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DECARBONISATION THROUGH INNOVATION

How to widen the valley of opportunity for industrial heat pumps?

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Abstract

Strategies to deliver CO_2-neutral heat to industrial processes mostly involve electrification. In view of operational costs, heat pumps are preferred over E-Boilers due to higher Coefficients of Performance (COP) that can be achieved. On first sight an obvious integration concept is to replace a fossil-fuel fired boiler by a *central* heat pump. This results in a high capacity heat pump with an attractive CAPEX per unit power. However, such an arrangement typically result in COPs of about 1.8 or lower. Thus the Return on Investment (ROI) is only acceptable in a few countries where the electricity to gas price ratio is very low. Clearly no market on a European scale can be expected. This defines the *right* slope of the "valley of opportunities". From a thermodynamic perspective, a *local* heat pump close to a process is preferable. In this case the difference between heat delivery temperature and waste heat temperature is smallest. This leads to very attractive COPs. However, the smaller capacity results in a high CAPEX per unit power. This makes the ROI again not acceptable. This defines the *left* slope of the valley.
We present multiple options to widen the valley. First we discuss technological developments leading to a higher COP and a lower CAPEX, bringing the left slope down. Next, we show that cooperation between heat pump supplier and process experts of the customer can lead to a design with lower heat delivery temperatures. Another solution is to deliver the heat at multiple temperature levels. In this way we bring the right slope down. We conclude that this approach enables us to engineer solutions tailored for the customer. Doing so, we offer attractive heat pump solutions for a wide range of operational situations.

Keywords: High Temperature Heat Pumps; Steam Heat Pump; Heat Pump Integration; Decarbonizing Industrial Heat; Business Case Analysis

1. Introduction

Decarbonizing industrial heat is both essential and challenging. This heat demand can be decarbonized via electrification using high temperature heat pumps (HTHPs). Bless et al. (2017) [1] theoretically analyzed various methods for producing saturated steam at 3 bar(a), including vapor compression, direct electrical heating, gas heating, heat pumps with waste heat use, and combinations thereof. In conclusion, HTHP technology was cost-competitive depending on the availability of waste heat and the electricity-to-gas price ratio. Ramirez et al. presented an analysis of a steam heat pump showing that a temperature lift up to 90 °C and a condensation temperature up to 160 °C is feasible [2]. A novel method to find a configuration with multiple heat pumps on an industrial scale has been presented by Padellés et al. [3].

Heat transport for industrial processes is mostly performed by steam. Heat pump technologies able to generate steam are now widely available [4]. This paper discusses integration strategies for high temperature steam generating heat pumps delivering steam at temperatures between 100 and 200 °C and thermal powers from 1 to 20 MW - equivalent to steam flows of approximately 1.5 to 30 ton/hr.

A state-of-the-art industrial process heat delivery system consists of a steam boiler using a fuel to produce steam from boiler feed water. The boiler is further equipped with an economizer and a flue gas condenser. The

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efficiency of such a boiler is largely independent on the pressure at which steam is produced. Therefore it is economical to centralize steam production in a boiler house at a pressure higher than the highest pressure needed by the processes in the factory. Steam is distributed throughout the factory at this high pressure (the high pressure means pipe diameters can be minimized) and is locally reduced in pressure according to the needs of the processes. Condensate resulting from steam delivering its heat to a process is transported back into the boiler house to be reused as boiler feedwater. In Fig. 1 a sketch is shown indicating the configuration described in this paragraph.

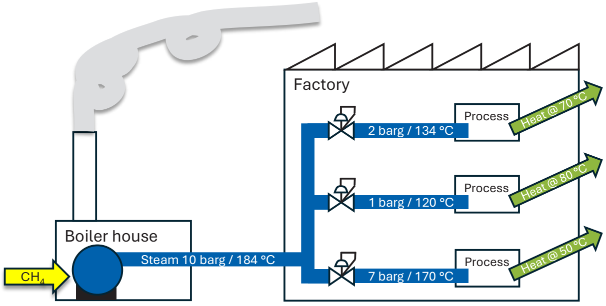

Figure 1. Traditionally, heat is delivered to processes in a factory by steam generated through burning of fossil fuels such as natural gas. Steam is centrally generated at a relatively high pressure in a boiler house. It is then distributed through the factory and reduced locally to the pressure and temperature required by the process. Not drawn is that the condensate that is produced at the processes is fed back to the boiler house to be reused, after deaeration, as boiler feed water.

