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Retrofit of a Galvanisation Plant using Advanced Heat Pump Bridge Analysis

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This paper addresses the need for retrofit approaches that simultaneously improve heat integration through heat exchangers and heat pumps considering process restrictions and an economic analysis framework. For this purpose, the Heat Pump Bridge Analysis method is extended to include the targeting of economic break-even points for heat pumping and the investigation of different modelling levels. For evaluation purposes, the case study of an electroplating process is used where retrofit safety-relevant process restrictions must be considered. The results include two heat recovery systems with one or two heat exchangers according to this grey box approach. The concept with only one heat recovery exchanger fulfils the economic requirements for full supply by heat recovery and heat pumps with an electricity-to-reference price ratio of 1.8 compared to the concept with two heat recovery exchangers or the white box approach, which ignores the process restrictions.

1. Introduction

Increasing and fluctuating energy prices and dependence on fossil energy sources from crisis regions are reasons for companies transforming traditionally fossil steam supply systems towards zero or low carbon ones. For the decarbonization by 2050, as decided by the European Green Deal, a decreasing emission factor of the electricity mix can be assumed. Against this background, electrification by heat pumps is a promising option, as they can upgrade waste or ambient heat. The temperature range up to 250 °C which is achievable for heat pumps accounts for nearly 40 % of total industrial process heat demand and is mostly based on fossil fuels like natural gas. A lack of knowledge about meaningful application potential and integration points, as well as historically grown energy supply systems, hinder more widespread use (Boer et al., 2020).

The established integration principles based on the idealized graphical representation of the Grand Composite Curve (GCC) as method of Pinch Analysis do not always correspond to the practical restrictions of practice such as spatial and temporal distances as well as safety and process-relevant aspects, which leads incorrect targeting of integration points (Townsend and Linnhoff, 1983). Schlosser et al. (2021) introduced the Heat Pump Bridge Analysis (HPBA), which allows the determination of the technical-economic potential of heat pumps considering process and economic restrictions. The method is based on the Modified Energy Transfer Diagram (METD) developed by Walmsley et al. (2017) and elaborated by Lal et al. (2018), which enables the graphical determination of retrofit options and their heat recovery potential. An important advance in this work, compared to the bridge analysis originally introduced by Bonhivers et al. (2014), is the identification and representation of segments with heat surplus or deficit as well as the labelling of the involved process streams in the METD. The method aims at increasing the heat recovery rate and, for the selection and integration of suitable HTHPs, matches the process requirements with the efficiency and application limits of heat pumps of different technological readiness levels.

Electroplating processes are suitable for the implementation of heat recovery and the integration of heat pumps due to the simultaneous occurrence of heat sources and heat sinks at different temperature levels. Existing process conditions in form of steam-based plants and corrosion-resistant equipment hinder the implementation potential of heat recovery and heat pumps. For this reason, an approach is needed to target the technical and

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economic potential for heat recovery and heat pumps with different degrees of freedom. Therefore, this paper aims to extend HPBA by choosing different modelling depths and applies the method to the case study of electroplating.

2. Materials and methods

2.1 Targeting method

The approach for identifying technical and economic potential for the use of heat pumps can be found in detail in the paper of Schlosser et al. (2023). This section presents the targeting method using an illustrative case study from Klemeš et al. (2014). It is a classical four-stream heat exchanger network (HEN), which has been re-scaled to an appropriate temperature level for the application of heat pumps. To represent the existing HEN, so-called Exchanger Grand Composite Curves (EGCC) are constructed for individual heat exchangers from the Shifted Composite Curves (SCC) according to Figure 1a and Figure 1b. The METD is constructed by superimposing the individual curves of each EGCC. The sum of all enthalpy flow values $\dot{H}_{i(j)}$ of the superimposed heat exchangers j within the temperature interval i represents the heat cascade $\dot{H}^*_{i(j)}$.

