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WASTE HEAT UTILISATION IN SLOVENIA: SOURCE-SINK MATCHING AND ECONOMIC SCREENING

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Abstract Waste heat can contribute to heat supply only where the source characteristics match local demand and integration costs remain acceptable. This paper develops a source-sink framework for Slovenia that combines thermal quality, recoverable capacity, temporal availability, spatial proximity, demand characteristics, infrastructure requirements and delivered-heat cost. It distinguishes theoretical, technically recoverable, and economically usable heat, and examines data centres as an emerging source with limited internal thermal demand. For Slovenia's existing data-centre stock, recoverable heat is nationally modest and relevant mainly locally; scenarios for 15 and 30 MWth systems at 3,000 equivalent full-load hours yield about 45 and 90 GWh annually. Economic screening shows that the viability improves with a higher source temperature and utilisation, shorter connections, and moderate integration costs, whereas the delivered heat may exceed 100 €/MWh under unfavourable conditions, even when the source heat is free. The results support selective site-specific assessment and early heat-reuse planning for the future energy-intensive infrastructure.

Keywords

waste heat,
source-sink matching,
district heating,
Slovenia,
heat pump,
economic screening,
heat reuse

1 Introduction

1.1 Waste heat as a system-level energy resource

Waste heat is an unavoidable consequence of energy conversion and industrial activity, but its existence does not imply that it can be used economically. The practical value of a waste-heat source depends on its temperature, thermal capacity, temporal availability, spatial relation to heat demand and the infrastructure required for recovery and delivery. Consequently, the theoretical waste-heat availability, technically recoverable heat and economically usable heat, represent different quantities and should not be treated interchangeably (Brueckner et al., 2014; Forman et al., 2016; Papapetrou et al., 2018; Woolley et al., 2018).

Industrial waste-heat studies have focused traditionally on energy-intensive manufacturing sectors, including ferrous and non-ferrous metallurgy, chemicals, mineral processing, paper production and other high-temperature processes (Brueckner et al., 2014; Forman et al., 2016; Papapetrou et al., 2018). Historically, these activities generated large concentrated heat flows, because substantial quantities of primary energy were converted at elevated process temperatures.

The structure of industrial energy use, however, is not static. Over several decades, rising energy costs, process optimisation, environmental requirements and energy-efficiency regulation have strengthened incentives for equipment modernisation, heat integration and the recovery of process energy. In many conventional process industries, an additional advantage is that significant thermal demand is present on the same industrial site. Recovered energy can therefore often be redirected internally for preheating, drying, steam generation, process water heating, or other thermal loads (Papapetrou et al., 2018; Woolley et al., 2018).

This historical development is relevant for the interpretation of waste heat as an energy resource. Technically available heat does not become useful merely because it exists. Its utilisation becomes more likely when the technological capability, economic incentives and regulatory conditions develop simultaneously. Industrial modernisation has therefore reduced specific energy consumption in many applications, and increased the internal use of recoverable energy where process conditions permit. The remaining waste-heat resource is, consequently, determined

not only by the production volume, but also by the degree of energy integration already achieved within the process.

Where internal reuse is not possible or sufficient, external heat demand becomes necessary. District-heating systems are particularly relevant, because they aggregate the spatially concentrated demand and can connect otherwise independent thermal sources and consumers. The feasibility of such integration nevertheless remains source- and site-specific. Previous studies have shown that spatial proximity, temperature compatibility and temporal matching influence both the technically usable potential and economic performance strongly (Bühler et al., 2017, 2018).

1.2 Waste-heat utilisation in the Slovenian context

Slovenia combines geographically dispersed waste-heat sources with an established, but heterogeneous district-heating sector. In 2024, 122 heat distribution systems operated in 68 municipalities, supplying heat to more than 150,000 consumers. This infrastructure provides the potential for external heat utilisation, but the national aggregate statistics alone cannot determine whether individual sources and sinks are technically compatible.

A national assessment must therefore avoid two simplifying assumptions. The aggregate sectoral energy consumption cannot be converted directly into recoverable waste heat without information on the process conditions and existing internal recovery, and an identified waste-heat source cannot be considered usable independently of the receiving demand.

This distinction is especially relevant in a small and spatially heterogeneous energy system. A nationally modest source can be important to an individual local network, while a larger source may have limited value when no suitable sink is nearby. The relevant scale of assessment is therefore often regional or site-specific rather than purely national.

1.3 Data Centres as an Emerging Waste-Heat Source and Objective of the Paper

The transition towards a more digital economy introduces a new class of energy-intensive infrastructure. Data centres consume substantial amounts of electricity, most of which is, ultimately, converted into heat that must be removed continuously (Wahlroos et al., 2017; Yuan et al., 2025). Unlike many conventional process industries, however, data centres generally have little internal thermal demand, and therefore depend on external heat sinks to use the recovered heat.

This makes them particularly relevant from a planning perspective. For new facilities, the location, cooling architecture and external heat integration can still be influenced before a long-lived infrastructure is fixed. Proximity to a suitable heat demand can therefore be considered alongside access to the electricity grid, telecommunications infrastructure, land availability and cooling requirements.

The European Energy Policy reflects this issue increasingly. Directive (EU) 2023/1791 and the associated reporting framework strengthen the consideration of data-centre heat recovery, subject to technical and economic feasibility (European Parliament and Council of the European Union, 2023; European Commission, 2024).

Data centres are examined in this paper, not because they currently represent the largest waste-heat resource in Slovenia, but because they constitute an emerging form of energy-intensive infrastructure, for which several decisive source–sink variables can still be influenced during the project’s development.

The paper develops a source–sink screening framework for the Slovenian heat-supply context, formulates an economic assessment based on consistent system boundaries and the cost of the heat supply actually displaced, and applies the framework quantitatively to the current and prospective role of data-centre waste heat in Slovenia.

2 Waste Heat as a System Resource

Waste heat is not a uniform energy source. Its practical value depends on the physical characteristics of the rejected heat, the operating conditions of the source process, and the requirements of the receiving heat demand. The temperature provides an initial indication of heat quality and influences the recovery technology strongly, but thermal capacity, annual availability, temporal profile, heat-transfer medium, continuity of operation and location are equally relevant (Brueckner et al., 2014; Papapetrou et al., 2018; Woolley et al., 2018; Bühler et al., 2017, 2018; Jouhara et al., 2018).

A system-level assessment must therefore distinguish between source characterisation and utilisation potential. Two sources with similar annual rejected energy can have very different practical values if they differ in temperature, continuity, location, or compatibility with nearby demand (Table 1).

2.1 Classification of Waste Heat

Waste heat can be classified using several complementary criteria. The temperature is the most direct indicator of thermodynamic quality. Reviews of industrial waste-heat recovery commonly distinguish low-, medium-, and high-temperature sources, although numerical boundaries vary across applications (Brueckner et al., 2014; Papapetrou et al., 2018; Jouhara et al., 2018). For screening purposes, the following ranges are used:

- low-temperature waste heat: below approximately 40 °C;
- medium-temperature waste heat: approximately 40–100 °C;
- high-temperature waste heat: above approximately 100 °C.

These ranges are engineering screening categories rather than strict thermodynamic boundaries. Low-temperature heat generally requires temperature upgrading for conventional district heating or industrial applications. Medium-temperature heat can support process preheating, return-line integration, heat-pump upgrading, or direct use in lower-temperature systems. High-temperature sources offer a wider range of direct recovery options, and can also enable steam production or power recovery when the temperature and thermal capacity are sufficient (Table 2).

The thermal capacity describes the instantaneous magnitude of the source. If $Q_{\text{source}}(t)$ denotes source thermal power, the corresponding annual rejected energy is

$$E_{\text{source}} = \int_0^{8760} Q_{\text{source}}(t) dt \quad (1)$$

The annual energy alone does not describe usability. A nearly continuous source and an intermittent high-power source can deliver the same annual energy while requiring different strategies for recovery, storage and integration.

Temporal availability should therefore be treated as a separate source characteristic. Waste-heat sources can be continuous, cyclic, production-dependent, intermittent, or seasonal. The operating profile determines whether the source availability coincides with the heat demand at the receiving end.

