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Research paper

# An analytical solution to optimal heat pump integration

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ABSTRACT

Heat pump integration has a large potential for reducing carbon emissions and operating costs of industrial processes. The Break-even COP method determines the maximum economically- or environmentally feasible heat pump temperature and the level of process heat electrification under specified economic conditions. However, this method fails to capture the optimal heat pump temperature and the possible emissions- and costs reduction in sensible heat processes. The present work introduces an analytical equation based on the Lorenz efficiency approach to determine the optimal heat pump sink temperature, maximizing the operating costs savings or the emission savings. Furthermore, it advances the break-even method to account for heat pumps with a temperature glide by applying a Lorenz efficiency approach. The method is applied to a spray-drier case study, showing a reduction on operation costs of 7.8 % and emissions by 11.9 % by a partial process electrification of 32 %. A parameter study is conducted, underscoring the importance of accurate predictions of the Lorenz efficiency factor and the electricity-to-fuel price and emissions ratios in heat pump integration studies.

## 1. Introduction

Addressing climate change urgently requires decarbonizing the industrial sector. The electrification of the supply of process heat is considered as a major pathway towards achieving this goal [1]. Industrial heat pumps offer a highly efficient technology for electrification by upgrading waste heat to usable process heat. Many studies regarding industrial heat pumps deal with identifying the optimal integration point [2–5]. This is a crucial step, as the heat pumps coefficient of performance (COP) depends strongly on the temperature lift between heat source and heat sink and thus, on its integration point. Overall, the optimum of heat pump integration is defined by the trade-off between a decrease in heat pump COP when increasing the temperature lift and an increase in heat that is supplied by the heat pump. This trade-off then drives the economics behind the heat pump integration.

### 1.1. State of the art

In the current literature, the optimum heat pump integration has commonly been determined by a combination of mathematical optimization and Process Integration methods [6]. Schlosser et al. [7] introduced the break-even targeting, in which the minimum required heat pump COP is determined to provide an estimation on which COPs are viable without additional operating expenses (OPEX). This concept has been expanded to determine the economically or environmentally feasible temperatures achievable with industrial heat pumps. This included a review on existing heat pump integration case studies and heat pump concepts [8]. The break-even concept has since then been utilized to find effective placements of heat pumps into existing heat recovery networks [9] and investigate the viability of heat pump technologies with different price ratios of electricity and gas in the design of a milk spray dryer [10].

To calculate the break-even heat pump heat sink temperature, it is important to define the relation between the expected efficiency of the heat pump and the temperatures involved in the process. The expected COP of a heat pump can be estimated by introducing a Lorenz [11] or Carnot efficiency [12] based on the theoretical maximum COP (Carnot or Lorenz processes). The problems arising by the use of such efficiencies based on a Second Law analysis have been studied by Lior and Zhang [13]. In the context of industrial heat pumps, especially in the case of sensible heat processes, the Lorenz efficiency becomes the preferred option over the Carnot efficiency to estimate the COP [14], as it does take into consideration the temperatures glides on the sink and the source and thus provides the correct reference process.

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**Nomenclature**

**Acronyms**

| | |
|---|---|
| BE | Break-Even |
| CAPEX | Capital expenditure (€) |
| COP | Coefficient of performance (–) |
| DLR | German Aerospace Center |
| GCC | Grand Composite Curve |
| HP | Heat pump |
| HTHP | High Temperature Heat pump |
| HU | Hot utility (kW) |
| NPV | Net present value (€) |
| OPEX | Operational expenditure (€) |

**Latin symbols**

| | |
|---|---|
| $\dot{Q}$ | Heat flow rate (kW) |
| i | Discount rate (%) |
| n | Investment lifetime (y) |
| P | Power (kW) |
| R | Cash flow (€) |
| r | Ratio (–) |
| s | Operational cost savings (%) |
| T | Temperature (°C) |

**Greek symbols**

| | |
|---|---|
| $\eta$ | Efficiency (–) |

**Subscripts**

| | |
|---|---|
| E | Electrified |
| elec | Electricity |
| em | Emissions |
| in | Inlet |
| invest | Investment |
| opt | Optimum |
| out | Outlet |
| p | Price |
| p,f | Process final |
| p,i | Process inlet |
| sink | Heat sink side of the heat pump |
| source | Heat source side of the heat pump |
| tot | Total |

### 1.2. Contribution and research question

The break-even concept serves as a upper limit to the heat pump heat sink temperature that can be economically reached, but it does not determine the actual optimum sink integration temperature, which is a trade-off between the heat coverage and COP of the heat pump. Furthermore, the break-even temperature is based on a Carnot efficiency heat pump, which is inaccurate for process heat requirements with a temperature glide.

Thus, this study introduces an analytical equation to determine the economically or environmentally optimal heat pump heat sink temperature, the relative amount of process heat electrification by a heat pump and the associated cost- or emission savings.

The research addresses the following research questions:

- Is there an optimal heat sink temperature and heat load for heat pumps in sensible heat processes?
- If so, can this optimum be determined analytically?

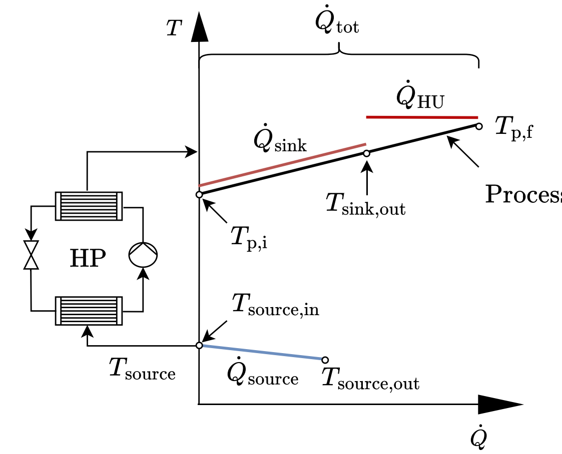


**Fig. 1.** Overview over the used terms and values for heat pump integration. Furthermore, a partial electrification of the process heat demand by a heat pump is visualized.

- How does the degree of process heat electrification depend on the process temperature requirements and the economic conditions?
- What are the greatest levers driving the electrification of process heat by industrial heat pumps?

## 2. Method

This chapter describes the basics of heat pump integration, heat pump modeling and heat pump efficiency estimation approaches. Consequently, the break-even method is explained. The chapter concludes by introducing the equations to determine the optimal heat pump integration.

