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District heating supply optimization under positive energy district targets: A waste-heat dominated case study

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ABSTRACT

Positive Energy Districts (PEDs) represent a transformative approach to reducing urban carbon emissions. Yet the role of district heating (DH) under PED constraints remains underexplored. This paper investigates how PED-specific requirements shape cost-optimal DH supply portfolios. To this end, we extend an existing DH supply model to optimize investment and dispatch under PED requirements. The enhanced model incorporates sector coupling with electricity and PED-specific constraints, including net energy positivity. In addition, the model integrates building renovation decisions by allowing improvements to the building envelope that reduce the space heating demand based on a marginal cost curve of energy savings. The resulting model is used to analyze a waste-heat dominated case study in Slovenia. Results reveal that incorporating PED constraints into the optimization changes the technology portfolios, steering investments toward renewable and electrified heating solutions while utilizing energy storage and improving operational flexibility. CO_2 emissions can be cut by more than 30% while total system cost only increases by 9.6%. By implementing more stringent PED constraints (quarterly versus yearly net zero energy balances), CO_2 emissions can be further reduced, but the levelized cost of heat increases. These findings are derived from a single case study with DH-focused system boundary; results may differ if additional end-uses (e.g., mobility or process electricity/heat) or alternative local energy resources are included. When designing incentives to make the transition from normal urban areas to PEDs possible, policymakers need to take into account the trade-off between system cost, CO_2 emissions and increased cost for the individual consumer.

1. Introduction

The built environment is key to Europe's ambition of becoming climate neutral by 2050 (European Commission, Directorate-General for Energy, 2025). In parallel, cities are responsible for an estimated 75% of global energy consumption and generate 70% of the world's greenhouse gas (GHG) emissions, making them critical for the implementation of decarbonization strategies (International Energy Agency (IEA), 2024). In response, the European Commission launched the Strategic Energy Technology (SET) Plan in 2007 to accelerate the deployment of low-carbon technologies (European Commission - Energy, 2025). Action 3.2 of the SET Plan "Smart Cities and Communities" set the flagship target of creating 100 Positive Energy Districts (PEDs) by 2025 as living laboratories for sustainable urbanization (JPI Urban Europe, 2025).

A PED is "an energy efficient and energy flexible urban area or group of connected buildings that produces net zero greenhouse gas emissions and actively manages an annual local or regional surplus of renewable energy" (JPI Urban Europe, 2025). To achieve this ambition, PEDs must simultaneously (i) enhance end-use energy efficiency, (ii) maximize on-site renewable energy utilization, and (iii) provide the flexibility needed to balance variable supplies with local demand. Urban areas provide the opportunity of optimized multiple energy carrier use and offer further synergies in terms of energy generation, consumption, and storage (Lund et al., 2017). Among the energy needs of European urban areas, space and water heating constitute one of the largest energy demands and remain a major barrier to achieve PED targets due to long-standing dependence on fossil fuels. In this context, fossil-fueled units may still play a transitional role in PEDs as peak-load and backup technologies, but their operation must be progressively reduced and ultimately offset or replaced to comply with PED requirements on renewable supply and net-zero emissions. District Heating (DH) systems provide centralized heat distribution to multiple buildings, offer a viable pathway for urban decarbonization by leveraging sector coupling, excess heat recovery, and integration of Renewable Energy Sources (RES) (Lund et al., 2018). The modernization

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of DH systems is closely aligned with PED objectives, as it supports decarbonization, energy efficiency, and flexible energy management. Fourth-generation District Heating (4GDH) and low-temperature thermal source networks, sometimes called fifth-generation District Heating and Cooling (5GDHC) networks (IEA DHC, 2024), are increasingly recognized as key enablers of this transition. For instance, a comprehensive review by Olsthoorn et al. (2016) examined the integration of RES such as solar and waste heat into low-temperature DH systems, highlighting the potential for increased energy efficiency and environmental benefits. DH networks also support decarbonization by utilizing excess heat from industries, power plants, and data centers (Manz et al., 2023; Tervo et al., 2025).