The heat-transfer medium also affects recoverability. Waste heat can occur in cooling water, process liquids, steam, exhaust gases, ventilation air, or other process streams. Liquid streams generally simplify the heat exchange and transport, while gaseous, contaminated, or chemically aggressive streams can require larger heat-transfer surfaces, intermediate circuits, or specialised materials (Jouhara et al., 2018).

Table 1: Principal characteristics of waste-heat sources relevant to utilisation

Characteristic	Parameter	Relevance
Temperature	T_{source}	Determines the heat quality and required temperature upgrading
Thermal capacity	$Q_{\text{source}}(t)$	Determines the instantaneous contribution to a heat sink
Annual availability	E_{source}	Indicates the total annual thermal energy available
Temporal profile	Operating profile	Determines coincidence with the heat demand
Heat-transfer medium	Liquid, gas, vapour, air, other	Affects the recovery and heat-exchanger configuration
Continuity	Continuous, cyclic, intermittent, seasonal	Affects the utilisation and storage requirements
Location	Source coordinates and distance to the sink	Determines the transport and connection requirements

The location determines the practical relevance of low- and medium-temperature heat, because external use requires a dedicated thermal transport infrastructure. Increasing the source–sink separation generally increases the pipeline investment, pumping requirements and thermal losses. Spatial studies of industrial excess heat, therefore, combine source characteristics with the location of potential users (Bühler et al., 2017, 2018).

Table 2: Indicative temperature classification of waste heat

Temperature class	Indicative range	Typical sources	Typical utilisation routes
Low temperature	<40 °C	Cooling water, refrigeration, wastewater and conventional cooling systems	Heat pumps, low-temperature heating and preheating
Medium temperature	40–100 °C	Warm cooling water, compressors, condensers, process cooling	District heating, process preheating and heat pumps
High temperature	>100 °C	Furnaces, kilns, exhaust gases, high-temperature process streams	Direct process heat, steam production, district heating and power recovery, where appropriate

Temperature classification provides only the first screening step. The recovery technology must be selected based on the source temperature, sink temperature, source capacity, operating profile and source–sink distance.

2.2 Theoretical, Technical and Economic Potential

Waste-heat assessments must distinguish between the heat rejected by a process and the fraction that can be recovered and used. Regional and national studies commonly separate the theoretical, technical and economic potential (Brueckner et al., 2014; Papapetrou et al., 2018):

$$E_{\text{theoretical}} \geq E_{\text{technical}} \geq E_{\text{economic}} \quad (2)$$

The theoretical potential represents the thermal energy rejected within the selected system boundary. For rejected thermal power Q_{rejected} ,

$$E_{\text{theoretical}} = \int_0^{8760} Q_{\text{rejected}}(t) dt \quad (3)$$

This quantity describes the gross thermal stream leaving the process, and does not imply technical recoverability or practical use.

The technical potential is the fraction that can be recovered under technically feasible operating conditions:

$$E_{\text{technical}} = \int_0^{8760} Q_{\text{recoverable}}(t) dt$$

$$Q_{\text{recoverable}}(t) \leq Q_{\text{rejected}}(t) \quad (4)$$

The technical recoverability depends on the process outlet-temperature limits, heat-transfer characteristics, heat-carrier properties, source variability, heat-exchanger constraints, required temperature upgrading, and the availability of a technically compatible sink. Sector- and temperature-specific analyses show that this step can reduce gross waste-heat estimates substantially (Papapetrou et al., 2018).

The economic potential is the technically recoverable fraction for which recovery and delivery remain economically preferable to the relevant alternative heat supply. It depends on the recovery equipment, temperature upgrading, thermal transport, connection infrastructure, auxiliary electricity, operation and maintenance, and, where applicable, the contractual value assigned to the source heat.

Economic potential is therefore not an intrinsic property of the source. Changes in electricity prices, investment cost, annual utilisation, heat demand, or the cost of alternative heat production can alter the economically usable fraction without changing the physical source itself.

National or regional aggregation should therefore be interpreted cautiously. Summing the estimated process heat losses can indicate the gross resource magnitude, but it can overstate the amount that can be contributed to an actual heat-supply system (Brueckner et al., 2014; Papapetrou et al., 2018). A defensible assessment must establish the source–sink compatibility before evaluating the economic feasibility.

2.3 Source–Sink Matching Framework

The transition from technically recoverable heat to usable heat requires simultaneous evaluation of the source and the receiving demand. The framework used here considers four dimensions: temperature compatibility, capacity compatibility, temporal coincidence and spatial proximity (Woolley et al., 2018; Bühler et al., 2017, 2018; Dorotić et al., 2022).

Temperature compatibility

The source temperature must be compared with the temperature required by the receiving system. A simplified temperature lift is

$$\Delta T_{\text{lift}} = T_{\text{sink}} - T_{\text{source}} \quad (5)$$

Direct heat exchange can be possible when the source temperature exceeds the required sink temperature by a sufficient margin. Temperature upgrading is required if the source temperature is lower.

For heat-pump integration, a larger temperature lift generally reduces COP and increases electricity consumption. The same source can therefore have different values in different receiving systems.

Capacity compatibility

At any time t , the directly usable heat cannot exceed either the available source power or simultaneous demand:

$$Q_{\text{use}}(t) = \min[Q_{\text{source}}(t), Q_{\text{sink}}(t)] \quad (6)$$

Nominal capacities alone are therefore insufficient for sizing. Oversizing relative to the maximum source output can reduce the annual utilisation if the receiving demand is low for much of the year.

Temporal compatibility

The annual usable heat is

$$E_{\text{use}} = \int_0^{8760} Q_{\text{use}}(t) dt \quad (7)$$

$$E_{\text{use}} \leq E_{\text{source}} \quad (8)$$

A simple utilisation indicator is

$$f_{\text{use}} = \frac{E_{\text{use}}}{E_{\text{source}}} \quad (9)$$

A source with a high theoretical or technical potential can still have a low utilisation fraction if heat is available when the demand is absent. Short-term storage can reduce short-duration mismatches, but does not necessarily resolve a seasonal imbalance.

Spatial compatibility

External utilisation requires thermal transport between the source and the sink. The source–sink distance can be denoted as

$$d = d(\text{source}, \text{sink}) \quad (10)$$

Increasing the distance generally raises the pipeline investment, pumping requirements and heat losses. The economic effect also depends on the thermal capacity, operating hours, temperature level and the physical connection route.

A straight-line distance alone is therefore insufficient. The practical feasibility can depend on the road and utility corridors, the terrain, property constraints, network geometry and the feasible hydraulic connection point.

The temperature, capacity, time and distance must be considered jointly. A large source can have limited value if it is remote from the demand; a nearby source can remain unattractive if it requires excessive temperature upgrading; and a technically compatible source can still achieve low annual utilisation if its operating profile does not coincide with the demand.

Figure 1 summarises the framework developed in Section 2, showing how the waste-heat source characteristics and receiving-sink requirements are filtered progressively through source–sink matching, technical recovery and integration and economic screening, to distinguish the theoretical potential from the technically recoverable and economically usable heat.

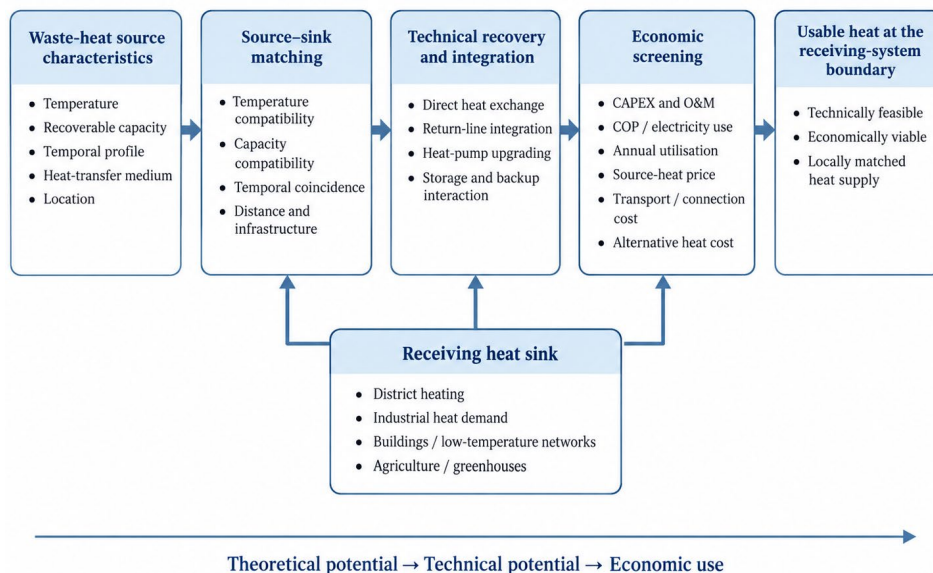


Figure 1: Source–sink matching and economic screening framework for waste-heat utilisation

3 Waste-Heat Sources and Heat Sinks in Slovenia

The national statistics describe the sectoral energy use and infrastructure more reliably than site-level waste-heat flows. The purpose of this section is therefore to identify the relevant source categories and potential heat sinks in Slovenia, rather than to derive a national total for waste heat. Quantitative recovery estimates require site-level information on temperature, flow, operating profile and location.