At first sight, the most logical point to integrate a heat pump is at the location of the boiler house, as depicted on the right in Fig. 2. Benefits are larger and more stable heat demands. In the experience of the authors the steam delivery temperature is 180°C or higher and a typical waste heat temperature is 60°C or lower. Thus this centralized configuration would result in a Coefficient of Performance (COP) of about 1.8, assuming a Carnot efficiency of 50% [5]. For many countries in Europe this COP is lower than price ratio between electricity and gas [6], meaning that such a central heat pump costs money every hour it is used. Clearly, this heat pump will not be sold to customers that want a positive return on investment. We call this barrier the “low-COP-barrier”. In the metaphor of the valley, this is the right wall of the valley, which we explain in more detail below.

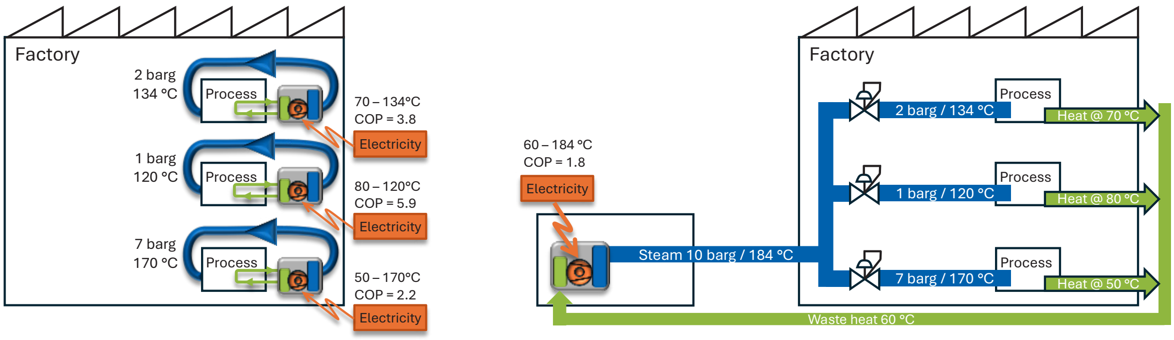

Figure 2. On the left side local integration of the heat pump with the processes is shown. Due to the close proximity to the processes, the waste heat temperature is high. Further, the process heat can be delivered at a lower temperature. These two effects limit the temperature lift and thereby increase COP. On the right side a configuration is shown where the gas fired boiler is replaced by a central heat pump.

To increase COP, a better approach is to integrate a heat pump close to a process. This is shown in Fig. 2 on the left side. Close to the process the waste heat can be captured at a high temperature, for instance by direct heat exchange with the heat pump evaporator. A similar argument holds at the hot side of the heat pump, where we can deliver heat at a temperature very close to the temperature that the process needs. These two factors limit the temperature lift. Since the COP of a heat pump is inversely proportional to the temperature lift, this is a clear benefit. However, there is a flip side which is related to the smaller size of local heat pumps compared to central heat pumps. The smaller heat pump size increases the CAPEX relative to its capacity. Furthermore, the integration factor (i.e. costs including integration relative to the CAPEX for the heat pump itself) is larger for smaller heat pumps. This is because of limitations such as available space and lack of infrastructure, both of which are no issue at the existing boiler house. Finally, a local heat pump will show a smaller utilization.

