivity analysis. Various scenarios are considered, showing that the payback period of the high-temperature heat pump only can be as short as 5 years, and of the complete reversible unit lower by about 20% in some conditions. Therefore, the reversibility option except from introducing superior flexibility on operation, it also enhances the cost-effectiveness and fully justifies the more complex configuration.

1. INTRODUCTION

ORC units are being increasingly applied in industry for the exploitation of waste heat sources and their conversion to electricity. The main parameters that greatly decide their cost-effectiveness are their size and heat source temperature level, assuming that integration aspects are resolved. In general, the ORC size should be as high as possible (Braimakis and Karellas, 2017), in order to reduce the specific cost, in €/kW, and bring a high impact to the industry with a short return on investment (i.e. significant increase of energy efficiency with a payback period of less than 5 years). This is usually interpreted as the available heat source amount to be exploited, preferably over 1-2 MW. At the same time, efforts are made on exploiting heat sources of high temperature (e.g. more than 150-200 ^{o}C), increasing the ORC thermal efficiency and leading once again to the reduction of the specific cost (Preißinger et al., 2016).

The combination of these two main aspects, i.e. large size and high temperatures, ensures to a great extent the success of a waste heat recovery project.

For applications at industrial sites with low amounts of waste heat (e.g. less than 0.5-1 MW), even if the heat source is at high temperature, the specific cost of the ORC does not allow for a short payback period in most of the cases. However, the number of these sites is very high, since the majority of the EU industrial sites are small/medium with waste heat in this range (Papapetrou et al., 2018). Apart from these, many large industries have this amount of waste heat in a limited number of processes, and it is not always feasible to collect such heat sources in one place to be recovered.

In case the waste heat temperature is low, e.g. below 100 ^{o}C, the ORC efficiency is less than 5-6%, making it once again not attractive from financial point of view. The exception is geothermal ORC units, which are large plants at the MWe scale, operating with a high capacity factor, possibly at CHP mode as well, to ensure their profitability (Van Erdeweghe et al., 2019).

In order to overcome these two drawbacks, the ORC flexibility can be enhanced by reversing its cycle and operating as a heat pump. This can be done with small modifications and a minor cost increase, once the same expander operates as compressor. The reverse cycle is a high-temperature heat pump for upgrading the waste heat at a temperature of up to 150 ^{o}C. This configuration operates according to the real-time need of the industry, either process heat or electricity.

Reversible heat pump/ORC units have been proposed for domestic applications combined with solar collectors for heating and electricity production (Dumont et al., 2015), showing that it is possible to use the same volumetric machine for the compressor/expander and keep a high isentropic efficiency, although one mode will be under-performing. A similar set-up can be also applied for energy storage applications (Staub et al., 2018), by using the excess electricity to drive the heat pump and store the produced (high-temperature) heat. This heat supplies the ORC for power production, when needed. This work identified that a separate compressor and expander should be used to maximize the system performance, especially in large-scale applications. As it will be shown later in this work, the pressure/volume ratios of the volumetric machine examined are not that far in both modes, making it possible to use the same machine and reduce the capital cost.

The current work examines the application of the reversible high-temperature heat pump/ORC unit in an industry and conducts detailed cost analysis, in order to identify the expected benefits. For that purpose, different energy prices for electricity and gas are considered. The main scope is to identify the potential of such unit, and examine whether this concept has more benefits than a separate high-temperature heat pump or ORC for the same conditions, especially for the industry sizes and temperature levels that are not favourable for the ORC technology. Therefore, the focus is not on the technical details, providing only the necessary system performance to conduct this kind of analysis, based on cycle simulations. As soon as the results are promising, future work will focus on the further investigation of the technical aspects of this reversible unit, accompanied with a detailed numerical analysis of the cycle and the expected isentropic efficiencies of the compressor/expander.