### 2.1. Heat pump integration

In general, heat pump integration relies strongly on the temperatures at which the heat pump is integrated and thus, the associated process streams. The temperature difference between the source heat stream and sink heat stream is considered as temperature lift of the heat pump. This temperature difference drives the COP (Eq. (2)). Consequently, the choice of the integration temperatures and heat flow rates strongly influences the energetic and economic performance of the heat pump. For latent fluid streams, that barely change their temperature during heat addition or heat rejection, the choice of heat pump heat sink temperature $T_{\mathrm{sink}}$, heat sink heating capacity $\dot{Q}_{\mathrm{sink}}$ and heat source temperature $T_{\mathrm{source}}$ is trivial. The lowest possible temperature lift is chosen and the heat pump's heating capacity is maximized.

However, if the process stream which requires heat – generally referred to as cold stream – has a temperature glide, a trade-off exists. If the delivered heat load by the heat pump is increased, the heat pump's heat sink temperature has to be increased and thus the COP of the heat pump decreases. Thus, more of the process heat requirement is supplied by the heat pump, however, less efficiently. Fig. 1 shows heat pump integration in a T-Q diagram. The black line indicates the temperature glide of the process stream. The process heating requirement starts at temperature $T_{\mathrm{p,i}}$ and requires heating until the process final temperature $T_{\mathrm{p,f}}$. Furthermore, the heat pumps heat source heat load is indicated by $\dot{Q}_{\mathrm{source}}$.

In Fig. 1, process heating is conducted partly by a heat pump and the residual heat required to reach the process final temperature is supplied by hot utility (HU). The process total required heat rate is indicated by $\dot{Q}_{\mathrm{tot}}$. The degree of electrification ($r_{\mathrm{E}}$) by the heat pump, also referred to as heat coverage, is defined as the share of the total process heat demand that is covered by the heat pump, as illustrated in (Eq. (1)).

$$r_{\mathrm{E}} = \frac{\dot{Q}_{\mathrm{sink}}}{\dot{Q}_{\mathrm{tot}}} = \frac{T_{\mathrm{sink,out}} - T_{\mathrm{p,i}}}{T_{\mathrm{p,f}} - T_{\mathrm{p,i}}} \tag{1}$$

### 2.2. Heat pump modeling

The COP is defined as the ratio of supplied heat and heat pump work (Eq. (2)). The Carnot reference process provides an idealized COP, which can be determined using Eq. (3). By putting the real COP and the idealized COP into reference, a Carnot efficiency is determined (Eq. (4)). This efficiency is commonly used to model or characterize heat pumps.

$$\mathrm{COP} = \frac{\dot{Q}_{\mathrm{sink}}}{P_{\mathrm{hp}}} \tag{2}$$

$$\mathrm{COP}_{\mathrm{Carnot,ideal}} = \frac{T_{\mathrm{sink,out}}}{T_{\mathrm{sink,out}} - T_{\mathrm{source,in}}} \tag{3}$$

$$\eta_{\mathrm{Carnot}} = \frac{\mathrm{COP}}{\mathrm{COP}_{\mathrm{Carnot,ideal}}} \tag{4}$$

However, the Lorenz reference process presents the theoretical maximum COP achievable. This is specifically important in sensible heat processes. The idealized Lorenz COP is defined by Eq. (5) as the ratio of logarithmic mean temperature (Eq. (7)) of the heat sink and the difference between the log mean temperatures of the heat sink and heat source.

$$\mathrm{COP}_{\mathrm{Lorenz,ideal}} = \frac{\overline{T}_{\mathrm{sink}}}{\overline{T}_{\mathrm{sink}} - \overline{T}_{\mathrm{source}}} \tag{5}$$

With the logarithmic mean temperature of the source as:

$$\overline{T}_{\mathrm{source}} = \frac{T_{\mathrm{source,in}} - T_{\mathrm{source,out}}}{\ln\left(\frac{T_{\mathrm{source,in}}}{T_{\mathrm{source,out}}}\right)} \tag{6}$$

Analogously, the log mean temperature of the heat sink:

$$\overline{T}_{\mathrm{sink}} = \frac{T_{\mathrm{sink,out}} - T_{\mathrm{p,i}}}{\ln\left(\frac{T_{\mathrm{sink,out}}}{T_{\mathrm{p,i}}}\right)} \tag{7}$$

Consequently, the efficiency relative to the Lorenz cycle is:

$$\eta_{\mathrm{Lorenz}} = \frac{\mathrm{COP}}{\mathrm{COP}_{\mathrm{Lorenz,ideal}}} \tag{8}$$

The Lorenz cycle represents the true thermodynamic limit for sensible heat processes, whereas the Carnot cycle is a simplified subset of the more comprehensive Lorenz cycle [11]. By including more information such as the inlet temperatures of the sink and source of the heat pumps, the Lorenz efficiency can be used to more accurately estimate the performance of the heat pump [12]. COP estimation methods vary in complexity and accuracy [14], including regression-based methods such as the methods proposed by Jesper et al. [15] or thermodynamic-based methods as the method proposed by Jensen et al. [16]. However, most methods rely on the Lorenz efficiency as a benchmark for acceptable accuracy, as the temperature glide of the sink and source significantly impacts the heat pump performance. A factor not accounted for when using the Carnot efficiency to estimate the COP [17].

### 2.3. Break-even of heat pump integration

The break-even point for heat pump integration defines the minimum efficiency required for a heat pump to avoid incurring additional costs during the electrification of process heat. Consequently, any COP larger than the break-even will achieve savings. The break-even can be defined both for cost or emission break-even. This section will describe the state-of-the-art break-even and introduce the Lorenz break-even for sensible processes.