$$\dot{H}^*_{i(j)} = \dot{H}_{i(j)} + \dot{H}_{i(j-1)} \tag{1}$$

If the enthalpy flows $\dot{H}_{i(j)}$ of each EGCC are plotted on the x-axis as a function of the shifted temperature T_i^* on the y-axis, the outer curve of the METD is obtained (Figure 1c) and mirrors the conventional GCC but shifted to the right by the degree that the HEN does not meet the ideal Pinch targets. The recommended order of the heat cascade $\dot{H}_{i(j)}$ below the Pinch is cold utilities, followed by hot utilities and finally heat recovery exchangers. Above the Pinch, the METD starts with hot utilities, followed by the cold utilities and finally the heat recovery exchangers. Following these two principles is a prerequisite for the representation of the cumulative remaining heating or cooling demand at corresponding temperature level and the correct application of Eq(2) and Eq(3). The colour convention of the line in the METD is, as usual, blue for segments with heat deficit and red for segments with heat surplus.

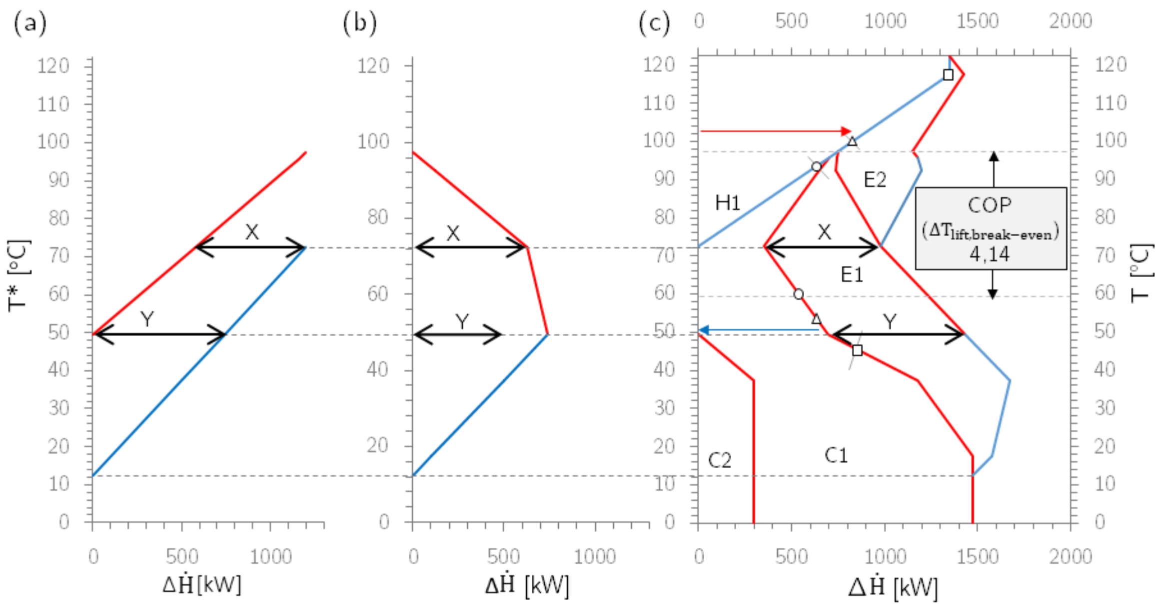

Figure 1: Construction of METD based on Composite Curves (Figure 1a), EGCC of every heat exchanger (Figure 1b) and targeting method based on the METD (Figure 1c) according to Schlosser et al. (2021)

In deviating from the proposed approach of Schlosser et al. (2021), this method investigates different modelling depths of the existing process conditions. According to the white box approach, the existing process conditions are soft (i.e., variable). The greatest optimisation potential exists. According to the grey box approach, existing process conditions are considered unchangeable due to process restrictions. Different retrofit options can be presented, and the heat pump potential can be targeted and analysed. The method presented in (Schlosser et al., 2020) enables the identification of integration points depending on the COP and technical potential of market-available heat pumps. Results are the heating $\dot{Q}_{h,HP}$ and cooling capacity $\dot{Q}_{c,HP}$ and their temperature levels.

$$\dot{Q}_{c,HP} = \dot{Q}_{h,HP} \cdot (1 - 1/COP) \tag{2}$$

$$\dot{Q}_{h,HP}(T^*_{t,Si}) = \dot{Q}_{c,HP}(T^*_{t,So}) \cdot \left(1 - 1/COP(\Delta T_{lift,crit})\right)^{-1} \tag{3}$$