3.1 Main Categories of Waste-Heat Sources in Slovenia

Industrial processes

Industry remains one of the most important categories of potential waste-heat sources in Slovenia. In 2018, manufacturing accounted for 82% of the final energy consumption in the industrial activities covered by the national statistics. Detailed energy-use data were reported for food production, paper and paper products, chemicals and chemical products, non-metallic mineral products and basic metals. In almost all of these activities, heat production accounted for the largest share of energy use; basic metals were the main exception, due to the importance of electrochemical processes (Statistical Office of the Republic of Slovenia, 2019).

The technical characteristics of industrial waste heat vary substantially between sectors and processes. High-temperature sources can include furnaces, kilns, dryers and exhaust streams, whereas cooling circuits, condensers and process-water systems generally provide lower-temperature heat (Papapetrou et al., 2018; Jouhara et al., 2018). The operating profiles also differ between continuous and batch production. Site-specific data are therefore required before industrial energy consumption can be translated into recoverable heat.

Power and combined heat and power plants

Thermal power generation and combined heat and power plants can provide residual heat from cooling systems, condensers and flue gases. In CHP systems, however, the useful cogenerated heat is already an energy product, and must be separated from the residual waste heat to avoid double-counting.

The recoverable residual fraction depends on the plant configuration, operating regime and existing heat-recovery equipment. Electricity production or fuel consumption alone is therefore insufficient for estimating usable waste heat.

Refrigeration and cooling systems

Refrigeration and cooling systems reject heat through condensers and cooling circuits. The relevant applications include food processing, cold storage, logistics, supermarkets and other facilities with substantial cooling demand.

These sources are typically low- to medium-temperature and can operate for long periods, but their value depends on their proximity to a suitable heat sink and on the coincidence between the cooling demand and heat demand.

Wastewater

Wastewater represents a distributed low-temperature heat source. In 2023, 256.4 million m³ of wastewater entered the Slovenian public sewerage system, of which 185.7 million m³ was treated (Statistical Office of the Republic of Slovenia, 2024). The total volume includes sanitary wastewater, industrial discharges, infiltration, rainwater and other flows, so it cannot be converted directly into recoverable thermal energy.

Wastewater heat recovery requires site-specific information on the flow, temperature, treatment configuration and proximity to demand. Treatment plants and major sewer collectors are therefore more relevant screening locations than the national aggregate wastewater volume.

Commercial and service-sector cooling

Commercial and service activities can generate recoverable heat from cooling, refrigeration and ventilation systems. The Slovenian service-sector energy use was approximately 16,000 TJ in 2024, with trade, accommodation and food services, health and social care, education, transport and storage, information and communication and public administration among the principal activities (Statistical Office of the Republic of Slovenia, 2025a).

These statistics identify sectors where cooling and building-services loads can be significant, but they do not quantify waste heat directly. The practical potential remains building and site-specific.

Data centres

Data centres form a smaller, but increasingly relevant source category. In 2023, 41 surveyed Slovenian data centres had a combined rated electrical power of 7,554 MW and consumed 36,833 GWh of electricity. Most facilities were small: 61% had rated electrical power below 100 kW, while only 7% were rated at 1 MW or more (Statistical Office of the Republic of Slovenia, 2025b).

The existing stock is therefore fragmented, but the data centres are relevant because their electricity consumption is concentrated, and their waste-heat characteristics depend strongly on the cooling architecture (Table 3).

Table 3: Indicative characteristics of the principal waste-heat source categories in Slovenia

Source category	Typical temperature level	Typical continuity	Indicative scale	Potential use
High-temperature industrial processes	Medium to high	Process dependent	Medium to large	Direct process use, district heating, steam, or power recovery
Industrial process cooling and condensation	Low to medium	Process dependent	Small to large	Heat pumps, process preheating, district heating
Residual heat from power and CHP plants	Low to medium/high	Plant-operation dependent	Large	District heating, process heat
Refrigeration and cooling systems	Low to medium	Often long operating periods	Small to medium	Building heat, district heating, local heat recovery
Wastewater and treated effluent	Low	Relatively continuous	Site dependent	Heat pumps, low-temperature networks
Commercial and service-sector cooling	Low	Building-operation dependent	Small to medium	Local building heat, district heating where concentrated
Data centres	Low to medium	Relatively continuous	Small to potentially large	Heat pumps, return-line integration, district heating

The Table provides a screening classification rather than a quantified national inventory. The source temperature, capacity, continuity and location must be verified at the site level.

3.2 Main Heat Sinks

District heating

District-heating systems are the most evident large external heat sinks, because they aggregate the thermal demand and already provide a heat distribution infrastructure. External waste heat can substitute part of conventional heat production through direct exchange, return-line integration, or heat-pump upgrading.

The main limitation is seasonal demand. The minimum summer load and the load-duration curve are therefore more informative for waste-heat integration than the annual heat consumption alone.

Industrial process heat

Industrial sites can act as sources and sinks simultaneously. Internal recovery is generally advantageous, because it avoids off-site transport, while cross-site exchange is relevant where neighbouring facilities have compatible temperature levels and operating schedules.

Public and commercial buildings

Hospitals, hotels, offices, educational complexes, shopping centres and similar buildings provide space-heating and domestic hot-water demand. The individual loads are smaller than major district-heating systems, but building clusters can provide useful local sinks, especially where the year-round hot-water demand improves utilisation.

Low-temperature heat networks

Low-temperature and ambient-loop networks can improve compatibility with low-grade waste heat by reducing the required temperature lift. Their value lies in improved source–sink matching rather than in increasing source availability (Puschnigg et al., 2021).

Agriculture and greenhouses

Greenhouses, drying, aquaculture and related agricultural applications can use low- and medium-temperature heat where suitable demand is located near the source. Their relevance is therefore primarily local.

Thermal storage

Thermal storage is not an independent final sink, because it does not create an annual heat demand. Short-term storage can reduce the hourly mismatch and support heat-pump operation, but it cannot compensate for a persistent seasonal surplus or insufficient annual demand.

3.3 District Heating in Slovenia

District heating is an established component of the Slovenian heat-supply system. In 2024, 122 heat-distribution systems operated in 68 municipalities through 51 distributors (Agencija za energijo, 2025). Distributors handled 1,955.7 GWh of heat for building heating and cooling, domestic hot water and industrial steam processes. Final consumers received 1,592.7 GWh, while the reported distribution losses amounted to 363.0 GWh. The systems supplied 156,754 consumers (Agencija za energijo, 2025).

The five systems with the longest recorded heat distribution networks in 2024 are Ljubljana, the Šaleška Valley, Maribor, Hrastnik, and Ravne na Koroškem. Their principal physical indicators are summarised in Table 4. The selection is based solely on network length, and does not constitute a ranking by annual heat demand, generation capacity, or the waste-heat absorption potential (Figure 2).