Despite a growing body of research on DH and PED, significant gaps remain in the understanding of how to optimally design and operate DH systems within the specific framework of PEDs. Existing studies often focus on electricity-centric PEDs (Casamassima et al., 2022), overlooking the complexities of thermal energy supply. Furthermore, there is a lack of optimization models that endogenously integrate PED-specific constraints, such as annual or seasonal net positive primary energy balances, and simultaneously co-optimize supply-side investment and demand-side reduction measures, like building refurbishment. Thus, this research addresses these gaps by answering the research questions below:

1. How do the PED targets shift the least-cost mix of DH supply technologies, storage capacities, and renovation measures compared to a baseline that minimizes cost alone?
2. What is the contribution of locally generated renewable electricity and power-to-heat technologies to meeting PED targets?
3. How does building renovation influence supply-side choices in achieving PED objectives, and what are the resulting trade-offs between investment cost, system flexibility, and CO_2 abatement?

This paper is structured as follows: Section 2 reviews the PED-specific modeling and DH systems. Section 3 outlines the methodology for optimizing DH supply and demand for PEDs. Section 4 describes the case study and scenario design. Section 5 presents the findings, and Section 6 concludes with key insights and recommendations for future research.

2. Literature review and key contributions

2.1. Positive Energy District (PED) concept

The PED concept represents a shift from single-building Net-Zero Energy Building (NZEB) thinking to district-scale energy planning, expanding through Positive Energy Blocks (PEBs) and related neighborhood concepts (Kozlowska et al., 2024). To accommodate diverse urban concepts, several PED typologies have been defined based on their energy boundaries: Autonomous PEDs (fully self-sufficient), Dynamic PEDs (grid-connected and interactive), and virtual PEDs (utilizing off-site renewable assets) (Albert-Seifried et al., 2022). Irrespective of the archetype, the central technical constraint is the achievement of an annual positive energy balance. To enable consistent comparison of electricity, heat, and mobility vectors, this balance is usually expressed either in primary energy terms or translated into CO_2 equivalent emissions, which focus on the climate impact (Gabaldón Moreno et al., 2021; Wang et al., 2025). However, treating the annual surplus as the sole metric risks overlooking the temporal flexibility that PEDs can offer. Bruck et al. (2021) critiques the standard annual definition, arguing that it implicitly treats the external grid as an infinite "virtual battery". Their analysis reveals that in climatically favored regions, annually balanced PEDs can actually destabilize the grid by causing massive export peaks in summer while remaining heavily import-dependent in winter. To address this limitation, this study introduces a Seasonal PED definition as a complementary and stricter temporal accounting approach, requiring the district to achieve a positive balance within seasonal (three-month) accounting windows. By constraining net-positivity over shorter periods, we expect a stronger incentive for local resource utilization, higher self-consumption, and reduced reliance on seasonal import-export compensation via the grid.

2.2. Technical solutions for PED

The reference framework issued by JPI Urban Europe organizes PED performance into three mutually dependent pillars: energy production, energy efficiency, and energy flexibility, and emphasizes that improvements across all three pillars must be achieved in parallel (JPI Urban Europe, 2025). Heller (2022) provides a comprehensive catalogue of over forty enabling technologies, categorized by Technology Readiness Level (TRL), which facilitates alignment between technological maturity and deployment ambition. Complementing this, Sassenou, Olivieri, and, Olivieri (2024) emphasizes the coordinated deployment of these solutions to enhance efficiency, renewable generation, flexibility, and cost-effectiveness.

Rooftop and façade integrated photovoltaics (PV) provide the backbone of renewable electricity supply in almost every documented PED initiative (Ahrens Kayayan et al., 2025; Bruck et al., 2021). Yet, as highlighted by Lindholm et al. (2021) "energy-onion" model, achieving dynamic PEDs in urban areas with high energy density and limited RESs is challenging. Similarly, Michellod et al. (2025) analyzed renewable self-consumption strategies in Swiss residential buildings, emphasizing their potential contribution to grid stability and overall PED formation. The study highlights the importance of using detailed performance indicators, both monthly and annually, in informing strategic energy policy and infrastructure planning.