2. Model

The effects described above have been put together in a simple economical model. This model uses assumptions based on industrial experience in designing and selling industrial heat pumps that produce steam. An industrial site is envisioned with a heat demand of 20 MWth that has many smaller processes on site. This thermal limit is chosen to reflect an industrial site at the lower limit for participation in the Emission Trading System (ETS) of the European Union. The site uses heat from a gas-fired steam boiler operating at 200°C (14.5 barg). The steam temperature is reduced throughout the factory, down to 110°C (0.5 barg) at the smallest processes. The smallest process is modelled as a distillation process such as described in the Open Source Basis of Design of Chivas Brothers [7]. This distillation process needs up to 1 MWth and upgrades heat from about 83 °C to 106 °C. As for the largest process, Standard Fasel has met several cases where waste heat is released from a factory via a central cooling loop to a cooling tower with a flow from the factory at 40 °C and cooled flow to the factory at 30 °C. Using such a cooling loop, the waste heat temperature has reduced that much, that the performance of a central heat pump is very low.

The model has been chosen to be as simple as possible therefore uses only linear relationships. Further, the following assumptions have been used:

- It is possible to integrate heat pumps with thermal outputs, Q, between 1.0 and 20 MWth. The lower value represents heat pumps that are locally integrated, while the heat pump with 20 MWth output is integrated at a central location similar to a gas-fired boiler. For plotting purposes it has been assumed that this range in thermal outputs is continuous.
- The source temperature, T_L, is 80 °C for the smallest thermal output and decreases for larger heat pumps to 30 °C. These values follow from the cases discussed above.
- The delivery temperature, T_H, on the other hand, increases linearly with heat pump size from 110°C for a small, locally integrated heat pump to 200 °C for a large, central heat pump.
- The Carnot efficiency is set at 50%, thus COP = $0.5\, T_H/(T_H - T_L)$. This value is based on a recent overview in an Annex 58 Task Report [5]. The heat pump COP is not strongly dependent on the size of the heat pump and a constant value is therefore justifiable.
- The capital expenditure (CAPEX), C, of the heat pump scales with the electrical power, Q/COP, with 1000 k€/MW, which roughly aligns with the data presented in [5] plus a fixed cost of 0.5 M€. This assumption is very dependent on the technology and not easily backed up by solid references at this point in time.
- The integration factor, I, is 2.0 for a small heat pump and reduces linearly to 1.5 for the largest heat pump.
- Utilization, U, is 8000 hours for the largest heat pump and decreases linearly to 6000 hours for the smallest heat pump.
- The gas price, P_{gas}, including non-recoverable taxes and CO_2 emission costs is taken as 60 €/MWh, based on the higher heating value (HHV) and the electricity price including non-recoverable taxes, P_{el}, as 100 €/MWh, thus the electricity to gas price ratio is 1.67.
- The efficiency of a gas fired boiler, η_{gas} is set at 90% (HHV), irrespective of the thermal power. This value reflects a typical industrial boiler.

The savings in operational expenditure (OPEX) per year, dO, of a heat pump operating on electricity when compared to a gas fired boiler is:

$$dO = Q\,U \frac{P_{gas}}{\eta_{gas}} - Q\,U \frac{P_{el}}{COP\,\eta_{el}}. \tag{1}$$

The OPEX of a heat pump is lower than the OPEX of a gas fired boiler if the electricity to gas price ratio times the ratio of boiler and electric efficiencies is larger than the COP of the heat pump. Since the ratio of boiler to electrical efficiencies is close to 1, a rule-of-thumb that was already used above is that the COP of a heat pump needs to be larger than the electricity to gas price ratio. The linear pay-back time, T_{lin}, is simply given by;

$$T_{lin} = \frac{C\,I}{dO}, \tag{2}$$

In Fig. 3 the linear pay-back time is plotted. Obviously using the assumptions above a somewhat counterintuitive conclusion arises that the pay-back time can actually show a minimum and both very small and very large heat pumps may have unattractive economics.

