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Improving energy efficiency of industrial heating systems through the use of heat pumps

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Abstract. The study aimed to justify a computational approach to improving the energy efficiency of industrial heat supply systems through the integration of heat pumps into circuits utilising low-grade and waste heat. As a result, a calculation framework was developed that integrates the waste heat source, heat exchanger, heat pump, industrial consumer and backup source into an energy balance based on indicators of heat load, electricity consumption, residual load, substitution rate and reduction in energy consumption. A systematic analysis of waste heat sources showed that flows with a regular supply and the technical capability for heat exchange have the highest calculated suitability for heat pump integration, in particular return water, cooling circuits, refrigeration machines and compressor units. Scenario modelling, assuming a constant useful heat load of 1,000 MWh, showed an increase in heat pump coverage from 250 MWh in the second scenario to 700 MWh in the fifth scenario, corresponding to an increase in the substitution rate from 0.25 to 0.7. Total energy consumption decreased from 1,000 MWh in the baseline scenario to 809.5 MWh in the second scenario, 705.3 MWh in the third scenario, 646.4 MWh in the fourth scenario and 500 MWh in the fifth scenario. The relative reduction in energy consumption increased from 19% in the preheating scenario to 50% in the combined system featuring a heat pump, a backup source and thermal storage. The study determined that an increase in thermal energy from the heat pump does not provide a proportional effect without incorporating the temperature head: in the fourth scenario, with a coefficient of performance of 2.8, electricity consumption amounted to 196.4 MWh, whereas in the fifth scenario, with a coefficient of performance of 3.5, a residual load of 300 MWh and a substitution ratio of 0.7, the lowest total energy consumption of the modernised system was obtained. The practical significance of the study is determined using the calculation framework for the preliminary engineering assessment of industrial heat pump systems

Keywords: temperature head; backup source; coefficient of performance; cooling circuits; compressor units; refrigeration units

Introduction

Industrial heat supply systems satisfy the technological, ventilation, heating and auxiliary thermal requirements of industrial facilities; therefore, their energy efficiency depends not only on the type of heat-generating equipment, but also on the organisation of internal heat flows. In production processes, low- and medium-potential heat sources are generated, associated with cooling circuits, compressor units, refrigeration machines, ventilation exhausts, recirculating water, condensate, wastewater and heated process media. In a traditional system, these flows are often excluded from the useful energy balance, whilst the heat demand is met by boiler plants, electric heaters or steam generators. In such a system, the heat pump enhances

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the temperature potential of the waste heat, returning it to the production or auxiliary heating network.

The issue of integrating heat pumps into district heating networks was explored by V.O. Derii *et al.* (2021), which examines the prospects for this technology through the lens of utilising low-potential heat sources in district heating systems. This approach is also applicable to industrial systems, as in both cases it involves connecting a secondary heat source to a consumer requiring a higher heat transfer fluid temperature. In the study by M. Shovkaliuk & I. Kononenko (2024), the efficiency of heat pumps is analysed by comparing energy supply modes, thermal load and operational performance. For industrial systems, this logic requires not a direct transfer of the building model, but a recalculation based on a process schedule, in which the process temperature, equipment operating time and the stability of the available waste heat source become the determining factors. The technological characteristics of industrial heat pumps, as discussed by S. Bobbo *et al.* (2024), relate to supply temperature, the choice of working fluids, the scale of thermal capacity, and the requirements for continuous operation within integrated production systems. This makes it possible to distinguish industrial heat pump systems from domestic heating equipment, as their efficiency is determined not only by the heat pump's Coefficient of Performance (COP), but also by the match between the waste heat flow and the specific process load. The engineering approach to utilising industrial waste heat in the study by V. Turek *et al.* (2024) is based on an assessment of its temperature level, availability, stability and the possibility of reintegrating it into the industrial energy system. In this context, the heat pump does not replace the entire heat supply system but forms an intermediate energy circuit that matches the low-temperature source with the useful heat load. The review by J. Jiang *et al.* (2022) on high-temperature industrial heat pumps shows that the expansion of their scope of application is linked to raising the supply temperature to a level suitable for technological processes. For industrial heat supply, this means that the temperature difference between the source and the consumer must be incorporated, as this difference influences the energy conversion coefficient and limits the practical application of the heat pump system.

The assessment of the European potential for industrial heat pumps in the study by A. Marina *et al.* (2021) links the feasibility of their implementation to the structure of industrial heat demand and the availability of accessible low-grade heat sources. This logic suggests that energy efficiency calculations should be based not on the abstract nominal capacity of the equipment, but on the balance between the actual heat resource, the consumption temperature and the production operating mode. R. Wang *et al.* (2024) examined high-temperature heat pumps for industrial processes using water as a refrigerant, shifting the focus to the environmental and thermodynamic parameters of the working cycle. In industrial applications, the choice of working fluid affects the permissible temperature range, operating pressure, design complexity and operational safety of the equipment. The fundamental principles, models and applied aspects of high-temperature heat pumps, as examined by H. Jouhara *et al.* (2024), provide a basis for interpreting such a system as a combination of a thermodynamic cycle, heat exchange equipment, oper ational control and integration with the heat consumer. For an industrial heat supply system, this means that the assessment must cover not only the heat generated, but also the source temperature, supply temperature, losses in heat exchangers, partial operating modes and the possibility of thermal storage. D. Ma *et al.* (2024) associated the problem of selection of working fluid for a high-temperature heat pump with the industrial utilisation of waste heat, where the temperature levels of the source and the load determine the suitability of a particular refrigerant. This consideration is of direct relevance to the calculation model, as changes in temperature head affect the COP and, consequently, the amount of electricity required to generate a given quantity of useful heat. R. Padullés *et al.* (2025) examine the operational flexibility of industrial heat pumps through their integration with stratified thermal storage and predictive control. This configuration can balance the uneven nature of the process load with the availability of waste heat and variable electricity costs, extending the energy efficiency calculation from a single cycle to the level of the heating supply system as a whole.

Consequently, modern studies establish a common engineering framework in which the industrial heat pump is viewed as a means of enhancing the thermal potential of secondary heat, rather than as an isolated source of heat generation. The issue of the design coordination of the waste heat source, the consumer's temperature level, the conversion coefficient, the proportion of replacement of conventional heat generation, and the total energy consumption in an industrial heat supply system remains unresolved. The study aimed to provide a theoretical justification and a computational assessment of improving the energy efficiency of industrial heat supply systems through the integration of heat pumps to utilise low-grade and waste heat. The main objectives of the study were: to systematise sources of waste heat in industrial heating circuits; to determine the engineering conditions for integrating a heat pump into an industrial heat supply system; to develop a calculation scheme for comparing the baseline and upgraded heat supply options; to assess changes in energy consumption, the conversion coefficient and the proportion of replaced thermal energy.

Materials and Methods

The study was conducted as a theoretical and computational investigation incorporating elements of methodological formalisation and aimed to develop a reproducible approach to assessing improvements in the energy efficiency of industrial heat supply systems through the integration of heat pumps into circuits utilising low-grade and waste heat. The primary methodological source for organising the energy analysis was the ISO 50001:2018 (2018), which was used in the study not as a source of specific thermal engineering formulas, but as a basis for establishing the logic of the energy comparison. The standard's approach was applied to determine the baseline energy consumption, select energy indicators, compare the initial and improved states of the system, and assess changes in energy performance following the implementation of energy efficiency measures. Based on this logic, in the model, the baseline scheme S1 was taken as the energy baseline for comparison, whilst scenarios S2-S5 were considered as modernisation options, for which the useful thermal energy from the heat pump, the electricity consumption of the heat pump system, the residual load of the backup source, the proportion of traditional heat generation replaced, and the relative reduction in final energy consumption were determined. The direct calculation relationships for COP, E_{el}, HP, K_{sub}, Q_{res}, E_{mod} and ΔE were formulated as a thermal balance model for the study and were used to quantitatively compare scenarios under a constant useful heat load of Q_{load} = 1,000 MWh over the calculation period. Since the accuracy of assessing industrial heat pump integration depends on a unified interpretation of thermal capacity, electrical power, and the heating, cooling and process usage modes of the equipment, the terminological basis of the study was formed by EN 14511-1:2022 (2022), which ensured a common interpretation of the performance indicators of heat pumps, air conditioners, liquid chillers and process chillers with electrically driven compressors. To ensure a methodologically consistent definition of the design conditions under which the thermal performance of heat pump equipment can be interpreted, EN 14511-3:2022 (2022) was used as the basis for distinguishing between nominal, test and design operating modes. As industrial heating systems do not operate in a single constant mode but often under variable process loads, the regulatory framework for consideration of part-load conditions and seasonal or operating performance was established by EN 14825:2022 (2022), which assessed the efficiency of a heat pump based on changes in operating conditions, temperature head and load duration.