The technical potential in the form of the Heat Pumping Recovery Rate (HPRR) ranges between the process energy demand described by the GCC or METD and the application limits of the heat pump technologies.

$$HPRR = \dot{Q}_{h,HP}/\dot{Q}_{h,tot} \cdot 100 \tag{4}$$

For each integration point, a critical break-even point of the electricity-to-reference price ratio r_p results according Eq(5), for which an investment is just about worthwhile in terms of Levelized Cost of Heating (LCOH). If an integration point is identified for each sink temperature $T^*_{t,Si}$ within the application limits of market-available heat pumps (Schlosser et al., 2020) as a function of Eq(2) and Eq(3), an economically critical temperature lift can be calculated on the basis of Eq.(5) and break-even curves can be derived for the resulting HPRR.

$$r_p = [((a + f_{M,ref}) \cdot c_{I,ref} - (a + f_{M,HP}) \cdot c_{I,HP})/(p_{ref} \cdot t_{FL})) + 1/\eta_{ref}] \cdot COP(\Delta T_{lift}) \tag{5}$$

2.2 Case study: Galvanisation site

Galvanisation processes usually consist of three treatment steps: pre-treatment, characteristic metal deposition and post-treatment. The main process of the anodising process is the anodic oxidation of the metal. As part of the pre-treatment, the workpieces are freed from grease, oil, and other residues of the manufacturing process caustic degreasing baths. The workpiece is subjected to a treatment in a gloss bath, which increases the degree of reflection using strong acids. This process requires the setting of an electric field. The main process consists of oxidation of the aluminium with the aim of strengthening the oxidation layer. The aim of the subsequent condensing process is to prevent the inclusion of corrosion-promoting substances by closing the pores at high temperatures. The illustration shows an excerpt of the process schematic with a typical energy supply system.

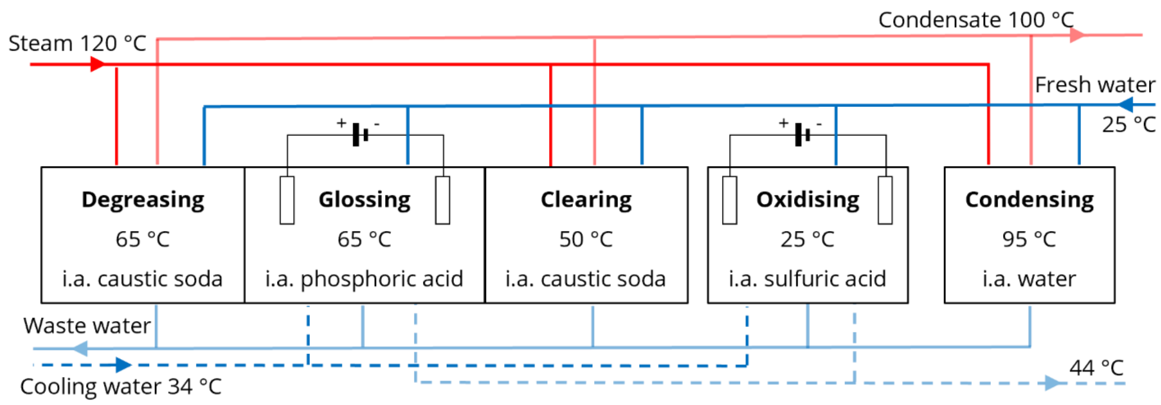

Figure 2: Conventional energy supply of typical anodising process (Schlüter and Bernabé-Moreno, 2022)

3. Results

White and grey box approaches are applied to model energy demand. The grey box approach differs from the white box approach in that the process-related restriction of an acidic process medium is considered by modelling intercooling circuits for process safety. The existing process conditions, which are based on steam among other things, are masked out for the energy demand modelling. In addition, the wastewater and fresh water supply flows are considered as soft data in the energy demand modelling.

The GCC for the white and grey box approaches are presented in Figure 3. In contrast to the grey box approach (Figure 3b), the white box approach (Figure 3a) is based on the original process requirements. Although the white box representation has a higher heat recovery potential and a higher Pinch Temperature, an economic integration of heat pumps for the grey box approach already takes place at a temperature level below 100 °C due to the lower Pinch Temperature and the shape of the GCC.