#### 2.3.1. Break-even COP

The economic feasibility of any heat pump integration is dependent on the savings in operational expenditures (OPEX) in comparison to the current business case. This needs to account for the added cost of the electricity consumed to run the heat pump. The operating costs without a heat pump integration are:

$$\mathrm{OPEX} = p_{\mathrm{fuel}} \cdot \dot{Q}_{\mathrm{tot}} \tag{9}$$

For a heat pump partially covering a given amount of the heat requirement ($\dot{Q}_{\mathrm{sink}}$) with a given efficiency (COP), the operating costs after heat pump integration are:

$$\mathrm{OPEX}_{\mathrm{elec}} = p_{\mathrm{fuel}} \cdot (\dot{Q}_{\mathrm{tot}} - \dot{Q}_{\mathrm{sink}}) + \frac{p_{\mathrm{elec}}}{\mathrm{COP}} \cdot \dot{Q}_{\mathrm{sink}} \tag{10}$$

which can be written as:

$$\mathrm{OPEX}_{\mathrm{elec}} = \frac{\dot{Q}_{\mathrm{sink}}}{\dot{Q}_{\mathrm{tot}}} \cdot \frac{p_{\mathrm{elec}}}{\mathrm{COP}} - \left(1 - \frac{\dot{Q}_{\mathrm{sink}}}{\dot{Q}_{\mathrm{tot}}}\right) \cdot p_{\mathrm{fuel}} \tag{11}$$

The break-even COP is defined as the point where electrification incurs no additional operating cost, meaning that Eqs. (9) and (10) are equal. Setting these equations equal gives:

$$\mathrm{COP}_{\mathrm{break\text{-}even}} = \frac{p_{\mathrm{elec}}}{p_{\mathrm{fuel}}} \tag{12}$$

Thus, the break-even happens when the COP equals the ratio of the specific cost of electricity over the specific cost of a reference fuel, which is defined as the price ratio ($r_{\mathrm{p}}$). A COP that is greater than the break-even COP will achieve savings. The concept of the break-even COP was first introduced by Schlosser et al. [7]. However, Eder et al. [18] was amongst the first to mention the importance of the price ratio.

$$r_{\mathrm{p}} = \frac{p_{\mathrm{elec}}}{p_{\mathrm{fuel}}} \tag{13}$$

Analogous, the price ratio can be replaced by the ratio of specific emissions ($r_{\mathrm{em}}$), which is the ratio of the carbon intensity of the electricity grid ($\mathrm{CI}_{\mathrm{elec}}$) and carbon intensity of the reference fuel ($\mathrm{CI}_{\mathrm{fuel}}$). In the following equations the price ratio ($r_{\mathrm{p}}$) and the emission ratio ($r_{\mathrm{em}}$) are interchangeable.

$$r_{\mathrm{em}} = \frac{\mathrm{CI}_{\mathrm{elec}}}{\mathrm{CI}_{\mathrm{fuel}}} \tag{14}$$

#### 2.3.2. Break-even temperature using a Lorenz efficiency approach

As the break-even COP indicates the minimum efficiency of the heat pump in order to be economically and environmentally viable, the maximum sink temperature can be found based on the available source temperature, the break-even COP and the expected thermodynamic efficiency. In previous works, the Carnot efficiency (see Eq. (2)) is utilized to model the heat pump in relation to the temperatures of the sink and the source. In this paper, a Lorenz approach is proposed to estimate the COP, adopting Eq. (4) to consider the true thermodynamic limit and consider the temperature glides of the sink and the source of the heat pump. Therefore, by combining the definition of Break-even COP from Eq. (12) with Eqs. (5) and (8), the break-even logarithmic mean temperature of the sink can be found as:

$$\overline{T}_{\mathrm{sink,BE,Lorenz}} = \frac{\overline{T}_{\mathrm{source}} \cdot r_p}{r_p - \eta_{\mathrm{Lorenz}}} \tag{15}$$

Unlike the original definition utilizing a Carnot cycle approach, the approach adopting the Lorenz efficiency requires numerically solving for the outlet sink temperature from the logarithmic mean temperature of the sink with Eq. (7). The outlet sink temperature can then be used to obtain the degree of electrification with Eq. (1).

### 2.4. Optimal heat pump heat sink temperature for partial electrification of sensible heat processes

In deriving the optimal sink temperature, the following assumptions and considerations are made:

- The entirety of the heat demand consists of a sensible heat requirement with a constant heat capacity.

- The Lorenz efficiency ($\eta_{\text{Lorenz}}$) of the heat pump process is constant and independent of the temperatures. However, the Discussion (Section 5) provides an analysis of this dependency and its impact.
- The method optimizes the savings in operational costs, and neglects the effect that the capital costs can have on the optimal heat pump size.

The break-even temperature represents an upper bound in economically-viable electrification and heat pump heat sink temperature. However, by definition, heat pump integration at this temperature would not introduce savings compared to the existent system. This section describes the method to calculate the sink temperature that maximizes savings in emissions or operating cost. The relative savings $s$ in OPEX are defined as:

$$s = \frac{\text{OPEX} - \text{OPEX}_{\text{elec}}}{\text{OPEX}} \tag{16}$$

By combining the definition for ratio of electrification (Eq. (1)) and the previous Eqs. (9)–(16) the relative OPEX savings are:

$$s = \frac{p_{\text{fuel}} - r_{\text{E}} \cdot \frac{p_{\text{elec}}}{\text{COP}} - (1 - r_{\text{E}}) \cdot p_{\text{fuel}}}{p_{\text{fuel}}} \tag{17}$$

The price ratio ($r_p$) defined previously (Eq. (13)) can be introduced to define the relative savings as:

$$s = r_{\text{E}} \cdot (1 - \frac{r_{\text{p}}}{\text{COP}}) \tag{18}$$

By inserting Eq. (1) and the definition of the Lorenz COP (Eqs. (5) & (8)), the Equation can be rewritten to:

$$s = \frac{T_{\text{sink,out}} - T_{\text{p,i}}}{T_{\text{p.f}} - T_{\text{p,i}}} \cdot (1 - \frac{r_{\text{p}}}{\eta_{\text{Lorenz}}} \frac{\overline{T}_{\text{sink}} - \overline{T}_{\text{source}}}{\overline{T}_{\text{sink}}}) \tag{19}$$

In order to determine the temperature that results in the maximum savings in operating costs, Eq. (19) is derived over $T_{\text{sink}}$. By setting the derivative to zero and rearranging the equation for $T_{\text{sink}}$, the optimal sink temperature of the heat pump for sensible heat processes is determined as:

$$T_{\text{sink,out,opt}} = \frac{\overline{T}_{\text{source}} \cdot r_{\text{p}}}{r_{\text{p}} - \eta_{\text{Lorenz}}} \tag{20}$$

The carbon emissions of heat pumps are related to the electricity consumption of the heat pump, and the emissions linked to heat pump and refrigerant production and refrigerant leakage are negligible when natural refrigerants are considered [19]. Therefore, the proposed Equation can be derived targeting the optimal reduction of $CO_2$ emissions by use of the ratio of specific carbon intensity ($r_{\text{em}}$) instead of the price ratio ($r_{\text{p}}$).