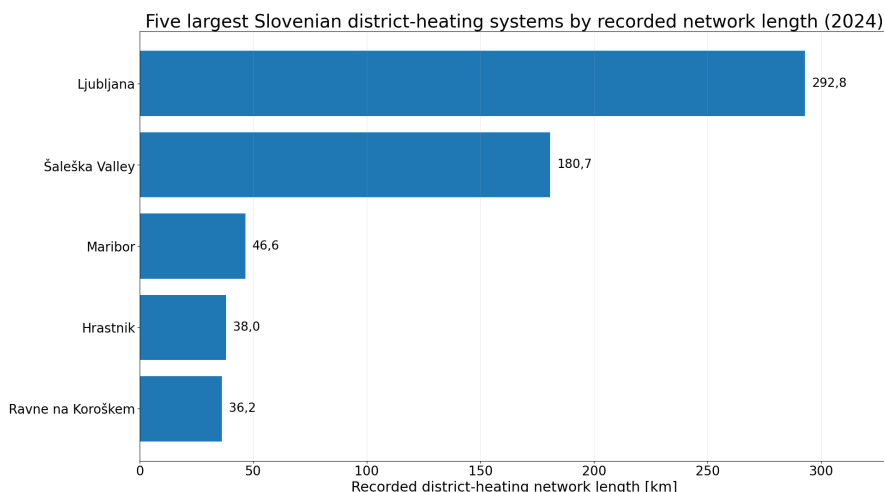


Figure 2: Five Slovenian district-heating systems with the longest recorded distribution networks in 2024.

Source: Agency for Energy (Agencija za energijo, 2025).

Table 4: Selected Slovenian district-heating systems used for system-scale comparison

System	Network length [km], 2024	Heat consumers, 2024	Published connection capacity [MW]	Capacity reference year
Ljubljana	292.8	71,772	1,177.4	2025
Šaleška Valley	180.7	12,220	184.0	2026
Maribor	46.6	16,165	114.40	2019
Hrastnik	38,0	1,693	n.a.	—
Ravne na Koroškem	36.2	2,674	33.5844	2019

Source: Network length and consumer data: Agencija za energijo (2025). Connection capacities: the individual operator and municipal sources are cited below.

The network length and consumer data come from the harmonised national source (Agencija za energijo, 2025). The aggregate connection capacity is not available in one comparable National Table, so the values originate from the latest public sources identified for individual systems: Ljubljana (Javno podjetje Energetika Ljubljana, 2026), the Šaleška Valley (Komunalno podjetje Velenje, 2026), Maribor (Mestna občina Maribor, Nadzorni odbor, 2021) and Ravne na Koroškem (Občina Ravne na Koroškem, 2023). For Hrastnik, a consistent aggregate connection-capacity value was not identified; the operator reports plant and system

characteristics instead (Petrol d.d., 2026). The generation capacity is therefore not substituted for connection capacity.

The five systems together account for 594.3 km of the recorded distribution network. Ljubljana and the Šaleška Valley account for 473.5 km, or approximately 79.7% of the group's combined network length. These figures illustrate the differences in the physical scale, but do not quantify the waste-heat absorption potential.

For waste-heat integration, the critical system parameters are the hourly heat demand, the load-duration curve, the minimum summer load, the supply and return temperatures, the network losses, pumping requirements, feasible hydraulic connection points, and the distance and route between the source and the network. The existing base-load, peak and backup production must also be considered.

A harmonised comparison of annual heat delivery for the five individual systems is not included, because comparable values using a common reporting year and system boundary were not available in the reviewed sources. Combining operator-specific annual data from different years or reporting conventions would imply a degree of comparability that the data do not support.

Slovenian district-heating systems should therefore be treated as heterogeneous potential heat sinks. Large networks may provide greater absorption opportunities, but smaller systems can also be attractive when the source and sink are close, temperatures are compatible and the demand is sufficiently stable.

4 Data Centres as an Emerging Waste-Heat Source

Data centres differ from many conventional waste-heat sources, because a large share of their electrical input ultimately manifests as heat that must be removed continuously. Their practical value as heat sources depends primarily on the cooling architecture, recoverable temperature, and compatibility with the receiving heat demand (Wahlroos et al., 2017; Yuan et al., 2025; Oltmanns et al., 2020; Feike et al., 2021).

4.1 Cooling Technologies and Recoverable Temperature Levels

Air cooling

Conventional air-cooled data centres transfer heat from information technology equipment to the room air, and, subsequently, to air- or water-based cooling systems. Recoverable temperatures around 25–35 °C are representative of room-air-based recovery configurations, although the actual values depend on the equipment and operating conditions (ASHRAE, 2023; Oltmanns et al., 2020).

Chilled-water systems

Chilled-water architectures provide a convenient hydraulic interface for external heat recovery, but the available water temperature is usually low. A representative useful recovery interface lies approximately in the 15–30 °C range (ASHRAE, 2023; Oltmanns et al., 2020).

Direct-to-chip liquid cooling

Direct-to-chip cooling transfers heat from high-heat-flux components to a liquid circuit, eliminating the intermediate heat-transfer steps and enabling higher coolant temperatures.

ASHRAE liquid-cooling classes include W17, W27, W32, W40, W45 and W+, where the number denotes the maximum facility supply-liquid temperature and W+ represents operation above 45 °C (ASHRAE, 2021, 2023). These classes describe the allowable facility supply temperatures, not the district-heating delivery temperatures.

Depending on the system configuration and heat load, return water temperatures of approximately 35–50 °C can be achieved (Oltmanns et al., 2020; Feike et al., 2021).

Warm-water liquid cooling

Warm-water liquid cooling operates deliberately at elevated coolant temperatures, and is therefore particularly favourable for heat recovery. (Oltmanns, et al., 2020) reported a recoverable heat source at approximately 45 °C in a hot-water-cooled HPC system, while (Feike, et al., 2021) evaluated heat-pump integration for a system operating at approximately 40–45 °C. Other high-temperature data-centre studies consider source-water temperatures of approximately 50–60 °C (Wang et al., 2024). The achievable temperature remains design dependent.

Table 5: Indicative data-centre cooling concepts and recoverable heat-temperature levels

Cooling concept	Indicative recoverable temperature	Implication for district heating
Air cooling / room-air recovery	~25–35 °C	Large temperature lift; a heat pump is normally required
Chilled-water architecture	~15–30 °C at a useful water interface	Technically usable, but a relatively high heat-pump electricity demand
Direct-to-chip liquid cooling	~35–50 °C return, design dependent	Reduced temperature lift; suitable heat-pump source
Warm-water liquid cooling	~45–60 °C return, design dependent	Favourable for return-line integration or smaller heat-pump lift

The ranges in Table 5 are screening values rather than design specifications. The actual values depend on the cooling-system configuration, coolant flow, and operating load (Figure 3).

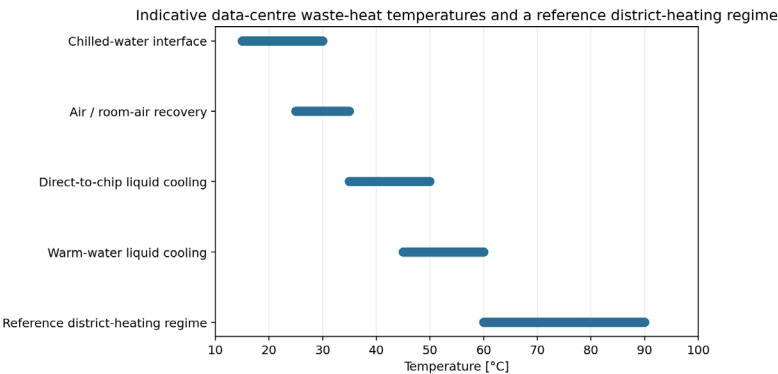


Figure 3: Indicative temperature ranges of data-centre waste-heat sources compared with a demanding 90/60 °C district-heating reference regime.

4.2 Integration Pathways

The integration pathway depends primarily on the relation between the recoverable source temperature and the temperature required by the receiving system.

Direct heat exchange

Direct heat exchange is possible when the available source temperature exceeds the required sink temperature by a sufficient margin. This condition is uncommon for conventional high-temperature district heating, but can occur in low-temperature networks or during periods of reduced network temperature.

Return-line integration

When the recoverable temperature approaches the district-heating return temperature, the data-centre heat can preheat the return line, reducing the duty of a subsequent heat-pump stage or a conventional heat source. (Feike, et al., 2021) demonstrated this concept using heat from a hot-water-cooled HPC system.

Heat-pump upgrading

When the source temperature is below the required delivery temperature, a heat pump provides the necessary temperature boost. The higher source temperature and lower sink temperature reduce the temperature lift and generally improve the coefficient of performance.