In terms of the grey box approach, the design of exchangers E1 and E2 is based on the soft streams of wastewater, cooling water and fresh water to avoid interference with the process. The fresh water, F4 and F5, is heated first by the cooling water from the polishing process (F1) and then by the wastewater (F3). The targeted heat recovery potential of 151.5 kW can almost be achieved (8.5 kW left). Since the operation of the heat exchanger E2 requires storage management, it is also conceivable to operate the HEN from Figure 4 without E2, decreasing heat recovery by 75 kW. In the following section, both retrofit options are analysed using the targeting method for their technical and economic potential. The idealised representation in Figure 3a does not consider existing utilities and/or heat exchangers of an existing heat recovery systems unlike Figure 3b.

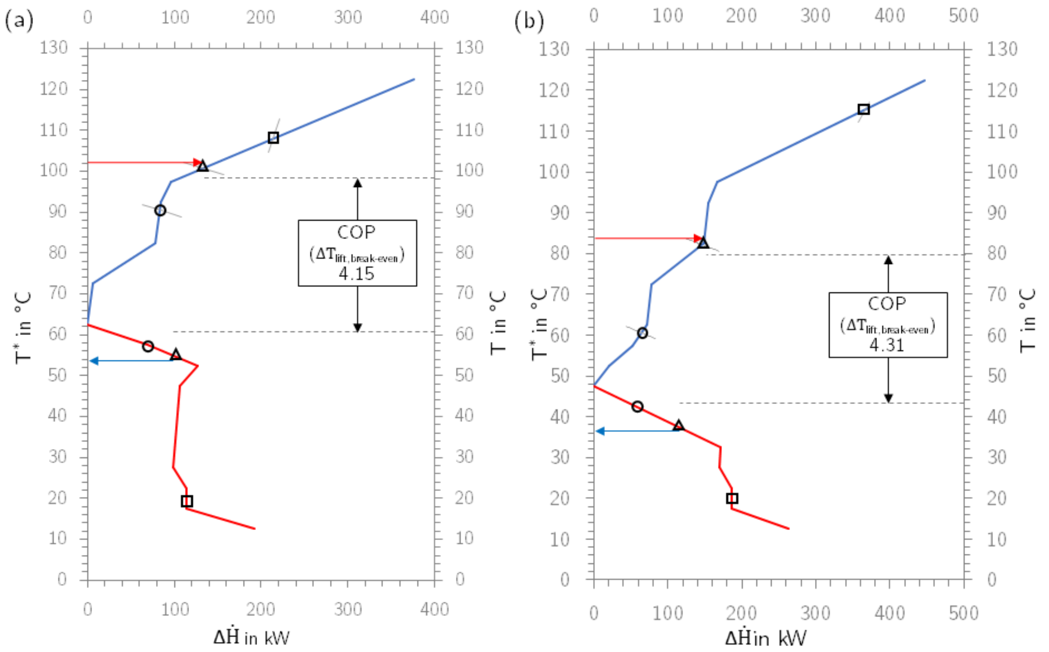

Figure 3: Grand Composite Curves of anodising process modelled by white box approach (Figure 3a) and by grey box approach (Figure 3b) based on Schlosser (2020)