2. REVERSIBLE CONFIGURATION AND OPERATING CONDITIONS

2.1 Reversible configuration

The cycle with the reversing of the compressor to operate as expander is shown in Figure 1. Compared to a standard heat pump cycle, the additional components are: (1) an ORC pump placed in a parallel circuit to the expansion valve with the use of a three-way valve, (2) an air-cooled condenser for heat rejection, and (3) three-way valves to direct the refrigerant to the compressor outlet, when operating as ORC. Except from the above, the oil circuit should be adjusted, since the oil separator of a standard screw compressor is driven by the discharge/supply pressure difference. This is not possible in expander mode, requiring an additional oil pump for this process (not depicted in Figure 1), and possibly an oil separator. The reversible cycle is always supplied with waste heat at 100 ^{o}C. At heat pump mode, electricity is used to upgrade this heat to a higher temperature (up to 150 ^{o}C), which is used for process heat. At ORC mode, the waste heat is converted to electricity and the condenser heat is rejected to the ambient. The three-way valves are actuated according to the operating mode.

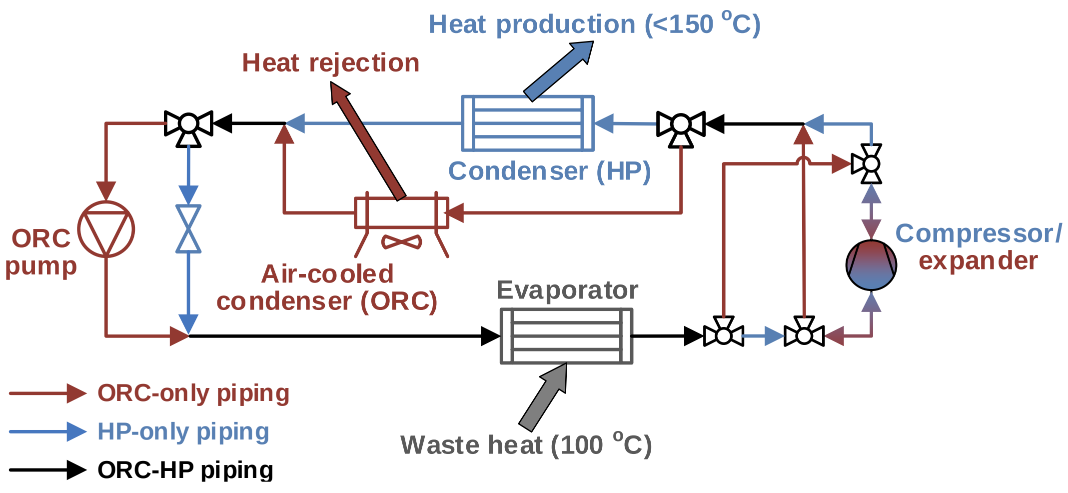

Figure 1: Reversible heat pump/ORC unit

2.2 Operating conditions and performance data

The main challenge in such reversible cycles is to achieve high isentropic efficiency for the compressor and expander. A screw-type volumetric machine is considered, since it can easily reach the necessary sizes of some hundred kW of heating or some tens kW of power production. Moreover, its reversing can be straightforward, with the main modification on its lubrication at expander mode.

The operating conditions greatly decide the cycle properties at each mode, resulting to the main specifications of the volumetric machine shown in Table 1. These values have been obtained with the refrigerant R1234ze(Z), an HFO with zero ODP and ultra-low GWP. Its thermodynamic properties are very similar to the HFC R245fa, which is suitable for high temperature heating (Arpagaus et al., 2018), but has a high GWP. The cycle simulations have been conducted with a typical superheating and subcooling of 5 K, as well as a 5 K pinch point temperature difference in the heat exchangers. The ambient temperature is 20 °C, and in case a lower temperature is applied (e.g. for winter conditions) the volume ratio of the expander is increased.

Table 1: Main specifications of the compressor and expander at HP and ORC modes

Mode:	Heat pump (compressor)	ORC (expander)
Inlet temperature (°C)	95	95
Outlet temperature (°C)	150	45
Inlet specific volume (m^3/kg)	0.015	0.10
Outlet specific volume (m^3/kg)	0.0035	0.015
Volume ratio (-)	4.29	6.67
Pressure ratio (-)	2.97	6.15

The inlet temperature to the compressor/expander is the same, since the organic fluid has been evaporated by waste heat (e.g. hot water at 100 °C). What should be noticed is the difference of the volume ratios between the two modes. This ratio at the compressor is within the range that screw compressors show their maximum isentropic efficiency, close to 75%. On the other hand, for the expander this is much higher and reduces its performance, resulting to a lower thermal efficiency. Similar findings, but for different conditions and application, have been also concluded in an experimental study (Dumont et al., 2015).