A GEA RedGenium operating point with a secondary source-water circuit of 37/32 °C and a heating-water circuit of 70/90 °C reports COP values of approximately 4.27–4.34 (GEA Group, 2026). A SABROE HeatPAC operating point with a cold-side water circuit of 40/35.9 °C and a hot-side circuit of 40/85 °C reports a COP of approximately 4,4 (Johnson Controls / SABROE, 2024).

When the source temperatures are lower or the target temperatures are higher, two-stage, cascade, or other advanced heat-pump configurations can become

advantageous. High-temperature heat-pump studies for data-centre recovery consider delivery temperatures up to approximately 120 °C (Wang et al., 2024), while trans critical CO₂ systems have also been analysed (Li et al., 2021).

Table 6: Indicative district-heating integration pathways according to the data-centre heat temperature

Recoverable heat temperature	Typical integration pathway	Main technical consideration
~15–30 °C	High-lift heat pump	High compressor electricity demand; a large source flow may be required
~25–40 °C	Heat-pump upgrading to the required delivery temperature	Conventional low-temperature waste-heat recovery case
~35–50 °C	Heat pump and/or return-line preheating	Reduced temperature lift and improved heat-pump performance
~45–60 °C	Return-line integration; booster heat pump where required	Favourable match to lower-temperature networks
≥60 °C	Direct exchange, where network conditions permit; booster heat pump, where required	Hydraulic separation, delivery temperature, and network control

The ranges are indicative rather than rigid thresholds, because the heat-exchanger approach temperatures, network operating conditions and seasonal variations can shift the preferred integration pathway (Table 6).

Thermal storage and peak supply

Data-centre heat is generally better suited to base-load or intermediate-load supply than to peak demand. Short-term storage can reduce the hourly mismatch and heat-pump cycling, while the existing or dedicated peak and backup sources remain necessary during high-load periods or source outages. Storage does not eliminate the persistent seasonal surplus, so the recovery capacity should be sized against usable demand rather than the maximum recoverable source power.

4.3 Heat-Pump Energy Balance

In the following analysis, recoverable waste heat refers to the thermal energy recovered from the data-centre cooling system at the heat pump's source side. Useful delivered heat refers to the thermal energy supplied at the heat-pump outlet or, more generally, at the receiving-system boundary. For heat-pump integration, useful

delivered heat therefore consists of the recovered source heat and the electrical energy supplied to the heat pump.

Where a heat pump is required, the coefficient of performance in the heating mode is defined as

$$COP = \frac{Q_{DH}}{P_{el,HP}} \quad (11)$$

where COP is the heat-pump coefficient of performance in the heating mode, Q_{DH} is the useful thermal power delivered at the heat-pump outlet, and $P_{el,HP}$ is the electrical power input to the heat pump.

Neglecting the auxiliary losses outside the heat-pump control volume,

$$Q_{DH} = Q_{WH} + P_{el,HP} \quad (12)$$

where Q_{WH} denotes the thermal power recovered from the data-centre cooling system.

Combining (11) and (12) gives

$$Q_{WH} = Q_{DH} \left(1 - \frac{1}{COP}\right) \quad (13)$$

and

$$P_{el,HP} = \frac{Q_{DH}}{COP} \quad (14)$$

The formulation is independent of the absolute data-centre size, and can therefore be normalised to 1 MW_{th} of useful heat output.

For the illustrative reference value COP of 4.3, equations (13) and (14) give

$$Q_{WH} = 0,767 Q_{DH}$$

and

$$P_{\text{el,HP}} = 0,233 Q_{\text{DH}}$$

Thus, each 1 MW_{th} of useful delivered heat requires approximately 0.767 MW_{th} of recovered data-centre heat and 0.233 MW_{el} of heat-pump electricity (Figure 4).

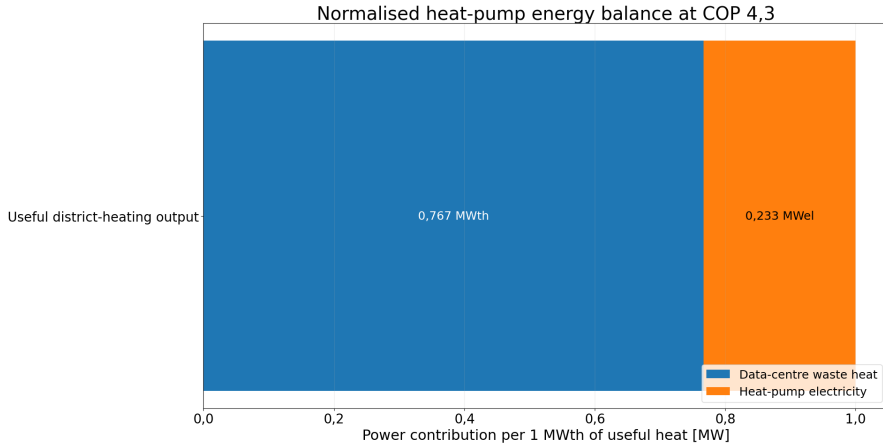


Figure 4: Normalised heat-pump energy balance at COP = 4.3 per 1 MW_{th} of useful delivered heat.

The COP value of 4.3 is used only as a reference scenario. It is consistent with the selected manufacturer's operating points, but is not a validated design COP for a particular data centre or district-heating system. The actual performance depends on the source and sink temperature profiles, heat-pump configuration, part-load behaviour and auxiliary consumption.

4.4 Temporal Characteristics of Data-Centre Heat

Data-centre waste heat is comparatively continuous, whereas the district-heating demand is strongly seasonal. This mismatch can limit the annual utilisation, even when the source availability is high (Wahlroos et al., 2017; Olthmanns et al., 2020; Feike et al., 2021; Li et al., 2021; Jürgens et al., 2024).

For a simplified annual assessment, the operation can be represented by the equivalent full-load hours. For an installed useful heat-output capacity Q_{HP} ,

$$E_{\text{DH}} = Q_{\text{HP}} h_{\text{eq}} \quad (15)$$

where h_{eq} denotes the equivalent full-load hours.

At constant reference COP,

$$E_{WH} = E_{DH} \left(1 - \frac{1}{COP}\right) \quad (16)$$

and

$$E_{el,HP} = \frac{E_{DH}}{COP} \quad (17)$$

For a normalised useful heat-output capacity of 1 MW_{th} and a COP of 4.3:

Table 7: Normalised annual energy balance per 1 MW_{th} of useful heat-pump output at COP = 4.3

Equivalent full-load hours [h/a]	Useful delivered heat [GWh/a]	Data-centre waste heat [GWh/a]	Heat-pump electricity [GWh/a]
2.000	2,000	1,535	0,465
3.000	3,000	2,302	0,698
4.000	4,000	3,070	0,930

At 3,000 equivalent full-load hours, 1 MW_{th} of installed useful heat-output capacity therefore supplies 3,000 GWh/a, requiring approximately 2.302 GWh/a of recovered source heat and 0,698 GWh/a of heat-pump electricity (Table 7).

Equivalent full-load hours are useful for screening, but do not capture the actual temporal interaction between the source and the sink. Project design, therefore, requires hourly, or sub-hourly source and demand profiles, in which the seasonal mismatch, part-load COP, or storage operation affects utilisation materially.

5 General Economic Framework for Waste-Heat Utilisation

The economic assessment of waste-heat utilisation requires a system boundary that is consistent with the technical source–sink framework. The relevant quantity is not the nominal heat value at the source, but the cost of useful heat delivered to the receiving system. Recovery equipment, temperature upgrades, transport, connection infrastructure, auxiliary electricity, and operation and maintenance can all contribute

materially to this cost. Large-scale heat-pump projects also show that a substantial fraction of the investment can arise outside the heat-pump unit itself, including source-side equipment, civil works, piping and other balance-of-plant components (Pieper et al., 2018).

In the present framework, the economic system boundary extends from the recoverable waste-heat interface at the source to the point where useful heat is delivered to the receiving heat system. The costs downstream of this boundary are excluded, such as the existing district-heating distribution, retail billing, taxes and consumer-side charges. This distinction prevents a direct comparison between a generation or integration cost and a final household tariff, since the two quantities represent different system boundaries.