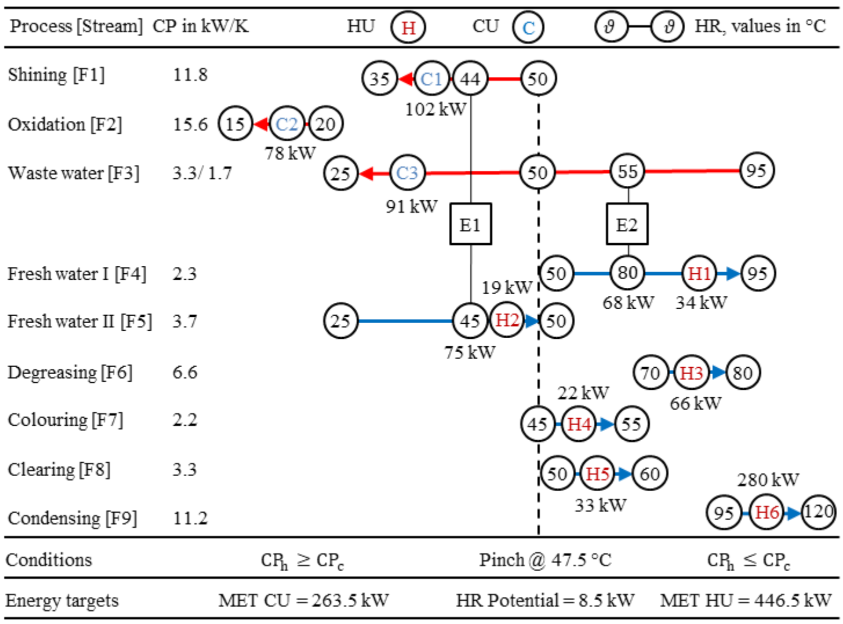

Figure 4: Heat exchanger network containing heat recovery exchanger E1 and E2

The two identified retrofit options with one ('1 HEX') and two ('2 HEX') heat exchangers were transformed into the METD according to the Section 2.1. Figure 5 show the METD, the potential limits and two bridges each for the HEN '2 HEX' (Figure 5a) and the HEN '1 HEX' (Figure 5b). At the Pinch Temperature, the heat recovery potential for the two options can be read by the distance between the outer right METD curve and the y-axis. The reference variable of the heat pump bridge in Figure 5a for full coverage of the heat demands H2, H3, H4 and H5 is the temperature level $T^*_{t,si}$ = 82.5 °C. The corresponding evaporator capacity lie in the intersection of the COP curve with the cooling demands C1 and C3. Apart from the economic variant, it may make sense to accept efficiency losses to fully cover streams and save heat exchangers. In this example, this is achieved for C1 with a COP of 4.12. In Figure 5b, the heat recovery potential increases by the 68 kW of the excluded heat exchanger E2. The accurate mapping of the net heating demand above and the net cooling demand below the Pinch by the METD enables the targeting of cascaded heat pumps. The targeting aims to cover the cooling demand of $\dot{Q}_c$ = 228 kW at the temperature level of $T^*_{t,so}$ = 32.5 °C. The bottom cycle heat pump uses this heat source to cover the heat deficit of H2, H4, H5 and partially H1 at a usable average temperature level of $T^*_{t,si,1}$ = 72.5 °C. This results in a COP of the first stage of 4.8 for a temperature lift of ΔT_{lift} = 32 K. The excess condensing capacity of 168 kW supplies the evaporator of the second heat pump stage in parallel. The top cycle heat pump now reaches a temperature of $T^*_{t,si,2}$ = 106 °C and a condenser capacity of $\dot{Q}_{h,HP}$ = 214 kW with a COP (ΔT_{lift} = 33.5 K) of 4.7. For the overall system of the cascaded heat pump, a COP of 3.15 results.