Under these conditions and with the use of an isentropic efficiency of 75% at heat pump mode and 65% at ORC mode, the resulting performance values based on standard cycle simulations are: (1) COP equal to 3.5 at heat pump mode, and (2) thermal efficiency equal to 4.5%. The performance of the reversible unit will be used in the next sections to identify the potential of such configuration at industrial settings, as a function of the related costs and savings.

3. ECONOMIC FIGURES

3.1 Capital and running costs

The cost analysis examines the capital cost of the reversible unit. This process is based on the estimated specific cost at heat pump mode in the range of 200-800 €/kW, which covers the entire range of reported values in the literature (Arpagaus et al., 2018; Kosmadakis, 2019), with the reference/standard value of 500 €/kW. To account for the reversing cost in the total capital cost, the ORC electric capacity is calculated in each case (based on the compressor capacity) that defines the ORC pump size. This reversing cost is then equal to 25% of the cost of this equivalent ORC-only unit, with the use of a specific cost of 3000 €/kWe (typical for this capacity range). This 25% fraction is divided to: (1) 20% for the pump, an average value for cases with low-temperature heat input (Braimakis and Karellas, 2017), and (2) 5% for the different minor parts, in order to account the additional components and cycle complexity to operate in reverse (e.g. valves, oil circuit). Finally, the running cost concerns the operation and maintenance, and is equal to 1% of the total capital cost.

3.2 Savings and discounted payback period

The annual benefits include fuel savings due to the heat production, and electricity savings due to the electricity production. The electricity consumption of the heat pump is also taken into account in the calculation of the net annual savings. The fuel savings concern a lower gas consumption for process heat. The latest gas and electricity prices (EU average) for small/medium-sized industrial consumers are used, 0.036 and 0.07 €/kWh respectively, excluding taxies and levies (Eurostat, 2019). A capacity factor of 90% is always considered. With constant annual cash flows, the discounted payback period (PBP) is calculated by Equation (1) (Bhandari, 2009), using a constant discount rate (*r*) of 3%.

$$PBP = \frac{ln\left(\frac{1}{1-\frac{C_{in}r}{E_S-C_r}}\right)}{ln(1+r)} \tag{1}$$

where C_{in} is the initial capital cost of the reversible unit, C_r is the annual running cost, and E_s are the net annual savings (in €/year).

4. RESULTS AND DISCUSSION

4.1 Industrial case study

A typical small/medium industrial site is examined. The critical aspect is to identify the relative temporal variation of waste heat and heating demand. At moments, when waste heat is available but no heating is required (no thermal storage exists), the unit operates at ORC mode. If heat is needed, then the heat pump mode is preferred, exploiting all waste heat. A simplified (reference/standard) hourly profile during a day has been then generated and introduced in the calculations, as shown in Fig. 2a. Two alternative profiles are also shown (Fig. 2b), which will be discussed later in this work (one with extended heat demand and another with higher waste heat available).

Based on these profiles, the results except from the reversible unit, also concern an ORC-only or heat pump-only solution. It is assumed here that electricity production by the reversible unit is always absorbed by the industrial site, since its amount is low compared to the total electric needs.

Different levels of the heat pump capacity are examined from 100 up to 1000 kW, covering a different fraction of the heating demand. The energy production of the reversible cycle is presented in the next section for the specific profile that is repeated every day of the year.

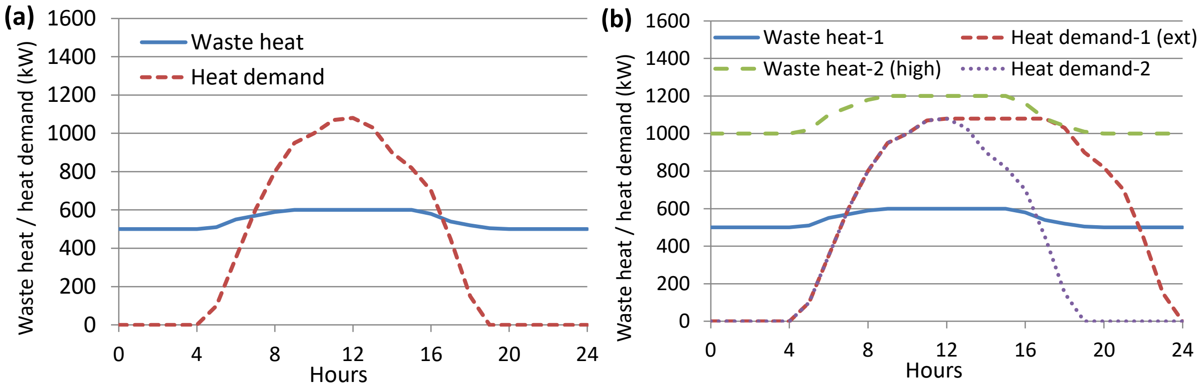

Figure 2: Waste heat and heating demand during a day for a reference profile (a) and two alternatives (b)