The resulting levelised cost should be interpreted as a screening indicator. Project-specific investment costs can vary substantially with the heat source, temperature level, capacity, distance, route conditions and connection requirements (Pieper et al., 2018). Technology catalogues can provide reference values where project-specific quotations are unavailable, but such values do not replace the engineering design or supplier data (Danish Energy Agency, 2026).

5.1 Cost Components

The levelised cost of useful heat recovered from a waste-heat source can be decomposed into the components of recovery, upgrading, transport, integration and operation. Using a common delivery boundary,

$$LCOH_{WH} = C_{\text{recovery}} + C_{\text{upgrade}} + C_{\text{transport}} + C_{\text{integration}} + C_{\text{operation}} \quad (18)$$

where all the terms are expressed per unit of useful heat delivered at the receiving-system boundary.

For a project using a heat pump and dedicated connection infrastructure, a more explicit formulation is

$$LCOH_{WH} = \frac{(CAPEX_{rec} + CAPEX_{HP} + CAPEX_{pipe} + CAPEX_{conn})CRF + OPEX_{fix}}{E_{use}} + OPEX_{var} + C_{el} + C_{source} \quad (19)$$

where $CAPEX_{rec}$ is the source-side recovery investment; $CAPEX_{HP}$ is the heat-pump investment; $CAPEX_{pipe}$ is the thermal transport investment; $CAPEX_{conn}$ is the receiving-system connection and hydraulic integration; $OPEX_{fix}$ and $OPEX_{var}$ are the fixed and variable operation and maintenance costs; E_{use} is the net annual useful heat delivered at the selected receiving-system boundary after losses within that boundary; C_{el} is the specific heat-pump electricity cost; and C_{source} is the contractual cost assigned to the recovered waste heat.

The pumping electricity, transport losses and other auxiliaries must be represented consistently with this boundary, either explicitly, or within the corresponding variable-cost and energy terms.

The capital recovery factor is

$$CRF = \frac{r(1+r)^n}{(1+r)^n - 1} \quad (20)$$

where r is the real discount rate, and n is the economic lifetime in years.

The project investment boundary should extend beyond the heat-pump package itself. Pieper et al. (2018) showed for large-scale district-heating heat-pump projects that a substantial part of the total investment can arise from the source systems, civil works, piping and other project components. The reported allocation should not be transferred as a universal percentage to other projects, but it demonstrates why the heat-pump purchase cost alone is an insufficient proxy for the total project investment.

The transport cost is particularly site-dependent. The pipeline length, thermal capacity, pipe diameter, route conditions, operating temperature and utilisation all affect the specific cost of the delivered heat. A short connection between a source and an existing district-heating main can therefore have a substantially different cost

structure than that of an otherwise similar source located several kilometres from the receiving network.

The denominator E_{use} is equally important. The fixed investment is recovered over the useful heat actually delivered rather than over the theoretical annual heat available at the source. Low annual utilisation, therefore, increases the capital component of $LCOH_{\text{WH}}$, even if the installed capacity and source availability remain unchanged.

5.2 Heat-Pump Electricity Cost

For the heat-pump control volume defined by the useful heat output, the required compressor electricity per unit of useful heat delivered is $1/\text{COP}$. At a constant electricity acquisition price p_{el} , the corresponding specific electricity cost is

$$C_{\text{el}} = \frac{p_{\text{el}}}{\text{COP}} \quad (21)$$

Equation (21) shows directly why both electricity prices and heat-pump performance influence the waste-heat economics strongly. The same increase in electricity prices produces a larger increase in heating costs when COP is low than when COP is high.

The relationship also links the economic model to the source and sink temperatures. The COP should not be treated as an independent economic parameter: it is determined by the operating temperatures, heat-pump configuration and part-load behaviour (Pieper et al., 2021). A fixed COP is therefore appropriate only for a clearly identified reference scenario.

For screening purposes, sensitivity should, at a minimum, consider the electricity acquisition price, the heat pump COP, and the annual useful heat delivered, or the equivalent full-load hours. The electricity prices and COP affect the operating costs directly, whereas the annual utilisation affects primarily the specific contribution of fixed investment and fixed O&M.

If the installed thermal capacity is Q_{HP} and annual operation is represented by equivalent full-load hours h_{eq} ,

$$E_{\text{use}} = Q_{\text{HP}} h_{\text{eq}} \quad (22)$$

and the annualised capital component is

$$C_{\text{cap}} = \frac{CAPEX_{\text{tot}} CRF}{Q_{\text{HP}} h_{\text{eq}}} \quad (23)$$

where

$$CAPEX_{\text{tot}} = CAPEX_{\text{rec}} + CAPEX_{\text{HP}} + CAPEX_{\text{pipe}} + CAPEX_{\text{conn}}.$$

Equation (23) explains the strong economic importance of utilisation. An installation designed for a large nominal source capacity but used for relatively few hours can have a high specific capital cost, even where the waste heat itself has no contractual purchase price.

The equivalent full-load hours remain a simplified representation. A detailed feasibility analysis should use time-dependent electricity prices, heat-pump performance, and source–sink profiles where available. Hourly modelling of large heat pumps has been used to account explicitly for seasonal source temperatures, capacity constraints and variations in the COP (Pieper et al., 2019).

5.3 Cost of the Waste-Heat Source

Waste heat is described frequently as free, because it is a by-product of another process. This assumption is not generally valid from a project-economic perspective.

If the source owner provides recovered heat without a transfer payment,

$$p_{\text{WH}} = 0 \quad (24)$$

This does not imply that the useful heat delivered is free, as recovery, upgrading, transport, connection and operating costs still apply.

Where the source owner charges for recovered heat, the source term depends on the amount of source heat required per unit of useful heat. For the idealised heat-pump balance,

$$C_{\text{source}} = p_{\text{WH}} \left(1 - \frac{1}{\text{COP}} \right) \quad (25)$$

Equation (25) assumes that the contractual measurement boundary coincides with the waste-heat input to the heat pump, and that the additional losses between the commercial source boundary and the heat pump are negligible, or accounted for elsewhere.

For a more general project with recovery or transport losses, the source term can be written as

$$C_{\text{source}} = p_{\text{WH}} \frac{E_{\text{WH,purchased}}}{E_{\text{use}}} \quad (26)$$

Here, $E_{\text{WH,purchased}}$ denotes the thermal energy purchased at the contractual waste-heat transfer point. This form is preferable when the commercial transfer point, heat-pump source boundary and final delivery boundary do not coincide.

The source price can reflect different contractual arrangements. The source owner may provide heat at zero price, charge for it as an energy product, or contribute to the recovery infrastructure if the heat export reduces its own cooling requirement. Conversely, the receiving heat utility may finance the source-side recovery equipment in return for a lower long-term heat price. The economic value of waste heat is therefore both contractual and thermodynamic (Jerez Monsalves et al., 2024; Moser & Jauschnik, 2023).

No universal source price should be assigned to waste heat. Its acceptable value depends on the receiver's avoided heat-production cost, the investment allocation between the parties and any avoided cooling cost at the source.

5.4 Economic Decision Criterion

The economic viability should be evaluated against the cost of the heat supply that the waste heat actually displaces. The relevant condition is

$$LCOH_{WH} < C_{\text{alternative}} \quad (27)$$

where $C_{\text{alternative}}$ represents the comparable cost of supplying the same useful heat from the relevant alternative.

Depending on the receiving system, the alternative can be heat from a gas-fired boiler, biomass heat, heat from an existing or new CHP plant, purchased external heat, another large-scale heat pump, or another planned replacement technology.

The comparison must use consistent system boundaries. If $LCOH_{WH}$ includes the investment, fixed O&M and variable operation over the project lifetime, it should not be compared only with the fuel component of an alternative new-build technology. Conversely, if the decision concerns short-term dispatch against an already installed boiler, the relevant comparator can be the avoidable marginal cost rather than the full levelised cost of that boiler.

Two economic decisions should therefore be distinguished. Operational substitution refers to waste heat displacing variable production from an existing installed capacity. Investment substitution refers to waste-heat recovery, avoiding or replacing investment in another heat-production technology. For operational substitution, $C_{\text{alternative}}$ should represent the avoidable costs that vary with the output, including fuel, the relevant variable O&M, and, where applicable, the emission costs. For investment substitution, an annualised or levelised full cost of the alternative is the more appropriate benchmark.

