Opportunities for high-temperature heat pumps as grid flexibility providers

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Electrification of the process of heat generation is essential to reduce fossil fuel use in industry. High-temperature heat pumps can efficiently convert power to heat up to 200 °C where waste heat is available. The study discusses the need for a more in-depth modelling of industrial processes and their ability to accommodate variable electric loads in order to quantify the real impact on the grid of high-temperature heat pumps integration. It further shows how industrial heat pumps can contribute to the grid's frequency containment reserve and stability.

Introduction

Thermal processes represent a significant fraction of industrial energy consumption. Due to the high temperatures involved, industrial heat is considered hard to decarbonise, and the sector still highly relies on fossil fuels. However, thanks to technological innovation, efficient high-temperature heat pumps (HTHPs) are becoming more and more available in the market, representing a promising solution for the electrification of industrial heat. These technologies could unlock the electrification of thermal processes and ensure high efficiencies thanks to the possibility to recover waste heat sources and upgrade them at temperatures up to 200°C. Moreover, the coupling of these devices with thermal energy storage (TES) would unleash a flexibility potential deriving from the industrial sector electrification. The deployment of Demand Side Management (DSM) strategies in high energy-intensive processes could lead to significant benefits for both industrial actors and grid operators in terms of balancing, cost of energy, renewable integration and overall carbon emissions reduction.

Nevertheless, to enable the large deployment of high-temperature heat pumps and thermal storage in the industry, it is of utmost importance to increase awareness of the benefits these technologies could bring both to the manufacturing sector and the energy system. This paper discusses the most relevant aspects and research gaps for system-level analysis. Furthermore, the end-user level implementation is analysed through a HTHP performance analysis.

System level analysis

Energy systems need more flexibility, which according to the International Energy Agency, can be defined as the extent to which a power system can modify electricity production or consumption in response to variabilities. With the integration of higher shares of non-dispatchable renewables sources, the flexibility is expected to be provided more and more from the demand side through the uptake of Demand Response (DR), which includes a series of actions aiming at modifying the energy load in response to price signals, generally during periods of peak demand. Large electricity consumers such as energy-intensive industries are considered good candidates for flexibility provision in the short-medium term and are already part of the portfolios of aggregators, monetizing their services to the grids on electricity and ancillary markets. Although the current industrial energy demand for thermal processes is still mainly supplied by fossil fuels, significant decarbonisation and electrification of the sector is expected in the upcoming years. The importance of industrial thermal demand electrification and its potential benefits have been demonstrated by many studies in recent years as well as the need for R&D on heat pumps that are promising technologies to provide flexibility to the grid.

The main Demand Side Management strategies for enhancing the flexibility of industrial thermal loads can be summarised in three categories: (i) process rescheduling (typically described as "load shifting"), (ii) thermal inertia exploitation of the process and (iii) use of thermal buffers. The variation of the final thermal energy demand associated with these three types of flexibility is represented in Figure 1.

In general, the less viable flexibility option is represented by rescheduling since the latter has a high impact on the industrial processes. Process rescheduling options find their application in cases characterised by intermittent operations, such as refrigeration systems and electric arc furnaces. Instead, the exploitation of thermal inertia could be easily implemented in those processes that present at least a limited tolerance in the operating temperatures of their processes, such as the majority of the pulp & paper or food sector processes. Finally, the integration of a thermal storage system is suitable for