4.2 Heat and electricity production

The first priority is to cover the heating demand by operating the reversible unit at heat pump mode. At moments with no need for heating, the operation is switched to ORC mode for electricity production. Based on this strategy and the reference load profile of Fig. 2a, the resulting energy production of the reversible unit per year is shown in Fig. 3, as a function of the heat pump capacity. The electricity consumption at heat pump mode is also depicted.

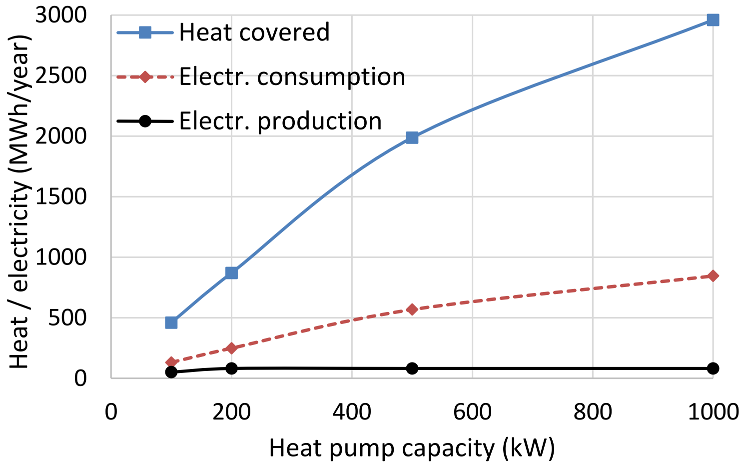

Figure 3: Heating and electricity flows per year of the reversible unit as a function of the heat pump capacity

For higher heat pump capacity, the high-temperature heat production increases as well. This makes it possible to increase the capacity of the volumetric machine reaching a higher electrical capacity at ORC mode (from 14 up to 23 kWe), with a similar increase of the electricity production (although small). In any case, the energy production by the ORC is much lower than heating production, due to the low thermal efficiency for low-temperature heat recovery.

4.3 Payback period of the reversible unit

By using the average energy prices for gas and electricity, the calculated discounted payback period of the heat pump-only, ORC-only, and of the reversible unit is shown in Fig. 4, as a function of the heat pump capacity (for the ORC-only, its capacity is adequate to utilize all waste heat).

For this low-temperature waste heat application, the ORC-only payback period is about 7 years, justifying its low market potential under these conditions and small scales. For the heat pump-only unit, things are more favourable for small capacities, making it possible to achieve even 5.5 years for a 100-kW unit. The economics are improved by the reversible unit, with a more favourable PBP than the ORC-only solution for a scale up to 600 kW, and always shorter than the heat pump-only case.

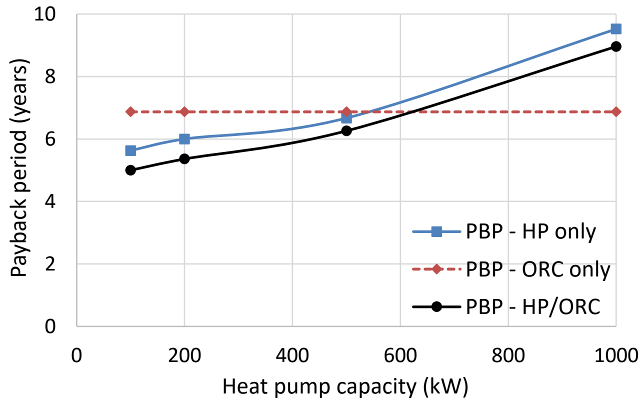

Figure 4: Payback period of the (1) heat pump only, (2) ORC only, and (3) reversible unit, as a function of the heat pump capacity (not applied for the ORC-only solution) for the standard load profile

It becomes clear that the cost-effectiveness of the reversible unit has greatly to do with the hours that heating demand is needed, as will be shown in the next section.