To substantiate the overall role of heat pumps in the transition from conventional heat generation to electrified heat supply systems, an analytical report by the International Energy Agency (2022) was used, in which heat pumps are considered as a technology for reducing fossil fuel use and improving the energy efficiency of the heating sector. Within the scope of this study, this document was used as a framework for interpreting heat pump modernisation at the level of energy policy and industrial decarbonisation, whilst the direct calculation was based on an engineering comparison of the baseline and modernised variants of industrial heat supply. The subject of the methodological analysis was a generalised industrial heat supply system in which the useful heat load is provided by a traditional heat source or a combined scheme with a heat pump utilising waste heat from process or auxiliary operations. The analysis covered low-grade heat sources, an intermediate heat exchange circuit, a heat pump unit, a heat consumer, a backup or peak heat source, and the energy connections between these elements. In the calculation model, the heat pump system was considered as a generalised industrial vapour-compression heat pump with an electrically driven compressor, integrated into the waste heat utilisation circuit via an intermediate heat exchanger. The basic technical assumption was a system with a compression cycle, in which the compressor raises the thermal potential of low-grade heat to the level required by an industrial consumer. The specific make of equipment, the compressor design and the type of refrigerant were not specified, as the study was not aimed at the technical and commercial selection of a heat pump system from a particular manufacturer. At the same time, their impact on energy efficiency in the model was taken into account indirectly via the scenario-based COP value, which varied depending on the temperature head between the waste heat source and the consumer. For industrial scenarios S2-S5, COP values were taken in the range of 2.8-4.2, corresponding to various conditions for increasing the temperature potential: from preheating the heat transfer fluid under moderate temperature head to medium-temperature process consumption with a higher load on the compressor. This approach addressed the influence of the type of heat pump cycle, compressor operation and the potential operating environment on the calculated coefficient of performance without restricting the model to a single specific piece of equipment.

Five computational and modelling scenarios, S1-S5, were developed for a comparative analysis. Scenario S1 represented the baseline industrial heat supply system without the reuse of waste heat and without a heat pump. Scenarios S2-S5 described the progressive expansion of heat pump integration: S2 – preheating of the heat transfer fluid, S3 – covering the low-temperature auxiliary load, S4 – meeting medium-temperature process demand, S5 – a combined system with a heat pump, a backup source and thermal storage. All scenarios were compared under the same assumed useful heat load Q_{load} = 1,000 MWh over the design period. The comparison was conducted based on the following indicators: useful heat energy generated by the heat pump Q_{HP}, COP, heat pump electricity consumption E_{el}, HP, the replacement rate of conventional heat generation K_{sub}, the residual load of the backup or peak source Q_{res}, the total energy consumption of the modernised system E_{mod}, and the relative reduction in energy consumption ΔE compared to the baseline scheme S1. This method of comparison assessed not only the increase in the proportion of heat pump coverage, but also the influence of temperature head and COP on the system's total energy consumption. The scenarios were developed using a parametric variation approach aimed at replicating typical conditions for industrial heat supply without reference to any specific industrial facility. The scenarios were not based on empirical data from a single industrial facility, but were developed as computational and modelling variants based on the generalised approaches of the International Energy Agency (2022) regarding the use of heat pumps for the electrification of heat supply, the utilisation of low-potential heat sources, and the improvement of the energy efficiency of heating systems.

Therefore, the values of Q_{HP}, COP, K_{su}b and the operating duration of the heat pump circuit in scenarios S2-S5 should be interpreted as controlled design assumptions selected to test the sensitivity of the energy balance to the proportion of heat pump coverage and temperature conditions, rather than as measurement results from a specific facility. Five groups of factors determining the energy performance of heat pump integration were varied: the temperature level of the waste heat source – approximately 25 to 35°C; the required heat transfer fluid temperature on the industrial consumer side – 55 to 75°C; the temperature difference between the source and the consumer – from 25 to 50°C; heat pump COP – from 2.8 to 4.2; the proportion of the heating load that can be replaced by a heat pump – from 0.25 to 0.7 for the modernised S2-S5 scenarios, and from 0 to 0.7 when considering the baseline S1 scenario; operating time of the heat pump system within the calculation period – from 2,000 to 5,000 hours/year. These ranges were adopted as design and modelling assumptions for comparing scenarios, rather than as measurement results from a specific facility. This scenario structure separated the influence of temperature head from the influence of operating duration and the proportion of replacement of conventional heat generation.

The methodological section was based on a systematic, structural-functional and parametric analysis of industrial heating circuits and was implemented as a formalised calculation circuit: "waste heat → heat pump → increase in thermal potential → useful heat load → comparison with a reference heat source". The calculation period was taken as a notional annual operating interval of the industrial heat supply system, within which the useful heat load amounted to Q_{load} = 1,000 MWh. In the first stage, which corresponded to the formulation of the model's initial conditions for the calculation period, the characteristics of the waste heat source were determined: temperature, available thermal power, duration of supply, stability of the heat flux, and the possibility of heat transfer via a heat exchanger. For scenarios S2-S5, the duration of effective use of the heat pump circuit was set within the range of 2,000-5,000 hours/year, depending on the type of integration and the stability of the waste heat source. In the second stage, the parameters of the industrial consumer were specified: the required heat transfer fluid supply temperature, consumption mode, the proportion of the heat load that can be covered by the heat pump, and the residual demand to be met by a backup or peak source. In the third stage, the electricity consumption of the heat pump system, the amount of thermal energy from the conventional source that was replaced, the residual load on the backup source, and the change in the system's total final energy consumption compared with the baseline S1 configuration were determined for each scenario.

The key energy performance indicator was the heat pump's COP, defined as the ratio of useful thermal energy transferred to the industrial consumer to the electrical energy consumed by the heat pump system. In the calculation model, COP was not treated as a fixed nominal value, since for industrial heat supply, the temperature difference between the waste heat source and the consumer is the determining factor. As the required supply temperature increases or the source temperature decreases, the compressor's workload increases, which alters the electricity consumption per unit of useful heat produced. Therefore, for each scenario, the COP was linked to the operating temperature conditions rather than being set as a universal value for the entire system. The calculation of energy performance indicators was conducted using a system of basic thermodynamic relationships. The heat pump's coefficient of performance was determined using formula (1):

$$\mathrm{COP} = \frac{Q_{HP}}{E_{el,HP}}, \tag{1}$$

where Q_{HP} – useful thermal energy generated by a heat pump and supplied to an industrial consumer, kWh; $E_{el,HP}$ – electricity consumed by the heat pump system, kWh.

Power consumption of the heat pump required to cover a specified portion of the industrial heat load was determined as (2):

$$E_{el,HP} = \frac{Q_{HP}}{\mathrm{COP}}. \tag{2}$$

The proportion of traditional heat generation replaced by a heat pump was calculated using equation (3):

$$K_{sub} = \frac{Q_{HP}}{Q_{load}}, \tag{3}$$

where K_{sub} – proportion of traditional heat generation being replaced; Q_{load} – total useful heat load of the industrial system, kWh.

The residual heat load, which is to be covered by a reserve or peak heat source, was determined using equation (4):

$$Q_{res} = Q_{load} - Q_{HP}, \quad (4)$$

where Q_{res} – residual heat load after the heat pump has met part of the demand, kWh.

Total energy consumption of the upgraded system was calculated by accounting for the electricity consumed by the heat pump and the energy required to cover the residual load (5):

$$E_{mod} = E_{el,HP} + E_{res}, \quad (5)$$

where E_{mod} – total energy consumption of the modernised district heating system, kWh; E_{res} – energy from the backup or peak source, kWh.