Improving building energy performance is crucial for achieving PED goals. Bruck et al. (2022a) underline the critical role of retrofitting existing structures, noting that approximately 75% of the EU's building stock is currently energy inefficient. A case study in Balaguer, Spain, by Guarino et al. (2023) highlights how targeted renovations significantly reduced primary energy consumption, demonstrating the transformative potential of retrofit strategies for existing urban areas. Complementarily, Gouveia et al. (2021) examined historic districts in Lisbon, revealing that combining renovation measures with building integrated photovoltaics (BIPV) effectively reduced annual space heating and cooling demands by up to 84% and 19%, respectively.

Technological solutions within PEDs vary notably according to local climate conditions. Leone et al. (2023) highlights the climate-specific nature of technology adoption, identifying that continental districts commonly employ waste-heat recovery systems, biomass combined heat and power (CHP), district heating networks (DHNs), and centralized heat pumps. Conversely, Mediterranean districts predominantly favor decentralized heat pump solutions. The integration of heat pumps and thermal energy storage (TES) technologies is crucial for maintaining a district energy balance and enhancing flexibility. Laitinen et al. (2021) emphasizes the roles of these technologies in their techno-economic analysis, demonstrating that investments in heat pumps and heat storage remain economically attractive even when energy self-sufficiency targets are relaxed from a 100% self-sufficiency ratio (SSR). Their optimization model shows that these technologies significantly contribute to minimizing life cycle costs (LCC) within PED implementations.

2.3. Tools and methods for PED optimal design

The transition from individual building-level analysis to broader district-scale planning offers additional opportunities for energy efficiency strategies and CO_2 emission reduction (Brozovsky et al., 2021). It also requires new methodologies and metrics specifically tailored for PEDs (Ala-Juusela et al., 2016). PED design encompasses energy generation, efficiency improvements, and surplus energy management, presenting complexities and trade-offs beyond the scope of tools previously developed for nearly zero energy buildings (nZEBs) (Natanian et al., 2024). To address these complexities, optimization-based approaches have emerged as essential tools, providing systematic evaluation of optimal configurations over extended time horizons. Bruck et al. (2022b) developed a mixed-integer linear program (MILP) for optimizing PED design and operation, maximizing net present value (NPV) across diverse European contexts. Extending this work, Bruck et al. (2022a) incorporated techno-economic analyses of building retrofits, emphasizing their critical role in PED strategies. Similarly, Volpe et al. (2022) proposed optimization methods specifically designed to evaluate optimal energy distribution flows within PED neighborhoods. Laitinen et al. (2021) presented an optimization model balancing life cycle costs and SSR in a district in Helsinki, demonstrating that partial energy self-sufficiency (positive energy zones) is economically and technically more feasible than complete energy autonomy.

Dynamic energy modeling integrated with life cycle assessment (LCA) further supports comprehensive PED evaluations by combining short-term operational efficiencies with long-term sustainability metrics. Di Pilla et al. (2025) utilized this method to assess a Mediterranean university district, achieving significant reductions in both life cycle energy use and annual demand, yet highlighting the necessity of more holistic solutions for true PED-level net positivity. Environmental performance assessments, including carbon footprint analyses, have also proven critical. Kim et al. (2019) evaluated a net zero energy community incorporating heat pumps, solar thermal systems, seasonal thermal energy storage, and DHNs, resulting in a 61% reduction in CO_2 emissions compared to the baseline scenarios. Similarly, Orehounig et al. (2014) reported an 86% CO_2 emission reduction in a Swiss village leveraging biomass-based DHNs, PV panels, and small hydropower. Gabaldón Moreno et al. (2021) proposed a district-level methodology to explicitly evaluate net CO_{2eq} emissions, considering both imported primary energy emissions and emissions avoided through RES exports.

Multi-scenario modeling frameworks proposed by Costanzo et al. (2024) emphasize the necessity of considering multiple pathways ranging from individual thermal measures to integrated electrification, renewable integration, and building envelope retrofits to accommodate diverse user needs and optimize early-stage PED planning. Battaglia and Vanoli (2024) shows that coupling surplus renewables to Power-to-X pathways (power-to-heat, power-to-gas, and power-to-power) in a newly planned Southern-Italian district can cut down primary-energy demand by about 20% while cutting CO_2 emissions by roughly one-third, underscoring sector-coupled conversion as a viable route to positive energy performance.