4.4 Payback period of the reversible unit with different load profiles

For an extended period of heat demand presented in Fig. 2b, the heat pump is utilized for more hours per day, reducing the ORC operation accordingly. The resulting PBP is shown in Fig. 5a.

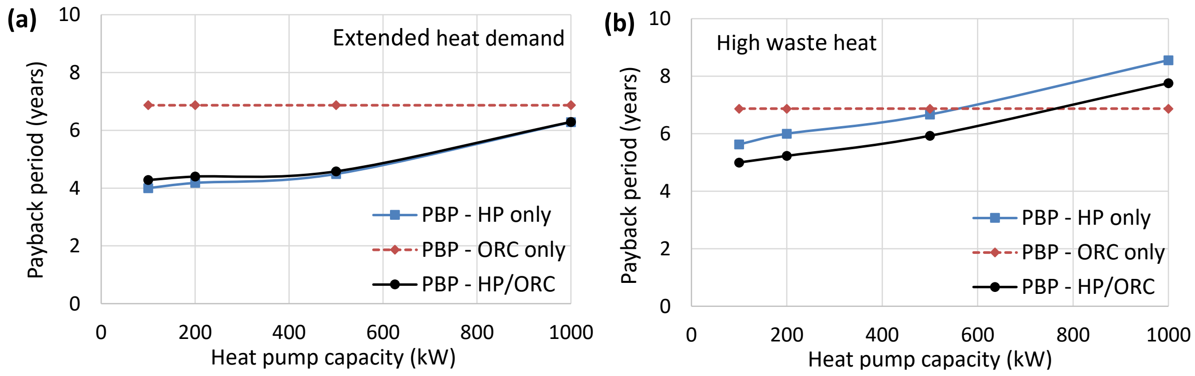

Figure 5: Payback period of the (1) heat pump only, (2) ORC only, and (3) reversible unit, as a function of the heat pump capacity (not applied for the ORC-only solution) for the extended load profile (a) and the high waste heat profile (b)

The ORC mode is applied for few hours per day (5 in total), introducing minor benefits to the reversible unit. On the contrary, the capital cost is increased, showing a slightly longer payback period than the heat pump only solution. Once again the PBP for the 1000-kW heat pump capacity is much longer, since this capacity is slightly higher than the maximum load of the heat demand.

In order to eliminate this deficit, another load profile is examined, which is similar to the first (reference) one with the same heating demand, but with a higher available waste heat, as previously shown in Fig. 2b. The discounted payback period is shown in Fig. 5b. For the low capacity range, the results are exactly the same as with the reference load profile of Fig. 2a. The cost-effectiveness of the reversible unit is improved and a shorter payback period is achieved for an even higher heat pump capacity of about 750 kW, compared to the ORC-only solution.

4.5 Sensitivity analysis of cost parameters

All previous results have been obtained with the average EU energy prices and typical specific costs of high-temperature heat pumps (500 €/kW) and small-scale ORC units (3000 €/kWe). However, especially the energy prices can greatly vary between EU countries, and a sensitivity analysis is thus required to identify their effect on the PBP. The main parameters examined are shown in Table 2.

Table 2: Main parameters of the sensitivity analysis

	Min	Standard	Max
Gas price (€/kWh)	0.020	0.036	0.050
Electricity price (€/kWh)	0.050	0.070	0.110
Specific heat pump cost (€/kW)	200	500	800
Specific ORC cost (€/kWe)	2000	3000	5000

For the reference load profile of Fig. 2a, the payback period as a function of the energy prices is given as a contour map in Fig. 6 (for a 500-kW heat pump with the standard specific costs).