The relative reduction in energy consumption compared with the baseline scenario was calculated using formula (6):

$$\eta_E = \frac{E_{base} - E_{mod}}{E_{base}} \times 100\%, \quad (6)$$

where E_{base} – energy consumption of the basic heat supply system, kWh; E_{mod} – energy consumption of the upgraded system with a heat pump, kWh; η_E – relative reduction in energy consumption, %.

The comparison between the baseline and upgraded scenarios was based on the energy balance of the useful heat load. In the baseline scenario, the entire heat demand was met by a conventional source, and the waste heat flow was not reused. In the upgraded version, part of the useful heat load was covered by a heat pump, whilst the conventional source remained in place for peak loads, backup, or temperature ranges where the heat pump system could not provide the required output. The calculation involved determining the useful thermal energy produced by the heat pump, the electricity consumed to generate it, the residual heat load on the base source, the proportion of traditional heat replaced, and the relative reduction in energy costs.

The calculation model involved using the derived relationships to determine the energy performance indicators for each scenario in turn. The heat pump's electricity consumption was determined via useful thermal energy and COP; the displaced thermal energy was treated as the portion of the industrial heat load covered by the heat pump system; the residual load of the conventional source was determined as the difference between the total heat demand and the heat supplied by the heat pump. Relative energy savings were established by comparing the total final energy consumption of the baseline scheme with the final energy consumption of the upgraded scheme over the calculation period. Within the model, the thermal energy Q_{load}, Q_{HP} and Q_{res} characterised the useful or residual heat load of the system, whilst E_{el} and HP represented the electrical energy consumed by the heat pump to generate useful heat. In the event that the heat pump did not fully cover the load, energy from a backup or peak source was additionally introduced into the balance, which prevented the effect of heat pump integration from being overstated.

A parametric analysis was conducted for five typical industrial operating modes: a base system without reuse of waste heat; use of waste heat for preheating the heat transfer fluid; covering a low-temperature auxiliary load; meeting medium-temperature process demand; combined operation of a heat pump with a backup source and thermal storage. For each mode, the temperature compatibility of the source and consumer, the calculated COP, the proportion of thermal energy substitution, the residual load of the backup source, and the change in total final energy consumption were assessed. In scenario S5, thermal storage was treated as a simplified operational element that does not generate additional heat but merely transfers part of the available thermal energy over time to align the heat pump's operating schedule with the industrial consumption schedule. The storage capacity in the calculation model was defined not by the tank's geometric volume, but by the nominal useful stored heat sufficient to ensure an increase in the effective operating time of the heat pump circuit to 5,000 hours/year. Heat losses during storage were taken as a rough estimate of 5% of the stored heat, and the charge/discharge cycle was interpreted as a daily or shift-based balancing of the imbalance between the inflow of waste heat and consumption. In this regard, the S5 scenario should be regarded as a preliminary calculation of the impact of storage on the energy balance, rather than as a detailed dynamic model of the storage tank, heat transfer fluid stratification, or hourly charging and discharging patterns. This approach has made it possible to compare not just individual equipment specifications, but the systemic effect of integrating a heat pump into an industrial heating network, incorporating reserve capacity and the potential for load smoothing.

The computational implementation of the calculation approach was conducted in Python 3.12, which was used to generate scenarios, process temperature and energy parameters, calculate the heat balance, and compare the baseline and upgraded variants. The NumPy library was used to process arrays of calculated values, perform parametric calculations and verify the dependence of results on changes in temperature head and COP. The panda's library was used to structure input and output data, group scenarios, generate summary tables, calculate integral indicators, and prepare data for graphical presentation of results. This software implementation ensured the reproducibility of calculations, as all scenarios were processed using the same formulas and a single energy balance sequence.

Results

Base calculation framework for assessment of industrial heat pump integration

Following the systematisation of the initial parameters for industrial heat pump integration, a calculation framework was established to compare the baseline and upgraded heat supply systems. The study established that an energy comparison of such schemes should not be based on a single performance indicator of the heat pump, but on the interrelationship between base energy consumption, useful heat load, temperature conditions of the waste heat source and the consumer, the heat output from the heat pump, electricity consumption, residual load and the total reduction in energy costs. The generalised system of parameters obtained for further comparative analysis is presented in Table 1.

Table 1. Regulatory standards for the assessment of basic and modernised industrial district heating system

Settings panel	Standardised element in the calculation scheme	Role in the basic heat supply system	Role in the upgraded heat pump system
Base energy consumption	Initial energy consumption of the district heating system	Determines the energy required to meet the entire heating load using a conventional source	Used as a reference point after the heat pump is switched on
Useful heat load	Amount of heat required by an industrial consumer during the billing period	Fully covered by a traditional heat source	Distributed between the heat pump and the backup or peak-load source
Temperature conditions at the source and the consumer	Exhaust heat temperature, supply temperature and temperature head	No separate heat recovery system is formed	Determine the operating conditions of the heat pump and the COP value
Heat pump performance figures	Q_{HP}, and COP as interrelated energy quantities	These are not included in the basic diagram due to the absence of a heat pump circuit	These figures indicate the amount of useful heat and the electricity required to generate it
Replacement of conventional heat generation	The proportion of the load covered by the heat pump, and the remainder covered by a conventional source	The entire burden remains with the traditional source.	Part of the load is transferred to the heat pump, with the remainder covered by a backup source.
Overall energy performance	Total energy consumption following heat pump integration	Serves as a starting point for comparison	Determined by the heat pump's electricity consumption and the energy from the backup source

Source: compiled by the author based on ISO 50001:2018 (2018), EN 14511-1:2022 (2022), EN 14511-3:2022 (2022), EN 14825:2022 (2022), International Energy Agency (2022) covering calculated dependencies (1-6)

As shown in Table 1, the initial calculation framework establishes an integrated system for evaluating industrial heat pump integration, in which each parameter has a specific role in comparing the baseline and upgraded heat supply schemes. Base energy consumption serves as a reference level for subsequently determining the relative reduction in energy costs, whilst the useful heat load provides a uniform basis for comparison between the two system options. The temperature conditions of the waste heat source and the industrial consumer determine the operational suitability of the heat pump, as it is the temperature difference that influences the COP and, consequently, the electricity consumption of the heat pump system. The Q_{HP}, $E_{el,HP}$ and COP indicators characterise the energy efficiency of the heat pump circuit, whilst the ratio between Q_{HP}, Q_{load} and Q_{res} reflects the distribution of the heat load between the heat pump and the backup or peak source. The overall energy performance is determined via E_{mod}, which combines the heat pump's electricity consumption and the energy from the backup source, and via the η_E indicator, which quantifies the reduction in energy consumption compared to the baseline scenario. Thus, the resulting calculation framework provides a logical transition from a qualitative description of industrial heat pump integration to a quantitative assessment of its energy performance. By aligning the parameters E_{base}, Q_{load}, Q_{HP}, $E_{el,HP}$, Q_{res}, E_{mod}, COP, K_{sub} and η_E, it is possible to subsequently analyse the baseline and upgraded systems under identical design conditions, without mixing the heat load, electricity consumption and the proportion of replacement of the conventional source. This provides the basis for a subsequent energy balance based on equations (1-6) and for identifying scenarios in which the use of a heat pump reduces the total energy consumption of the industrial heat supply system.

Integration of waste heat sources into an industrial heat pump circuit

The structuring of industrial heat pump integration established a sequential circuit for the transfer and enhancement of the thermal potential of waste heat. In this circuit, waste heat is transferred to an intermediate heat exchanger, then to the heat pump, after which useful thermal energy is directed to the industrial consumer, whilst a backup or peak source covers the remaining load. The resulting block diagram allows the physical elements of the system to be linked to the calculated energy balance parameters: the heat pump provides Q_{HP}, the conventional source covers Q_{res}, and the total system load is represented as Q_{load}. The block diagram of the integration of a heat pump into an industrial heat supply system is shown in Figure 1.