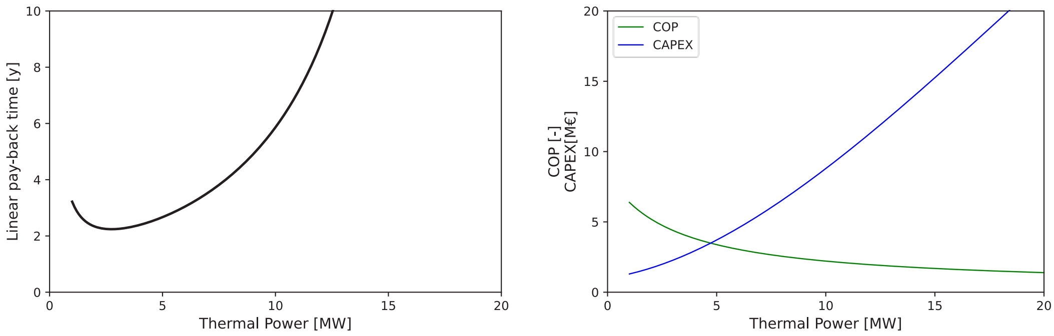

Figure 3. The graph on the left shows the valley of opportunity for industrial heat pumps under the assumptions outlined in the text. The left wall in this curve shows the effect of a high price per MW, whereas the right wall shows the effect of a lower COP when the heat pump is made larger. The lower COP values in the latter case mean a higher electricity demand. The graph on the right shows the most important factors for the valley shape. In blue the CAPEX is shown which has a fixed component, leading to a higher cost per MW for smaller size. In green the COP is plotted that drops with size, due to the high temperature lift needed in case of a drop-in replacement of a fossil-fuel fired boiler by a central heat pump.

3. Options to widen the valley

The left wall of the valley is characterized by many small heat pumps which are capable of very high COPs due to the low heat demand temperature and high waste heat temperatures. However, the costs for these heat pumps including integration are high compared to their thermal output. Over time, standardization and economies of scale will result in lower pay-back times, increasing the potential for adaption in industries. Governmental incentives will accelerate these developments. Integration costs and reluctance to install multiple smaller installations instead of a single larger installation are barriers that are likely harder to overcome.

The other side of the valley is characterized by larger heat pumps which possess better ratios between thermal output and costs. The limiting factor here is the temperature lift, the difference between the heat supply temperature and the waste heat temperature. Investments in the heat supply system in a factory can bring the average supply temperature down. Often, part of the heat demand can be delivered by a hot water circuit instead of a steam system. Furthermore, the pressure and thereby temperature at which steam is delivered can typically be reduced since the steam pressure at the process is low and the pressure is reduced before the process. Obviously this means an investment in the steam distribution network, since the a lower distribution pressure means lower steam densities and therefore requires larger piping diameters. A similar approach can be followed to increase the temperature of the waste heat that is released. It goes without reasoning that reducing temperature differences in a heat exchange process is a good strategy. Optimizations of process equipment can lead to a higher waste heat temperatures. From the perspective of a supplier of industrial heat pumps this means that a much deeper insight in the processes of the client is needed in order to be able to propose the best solution.

A interesting solution is a heat pump that is tailored for the factory. Mixing of waste heat streams, which increases entropy and thus reduces COP of a heat pump can be prevented by heat pumps with multiple waste heat inlets. A similar strategy can be applied to the outlet of a heat pump. Using multiple outlets process heat can be delivered at temperatures close to the required process temperatures. Fig. 4 gives an example of such a highly integrated heat pump. The figure shows how a factory with a cooling system, a distillery process and high temperature heat demand can be electrified by a heat pump that integrates multiple in- and outlets. Such proposals enable high COPs, deliver heat to smaller and larger processes while having an attractive business case for the client.