Eq. (20) shows that:

- The optimal sink temperature of the heat pump does not depend on the process target temperature or the amount of heat required.
- The optimum is solely dependent on the log mean heat source temperature ($\overline{T}_{\text{source}}$), the price ratio ($r_{\text{p}}$) and the Lorenz efficiency ($\eta_{\text{Lorenz}}$).
- The sink temperature is directly connected with the degree of electrification, due to the linear temperature profile (Eq. (1))

Note that, for cases where the determined sink outlet temperature ($T_{\text{sink,out,opt}}$) is lower than the process inlet temperature ($T_{\text{p,i}}$), heat pump integration is not economically beneficial and savings are not possible.

On the other hand, if the sink outlet temperature found by Eq. (20) is higher than the final process temperature ($T_{\text{p,f}}$), the maximum savings are achieved by fully electrifying the process; and the outlet sink temperature corresponds to the final process temperature.

**Table 1**
Summary of the parameters used in the case study.

| Parameter | Value |
|---|---|
| $T_{\text{p,i}}$ (°C) | 55 |
| $T_{\text{p,f}}$ (°C) | 230 |
| $T_{\text{source,in}}$ (°C) | 20 |
| $T_{\text{source,out}}$ (°C) | 10 |
| $\eta_{\text{Lorenz}}$ (–) | 0.55 |
| $r_p$ (–) | 2.2 |
| $r_{em}$ (–) | 1.9 |

### 2.4.1. Optimal degree of electrification

The optimal degree of electrification can then be determined by inserting the optimal heat sink outlet temperature into Eq. (1)

$$r_{\text{E,opt}} = \frac{T_{\text{sink,out,opt}} - T_{\text{p,i}}}{T_{\text{p.f}} - T_{\text{p,i}}} \tag{21}$$

Consequently, the expected, maximum savings can be determined with:

$$s = r_{\text{E,opt}} \cdot (1 - \frac{r_{\text{p}}}{\eta_{\text{Lorenz}}} \frac{\overline{T}_{\text{sink,opt}} - \overline{T}_{\text{source}}}{\overline{T}_{\text{sink,opt}}}) \tag{22}$$

## 3. Description of the case study

To demonstrate the usage and benefit of the presented method, a case study is conducted. The case study is closely aligned with the process heat demand of a spray dryer, taken from the work of Liang et al. [20]. After heat recovery, the spray dryers supply air stream has a heating requirement from 50 °C to 230 °C of 4800 kW. The heat source of the heat pump is considered to be ambient air at 15 °C. The heating demand of 4800 kW at 6000 operating hours annually equates to an energy demand of roughly 28,800 MWh or 103,680 GJ. The Eurostat gas and electricity price data [21,22] for large consumers in the consumption range show that most countries have a price ratio above 1.5 with the exception of Sweden and Finland. Including the European Union Emissions Trading System (EU-ETS) cost, a ratio of 2.2 is assumed in order to provide realistic values within the case study. This value aligns with the observed mean price ratios between 2021 and the end of 2023 of Germany, taken as reference. But other ratios in Europe are be similar, such as Denmark (1.6), Bulgaria (2.4), Greece (2.6), France (1.9) and Latvia (1.9). The full dataset is visualized in the Appendix A.1.

Additionally, the reduction of carbon emissions after heat pump integration is calculated from the estimated carbon intensity from ElectrictyMaps [23]. Assuming an emission for natural gas of 208 kg $CO_2$eq./MWh [24] and a boiler efficiency of 95%, the emissions ratio was 1.9 in the case of Germany during the same period between 2021 and the end of 2023. The plant is assumed to be in Germany. Thus, a electricity price of 132 (€/MWh) and a gas price of 60 (€/MWh) is applied, based on the Eurostat data [21,22]. Within the case study, a brief techno-economic evaluation is conducted after determining the optimal heat pump integration. The net present value is determined according to Eq. (23). Wherein $R_x$ are the cash flows in year x. $n_{\text{invest}}$ is the investments lifetime and i is the discount rate. The initial, negative cash flow is the capital expense by integrating a heat pump. A specific investment cost $p_{\text{HP,spec}}$ is applied. Walden et al. [25] compared a variety of heat pump cost functions, with most functions converging to below 500 €/kW$_{\text{th}}$ at heat pump capacities of 1 MW$_{\text{th}}$ or larger.

$$\text{NPV} = \sum_{x=0}^{n_{\text{invest}}} \frac{R_x}{(1+i)^x} \tag{23}$$

Regarding the assumed heat pump efficiencies: Lorenz efficiencies (Eq. (8)) of existing industrial heat pumps vary between 0.4 and 0.6 [26]. A recent study from Andersen et al. [27] simulated 1056 heat

**Table 2**
Economic and emission parameters for the techno-economic evaluation of the heat pump integration in the case study.

| Parameter | Value |
|---|---|
| $p_{elec}$ (€/MWh) | 132 |
| $p_{gas}$ (€/MWh) | 60 |
| $CI_{elec}$ (kg $CO_2$eq./MWh) | 425 |
| $CI_{gas}$ (kg $CO_2$eq./MWh) | 219 |
| $p_{HP,spec}$ (€/kW$_{th}$) | 500 |
| $n_{invest}$ (y) | 10 |
| Operating hours (h) | 6000 |
| Discount rate (%) | 7 |

pump models under 1124 different temperature conditions with a temperature lift up to 150 K. The Lorenz efficiency of the best-performing heat pumps varied from 0.39 to 0.69 in the studied temperature range, with a mean value of 0.55. In the case study, a constant Lorenz efficiency of 0.55 will be applied, which fits to the results of the COP from Andersen et al. with an $R^2$ of 0.87 according to Jensen et al. [14].

All parameters used for the heat pump integration of the case study are summarized in Table 1 with the economic parameters and absolute values in Table 2.

Additional investigations on these parameters are included in this work to illustrate the application of the method and impact of different assumptions.

## 4. Results

This section examines the spray dryer case and illustrates the existence of the optimal heat pump heat sink temperature. Consequently, the impact of the key parameters and their sensitivities of the analytical equation for optimal heat pump integration (Eq. (20)) is explored.