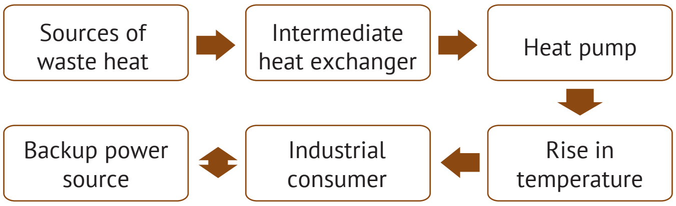

Figure 1. Schematic diagram of the integration of a heat pump into an industrial heating system utilising waste heat

Source: constructed by the author based on the design circuit for industrial heat pump integration, incorporating the terminology provisions of EN 14511-1:2022 (2022), approaches to determining the characteristics of heat pumps in accordance with EN 14511-3:2022 (2022) and the energy framework of ISO 50001:2018 (2018)

Analysis of Figure 1 showed that industrial heat pump integration has a series-balance structure, in which the waste heat source is not utilised directly, but passes through an intermediate heat exchange circuit and a heat pump. This means that heat from a production or auxiliary process is first extracted as a low-potential flow, after which its temperature is raised in the heat pump to levels suitable for an industrial consumer. In this scheme, the heat pump generates a useful heat flow Q_{HP}, which covers part of the total load Q_{load}, whilst the backup or peak source retains the function of supplementing the system and meets the residual demand Q_{res}. The relationship between Q_{load}, Q_{HP} and Q_{res} is subsequently quantified using formula (4), and the heat pump's contribution to covering the industrial load Q_{load} is calculated using formula (3). Thus, the diagram presented captures not only the technical sequence of heat flow, but also the calculation logic of the subsequent energy balance: the greater the proportion of Q_{HP} covered by Q_{load}, the lower the requirement for Q_{res} becomes; however, the final energy efficiency depends on the temperature head, COP and electricity consumption of the heat pump system. An analysis of waste heat sources has shown that their suitability for use by heat pumps is determined not only by temperature but also by the stability of the supply, operating duration, purity of the medium, and the possibility of heat transfer via an intermediate heat exchanger. A summary of waste heat sources in industrial systems and the conditions for their use by heat pumps is presented in Table 2.

Table 2. Sources of waste heat in industrial systems and the conditions for their use by heat pumps

Source of waste heat	Source of heat flux	Possible applications following a heat pump	Eligibility criteria for Q_{HP}s
Ventilation emissions and exhaust air	Low- or medium-temperature flow, depending on the ventilation mode	Preheating of supply air, low-temperature heating, auxiliary heating circuits	Stable air flow rate, option of heat recovery, and sufficient inlet temperature at the heat exchanger
Recirculating water and cooling circuits	Flow with a relatively constant temperature, associated with the cooling of equipment	Heating of process water, maintaining the temperature for auxiliary processes, and supplying the low-temperature heating network	Continuous circulation, sufficient thermal capacity and the absence of contaminants that impair heat transfer
Compressor units	Average latent heat of compression and cooling in compressor equipment	Preheating of water, process heat supply at medium temperature	Alignment of compressor operating schedules with heat consumption schedules
Refrigeration units and condenser circuits	Consistent heat removal from the refrigeration cycle	Hot water supply, process heating, and heat recovery in auxiliary processes	Sufficiently high temperature in the condensing circuit and the technical capability to extract heat without disrupting the refrigeration cycle
Wastewater and industrial liquid streams	Low-flow stream with potential variations in temperature and flow rate	Preheating of water or coolant before the main heat source	Need for filtration, protection of the heat exchanger and ensuring stable thermal contact
Condensate and heated process media	Flow with an elevated temperature, which may be intermittent	Recovering heat for reuse in the production process, or preheating raw materials or the heat transfer fluid	Temperature compatibility with the load and the ability to ensure safe heat transfer

Source: compiled by the author based on ISO 50001:2018 (2018), EN 14511-1:2022 (2022), EN 14511-3:2022 (2022), International Energy Agency (2022)

Following Table 2, waste heat sources in industrial systems differ not only in terms of temperature but also in terms of heat flux stability, supply regime, heat transfer fluid quality and the technical feasibility of heat extraction. The most suitable flows for forming Q_{HP} are those that combine sufficient thermal capacity, regularity of supply and the ability to transfer heat via a heat exchanger without disrupting the main technological process. Recirculating water, cooling circuits, refrigeration units and compressor systems have the highest calculated suitability for heat pump integration, as their heat flow is usually associated with continuous operation of the equipment and can be aligned with the auxiliary or process requirements of the enterprise. Ventilation exhaust, wastewater and intermittent process media can also be used as sources of low-grade heat; however, their efficiency depends more on flow stability, filtration requirements, heat exchanger protection and operational compatibility with the consumer.

A review of the cited sources shows that the ability of waste heat to provide Q_{HP} is determined by a combination of three factors: the temperature suitability of the source, the stability of the heat flux, and the technical feasibility of transferring it to the heat pump circuit. These characteristics subsequently influence the useful thermal energy of the heat pump Q_{HP}, its electricity consumption $E_{el,HP}$, the proportion of traditional heat generation replaced K_{sub}, and the residual load Q_{res}. Consequently, the assessment of waste heat sources cannot be limited to a mere list of them: for industrial heat pump integration, the decisive factor is the extent to which a specific heat flow can consistently support the operation of the heat pump and reduce the load on the conventional heat supply source.

Development of computational and modelling scenarios for heat pump integration

As a result of the parametric generalisation of industrial heat pump integration, five calculation and modelling scenarios have been identified, reflecting varying degrees of heat pump involvement in meeting the useful heat load. Scenario S1 established a baseline scheme without the reuse of waste heat, whilst scenarios S2-S5 demonstrated a sequential expansion of heat pump coverage from preheating the heat transfer fluid to a combined scheme with a backup source and thermal storage. For the same useful heat load Q_{load} = 1,000 MWh, the scenarios differ in the amount of heat produced by the heat pump, the COP value, the proportion of load coverage and the duration of operation of the heat pump circuit. The resulting scenario framework for further energy comparison is presented in Table 3.

Table 3. Calculated and modelled scenarios for integrating a heat pump into an industrial heating system

Scenario	Nature of heat pump integration	Q_{load}, MWh	Q_{HP}, MWh	Temperature of the waste heat source, °C	Supply temperature to the consumer, °C	Temperature difference, °C	COP	Annual operating hours of the heat pump	Proportion of the load covered by the heat pump	Availability of a backup or peak power source
S1	Basic diagram without heat recovery	1,000	0	-	-	-	-	-	0	Yes, handles the full load
S2	Preheating of the heat transfer fluid using low-potential waste heat	1,000	250	30	55	25	4.2	2,000	0.25	Yes, covers the bulk of the load
S3	Coverage of low-temperature auxiliary load	1,000	400	30	65	35	3.8	3,200	0.4	Yes, boosts performance
S4	Ensuring average process heat consumption	1,000	550	25	75	50	2.8	4,200	0.55	Yes, required for peak and high-temperature operating conditions
S5	Combined system comprising a heat pump, a backup source and thermal storage	1,000	700	35	75	40	3.5	5,000	0.7	Yes, used for backup and to compensate for heat shortages

Source: developed by the author based on a method for the parametric evaluation of industrial heat pump integration, covering ISO 50001:2018 (2018), EN 14511-1:2022 (2022), EN 14511-3:2022 (2022) and EN 14825:2022 (2022)

According to Table 3, the scenarios developed reflected a gradual transition from the industrial system's complete dependence on a conventional heat source to a combined system in which the majority of the useful load was covered by a heat pump. In scenario S1, there was no heat pump circuit, so Q_{HP} was zero, and the entire load Q_{load} remained with the traditional source. In scenarios S2-S5, the heat pump provided between 250 and 700 MWh of useful heat over the design period, corresponding to a coverage ratio of 0.25 to 0.7. At the same time, the scenarios differed in temperature conditions: the temperature difference ranged from

25°C in scenario S2 to 5°C in scenario S4, which directly affected the COP. This approach made it possible to track how an increase in Q_{HP} affected the replacement ratio K_{sub}, the residual load Q_{res} and the total energy consumption of the upgraded system. A comparison of the scenarios showed that an increase in the heat pum p's load coverage ratio was not always accompanied by a proportional increase in energy efficiency. In scenario S4, the coverage ratio was 0.55, but the COP fell to 2.8 due to the maximum temperature head of 50°C, associated with an increase in the supply temperature to 75°C at a waste heat source temperature of 25°C. In scenario S5, with a temperature difference of 40°C and a COP of 3.5, the coverage ratio reached 0.7, as the combined system – with simplified thermal storage – increased the effective operating time of the heat pump circuit to 5,000 hours per year and reduced the residual load on the backup source. In this context, storage was not considered as an additional heat source but was treated as a control element that shifts part of the available waste heat over time and partially aligns the heat pump's operation with the consumption schedule. Therefore, the resulting reduction in total energy consumption in S5 should be interpreted as a preliminary calculation of the potential of the combined system, rather than as the result of detailed dynamic modelling of the heat storage system.