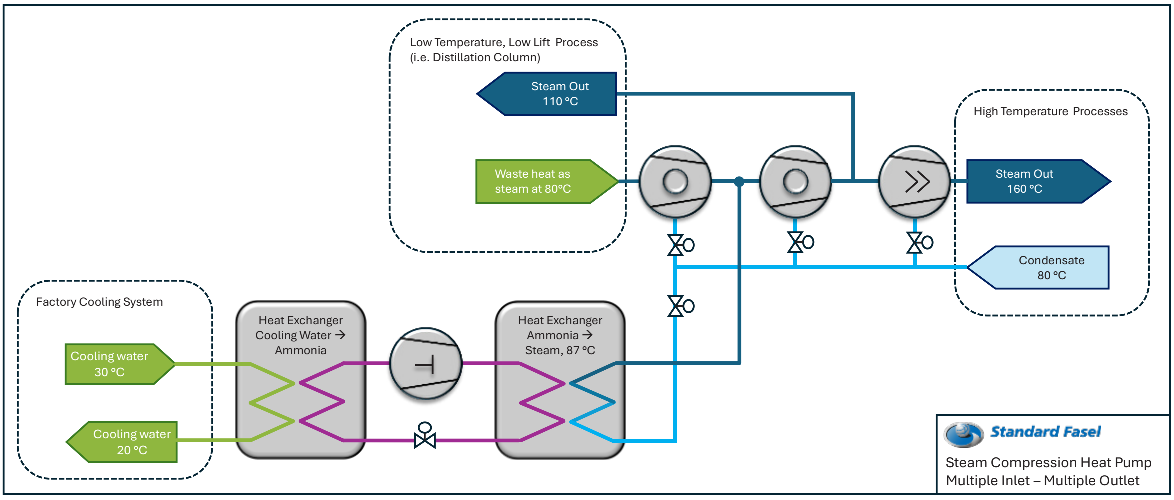

Figure 4. A schematic of a highly integrated heat pump. The heat pump uses waste heat input from a cooling system as well as heat from for instance a distillation process. Heat output in the form of steam is delivered at two temperatures. An outlet delivers low temperature heat to the distillation process. Using an additional steam compressor, a second outlet delivers steam at a higher temperature.

3.1.1. Updated model

The model presented earlier has been updated to reflect the options discussed. Updated assumptions in the model are:

- The temperature at which heat is delivered now scales from 110 °C for a small heat pump to a weighted average of 140 °C for the largest one. This reflects the improvements in the heat distribution network and the use of large heat pumps with multiple outlets.
- The waste heat recovery has been optimized for instance by the use of a heat pump with multiple inlets such that the waste heat for the largest process is now harvested at an weighted average value of 60 °C. Another important factor is the optimization of processes such that waste heat is released at higher temperatures, for instance by increasing the dew point of exhaust air.
- The Carnot efficiency has been improved from 50% to 55% for instance by using steam as the heat pump medium [5], [8].
- The CAPEX of the heat pump has been reduced to 80% of the price used originally. This is one the hardest factors to estimate. It is assumed that a 10% reduction in the total project cost due to a lower risk premium is achievable. Further, another 10% reduction in total project cost is due to higher volumes.

Several other opportunities have not been taken into account such as improving the waste heat temperatures. In Fig. 5 the resulting linear pay-back times are shown. Clearly much better business cases for industrial heat pumps are expected with these improvements taken into account. When full decarbonization is desired, more detailed methods such as described in [3] will likely result in a solution where an e-boiler provides some of the high temperature heat.

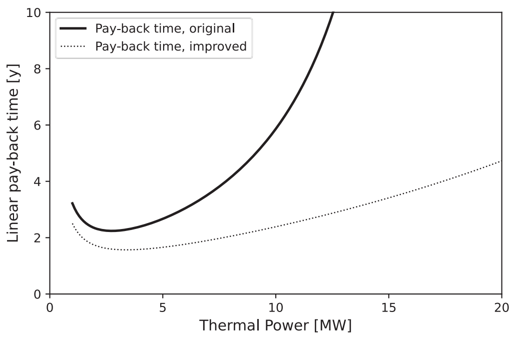

Figure 5. Improved pay-back times plotted as a dotted line. Improvements are detailed in the text and include delivery temperature reductions, efficiency improvements and a CAPEX reduction. The graph replicates the original curve as a solid line.

4. Conclusion

Above, it was shown that it is not economical to replace a fossil fuel fired boiler by a central heat pump. On the other hand, placing a heat pump at every single process in a factory is also not attractive. Through equipment standardization and economies of scale smaller heat pumps will become more attractive with an increasing installed base. The business case of larger installations, which are preferable in terms of costs and maintainability, can be improved by a careful assessment of improvements in the factory heat supply and waste heat removal networks. A heat pump that is able to use heat from multiple sources that delivers heat to multiple outlets can be a game-changer. Heat pump suppliers need to work together with clients to define and design solutions with attractive economical perspectives.

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