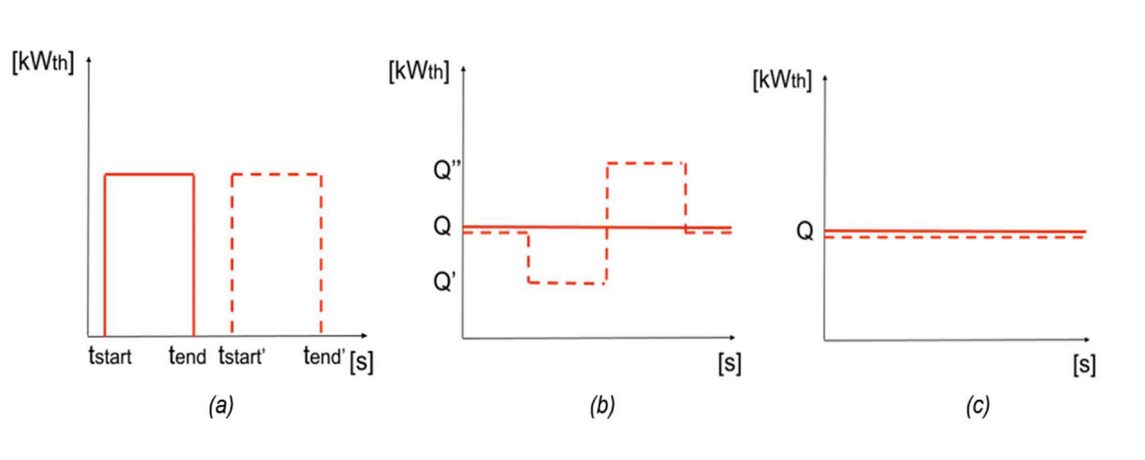

Figure 1: Industrial process thermal energy demand with adoption of different DSM schemes: load shifting (a), process thermal inertia (b), thermal buffer (c) [1]

all thermal processes since it does not affect their operations.

In order to perform a meaningful analysis at energy system level about the role of energy flexibility provided by industrial thermal processes with HTHP, some key aspects have to be taken into account in future research.

First of all, the industrial thermal processes need to be analysed in detail. The operating temperatures and detailed characteristics of the processes have to be considered to assess the integration potential of HTHPs. Neglecting the thermal behaviour of the technologies involved can lead to significant inaccuracies in the outcomes and estimation of HTHP efficiency. In this sense, process archetypes are suggested, representative of given processes, temperature levels and temperature glides (latent or sensible thermal processes).

Secondly, the model has to represent with the same accuracy both the supply side and demand side and their interaction. Previous studies [2] demonstrated the importance of integrated modelling approaches, which arguably lead to more realistic results and evaluations. Indeed, a detailed model of the industrial processes without the integration in an energy system model can be useful to perform a cost-benefit analysis from the consumer perspective under current market conditions (price-taker hypothesis), but fails in forecasting the impact of the energy transition on the future deployment and profitability flexible technologies in the industry. On the other hand, focusing on the representation of the energy system and representing the diversity of processes through a lumped load-shedding potential is an oversimplification, in particular in the case of thermal processes where neglecting the relationship between energy consumption and operating temperatures can

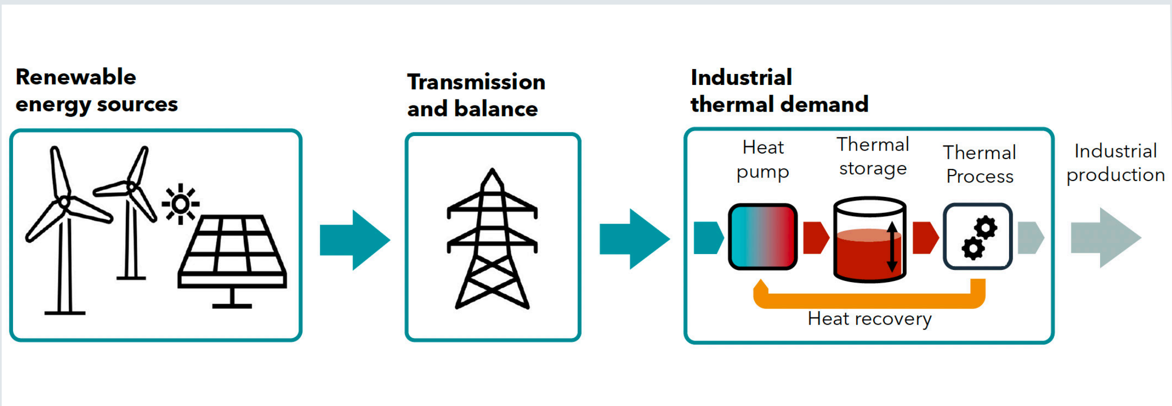

Figure 2 - System level integration of high-temperature heat pumps in industrial processes.

lead to important modelling errors. In this regard, an integrated modelling framework, such as Dispa-SET [3], is suggested. It is an open-source tool that can represent the operations of large-scale power systems with high level of detail with the aim to optimally solve the unit commitment problem for the chosen time horizon for each time step (1 hour). It is possible to integrate here, through the concept of process archetypes mentioned above, a heterogeneous thermal demand and, thus, an accurate efficiency of the HTHP (the COP, coefficient of performance, can be correctly calculated knowing the source and sink temperatures). Eventually, different penetrations of the HTHP can be considered; however, it is evident from preliminary analysis that an impact can be noticed only when the power installed reaches a minimum threshold compared to the total electric power generation at system level (e.g. in Belgium, about 200 MWel).