Thus, the developed system of scenarios facilitates the transition from a structural description of industrial heat pump integration to a quantitative energy comparison of the baseline and upgraded schemes. It shows that the effectiveness of heat pump use is determined not only by the amount of heat Q_{HP} transferred to the consumer, but also by the relationship between the temperature level of the waste heat source, the required supply temperature, the duration of equipment operation, the COP, and the proportion of reserve load Q_{res}. Therefore, scenarios S1-S5 form the basis for further determining $E_{el,HP}$, E_{mod} and η_E, i.e., for assessing the actual energy efficiency of heat pump modernisation in an industrial heat supply system.

Calculation of the energy balance for the baseline and upgraded scenarios

An energy comparison of scenarios S1-S5 revealed a gradual reduction in the total energy consumption of the industrial district heating system, accompanied by an increase in the proportion of heat supplied by heat pumps. The baseline scenario S1 recorded a reference energy consumption level of 1,000 MWh, whereas in the upgraded scenarios S2-S5, total energy consumption decreased depending on the volume of Q_{HP}, the COP value and the residual load Q_{res}. The greatest reduction was achieved in scenario S5, where a combination of 700 MWh of heat pump coverage and COP = 3.5 resulted in a reduction of E_{mod} to 500 MWh. The results of the energy balance calculation are presented in Table 4.

Table 4. Results of the energy balance calculation for the baseline and upgraded industrial district heating systems

Scenario	Q_{load}, MWh	Q_{HP}, MWh	COP	E_{el}, HP, MWh	K_{sub}	Q_{res}, MWh	E_{mod}, MWh	η_E, %
S1	1,000	0	-	0	0	1,000	1,000	0
S2	1,000	250	4.2	59.5	0.25	750	809.5	19
S3	1,000	400	3.8	105.3	0.4	600	705.3	29.5
S4	1,000	550	2.8	196.4	0.55	450	646.4	35.4
S5	1,000	700	3.5	200	0.7	300	500	50

Source: compiled by the author using equations (1-6), covering ISO 50001:2018 (2018), EN 14511-1:2022 (2022), EN 14511-3:2022 (2022), EN 14825:2022 (2022), calculated in Python 3.12 using NumPy and pandas

According to Table 4, the transition from the baseline system to a heat pump retrofit is accompanied by a reduction in total energy consumption in all scenarios where waste heat is utilised. In scenario S1, total energy consumption is 1,000 MWh, as a heat pump is not used and the entire load is covered by a conventional source. In scenario S2, the heat pump system provides 250 MWh of useful heat, reducing E_{mod} to 809.5 MWh and corresponding to a 19% reduction in energy consumption. In scenario S3, increasing Q_{HP} to 400 MWh raises the substitution ratio to 0.4, whilst total energy consumption falls to 705.3 MWh.

The most illustrative comparison is between scenarios S4 and S5. In scenario S4, the heat pump covers 55% of the useful load; however, due to a lower COP of 2.8, the heat pump system's electricity consumption rises to 196.4 MWh, whilst the relative reduction in energy consumption stands at 35.4%. In scenario S5, the heat pump's share of load coverage rises to 0.7, and due to a higher COP of 3.5, the total energy consumption of the upgraded system decreases to 500 MWh. This corresponds to a 50% reduction in energy consumption compared with the baseline scenario.

The results obtained show that the energy efficiency of heat pump integration is determined not only by the value of Q_{HP}, but also by a combination of the substitution ratio, the COP and the residual load Q_{res}. An increase in the heat produced by the heat pump reduces the load on the conventional source; however, at a lower COP, part of this benefit is offset by an increase in electricity consumption, $E_{el,HP}$. Therefore, the final indicator E_{mod} reflects not a mechanical substitution of thermal energy, but a balance between the useful heat from the heat pump, the electricity costs to obtain it, and the residual work of the backup or peak source. Thus, scenario S5 demonstrates the lowest total energy consumption among the options considered, as it combines the highest proportion of load coverage by the heat pump with a moderate COP value and a reduced residual load on the conventional source.

The effect of temperature head on COP, electricity consumption and the degree of substitution

A comparison of scenarios S2-S5 revealed that the heat pump's COP varies depending on the temperature difference between the waste heat source and the industrial consumer. To specify the design conditions in scenario S2, the temperature of the waste heat source was taken as 30°C, and the supply temperature to the consumer as 55°C, which corresponded to a temperature difference of 25°C and a COP of 4.2. In scenario S3, the source temperature was also assumed to be 30°C, the supply temperature 65°C, the temperature difference 35°C, and COP = 3.8. In scenario S4, which reflected average-temperature process consumption, the source temperature was 25°C, the supply temperature was 75°C, the temperature head was 50°C, and the COP dropped to 2.8. In scenario S5 for a combined system with a heat pump, a backup source and simplified thermal storage, the source temperature was set at 35°C, the supply temperature at 75°C, the temperature difference at 40°C, and the COP was 3.5. At a lower temperature difference, the heat pump system operates with higher energy efficiency, as less electrical energy is required to increase the thermal potential of the heat. In the preheating and low-temperature auxiliary load scenarios, the COP remained at 4.2 and 3.8, respectively, whilst in the medium-temperature process consumption scenario, it fell to 2.8. The dependence of the COP on the temperature difference is shown in Figure 2.

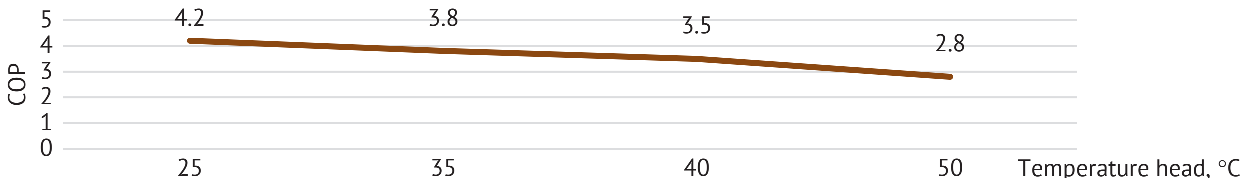

Figure 2. The dependence of the coefficient of performance (COP) on the temperature difference between the waste heat source and the industrial consumer

Source: compiled by the author based on EN 14511-1:2022 (2022), EN 14511-3:2022 (2022), EN 14825:2022 (2022), data was processed in Python 3.12 using NumPy and pandas

Following Figure 2, the heat pump's COP decreases as the temperature difference between the waste heat source and the industrial consumer increases. At a temperature difference of 25°C, the COP is 4.2, which corresponds to the heat transfer fluid preheating mode, when the heat pump operates with a relatively small increase in temperature potential. As the temperature head increases to 35°C, the COP drops to 3.8, and at 50°C, to 2.8, reflecting the rise in electrical costs for the compressor to raise the heat temperature. The scenario with a temperature head of 40°C has a COP of 3.5, i.e., it occupies an intermediate position between a low-temperature auxiliary load and a medium-temperature process load. This indicates that the energy efficiency of a heat pump is influenced not only by the heat output , but also by the thermal compatibility of the waste heat source with the consumer. A decrease in COP directly increases electricity consumption, , which is determined by formula (2); therefore, at a higher temperature head, part of the effect of replacing conventional heat generation is offset by higher electricity consumption. The proportion of replacement of conventional heat generation according to the calculation scenarios is shown in Figure 3.