At the European level, available tools mainly focus on building retrofit strategies and mapping PED initiatives (Turci et al., 2022). Lerbinger et al. (2023) presents a methodology to determine optimal decarbonization strategies integrating building-level energy supply decisions with DHN expansion. Sassenou, Olivieri, Civiero and, Olivieri (2024) introduces the PlanPED framework, which offers municipalities a three-phase process: diagnosis, design, and implementation for translating integrated energy planning into actual PED deployment. Finally, the accurate determination of primary energy and primary energy factors is central to PED assessment. Hirzel et al. (2023) highlights the complexity of these calculations, particularly in the context of increasing RES penetration.

2.4. Role of district heating in decarbonized energy systems

DH is widely recognized as a cornerstone for the decarbonization of urban energy systems. By aggregating demand across a large number of consumers, DH provides the necessary scale to integrate diverse low-carbon sources such as geothermal heat, ambient heat, and waste heat.

The evolution of DH networks illustrates their growing importance in sustainable energy transitions. Third-generation DH (3GDH) systems were traditionally based on centralized fossil-fuel plants and high supply temperatures. Fourth-generation DH (4GDH) lowered supply temperatures, enabling higher efficiency and greater integration of renewables and waste heat Lund et al. (2014). The most recent development, fifth-generation district heating and cooling (5GDHC), adopts ultra-low temperatures and bidirectional energy flows, allowing simultaneous integration of heating and cooling needs while enhancing compatibility with variable renewable energy (VRE) (Buffa et al., 2019). These evolutionary steps make DH not only more efficient but also more compatible with renewable energy integration and demand-side flexibility. As the penetration of VRE, such as wind and solar, increases, volatility in electricity supply creates challenges for grid stability (Bernath et al., 2021). Through large-scale heat pumps and power-to-heat integration, DH systems can absorb excess renewable electricity, provide peak shaving, and reduce marginal emissions. Recent reviews highlight the readiness of such technologies for integration into smart thermal grids (Akbarzadeh et al., 2024; Ochs et al., 2022). By doing so, DH evolves into an active player in the electricity market, offering critical flexibility services that enable cost-effective renewable integration.

Industrial and urban waste heat represents a large amount of untapped energy. Schmidt et al. (2020) estimate that the total amount of industrial waste heat in the EU exceeds the entire heating demand of its building stock. Recent studies quantify the availability of low-temperature industrial waste heat in the EU and UK, highlighting its significant potential for utilization in low-temperature DH (LTDH) networks through technologies such as heat pumps and Organic Rankine Cycles (ORC) (Kosmadakis, 2024). Beyond waste heat, DH can also integrate geothermal, solar thermal, and ambient heat sources. Thermal Energy Storage (TES) further strengthens the role of DH in future energy systems. TES can be deployed in short-term forms (e.g., insulated water tanks) or seasonal storage configurations (e.g., pits, aquifers). These systems allow the decoupling of electricity consumption (for charging) from heat delivery (for discharging), enhancing both operational flexibility and renewable utilization (Guelpa & Verda, 2019). Yang et al. (2021) demonstrates that large hot water tanks and seasonal pit storage are technoeconomically effective in shifting energy from hours to seasons, enabling high renewable energy shares and reducing electricity system peaks. System-level studies indicate that expanding efficient DH alongside demand reduction is a cost-optimal path to deep emission reduction. Connolly et al. (2014) shows that combining DH with energy efficiency measures achieves EU scale decarbonization targets at lower total system cost than individual heating pathways, while utilizing higher shares of RES.

In summary, DH has transitioned from a centralized heating utility to a cornerstone of decarbonized, renewable-integrated urban energy systems. Its ability to aggregate demand, harness local resources, provide low-cost storage, and couple the heat and electricity sectors makes it essential in the context of PEDs. This promising role motivates the need to investigate how DH can be optimally designed and operated within PED frameworks, which is the focus of the following section on research gaps and objectives.