The same principle explains why household heat tariffs are not suitable as the primary economic comparator. Retail tariffs may remain unchanged after a new source is introduced, covering network operations, fixed infrastructure, regulation, taxation and consumer billing. Economic attractiveness should therefore be

interpreted relative to the displaced heat-supply cost rather than the final consumer tariff.

5.5 Break-Even Waste-Heat Price

The contractual value of source heat can be expressed through a break-even condition. Let C_0 denote the levelised cost of useful heat excluding payment for the waste-heat source:

$$C_0 = \frac{CAPEX_{\text{tot}}CRF + OPEX_{\text{fix}}}{E_{\text{use}}} + OPEX_{\text{var}} + C_{\text{el}} \quad (28)$$

For the simplified heat-pump source-price formulation,

$$LCOH_{\text{WH}} = C_0 + p_{\text{WH}} \left(1 - \frac{1}{COP}\right) \quad (29)$$

The break-even source price is obtained by imposing

$$LCOH_{\text{WH}} = C_{\text{alternative}} \quad (30)$$

which gives

$$p_{\text{WH,max}} = \frac{C_{\text{alternative}} - C_0}{1 - \frac{1}{COP}} \quad (31)$$

The result represents the maximum price that can be paid per unit of source heat while keeping the recovered-heat option economically equivalent to the selected alternative, under the assumptions used to determine C_0 .

If $C_{\text{alternative}} \leq C_0 \Rightarrow p_{\text{WH,max}} \leq 0$. In that case, the project is not competitive, even when the waste heat itself is provided free of charge. The economic feasibility would then require lower capital and electricity costs, higher COP, higher utilisation, lower transport costs, or another improvement in the project configuration.

Conversely, a positive $p_{WH,max}$ indicates economic headroom that can, potentially, be allocated between the source owner and the heat utility. The resulting value is not a universal market value of waste heat. It is specific to the selected alternative, source–sink configuration, annual utilisation, electricity price, COP, transport distance, investment allocation and financial assumptions. It should therefore be interpreted as a project-specific negotiation boundary rather than as a nationally applicable waste-heat price.

6 Application to the Slovenian Context

Application of the source–sink framework to Slovenia requires distinguishing between theoretical heat generation, technically recoverable heat, and heat that can actually be delivered to a compatible sink. The national statistics support an order-of-magnitude assessment, but do not provide the spatial, thermal, and temporal resolution required for project-level feasibility.

For data centres, the available statistical basis allows a first national screening estimate. In 2023, 41 surveyed Slovenian data centres consumed 36,833 GWh of electricity and had a combined rated electrical capacity of 7,554 MW (Statistical Office of the Republic of Slovenia, 2025b). Since nearly all the electricity consumed ultimately appears as heat, the annual theoretical heat output is of the same order as electricity consumption.

Using an illustrative literature-based recovery envelope of 70–80% (International Energy Agency, 2025),

$$E_{WH,tech} = \eta_{rec} E_{el,DC} \quad (32)$$

With $\eta_{rec} = 0.70$ – 0.80 , Equation (32) gives approximately 25.8–29.5 GWh/a.

This range represents the technically recoverable source heat, not the national utilisation potential. The facilities are dispersed geographically; most are small, and the national statistics do not provide the source temperatures, cooling architectures, nearby heat demand, or feasible connection routes needed to determine the usable fraction.

If all the technically recoverable heat could be supplied to a suitable sink through a heat pump operating at the reference value $COP = 4.3$,

$$E_{DH} = \frac{E_{WH}}{1 - \frac{1}{COP}} \quad (33)$$

the corresponding useful-heat envelope would be approximately 33.6–38.4 GWh/a. This value indicates the technical scale only, and should not be interpreted as a forecast of the annual heat reuse.

6.1 Screening Criteria and Numerical Boundaries

Seven criteria are used for Slovenian screening: source temperature, recoverable thermal capacity, temporal availability, source–sink distance, heat-demand magnitude, the required temperature upgrading and the existing infrastructure.

Several criteria are effectively non-compensatory. Insufficient heat demand, an infeasible connection route, or an inability to achieve the required delivery temperature can prevent utilisation, regardless of the otherwise favourable source characteristics (Table 8).

Table 8: Technical screening criteria for Slovenian waste-heat projects

Criterion	Favourable	Conditional	Unfavourable
Source temperature	>45 °C or a small required lift	30–45 °C	<30 °C for conventional DH
Recoverable capacity	Well matched to the base or intermediate load	Partial utilisation expected	Exceeds the local usable demand strongly
Temporal availability	High coincidence with the sink demand	Moderate seasonal mismatch	Persistent mismatch
Source–sink distance	Short and technically simple connection	Moderate route length or complexity	Long or technically difficult connection
Heat-demand magnitude	High base-load absorption	Adequate only seasonally	Insufficient local heat demand
Expected COP	≈4 or higher	Approximately 3–4	Below 3
Existing infrastructure	Suitable network and electrical capacity available	Moderate adaptation required	Major new infrastructure required

The thresholds in Table 8 are screening values rather than design limits. The source temperature and expected COP indicate the likely difficulty of integration with conventional district heating, while the acceptable distance depends jointly on the thermal capacity, utilisation, route conditions and connection cost (Bühler et al., 2017, 2018). The project appraisal must therefore replace these screening categories with measured data on sources and sinks.

6 Realistic Project-Scale Scenarios

Aggregating the existing Slovenian data-centre stock into a single hypothetical heat source would be unrealistic, as the facilities are distributed spatially. Project-scale scenarios provide a more useful basis for examining future or expanded facilities.

Three useful delivered-heat capacities are considered: 5, 15, and 30 MW_{th}. They represent small, medium and relatively large recovery projects in the Slovenian context without assuming a hyperscale facility (Table 9).

At COP of 4.3, the heat-pump balance gives:

Table 9: Data-centre heat-recovery project scales at COP = 4.3

Useful heat output	Required DC source heat	Heat-pump electricity
5 MW _{th}	3.84 MW _{th}	1.16 MW _{el}
15 MW _{th}	11.51 MW _{th}	3.49 MW _{el}
30 MW _{th}	23.02 MW _{th}	6.98 MW _{el}

The annual useful heat depends on the utilisation. Continuous full-load operation throughout the year would be unrealistic for a district-heating sink with a strongly seasonal demand. A screening value of 3,000 equivalent full-load hours is therefore used to illustrate the annual scale, rather than as a universal utilisation assumption (Table 10).

Table 10: Annual useful heat at 3,000 equivalent full-load hours

Useful capacity	Annual useful heat
5 MW _{th}	15 GWh/a
15 MW _{th}	45 GWh/a
30 MW _{th}	90 GWh/a

The values show why the maximum theoretical source output should not be interpreted as the annual useful heat. Higher utilisation is possible where the receiving system provides sufficient base-load demand, but the published case studies also show strong dependence on the actual network load and operating conditions (Wahlroos et al., 2017; Socci et al., 2024).

6.3 Economic Screening Under Slovenian Conditions

Technical recoverability does not imply economic viability. The official Slovenian reference retail electricity price for an average non-household consumer in the second quarter of 2026 was 169.5 €/MWh, including VAT. For a VAT-registered project evaluated before recoverable VAT, the corresponding reference used here is 138.93 €/MWh (Ministry of Infrastructure and Energy, Portal Energetika, 2026). This value serves as a national screening input rather than a project-specific procurement price.

A complete recovery project includes more than the heat-pump package. Source-side recovery, hydraulic integration, piping, electrical connections and other balance-of-plant components can contribute materially to the total investment (Pieper et al., 2018; Danish Energy Agency, 2026). Three total-investment scenarios are therefore used: 800, 1,200, and 1,800 €/kW_{th}.

These are not quoted project costs in Slovenia. They represent progressively more demanding integration configurations for sensitivity analysis. The total CAPEX follows the investment boundary defined in Equation (19) and includes source-side recovery, heat-pump, piping and connection infrastructure.