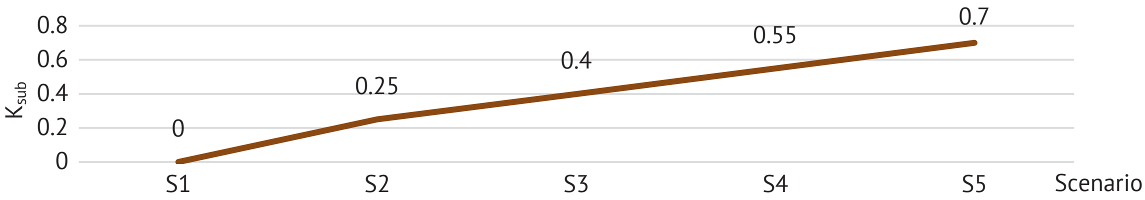

Figure 3. The proportion of traditional heat generation replaced by heat pumps in the projected scenarios

Source: calculated by the author based on the results of calculating the indicator using formula (3), incorporating the energy comparison methodology based on ISO 50001:2018 "Energy Management Systems – Requirements with Guidance for Use" (2018), data was processed in Python 3.12 using NumPy and pandas

As shown in Figure 3, the increase in the heat pump's contribution to meeting the industrial load occurs gradually: from zero in the baseline scenario S1 to 0.7 in the combined scenario S5. However, it is advisable to interpret the K_{sub} indicator in conjunction with COP and $E_{el,HP}$, as a high substitution rate may be accompanied by increased electricity consumption under unfavourable temperature conditions. Therefore, scenario S4, despite a greater volume of heat from the heat pump compared to S3, does not demonstrate a proportional increase in energy efficiency: a reduction in COP increases the electricity costs per unit of useful heat produced. In contrast, scenario S5 combines the highest value of K_{sub} with a moderate COP, which reduces the residual load of Q_{res} and provides a better balance between heat pump coverage and electricity consumption. Thus, the influence of the temperature head on the COP determines not only the operating efficiency of the heat pump but also the overall effectiveness of replacing conventional heat generation. For an industrial heat supply system, it is not the maximum increase in the Q_{HP} share that is mathematically justified, but rather a combination of source temperature, supply temperature, COP and K_{sub} that reduces E_{mod} whilst maintaining the minimum requirement for the Q_{res} reserve load. This means that heat pump integration should be assessed not by a single isolated indicator, but by the balance between the amount of useful heat that the heat pump can provide and the electricity required to generate it. At high temperature gradients, even significant load coverage may be accompanied by an increase in $E_{el,HP}$, which reduces the overall effectiveness of the upgraded system. In contrast, scenarios with moderate temperature head and a stable source of waste heat create more favourable conditions for heat pump integration, as they ensure a simultaneous increase in the substitution rate, a reduction in the heat pump's electricity consumption, and a decrease in the load on the backup source. Therefore, this combination of parameters can be used for a transition from the formal use of a heat pump to a real reduction in the total energy costs of an industrial heat supply system.

A summary of the conditions for the effective integration of a heat pump into an industrial heating system

An analysis of the results of the comparative calculations showed that the energy efficiency of integrating a heat pump is determined not only by the utilisation of waste heat, but also by the alignment between the source temperature, the consumer's heat load, the COP, the proportion of traditional heat generation replaced, and the residual role of the backup source. Under the baseline S1 scheme, the total energy consumption of the industrial system is 1,000 MWh, as the entire heat demand is met by a conventional source. In the modernised scenarios S2-S5, a gradual reduction in E_{mod} is observed: from 809.5 MWh in the preheating scenario to 500 MWh in the combined scheme with a heat pump, backup source and thermal storage. A comparison of the total energy consumption of the baseline and modernised systems under the calculated scenarios is shown in Figure 4.

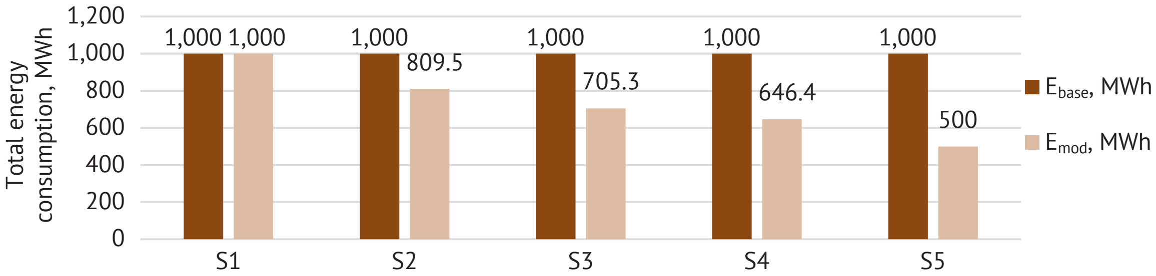

Figure 4. Comparison of the total energy consumption of the baseline and upgraded industrial district heating systems under the calculated scenarios

Source: compiled by the author based on the results of energy consumption calculations using equations (1-6), incorporating ISO 50001:2018 (2018), EN 14825:2022 (2022) and analytical data of International Energy Agency (2022), processed in Python 3.12 using NumPy and pandas

Following Figure 4, the highest total energy consumption is characteristic of the baseline scenario S1, in which waste heat is not returned to the system's energy balance. In scenario S2, the partial use of a heat pump for preheating reduces E_{mod} to 809.5 MWh, indicating a noticeable effect even with a small share of load coverage. In scenarios S3 and S4, a further increase in Q_{HP} reduces total energy consumption to 705.3 and 646.4 MWh, respectively; however, in S4, the effect is limited by a lower COP associated with a higher temperature level of process consumption. The lowest value of E_{mod} is obtained in scenario S5, where the combination of a higher proportion of heat pump coverage, moderate COP and thermal storage ensures a reduction in total energy consumption to 500 MWh.

The obtained results identified the conditions under which the integration of heat pumps leads to a reduction in the energy consumption of industrial district heating systems. These conditions relate not only to the characteristics of the heat pump itself, but also to the operational stability of the waste heat source, temperature compatibility with the consumer, the availability of a backup source, the possibility of thermal storage, and the coordination of the heat pump's operation with the process schedule. The generalised conditions for energy-efficient integration are presented in Table 5.

Table 5. Conditions for the energy-efficient integration of a heat pump into an industrial heating system

Condition for integration	Technical content of the condition	Impact on financial indicators	Expected outcome for the heating system
Stability of the waste heat source	Heat flow must be present for a sufficient portion of the design period and have a predictable flow rate	Improves the reliability of Q_{HP} formation and reduces fluctuations in the heat pump coating	Ensures a more consistent contribution from the heat pump towards meeting the industrial load
Sufficiently high temperature at the source	The temperature of the waste heat must be suitable for effectively increasing the thermal potential	Maintains a higher COP and reduces E_{el}, HP	Limits the heat pump system's electricity consumption per unit of useful heat
Moderate the supply temperature to the consumer	Consumers should require a temperature level that does not create excessive thermal stress	Helps preserve COP and reduce E_{mod}	Improves the energy efficiency of the upgraded system
Sufficient load substitution ratio	The heat pump should cover a significant portion of the Q_{load}, rather than operating solely in auxiliary mode	Increases K_{sub} and decreases Q_{res}	Reduces the load on the conventional heat supply source
Availability of a backup or peak power source	A conventional source is retained to cover heat deficits, peak loads or high-temperature sections	Ensures that Q_{res} is correctly included in the trial balance	Improves the system's operational reliability without overstating the performance of the heat pump
Heat storage capability	The thermal storage system stabilises fluctuations in the supply and consumption of waste heat	Stabilises the operation of the heat pump and helps to reduce peak Q_{res}	Ensures better alignment between the source schedule and the consumer schedule
Alignment with the production schedule	The operation of the heat pump must be aligned with the periods when waste heat is available and when heat is required	Increases actual uptake of Q_{HP}s and improves outcomes η_E	Enhances the overall impact of heat pump retrofitting

Source: compiled by the author based on the results of a computational analysis, covering ISO 50001:2018 (2018), EN 14511-1:2022 (2022), EN 14511-3:2022 (2022), EN 14825:2022 (2022), analytical report by International Energy Agency (2022), calculated in Python 3.12 using NumPy and pandas

Following Table 5, the energy-efficient integration of a heat pump is achieved when several conditions are met simultaneously. A stable source of waste heat ensures the regular generation of Q_{HP}, whilst a sufficiently high source temperature and a moderate supply temperature maintain an acceptable COP value. Under such conditions, the heat pump's electricity consumption $E_{el,HP}$ decreases, the substitution share K_{sub} increases, and the residual load Q_{res} shifts predominantly to a backup or peak function. The presence of thermal storage further improves the alignment between the irregular supply of waste heat and the industrial consumption schedule.