In this way, the impact on the electricity demand can be assessed in a precise manner, and the real potential of energy flexible operation of HTHP quantified (Figure 2).

Heat pump flexibility analysis

Only if the industrial heat pumps, that couple the electricity grid to the heat demand, can respond quickly to grid requirements the aforementioned thermal inertia of industrial processes can be exploited. The DLR Institute of Low-Carbon Industrial Processes evaluated the part load behaviour of their Brayton cycle heat pump prototype to assess its practical capabilities for load shifting. The prototype (see fig. 3) features a turbo compressor and turbine since turbomachines are readily available in multi-MW sizes for future industrial heat pumps. This way, the 200 kW thermal-output prototype with air as a working fluid is used to explore the specific transient behaviour of possible large-scale turbomachine-driven HTHPs. Brayton heat pumps generally offer a great deal of flexibility since the working fluid does not undergo a phase change. System pressure and source/sink temperature levels can be freely selected during the design process and varied independently during operation. When operating the heat pump, the compressor shaft speed can be varied to control the pressure ratio and, thereby, the temperature lift.

Industrial processes typically require a variable amount of process heat at constant temperatures. To meet this variable heat demand, the pressure levels within a closed-loop Brayton heat pump can be adjusted. This control technique is called fluid inventory control and involves releasing or injecting refrigerant into the working cycle. In [4], it is shown that part load operation at 25 % of design power is possible with negligible effect on the system efficiency.

Modelica was used to model fluid and heat transfers in the proposed Brayton heat pump, including dynamic effects such as thermal inertia and volume dynamics. Transient simulations of the heat pump show that the power consumption can be reduced by 80 % (or increased by 80 %) within 30 s from the nominal operation point.

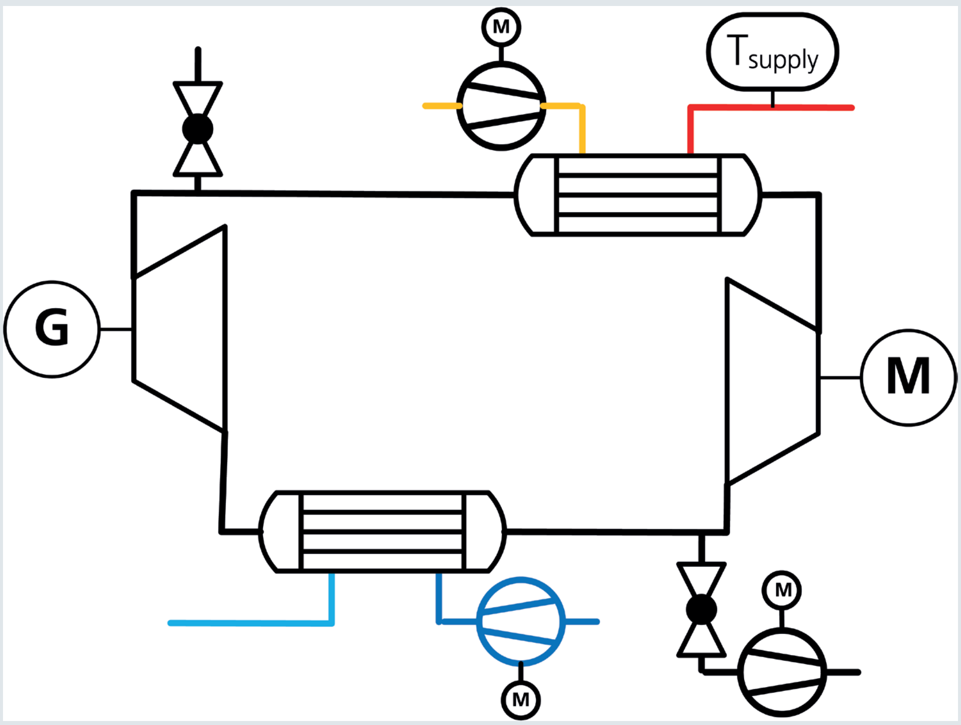

Figure 3 - Sketch of the Brayton cycle HTHP with heat source (blue) and heat sink (orange/red) and two discharge valves connecting the working cycle to the atmosphere and a vacuum pump

Figure 4 presents the system's response during a decrease of fluid inventory, which is accomplished through the removal of air via two discharge valves, leading to a reduction in pressure within the heat pump. This, in turn, results in a decrease in power consumption. To maintain a constant sink temperature, the mass flow rate of the heated fluid is adjusted using a suitable control mechanism.