### 4.1. Spray-dryer case study

Fig. 2 illustrates the OPEX savings generated by the integration of a heat pump for different sink temperatures. The black line represents the aggregate cost for each sink temperature, with the underlying cost structure visualized below it. As the heat pump sink temperature increases, the COP of the heat pump decreases, while the heating capacity increases. Consequently, the electricity costs rise, and the reference fuel costs decline. This shift occurs because, to meet the same process heat

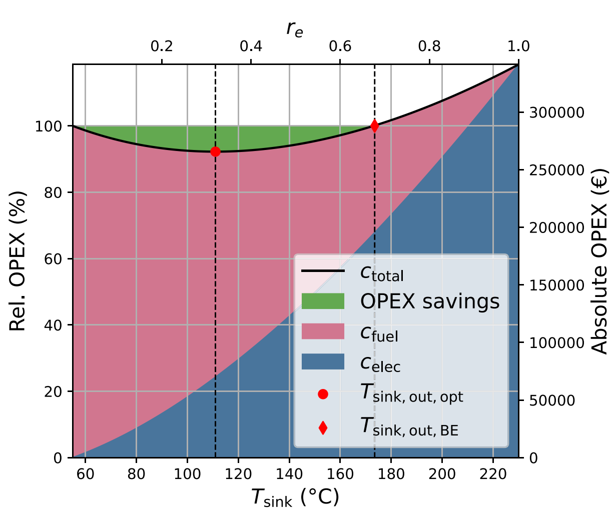


**Fig. 2.** The existence of an optimal sink temperature ($T_{sink,out,opt}$) and its associated operating cost savings. A breakdown of the cost for different sink temperatures is given. The Figure uses the values depicted in Table 1.

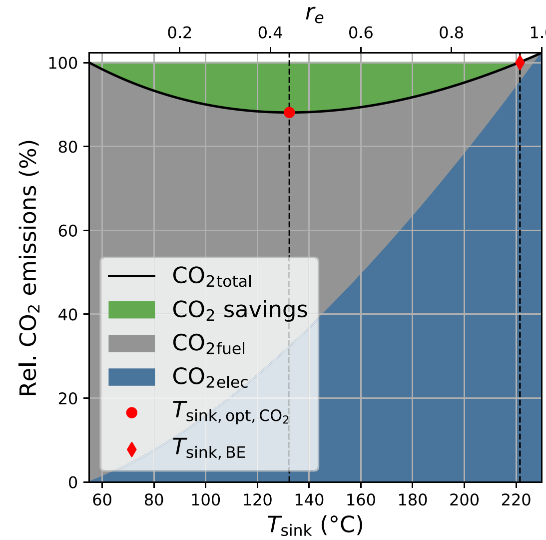


**Fig. 3.** Breakdown of the $CO_2$ emissions and savings by energy source and heat pump sink temperature.

demand, more electricity is utilized and less reference fuel is consumed. The integration of a heat pump results in enhanced energy efficiency, thereby yielding OPEX savings, as indicated by the green area. The Figure shows that any heat pump integration with sink temperatures ranging from 55 °C to 173 °C is economically beneficial. Additionally, the upper axis depicts the associated degree of electrification achieved by the heat pump.

The maximum electrification or maximum sink temperature that can be achieved while creating no additional operating cost is represented by the break-even temperature at 173 °C (Eq. (15)). While this temperature represents the maximum level of electrification that can be economically beneficial, the maximum savings that can be achieved are found when the heat pump is integrated at lower sink temperatures; in this case, 111 °C. An integration of a heat pump at this temperature saves 7.8%/year of the original operating cost accounting to 134,172 €/year.

The heating capacity of the heat pump can be derived using Eq. (1). In the case of the break-even temperature the heat pump would cover 67.3% of the process heat demand requiring a heating capacity of 3230 kW. However, in the economically optimal case the heat pump would cover 32.0% of the heat demand with a heating capacity of 1536 kW. Consequently, the capital expenses (CAPEX) of the heat pump equal 768.2 k€ at a specific investment cost of 500 €/kW. The simple payback period is calculated to be 5.7 years. Furthermore, the net present value (NPV) over an investment period of 20 years is projected to be 174 k€, indicating a highly favorable business case (Table 3).

Analogous to Figs. 2, 3 breaks down the relative $CO_2$ emissions. Any heat pump heat sink temperature between 55 °C and 221 °C will create $CO_2$ emission savings. In comparison to the OPEX optimal heat pump integration, a different sink temperature is optimal when maximizing the $CO_2$ emission savings. In the analyzed case, the emission optimal heat pump sink temperature at 132 °C. An optimal heat pump integration would result in a reduction of emissions of 733 tons of $CO_2$ per year (11.9%/year reduction). Table 3 shows the results of the techno-economic evaluation of the case study for different sink temperatures: economically optimal temperature ($OPEX_{opt}$), economical break-even temperature ($OPEX_{BE}$), emissions-optimal temperature ($CO_{2,opt}$) and emissions break-even temperature ($CO_{2,BE}$).

Table 3 illustrates that, for the case study, the economically optimal heat pump placement calculated with Eq. (20) is not only able to reduce the annual operation costs by 7.8%, but is also reducing $CO_2$ emissions by 11.1%. Likewise, the $CO_2$-optimal configuration is also

**Table 3**
Results of the case study.

| Parameter<br>Unit | $T_{sink,out}$<br>(°C) | $r_e$<br>(%) | COP<br>(–) | OPEX savings<br>(k€/year) | Emissions reduction<br>(ton $CO_2$eq./year) | $\dot{Q}_{HP}$<br>(kW) | $CAPEX_{HP}$<br>(k€) | $NPV_{10y}$<br>(k€) | PBP<br>(years) |
|---|---|---|---|---|---|---|---|---|---|
| $OPEX_{opt}$ | 111 | 32 | 2.9 | 134 (7.8%) | 682 (11.1%) | 1536 | 768 | 174 | 5.7 |
| $OPEX_{BE}$ | 173 | 67 | 2.2 | 0 | 569 (9.2%) | 3230 | 1615 | −1615 | – |
| $CO_{2,opt}$ | 132 | 44 | 2.6 | 117 (6.7%) | 733 (11.9%) | 2121 | 1061 | −237 | 9.0 |
| $CO_{2,BE}$ | 221 | 95 | 1.9 | −256 (−14.9%) | 0 | 4544 | 2272 | −4075 | – |

able to reduce OPEX by 6.7% while reducing up to 11.9% of emissions. On the other hand, the use of break-even temperatures result in higher degrees of electrification, but also in a smaller reduction of the annual emissions and costs. The OPEX break-even conditions would result in the electrification of more than 67% of the process heat demand and would be able to reduce emissions by 9.2%. However, this approach lacks economic incentives and does not achieve emissions reductions comparable to the optimized heat pump integration.

### *4.2. Influence of key parameters on the optimal heat pump integration*

In this section, the parameters that determine the optimal heat pump integration temperature, as defined in Eq. (20), are examined. The analysis demonstrates the applicability of the formula to various processes, considering different energy and emission prices dependent on the country's energy mix and varying heat pump configurations. Specifically, the analysis focuses on which parameters most significantly impact heat pump integration.