Using a 20-year economic life, a 5% real discount rate, fixed O&M of 2,000 €/MW_{th}·a, variable O&M of 2 €/MW_{th}, and the electricity price above, the screening costs in Table 11 are calculated according to Equations (19)–(23).

The screening scenarios do not resolve source–sink distance, pipeline length and diameter, pumping electricity, or thermal transport losses explicitly. These site-specific effects are represented only through the assumed aggregate integration cost. The results should therefore be interpreted as screening values rather than project-specific feasibility estimates. A detailed assessment requires the actual connection

route, hydraulic design, operating temperatures, pumping requirements and transport losses.

Table 11: Screening cost of useful heat, excluding payment for the waste-heat source

Scenario	COP	Total CAPEX [€/kW _{th}]	EFLH [h/a]	C ₀ [€/MWh _{th}]
Favourable	4.5	800	3,500	51.8
Conditional	3.5	1,200	3,000	74.5
Difficult	3.0	1,800	2,500	106.9

The spread is substantial. Before payment for the source heat, the C_0 ranges from approximately 52 €/MWh in the favourable case to approximately 107 €/MWh in the difficult case.

If an illustrative source-heat transfer price of $p_{WH} = 20$ €/MWh_{WH} is included according to Equation (29), useful-heat costs increase to approximately 67.3, 88.7, and 120.2 €/MWh for the favourable, conditional, and difficult configurations, respectively. Here, MWh_{WH} denotes a megawatt-hour of recovered waste heat measured at the contractual source boundary. The source price affects the result, but poor source–sink matching can dominate the total cost, even when the waste heat itself is inexpensive.

6.4 Break-Even Interpretation

The acceptable source-heat price depends on the cost of the heat supply that the recovered heat displaces. For an illustrative alternative heat cost of $C_{\text{alternative}} = 80$ €/MWh, the break-even relation gives approximately 36.3 €/MWh_{WH} for the favourable configuration, 7.8 €/MWh_{WH} for the conditional configuration, and –40.4 €/MWh_{WH} for the difficult configuration.

A negative break-even value indicates that the project is not economically viable relative to the selected alternative, even when the source heat is supplied free of charge. The feasibility would then require lower investment, higher utilisation, higher COP, lower electricity or transport cost, or a higher avoided heat-supply cost.

The 80 €/MWh value is an illustrative benchmark rather than a national Slovenian replacement-heat cost. The appropriate comparator depends on the receiving system, and on whether the waste heat displaces a short-run production, or substitutes a long-run investment.

The break-even value, therefore, represents the residual economic value of the source heat after accounting for the costs of recovery and delivery, not the inherent market price of the waste heat.

6.5 Data Centres as a Slovenian Opportunity

The quantitative screening indicates that the existing Slovenian data-centre stock represents primarily a local, rather than a national, heat-supply opportunity. Even the upper technical recovery envelope remains small relative to the national district-heating delivery, while the geographical fragmentation reduces the share that is practically usable further.

Future larger facilities can nevertheless become material heat sources for individual networks where sufficient coincident demand and acceptable integration conditions exist. Their main planning advantage is that the siting and cooling-system design can still be coordinated with potential heat reuse before the infrastructure is fixed.

Proximity to the district heating should therefore be treated as one siting criterion rather than an overriding requirement. The electricity grid access, telecommunications infrastructure, land, cooling requirements and sufficiently large heat demand must be considered simultaneously.

The cooling architecture affects the external heat value directly. Higher-temperature liquid cooling reduces the required temperature lift and heat-pump electricity demand relative to conventional low-temperature cooling (Yuan et al., 2025; Oltmanns et al., 2020; Feike et al., 2021; Wang et al., 2024). The benefit remains conditional on the receiving network having sufficient base-load demand; where the summer load is low, the recovery capacity should be sized against usable demand rather than the maximum source output.

7 Discussion and Conclusions

7.1 Discussion

The results show that the usefulness of waste heat in Slovenia cannot be inferred from the aggregate resource estimates alone. The national statistics can identify relevant source categories and approximate energy scales, but economically usable heat emerges only from specific source–sink combinations. Therefore, temperature, demand, temporal coincidence, and spatial proximity determine the practical potential more directly than the gross annual heat availability does.

This distinction is particularly important for data centres. Their present contribution to the Slovenian heat-supply system is limited by the small, geographically fragmented existing stock. However, the future facilities differ from many legacy industrial sources, in that several decisive integration parameters can still be influenced during project development. The siting, cooling-system selection, and the choice of the receiving heat system. can therefore affect recoverability before the long-lived infrastructure is fixed.

The economic screening also shows that feasibility is highly sensitive to project configuration. Under favourable combinations of source temperature, COP, annual utilisation and integration cost, the recovered heat can compete with the plausible alternative heat sources. When several conditions deteriorate simultaneously, however, the useful-heat cost can exceed 100 €/MWh, even before any payment for the source heat is included. The economic penalty is therefore cumulative rather than attributable to a single variable.

The break-even source-heat price provides a useful interpretation of this result. Waste heat does not possess an intrinsic economic value independent of its use. Its acceptable price is the residual value remaining after deducting the recovery, temperature upgrading, transport, auxiliary electricity and other integration costs from the cost of the displaced heat supply. A negative break-even price indicates that the source–sink combination is unattractive, even when the waste heat itself is free.

The results, therefore, favour early integration of heat-reuse considerations into the planning of the future energy-intensive infrastructure. For large new data centres, the value of heat recovery can depend as much on siting and cooling architecture as on the efficiency of the recovery equipment itself. The waste-heat policy should consequently prioritise technically compatible and economically justified source–sink combinations, rather than pursue heat recovery as an objective in isolation from local system conditions.

7.2 Conclusions

Waste-heat utilisation can contribute to the Slovenian heat supply, but its role is inherently selective. The strongest cases combine favourable thermal quality, persistent nearby demand and limited integration burden; the weakest cases combine low source temperature, long distance, seasonal mismatch, low utilisation and high project cost.

The results do not support a general policy of connecting every available waste-heat source to district heating. They support a targeted screening approach, followed by a detailed analysis only for source–sink combinations that satisfy both the technical and economic criteria.

The principal finding is therefore not that Slovenia has a large generic waste-heat resource, but that specific, well-matched waste-heat sources can provide an economically relevant local heat supply. In contrast, poorly matched sources remain unattractive despite their theoretical energy content.

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Povzetek v slovenskem jeziku

Izraba odpadne toplote v Sloveniji: povezovanje virov in ponorov ter ekonomski screening .

Odpadna toplota lahko prispeva k oskrbi s toploto le tam, kjer so značilnosti vira usklajene z lokalnim povpraševanjem in so stroški integracije sprejemljivi. Članek razvija okvir za presojo izrabe odpadne toplote v Sloveniji, ki povezuje toplotno kakovost, izkoristljivo zmogljivost, časovno razpoložljivost, prostorsko bližino, značilnosti toplotnega povpraševanja in infrastrukturne zahteve z ekonomsko presojo na podlagi stroška dobavljene toplote. Analiza razlikuje med teoretično razpoložljivo, tehnično izkoristljivo in ekonomsko uporabno odpadno toploto. Obravnavan je tudi razvoj energetske intenzivnih dejavnosti: tradicionalne procesne industrije so postopno izboljševale notranjo integracijo toplote, medtem ko digitalna infrastruktura ustvarja nove koncentrirane porabnike električne energije z omejenim lastnim toplotnim povpraševanjem. Podatkovni centri so zato obravnavani kot nastajajoča kategorija virov za zunanjo izrabo toplote. Za obstoječi slovenski fond podatkovnih centrov je izkoristljiva toplota na nacionalni ravni omejena in pomembna predvsem lokalno. Scenarijski izračuni kažejo, da bi sistema s toplotno močjo 15 in 30 MW pri 3,000 ekvivalentnih urah polne obremenitve letno dobavila približno 45 oziroma 90 GWh toplote. Ekonomski screening pokaže, da odpadna toplota ni nujno poceni vir. Upravičenost izboljšujejo višja temperatura vira, večja izraba, krajša razdalja in zmerni stroški integracije. V neugodnih pogojih lahko strošek dobavljene toplote preseže 100 €/MWh tudi pri brezplačni toploti na viru. Rezultati podpirajo selektiven in lokacijsko specifičen pristop.