2.5. Key contributions and novelties

The objective is to determine the cost-effective investment and operational pathways for DH systems to meet PED targets, providing actionable insights for urban planners and policymakers. For this purpose, we develop and apply an optimization model that embeds PED-specific energy balance constraints and explicitly couples heat and power sectors. The novelty of this study lies in the development and application of a PED-specific DH supply and investment optimization model that integrates both supply and demand-side measures to assess their combined effect on achieving PED targets. The main contributions are as follows.

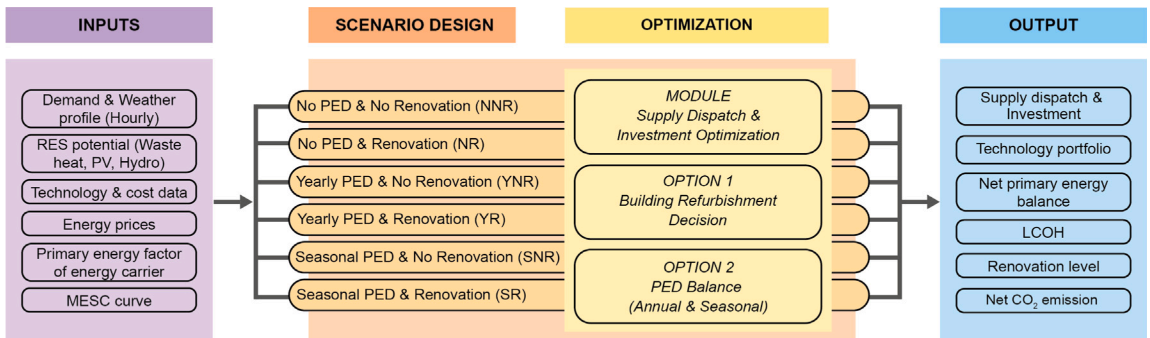


Fig. 1. Overview of the methodological framework.

- A PED-specific DH supply optimization framework is developed by extending the Hotmaps DH supply investment and dispatch model (TU Wien - Energy Economics Group, 2025a) by integrating net energy positivity, carbon neutrality, and refurbishment decision constraints.
- The role of sector coupling between heat and electricity is modeled by integrating renewable electricity sources (PV and excess hydropower) into the DH supply optimization model, providing insights into flexible, low-carbon DH supply strategies.
- The investment and operational pathways for renewable-based DH supply portfolios are optimized for a case study of the industrial zone of Labore in Kranj, Slovenia, evaluating the role of waste-heat recovery, PV, hydropower, and building renovation measures in reducing costs, emissions, and improving system performance.

3. Methodology

Fig. 1 presents the methodological framework of the study, structured into four components: Inputs, Scenario Design, Optimization, and Outputs. Inputs comprise hourly demand and weather data, renewable energy potentials, technology and cost parameters, energy prices, primary energy factors, and marginal energy saving cost curves Appendix A. The framework evaluates six scenarios combining two renovation strategies (none vs. with renovation) with three distinct PED accounting targets: No PED (Baseline), which serves as a purely cost-optimized reference without constraints; Yearly PED, which requires a net positive primary energy balance over the full year, and Seasonal PED, which enforces a stricter constraint requiring a net positive balance within each three-month season. The adopted spatial system boundary and PED accounting boundary used throughout the framework are summarized in Fig. B.9, with full details provided in Appendix B. The optimization framework consists of a core supply dispatch and investment module (Module 1), which can be complemented by two options: cost-optimal building refurbishment decisions (Option 1) and PED balance assessment (Option 2). The outputs include optimal dispatch and investment plans, technology portfolios, net primary energy balance, levelized cost of heat (LCOH), renovation levels, and net CO_2 emissions. All sets, parameters, and decision variables used in the model are listed in Appendix C.