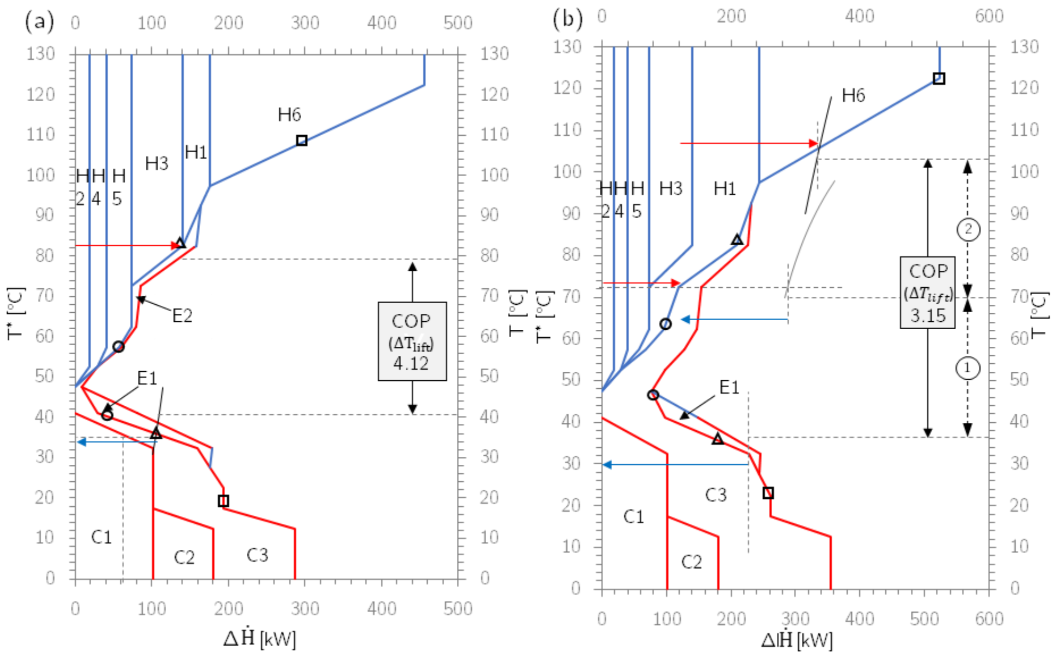

Figure 5: Heat pump bridge for full supply of H2 to H5 for HEN with E1 and E2 (Figure 5a) and Heat pump bridge using two-staged heat pump for HEN with E1 (Figure 5b)

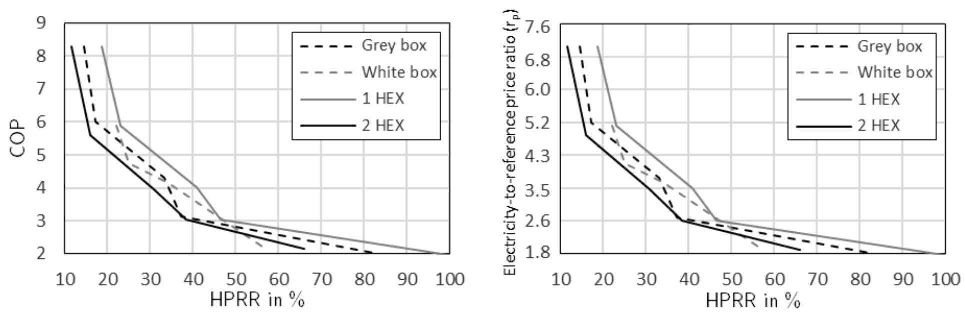

Figure 6: Technical potential (Figure 6a) and economical potential (Figure 6b) regarding economically critical electricity-to-reference price ratios of heat pump bridges for different HPRR

Figure 6 presents the technical (Figure 6a) and economic (Figure 6b) potential in terms of the necessary price ratio ensuring economic feasibility. The grey box and the retrofit option '1 HEX' show higher technical and economic potential than the one resulting from the white box approach. This also confirms the relevance of choosing a correct depth of analysis and a design based on the METD, as otherwise potentials will be incorrect or disregarded. It is evident that for price ratios of r_p = 2.6, heat pump concepts already achieve 40 to 50 % HPRR. The best option '1 HEX' reaches 100 % HPRR for price ratios of r_p = 1.8. Electricity-to-gas price ratios like this are already achieved in Scandinavian countries. In Germany and Europe, these were around 4 in 2021. Further alignment of the prices is expected to achieve the climate protection goals.

4. Conclusions

This paper presented a method for increasing heat recovery and targeting economic break-even conditions within the technical potential of market-available heat pumps during process retrofit and electrification. For an electroplating case study, the heat recovery potential could be almost completely achieved by adding two heat exchangers based on the grey box approach. On the other hand, there is the consideration of using only one heat exchanger and then economically covering the remaining heating demand completely for electricity-to-reference price ratios lower than 1.8 and with better absolute economic efficiency than the white box approach.

Nomenclature

C – Cold utility	HEX – Heat recovery Exchanger	f – maintenance factor
COP – Coefficient of Performance	HPBA – Heat Pump Bridge Analysis	p – energy price, €/kWh
E – Exchanger	HPRR – Heat Pump Recovery Rate	t – time, h
GCC – Grand Composite Curve	a – annuity factor	T – temperature, °C
H – Hot utility	CH – heat capacity flow rate, kW/K	η – efficiency ratio
HEN – Heat Exchanger Network	c – specific cost, €/kW_{th}	f – maintenance factor

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