#### *4.2.1. Energy prices and carbon intensity*

The economic conditions that determine the optimal sink temperature are captured by the energy price ratio $r_p$ of electricity over a reference fuel. In the investigated case, natural gas is considered as reference fuel. The energy price ratio can vary geographically, ranging, just in the EU in 2023, from 0.7 in Sweden to 3.2 in Croatia; as well as chronologically, from a ratio of 2.9 in 2023 to 2.1 in 2022 in the case of Germany. Similarly, the growth of electricity generation from renewable source and thus the decarbonization of the electricity grid in Europe affects the emissions ratio ($r_e$), which presents high variability similar to the price ratio. This trend will influence the price ratio due to renewable energy generation being a cheaper source of electricity as some studies show [28].

The large variation and uncertainty in the economic conditions affect the economic viability of heat pumps. Fig. 4 illustrates the difference in the optimal sink temperatures, and therefore the savings, given different price ratios. The remaining variables, such as source temperature, process temperatures and heat pump efficiency are fixed to the values displayed in Table 1. The price ratio applied in the case study is indicated by the grey square. If, the price ratio ($r_p$) is improved to 2 the optimal sink temperature would increase to 123 °C, with savings of 10% OPEX and a degree of electrification 39%. As previously pointed out, the chart can also be read for the ratio of carbon intensity ($r_{em}$). The grey plus marker shows the applied case study value of 1.9. Consequently, if optimized for a reduction in $CO_2$ emissions, the sink temperature can be read from this chart as 132 °C at 11.9% $CO_2$ savings and a degree of electrification of 44%.

The ratios ($r_{em}$ or $r_p$) significantly impact the sink temperature, and thus on the degree of electrification and the resulting savings. This is evidenced by the appearance of the ratio twice in Eq. (20).

#### *4.2.2. Heat pump performance*

Accurately estimating the performance of a heat pump based on the temperature requirements of the process is crucial for determining the optimal integration point for industrial heat pumps. The Lorenz efficiency factor, examined in this work, accounts for the temperature glide of both the sink and source of the heat pump. Using this factor significantly enhances the accuracy of COP estimation compared to

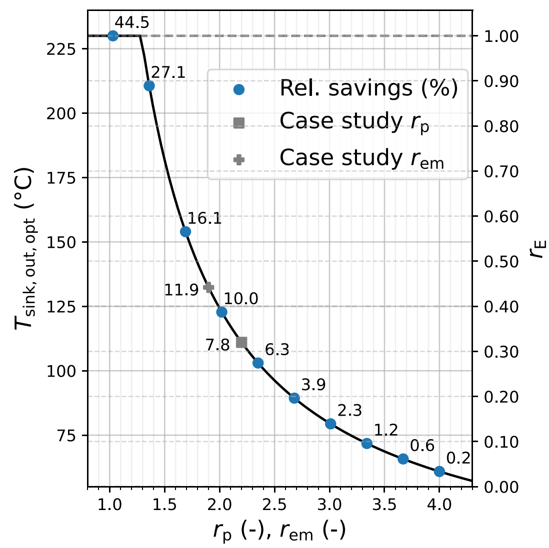


**Fig. 4.** Optimal heat pump heat sink temperature depending on different price or emission ratios. The secondary y-axis shows the associated degree of electrification ($r_E$). The remaining variables are fixed to the values from the case study (Table 1).

using Carnot efficiency, especially for sensible heat processes. However, assuming a fixed Lorenz efficiency may still lead to inaccuracies, as this factor's dependence on the heat pump temperatures could be significant [17].

Alternative, more accurate COP models consider the effect of the temperatures on the Lorenz efficiency, with some including also the pinch temperature difference, heat losses and expected isentropic efficiency of the heat pump compressor [14]. While the constant Lorenz efficiency of 0.55 has an $R^2$ of 0.87, on the COP of the 1024 temperature conditions simulated by Andersen et al. [27], the polynomial regression proposed in the original paper has an $R^2$ of 0.97 and the COP model from Jensen et al. can predict the Lorenz efficiency with an $R^2$ of 0.99 [16].

Fig. 5 shows the value of the optimal heat pump sink outlet temperature and degree of electrification in the case study for the range of Lorenz efficiencies of current heat pump technology [26]. The estimations of Andersen et al. and Jensen et al. are also shown.

Fig. 5 illustrates that the Lorenz efficiency of the heat pump plays a key role in finding the optimal sink temperature. The optimal sink outlet temperature varies from 80 °C to 150 °C in the studied range. While it is acceptable to assume a constant value for the Lorenz efficiency, the results show that this value must be carefully investigated and selected. With the temperature parameters of the case study, the COP estimation methods from Andersen et al. and Jensen et al. deliver similar results, with a Lorenz efficiency close to the constant value chosen for the case study of 0.55.

## 5. Discussion

The introduced method presents a simple and effective way to determine the cost- or emission optimal heat pump. The investigation of the case study and the parameter sensitivities has highlighted several key points for discussion.

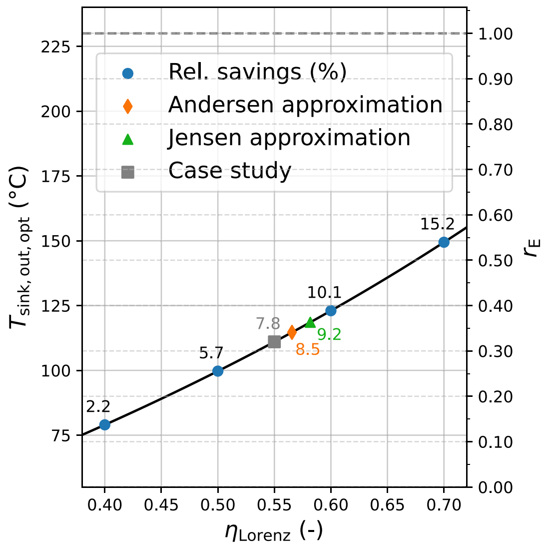


**Fig. 5.** The optimal heat pump heat sink temperature depending on different $\eta_{\text{Lorenz}}$ values and their associated OPEX or $CO_2$ savings. The secondary y-axis represents the corresponding degree of electrification ($r_E$), with the remaining variables set to the case study values (Table 1).