The optimization framework is based on an MILP model that optimizes operations and investments in DH supply systems while ensuring compliance with PED constraints. The approach is based on expanding the existing Hotmaps DH supply investment and dispatch model, incorporating sector coupling, integration of renewable electricity, and PED-specific constraints. The model determines optimal investment and operational scheduling decisions for a single representative year with hourly resolution, where investment (generation and storage capacities) and dispatch are co-optimized to minimize (total annual system cost - total annual revenue), while considering hourly demand, electricity prices, and available heat sources. The following subsections outline the key steps in the methodology:

3.1. DH supply and demand model for PED

The original Hotmaps DH generation model described in TU Wien - Energy Economics Group (2025b) was adapted and expanded to meet the specific requirements of supply optimization for PEDs. These adaptations include modifications to the objective function, incorporation of renewable energy technologies constraints (e.g., PV, hydro), new constraints related to electricity balance, and the inclusion of PED-specific energy balance constraints. The updated implementation of this extended model is available online (Patel, 2026).

The objective function was revised to account for the investment costs of renewable electricity sources, the cost of heat supply (based on the adjusted, lower demand in refurb mode), and the revenue derived from the export of electricity generated by onsite RES. The updated objective function minimizes the total cost of DH generation, refurbishment cost, and PV investment, accounting for revenues from electricity sales:

$$\min\left(c_{total} - rev_{total}\right) \tag{1}$$

The total cost, c_{total}, is defined as:

$$c_{total} = IC + OPEX_{fix} + OPEX_{var} + c_{cold} + c_{ramp} + c_{refurb} \tag{2}$$

The total revenue, rev_{total}, is defined as:

$$rev_{total} = R_{CHP} + R_{PV} + R_{Hydro} \tag{3}$$

Where, c_{total} is the total cost of DH generation, including fixed operational expenses, $OPEX_{fix}$, variable operational expenses, $OPEX_{var}$, ramping costs, c_{ramp}, cold start costs, c_{cold}, and investment costs, (IC). Notably, these investment costs also include the expenditure for renewable electricity capacity, such as PV installations. In parallel, the term rev_{total} sums up the revenue from exporting surplus electricity, which includes the electricity generated by CHP, hydro, and PV.

The demand constraint ensures that the thermal energy supplied meets the DH demand at all time steps:

$$\sum_{j,t} x_{th,j,t} + \sum_{hs,t}(x_{unload,hs,t} - x_{load,hs,t}) = d_t \tag{4}$$

where $x_{th,j,t}$ is the thermal generation from unit j at time t, $x_{unload,hs,t}$ is the thermal energy discharged from heat storage hs at time t, and $x_{load,hs,t}$ is the thermal energy charged into heat storage hs at time t. The thermal energy demand at time t is denoted as d_t.

A PV system was incorporated into the model as a new renewable electricity source. Hourly PV generation is parameterized based on solar irradiance, a performance ratio, and installed PV capacity. To represent realistic electricity flows, the extended model includes an explicit PV electricity balance: PV generation in each time step can either be self-consumed by electricity-to-heat technologies (e.g., heat pumps, electric boilers) or exported to the grid:

$$\mathrm{PV}_{\mathrm{gen},t} = \mathrm{PV}_t^{\mathrm{used}} + \mathrm{PV}_t^{\mathrm{export}}, \tag{5}$$

where PV_t^{used} is the total on-site PV electricity used at time step t, and PV_t^{export} is the total PV electricity export at time step t. To avoid unrealistic self-consumption, PV allocation to each electricity-consuming technology is bounded by its instantaneous electricity requirement:

$$\mathrm{PV}_{j,t}^{\mathrm{used}} \leq \frac{x_{\mathrm{th},j,t}}{\eta_{\mathrm{th},j,t}} \quad \forall\, j \in J_{\mathrm{elec}},\, t. \tag{6}$$

where $x_{\mathrm{th},j,t}$ is the thermal (or useful) output of technology j at time t, and $\eta_{\mathrm{th},j,t}$ its thermal efficiency or COP for heat pumps. This ensures that no device can draw more PV electricity than its instantaneous demand, preventing artificial oversizing of self-consumption and preserving a realistic operational framework. Eq. (6) is formulated only for the thermal demand as the district's non-heating electricity demand is not optimized endogenously; instead, it is treated exogenously and assumed to be fully supplied by locally available run-of-river hydropower (i.e., carbon-free within the chosen system boundary). Electricity enters the optimization only via electricity-consuming DH technologies (e.g., heat pumps, electric boilers) and via accounting of renewable electricity exports for the PED balance.