A summary of the results shows that the effectiveness of heat pump retrofitting is not determined solely by the installed capacity of the equipment or the maximum value of Q_{HP}. The decisive factor is the balance between temperature head, COP, heat pump operating time, the substitution rate, and the residual demand for conventional energy sources. According to the results of the comparative analysis, the best conditions are found in scenario S5, where E_{mod} is reduced to 500 MWh and the relative reduction in energy consumption reaches 50%. This confirms that, for industrial heat supply, the most effective approach is not the isolated replacement of the heat source, but the systematic integration of a heat pump with a waste heat source, a backup circuit and, where necessary, thermal storage.

A systematic comparison of the results showed that the key indicator of the energy efficiency of an industrial heat pump system is not merely the utilisation of waste heat, but the balance of heat flows between the source, the heat pump, the industrial consumer and the backup circuit. This is precisely why, in the calculation scenarios, the most effective solution was not the system with the maximum individual gain Q_{HP}, but a configuration in which the proportion of traditional heat generation replacement was combined with an acceptable COP, moderate temperature head and reduced residual load Q_{res}. For industrial heat supply systems, this means that the basic prerequisite for effective heat pump modernisation must be prior agreement on the temperature level of waste heat, consumption patterns, heat storage capacity and the role of the backup source. According to the results of the scenario comparison, option S5 best matched this logic, in which total energy consumption fell to 500 MWh, and the relative reduction reached 50%, confirming the feasibility of a combined system with a heat pump, a backup circuit and heat storage as a working configuration for further engineering justification.

Discussion

A comparison of the results obtained with the presented research into industrial heat pumps and waste heat recovery systems has shown that improving the energy efficiency of industrial heat supply depends not only on the choice of heat pump system, but primarily on the coordination of the source temperature, the heat consumption profile, the coefficient of performance and the residual role of the traditional heat source. T. El Samad *et al.* (2024) examined compressor systems for high-temperature heat pumps and demonstrated that the compressor, working fluid and temperature rise significantly influence the feasibility of using such systems for industrial waste heat recovery. In this study, this pattern was clarified through a scenario-based comparison, which showed that a heat pump system does not provide the same energy benefit across different industrial circuits. The problem of identifying and matching waste heat sources with consumers was addressed by M. Silva *et al.* (2024), where the recovery and reuse of heat are examined using tools to support the search for heat sources, consumers and possible links between them. A comparison with the data presented in the study showed that the calculated suitability of a source is determined not only by its temperature level, but also by the regularity of the heat flow, the technical feasibility of heat exchange, and the ability to consistently generate useful heat from the heat pump. The temperature compatibility of the source and the load is a key condition for effective integration, as discussed by J. Wu *et al.* (2025) on high-temperature heat pumps for carbon-neutral process heating. In the presented results, this pattern occurs through a change in the coefficient of performance depending on the temperature head: in scenario S2, with a temperature head of 25°C, the coefficient of performance was 4.2, whereas in scenario S4, with a temperature head of 50°C, it dropped to 2.8. The limitation of evaluating industrial heat pumps solely based on thermal capacity or the substitution rate is consistent with the conclusions of E. Bellos *et al.* (2025), where the feasibility analysis of high-temperature heat pumps involves the simultaneous consideration of energy, temperature and technical-economic conditions. In the results presented, this was reflected in scenario S4: despite a coverage ratio of 0.55 and thermal energy from the heat pump of 550 MWh, the lower coefficient of performance of 2.8 limited the reduction in total energy consumption. Strategies for the deployment of high-temperature heat pumps were addressed by A. Adamo *et al.* (2025) through political, market and technological prerequisites for their implementation. A comparison with the results obtained clarifies this framework at the level of engineering calculation: the 50% reduction in energy consumption in the S5 scenario cannot be explained solely by the electrification of heat supply. The sector-specific aspect of waste heat utilisation was explored by R. Wang *et al.* (2023), who propose an approach to the use of thermal resources in the steel industry. In the calculation scheme presented, this approach is specified by treating industrial waste heat as a resource requiring structured integration into the heat supply system via an intermediate heat exchanger, a heat pump and a consumption circuit, rather than as a secondary by-product flow.

The role of thermal storage in enhancing the stability of a heat pump system was highlighted by G. Agalave & P. Kulkarni (2026) in an analysis of an integrated heat pump and thermal storage system as a means of balancing heat production and consumption. Within the scope of the scenario assessment carried out, this approach is reflected in the fact that thermal storage is considered not as a separate source of energy savings, but as an element of operational coordination between the supply of waste heat, the operation of the heat pump and the industrial consumption schedule. The relationship between industrial waste heat, low-temperature heating networks and renewable energy sources is examined by M. Dokl *et al.* (2022) in the context of the technical and economic optimisation of low-temperature heat supply. The parallel with the results obtained lies in the fact that the efficiency of the system is determined not by a single heat source, but by the configuration of interactions between the source, the network, the consumer and auxiliary elements. The role of thermal storage and power-to-heat technologies in balancing energy systems was explored by M.N. Maruf *et al.* (2022). The results obtained complement this logic at the level of industrial heat supply: heat storage in scenario S5 provides not only operational flexibility but also reduces dependence on the instantaneous alignment between the availability of waste heat and heat demand. The relationship between the economic integration of a heat pump and load flexibility was analysed by J.V.M. Walden & P. Stathopoulos (2024). In the results presented, this relationship was evident in the differences between scenarios involving varying operating times of the heat pump circuit and different load coverage ratios. An additional aspect of the mismatch between the availability of waste heat and the need to utilise it is highlighted by J. Wang *et al.* (2024) using the example of data centres, where the energy, economic and environmental consequences of heat recovery are assessed under conditions of mismatch between the source and the consumer. In the results of this study, a similar problem is evident due to the need for a backup source and thermal storage: even where waste heat is available, its effective utilisation is only possible when the temperature level, supply schedule and consumption schedule are aligned.

The industrial application of high-temperature heat pumps was discussed by P.-M. Bever *et al.* (2024) in terms of temperature levels, technological requirements and the practical conditions for integrating such equipment into industrial thermal processes. In the presented calculation scheme, this approach is specified in that the efficiency of an industrial heat pump is determined not by the mere fact of its installation, but by the correspondence between the temperature of the waste heat, the required consumer temperature, the coefficient of performance and the proportion of traditional heat generation replaced. At the level of the global energy transition, the development of heat pumps is linked to the electrification of heat supply and a reduction in dependence on fossil fuels, as shown in the study by J. Rosenow *et al.* (2022). The data obtained clarify this general trend for the industrial system: the 50% reduction in energy consumption in the S5 scenario was achieved not only through electrification, but through the coordination of waste heat, heat pumps, backup sources and thermal storage. The practical aspect of using liquid flows as a source of waste heat is explored in the study by B. Considine *et al.* (2025), where resource monitoring and heat recovery at wastewater treatment plants are linked to the decarbonisation of the food and beverage industry. In this study, a similar approach was adopted in assessing wastewater and industrial liquid streams not as automatically suitable heat sources, but as resources whose efficiency depends on the stability of thermal contact, the quality control of the medium, and the technical feasibility of transferring heat to the heat pump circuit.