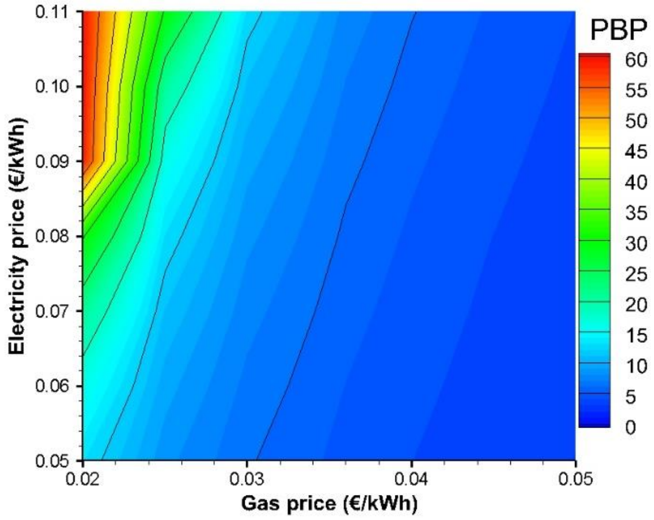

Figure 6: Variation of the payback period in years of the reversible unit for different gas and electricity prices

For low gas prices the fuel savings are reduced, greatly increasing the PBP. Moreover, the effect of the electricity price to the PBP is stronger than the gas price, due to the electricity cost required by the heat pump for its operation, which is much higher than the income from the ORC electricity production. The PBP can be shortened up to 3-4 years for high gas prices and any electricity price.

The effect of the heat pump and ORC specific costs on the discounted PBP is presented in Figs. 7a, b.

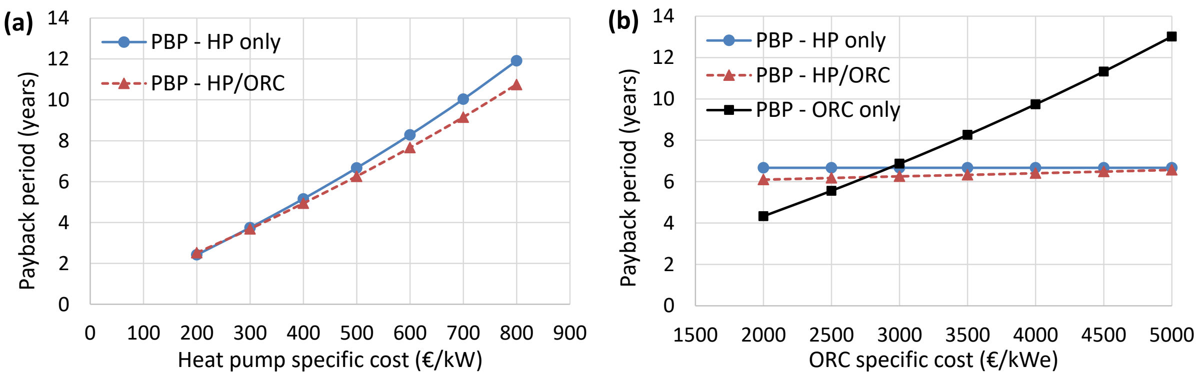

Figure 7: Sensitivity of the payback period of the HP-only, ORC-only and of the reversible unit as a function of the heat pump (a) and ORC specific costs (b) (for a 500 kW_{th} unit and standard load profile)

The heat pump specific cost greatly affects the PBP of the reversible unit, almost with a linear trend. The PBP can be as short as 2.5 years for the lowest specific cost. The scale of the heat pump has some role on this cost, which however is not within the scope of this work. On the other hand, the ORC specific cost has a negligible effect on the PBP of the reversible unit as shown in Fig. 7b, which is directly relevant to the reversing capital cost. Finally, these specific costs affect both the capital cost and the running cost, with the latter expressed as a fraction of the CAPEX.

5. CONCLUSIONS

The application of a reversible high-temperature heat pump/ORC in industrial settings is examined. Some highlights of its performance are provided, with the main focus on its energy production and cost-effectiveness for various load profiles. It has been shown that the payback period of the reversible unit is improved compared to the heat pump-only or ORC-only solutions, up to a specific capacity, directly relevant to the generated profiles. Apart from this, the reversible unit seems to provide an effective method for making more waste heat recovery solutions cost-effective in small/medium sized industries, in which the use of either a heat pump or ORC is not favored.

In any case, the payback period can be shortened up to 2-3 years with the energy prices for industrial consumers having the dominant role on this. This period also depends on the heat pump specific cost, while the ORC cost (for the reversing) has a negligible effect. The reversible unit seems to be a promising solution, if heat is needed for less time than waste heat is available, in order to exploit all the available heat amounts, and lead to significant energy savings. The future work will include site-specific load profiles to identify the exact potential of an industry, as well as a detailed cycle simulation for introducing part-load operation as well in the system performance.

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