3.2. Integration of building refurbishment decisions into the DH supply model

In this section, we extend our district heating supply optimization model to account for building envelope refurbishment decisions. The refurbishment decision is modeled by considering the potential for energy savings in a building's overall heat demand (only considering the reduction in space heating demand). This transforms the model from a purely supply-side optimization tool into one that co-optimizes both supply and demand.

For the case study, we used a piecewise linear approximation of the Marginal Energy Saving Cost (MESC) curve data of the Czech Republic from Hummel et al. (2020), since it exhibits similar characteristics of building stock and refurbishment cost structures to Slovenia. Following Hummel (2025), the MESC cost values were updated to current euros using construction cost indices (Eurostat) and an additional uplift factor to reflect a more realistic representation of renovation barriers and implementation constraints. In our implementation, this corresponds to multiplying the original cost values by 1.5 (cost-index update) and 1.8 (barrier uplift), i.e., a combined factor of 2.7. This allows for a representative approximation of the marginal cost of achieving incremental energy savings in the Slovenian context. The MESC curve used in this study is shown in Appendix A, Fig. A.8.

3.2.1. Modeling refurbishment as an investment decision

The decision to renovate buildings becomes a variable that the model can choose, rather than an external assumption. This is implemented using MESC curves from Hummel et al. (2020), which define the cost per unit of energy saved for progressively deeper levels of refurbishment. The total potential for space heating savings is divided into sequential blocks (e.g., seven blocks, each representing a 10% saving). The model can choose to invest in any fraction of these blocks, allowing for incremental and partial refurbishment measures. This is captured by a set of continuous decision variables,

x_i, for each block i.

$$x_i \in [0, 0.10] \quad \forall i \in \{1, \dots, 7\}. \tag{7}$$

which represents the fraction of the 10% block that is derived from the MESC curve. This continuous approach allows partial usage of a block so that the model "fills" the cheapest blocks first.

3.2.2. Costs and savings

Based on the values of the decision variables x_i, the model calculates the total fraction of space heating demand saved, f, by summing the fractions of all implemented blocks:

$$f = \sum_{i=1}^{7} x_i, \tag{8}$$

This total savings fraction is then used to compute two key outputs. First, the total annual energy saved in MWh, E, is calculated as:

$$E = P\,D\,f, \tag{9}$$

where D is the total thermal demand of the building, f is the total savings fraction, and P is the share of space heating in the total demand (set to P = 0.8, i.e., 80%).

Second, the total annualized cost of the refurbishment measures, C_{refurb}, is calculated by multiplying the energy saved in each block by its specific cost c_i (in EUR/MWh) from the MESC curve.

$$c_{\mathrm{refurb}} = \sum_{i=1}^{7} \left(x_i \cdot (P\,D) \cdot c_i \right), \tag{10}$$

where c_{refurb} is the total annualized refurbishment cost and, c_i is the specific marginal energy saving cost for block i.

This cost is then added to the main objective function.

3.2.3. The feedback loop: Demand adjustment

This module introduces the link between refurbishment decisions and the system's hourly heat demand constraint. For each hour t the demand after refurbishment d_t^r, is obtained from the original profile d_t by

$$d_t^r = d_t - \left(d_t \times P \times f \right). \tag{11}$$

where d_t^r is the post-renovation hourly heat demand at time t, and f is the total savings fraction of space heating demand as defined in Eq. (8).

Because demand now depends on the investment variable, the optimization simultaneously balances supply-side and demand-side investments. By capturing these interactions within a single optimization, the framework avoids the sequential approach in which demand is first forecast and supply is designed ex post. Instead, it yields a system-wide optimum that spans the building envelope through to the central generation plant.

3.3. Primary energy balance constraints for PEDs

The final aspect of the model adaptation was the introduction of primary energy balance constraints to ensure compliance with the definitions of PED. A PED is required to produce more energy than it consumes over a given period, typically one year. To capture this requirement, the primary energy balance is evaluated using Primary Energy Factors (PEFs), which provide a measure of the resource intensity associated with different energy carriers. All PEFs applied in this study are documented in the Appendix A, Fig. A.7(c) reports the hourly electricity import/export PEFs, while Table A.4 summarizes the fuel-related PEF assumptions. The total import and export of primary energy are calculated as follows.