The potential for the use of secondary heat for industrial steam generation is explored in the paper by J. Chen *et al.* (2025), in which a high-temperature carbon dioxide heat pump utilised heat from data centres as a source to increase the temperature potential. The results presented in the study are consistent with this approach due to the shared concept of thermal enhancement: a waste heat source should be evaluated not only based on the available heat flux, but also on its ability to provide the required supply temperature without an excessive reduction in the coefficient of performance. The problem of scaling high-temperature heat pumps from laboratory or pilot configurations to an industrial level is highlighted by J. Jeßberger *et al.* (2024) using the example of systems with the working fluid R1233zd(E). A comparison with the results obtained shows that scenario-based assessment of industrial heat pump integration must consider not only the calculated heat output from the heat pump, but also operational stability, temperature head and changes in the coefficient of performance when transitioning to higher loads. A combination of energy, economic and climate assessments of industrial waste heat recovery using heat pumps was presented by Y. Jovet *et al.* (2022). The results of the study support the following conclusion regarding energy consumption: the reduction in total energy consumption from 1,000 to 500 MWh in scenario S5 demonstrates that the calculation of the effect must incorporate not only the heat generated by the heat pump, but also electricity consumption, residual load and the overall reduction in energy costs. The operational stability of a large-scale heat pump, in particular the impact of fouling on heat exchange surfaces, is examined by J.J. Aguilera *et al.* (2024) in the context of monitoring, optimisation and the transition to a digital twin. In the results of the scenario comparison, this relationship is clarified by the fact that the energy performance of a heat pump system is linked to the stability of heat exchange; therefore, waste heat sources must be assessed not only in terms of temperature level but also in terms of heat exchanger operating conditions and the risk of impaired heat transfer. The rationale for increasing the thermal potential of heat for industrial process heating is evident in the thermodynamic analysis of the solar heat upgrade system conducted by P. Tzouganakis *et al.* (2025). The presented results are consistent with this approach due to the function of the heat pump in scenarios S2-S5: it does not simply replace a traditional source but converts low-potential or waste heat to a temperature level suitable for an industrial consumer, with the overall effect being limited by the temperature head. A thermo-economic comparison of Rankine organic cycles and high-temperature heat pumps in the study by E. Obika *et al.* (2025) shows that the choice of technology for recovering industrial waste heat depends on the working fluid, the temperature level and the cost of increasing the thermal potential. Within the scope of the data obtained, this conclusion is substantiated by calculations: the presence of waste heat alone does not guarantee an energy benefit if its temperature level is not aligned with consumer needs and results in a reduction in the coefficient of performance.

Thus, the results of the study have shown that improving the energy efficiency of industrial heat supply systems through the use of heat pumps must be based on the coordinated alignment of the waste heat source, the consumer's temperature requirements, the coefficient of performance, the proportion of traditional heat generation replaced, the reserve load, and the potential for thermal storage. It is precisely this coordination that determines whether waste heat will be converted into a real resource for the energy balance, rather than remaining a by-product heat flow without systematic utilisation. A systematic comparison of the established patterns with current research in the field of industrial heat pumps, high-temperature heat supply and waste heat recovery has confirmed that the key factors are the temperature compatibility of the source and the consumer, the stability of the heat exchange circuit, load flexibility and the presence of a reserve or storage element as conditions for a reproducible reduction in the energy consumption of an industrial heat supply system.

Conclusions

As part of this study, a theoretical and computational approach has been developed to assess improvements in the energy efficiency of industrial heat supply systems through the integration of heat pumps into circuits utilising low-grade and waste heat. The calculation framework developed for the baseline and upgraded heat supply options ensured a consistent comparison of the useful heat load, heat from the heat pump, electricity consumption of the heat pump system, residual load from the conventional source, and the total reduction in energy costs. The study established that a correct assessment of heat pump modernisation should be based not on the COP value alone, but on the relationship between the temperature level of the waste heat source, the supply temperature to the consumer, the proportion of traditional heat generation replaced, and the need for a backup or peak source. Structuring the industrial heat pump circuit has shown that waste heat only achieves its calculated value if it is transferred stably via an intermediate heat exchanger to the heat pump, where the useful heat flow Q_{HP} is generated, whilst the residual part of the load Q_{res} remains with the conventional source. A systematic analysis of waste heat sources has shown that the most suitable for integration are flows with sufficient thermal capacity, regularity of supply and technical feasibility of heat exchange, in particular return water, cooling circuits, refrigeration machines and compressor units.

Scenario modelling for S1-S5 showed a gradual transition from a baseline system without the reuse of waste heat to a combined system incorporating a heat pump, a backup source and thermal storage. With the same useful heat load of Q_{load} = 1000 MWh, the proportion of heat pump coverage increased from 0.25 in scenario S2 to 0.7 in scenario S5, whilst the amount of heat produced by the heat pump increased from 250 to 700 MWh. The energy balance calculation showed a consistent reduction in the total energy consumption of the modernised system: from 1,000 MWh in the baseline scenario S1 to 809.5 MWh in S2, 705.3 MWh in S3, 646.4 MWh in S4 and 500 MWh in S5. Accordingly, the relative reduction in energy consumption increased from 19% in the preheating scenario to 50% in the combined scheme with thermal storage. At the same time, a comparison of the scenarios confirmed that an increase in Q^{HP} does not automatically result in a proportional increase in energy efficiency, as a higher temperature head reduces the COP and increases the electricity consumption of $E_{el,HP}$. This was evident in scenario S4, where, at a coverage ratio of 0.55, the COP decreased to 2.8, limiting the overall effect compared to scenario S5.

A systematic comparison of the results showed that the key indicator of the energy quality of an industrial heat pump system is not merely the utilisation of waste heat, but the balance of the heat flow between the source, the heat pump, the industrial consumer and the backup circuit. The best conditions were achieved in scenario S5, where a combination of a replacement ratio of 0.7, COP = 3.5, a reduced residual load of Q_{res} = 300 MWh and the possibility of thermal storage ensured a minimum total energy consumption of E_{mod} = 500 MWh. The results obtained demonstrate that, for industrial heat supply, it is not the isolated replacement of a traditional heat source with a heat pump that is energy-efficient, but rather the systematic integration of a heat pump system with an available source of waste heat, an intermediate heat exchange circuit, a backup source and, where necessary, thermal storage. Further research should detail the temperature profiles of specific industrial processes, incorporating variable electricity tariffs, conducting a technical and economic assessment of the payback period, and validating the calculation scenarios against actual data from industrial heat supply systems.

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Conflict of Interest

None.

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Підвищення енергоефективності промислових систем теплопостачання шляхом використання теплових насосів

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Анотація. Мета дослідження полягала в обґрунтуванні розрахункового підходу до підвищення енергоефективності промислових систем теплопостачання через інтеграцію теплових насосів у контури використання низькопотенційної та скидної теплоти. У результаті сформовано розрахункову рамку, що об'єднує джерело скидної теплоти, теплообмінник, тепловий насос, промислового споживача та резервне джерело в енергетичний баланс за показниками теплового навантаження, електроспоживання, залишкового навантаження, частки заміщення та скорочення енергоспоживання. Систематизація джерел скидної теплоти показала, що вищу розрахункову придатність для теплонасосної інтеграції мають потоки з регулярним надходженням і технічною можливістю теплообміну, зокрема оборотна вода, охолоджувальні контури, холодильні машини та компресорні установки. Сценарне моделювання за однакового корисного теплового навантаження 1 000 МВт·год встановило зростання теплонасосного покриття від 250 МВт·год у другому сценарії до 700 МВт·год у п'ятому сценарії, що відповідало збільшенню частки заміщення від 0,25 до 0,7. Сумарне енергоспоживання зменшилося з 1 000 МВт·год у базовій схемі до 809,5 МВт·год у другому сценарії, 705,3 МВт·год у третьому сценарії, 646,4 МВт·год у четвертому сценарії та 500 МВт·год у п'ятому сценарії. Відносне скорочення енергоспоживання зросло від 19 % у сценарії попереднього підігріву до 50 % у комбінованій схемі з тепловим насосом, резервним джерелом і тепловим акумулюванням. Встановлено, що збільшення теплової енергії від теплового насоса не забезпечує пропорційного ефекту без урахування температурного напору: у четвертому сценарії за коефіцієнта продуктивності 2,8 електроспоживання становило 196,4 МВт·год, тоді як у п'ятому сценарії за коефіцієнта продуктивності 3,5, залишкового навантаження 300 МВт·год і частки заміщення 0,7 отримано найнижче сумарне енергоспоживання модернізованої схеми. Практична значимість полягає у використанні розрахункової рамки для попереднього інженерного оцінювання промислових теплонасосних схем

Ключові слова: температурний напір; резервне джерело; коефіцієнт продуктивності; охолоджувальні контури; компресорні установки; холодильні машини