### 5.1. Implications of the introduced equation

The optimal heat sink temperature of the heat pump are determined analytically resulting in a simple equation (see Eq. (20)) that can be used to obtain a preliminary estimation of the optimal heat pump placement. The optimal heat pump heat sink outlet temperature is only dependant on the price ratio of electricity and fuel, the source temperature and the Lorenz efficiency factor, which is assumed to be constant.

The parameters that define the optimal sink temperature are studied in detail to test the robustness of the results. A more detailed method to define the Lorenz efficiency such as the polynomial regression form Andersen et al. or the method from Jensen et al. is advantageous and can improve the accuracy of the results. However, such methods can increase the number of assumptions and necessary data collection and, additionally, require to be solved numerically. Thus, it could defeat the purpose of the method. An investigation to show that the temperature dependence of the Lorenz efficiency has little to no impact on the optimal sink temperature has been carried out. Fig. 6 shows the variability of the Lorenz efficiency factor according to the estimation methods from Andersen et al. [27] and Jensen et al. [16]. In Fig. 6a, the source temperature inlet is varied from 0 °C to the inlet process temperature, while the process temperatures and the temperature glide of the source is kept constant. Similarly, in Fig. 6b and Fig. 6c the process inlet and outlet temperatures are varied, respectively, while the remaining temperature parameters are kept constant as Table 1.

In the investigated temperature range, the assumption of a constant Lorenz efficiency factor that is independent from the temperatures of the process fall in the uncertainty range.

On the other hand, the economic conditions, represented by the price ratio; or the grid conditions, represented by the emissions ratio, have a major impact on the results. The high variability of these factors make them key for determining the correct heat pump configuration. Factors such as the development of the EU-ETS, the efficiency of the boiler or the price of fuel are important to accurately account for and have a major impact on the economic viability of heat pump integration.

Observations on the derived equation for the optimal sink outlet temperature (Eq. (20)) reveal that this temperature corresponds to the logarithmic mean temperature between the process inlet and sink outlet temperature under break-even conditions (Eq. (15)). This shows that the relationship between the optimal sink outlet and the break-even sink outlet temperatures is independent of economic conditions and is purely thermodynamic, depending solely on the process requirements.

### 5.2. Implications of the case study results

The results from the case study show a potential for reducing by almost 8% the annual operation costs or 12% of the carbon emissions associated with the process. The results highlight the importance of optimal placement of the heat pump into the process and the advantage of the introduced method in comparison to the break-even COP method found in literature. The OPEX break-even concept remains crucial, because industrial companies are increasingly interested in investing in technologies, which reduce their $CO_2$ emissions drastically, while not causing any additional operating cost. Furthermore, the results of the case study (Table 3) emphasize the different goals and incentives companies might have. Whether the main priority are minimizing the operating cost ($OPEX_{opt}$), maximizing the electrification without additional cost ($OPEX_{BE}$), maximum overall $CO_2$ reduction regardless of cost ($CO_{2,opt}$) or maximum electrification without any additional $CO_2$ emissions ($CO_{2,BE}$). The objectives and backgrounds companies have differ vastly, however, it should be part of the political and policy consideration to either improve the business cases of the $CO_2$ reduction cases ($CO_{2,opt}$ and $CO_{2,BE}$) or decrease the attractiveness of the OPEX-optimal case ($OPEX_{opt}$). However, the latter case might have implications since rather than a partial electrification it might result in no electrification all together. A remarkable take-away from the case study is, that decarbonization and electrification can provide a positive and attractive business case. Despite some industries typically avoiding investments with payback periods exceeding 3–4 years, the OPEX-optimal heat pump integration boasts a remarkable payback period of just 5.7 years. While the $CO_2$ optimal heat pump integration reduces an additional 51 tons of annual $CO_2$ emissions in comparison to the OPEX optimal case, it still provides a payback period of only 9 years.

### 5.3. Limitations of the method

The simplicity of the presented method implies significant shortcomings and inaccuracies in predicting the optimal partial process electrification. This method is particularly suited for sensible heat processes and assumes a single process with a constant heat capacity flow rate ($\dot{m}c_p$). While this can be reasonable for sensible heat utilities such as pressurized water or thermal oil loops, and processes like heating water or air for direct use, it does not account for latent heat utilities like steam or complexities such as multiple processes with different temperature requirements and different heat capacity flow rates. Additionally, this assumption overlooks the potential for direct heat recovery between other process streams that could be implemented before integrating a heat pump for partial process electrification.

Another limitation of the method is that the simplified economic approach optimizes the annual operating costs but does not directly consider the investment costs relative to the heating capacity of the heat pump. In this work, the preliminary economic feasibility study uses a specific investment cost to estimate the NPV and PBP of the operation-optimal heat pump temperatures. This approach remains inaccurate and highly uncertain, as it does not account for factors such as economies of scale or regional differences. It is important to acknowledge that, while the method captures the minimum operating costs, the optimal NPV or PBP may differ since the size of the heat pump impacts the required investment cost.

Lastly, as highlighted in the parameter study regarding the Lorenz efficiency factor and electricity-to-fuel ratios, the parameters that define the optimal sink temperature according to Eq. (20) can vary and require thorough examination. Existing methods can be used to increase confidence in the Lorenz efficiency factor. On the other hand, accurately determining the price ratio requires a deeper understanding of the energy system's development, including taxes, levies, and other factors that can unpredictably change the prices of fuel and electricity.

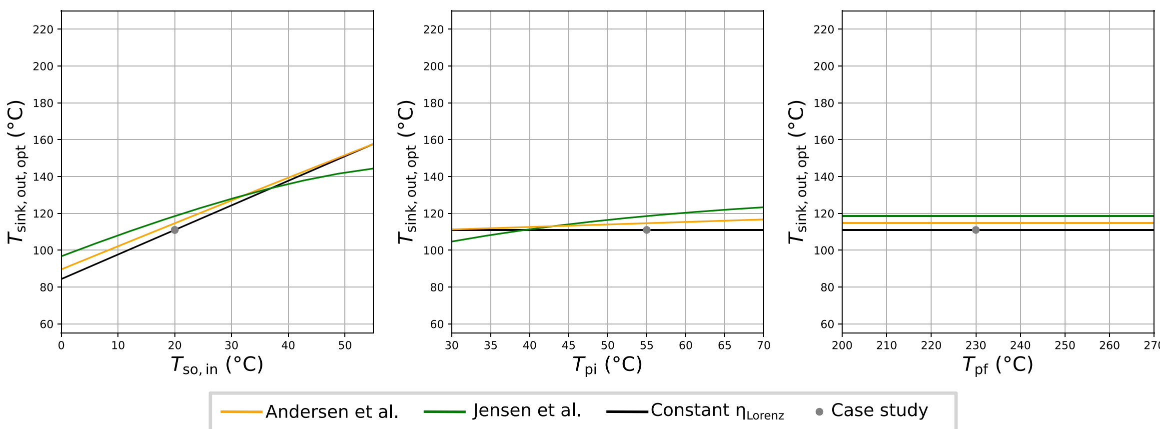


**Fig. 6.** Influence of the process temperatures on the optimal sink outlet temperature with different methods for estimating the Lorenz efficiency.