This fast behaviour demonstrates the possibility of using HTHPs to provide frequency containment reserve (FCR) for the electricity grid by reducing or increasing the electric demand. In order to offer this grid service, a utility must prove that it can adapt its load within 30 s and keep it at the deviated level for up to 15 minutes. Given the process' thermal inertia allows for power deviations as long as 15 min (see Fig. 1, this could offer an additional revenue stream or become a requirement for large industrial consumers joining the power grid in their effort to decarbonize and reduce fossil fuel use.

Conclusions

The opportunities for industrial heat pumps to offer grid services such as demand side management and frequency containment reserve need to be evaluated more thoroughly. Therefore a characterization and quantitative parameterization of industrial processes is needed. Also, large-scale industrial heat pump behaviour and their interaction with the connected industrial process must be analysed. The results of the heat pump prototype discussed in this article are promising since they suggest that industrial heat pumps could contribute to the frequency containment reserve that requires a response time of 30 s. Further research is needed in this direction in the near future to quantify and unlock the flexibility potential of industrial heat pumps.

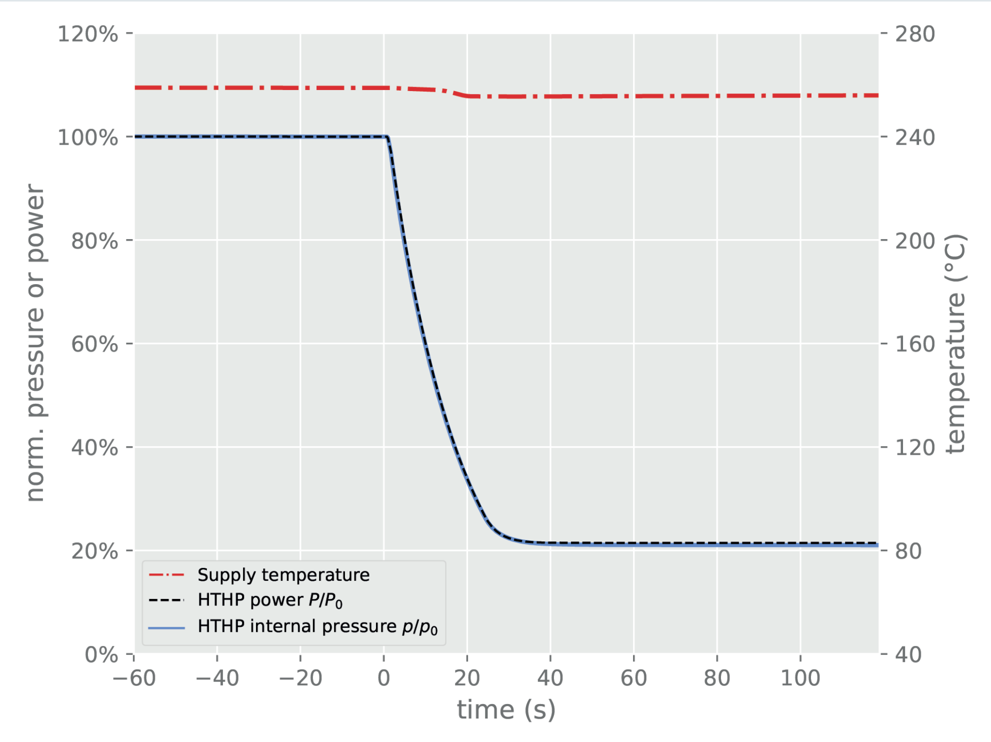

Figure 4: Power demand and supply temperature of a Brayton-cycle HTHP for a quick load reduction down to 20 % nominal power (model as in [5])

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