## 6. Conclusion

This paper introduces a method to calculate the economic- or emission-optimal heat pump integration for sensible heat processes. The method is represented by a straightforward equation derived from both energy efficiency and cost perspectives. The equation highlights the existence of an optimum in the trade-off between additional heat coverage of the heat pump and heat pump efficiency (COP). Furthermore, it is applicable to any process heat demand with a temperature glide. The current work challenges the concept of break-even COP found in existing literature, while maintaining relative simplicity.

The equation presented in this work shows that:

- The derived formula shows, that the optimal heat pump heat sink temperature and thus integration, is only dependant on the heat source temperature, the price or emissions ratio and the Lorenz efficiency.
- The maximum achievable cost or $CO_2$ savings can be easily estimated based on the optimal integration point.
- Integrating industrial heat pumps at the suggested temperature level offers a positive business case and incentivizes heat pump implementation.
- The electricity-to-fuel price and emission ratios are the single most important parameters due to their large variability and impact on the optimal heat pump integration. Informed research and assumptions on prices, along with projections of their development, are key for optimal process electrification.
- Economic and emissions -optimal heat pump sink temperature are lower than the Break-even targeting.
- The simplicity and generalization of the method strengthen its usefulness and applicability for estimations and preliminary assessments but reduce its accuracy. Therefore, it should be supplemented by more detailed modeling and economic calculations.

Heat pump integration for partial process electrification can be an option for immediate carbon emission reduction and economic benefits with the current energy system. The proposed method can be used to illustrate the viability of industrial heat pumps in sensible heat processes and evaluate industrial decarbonization pathways and strategies.

## CRediT authorship contribution statement

**Jasper V.M. Walden:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Roger Padullés:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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## Appendix

Additional investigations and data on this article are given below.

### *A.1. Case study for different countries*

In the analyzed case study (Section 3), a plant located in Germany is assumed. However, since the key parameter, the price ratio ($r_p$), is country-specific analysis for a variety of countries is carried out. Fig. 7 shows the price ratios (Eq. (13)) and carbon-intensity ratios (Eq. (14)) of EU countries. Below it, the resulting optimal degree of electrification (blue) and operating cost savings (orange) are shown. Additionally, the OPEX optimal heat pump integration generates $CO_2$ emissions savings, which are shown in green. In most cases, the electrification reduces $CO_2$ emissions. However, in the case of Poland, the emissions double due to its high specific carbon intensity of electricity. A key take-away is, that the heat pump integration at the optimal sink temperature is economically beneficial in every investigated country.

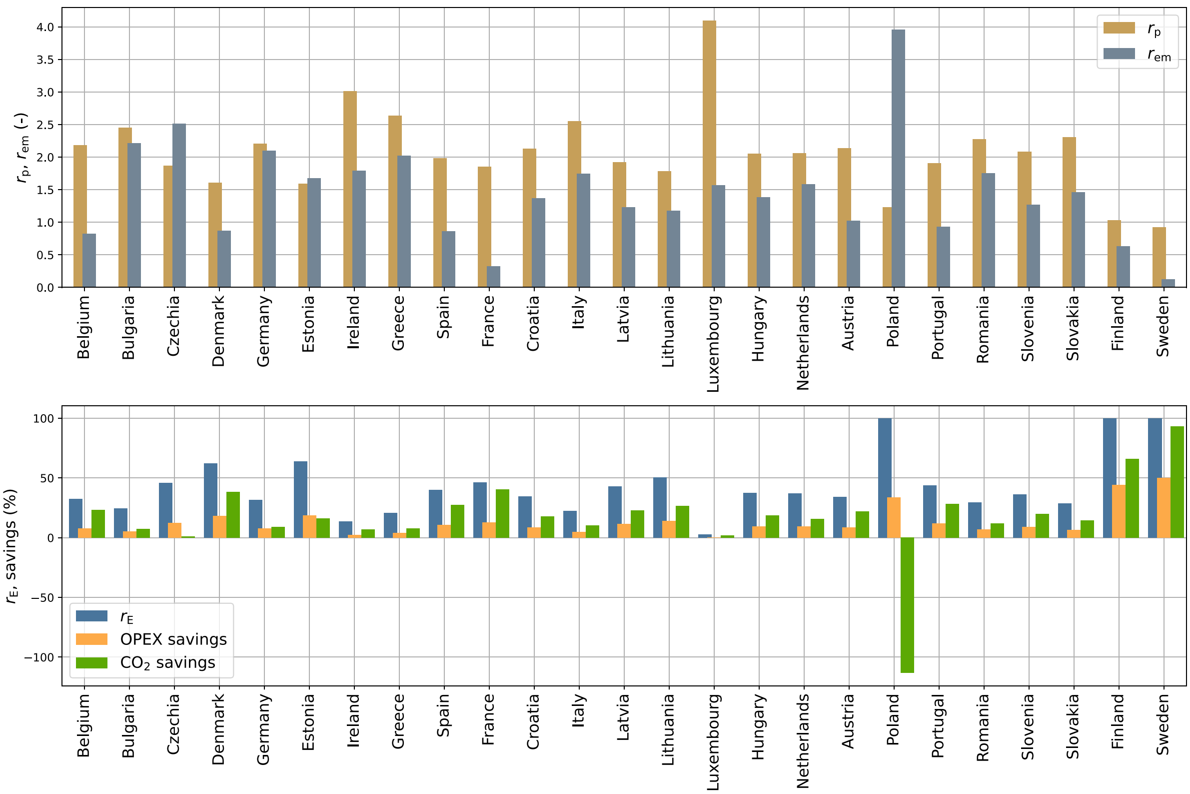


**Fig. 7.** Evaluation of the case study (Section 3) for different countries. The upper plot shows the mean price and emission ratios between 2021 and 2023 by country. The lower Figure visualizes the OPEX-optimal degree of electrification ($r_E$), the OPEX savings and the associated $CO_2$ savings.

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