3.3.1. Primary energy imports

The total imported primary energy is calculated based on the technologies used to meet DH demand and the electricity imported from the grid. Each energy carrier j (e.g., natural gas, biomass, or electricity) is associated with a PEF, which represents the amount of primary energy required to produce a unit of usable energy. For electricity, we use time-dependent (hourly) PEFs. The hourly import PEF reflects the average primary energy intensity of the grid mix in hour t, calculated from the hourly generation mix. The imports are calculated as:

$$PE_{import,t} = \sum_{j} \left(\frac{x_{th,j,t}}{\eta_{th,j,t}} \cdot PEF_j \right) + E_{import,electricity,t} \cdot PEF_{import,electricity,t}, \tag{12}$$

where $PE_{import,t}$ is the total imported primary energy at time step t, $x_{th,j,t}$ is the heat output of generation unit j, $\eta_{th,j,t}$ is its thermal efficiency, PEF_j is the primary energy factor of the fuel used by unit j, $E_{import,electricity,t}$ is the imported electricity at time step t, and $PEF_{import,electricity,t}$ is the primary energy factor of imported electricity, which may vary dynamically. This formulation ensures that all imported energy is expressed in terms of primary energy, capturing the resource intensity and environmental impact of external dependencies.

3.3.2. Primary energy exports

Locally generated electricity, for example from CHP plants, hydro units, or PV systems, can be exported to the grid and is credited as a benefit in the PED balance. The exported primary energy is calculated as:

$$PE_{export,t} = E_{export,RE,t} \cdot PEF_{export,electricity,t}, \tag{13}$$

where $PE_{export,t}$ is the exported primary energy at time step t, $E_{export,RE,t}$ is the exported renewable electricity (RE), and $PEF_{export,electricity,t}$ is the primary energy factor applied to exported electricity. The hourly export PEF is defined as an avoided (marginal) PEF: exported renewable electricity is assumed to displace marginal fossil-based generation in that hour. We therefore apply an avoided PEF that can exceed the hourly average mix. Note that electricity can be physically exported regardless of generation source; however, in the PED balance only renewable electricity exports are accounted for as $PE_{export,t}$, reflecting the PED's contribution to external energy flows.

3.3.3. Annual primary energy balance

To comply with the PED definition, the total exported primary energy must meet or exceed the total imported primary energy on an annual basis. This requirement is formulated as:

$$\sum_{t=1}^{8760} PE_{export,t} \geq \sum_{t=1}^{8760} PE_{import,t}, \tag{14}$$

where the summation over t spans the entire optimization horizon of one year. This constraint guarantees compliance with PED principles by requiring that net primary energy exports are greater than or equal to imports, thereby reducing energy dependency and maximizing local renewable generation.

4. Description of the case study and scenario design

This work focuses on a specific district in the industrial zone of Labore in the city of Kranj, Slovenia. The availability of extensive data, along with significant potential for waste heat recovery and integration of renewable energy sources, makes this district an ideal case study for evaluating the impact of PED constraints on generation mix and heating costs.

4.1. Case study: Industrial zone of Labore in Kranj, Slovenia

Kranj is the third-largest city in Slovenia, situated in the Gorenjska region and home to approximately 57,000 residents over an area of 143 km^2. As a participant in the "100 Climate Neutral and Smart Cities by 2030" initiative, Kranj is committed to sustainability and has been selected as a pilot site in the PEDvolution project, which aims to transform the city into a PED. The industrial zone of Labore in Kranj currently relies heavily on natural gas to meet its heat demand. The total annual heating demand amounts to about 35,000 MWh, with a peak heat demand of 13.44 MW. This demand is currently supplied by two natural gas boilers with capacities of 7 MW and 10 MW, as well as two natural gas CHP units with capacities of 1 MW and 3 MW. Although these natural gas-based systems provide a robust infrastructure for DH, they underscore the need for a strategic transition toward cleaner, low-carbon alternatives to achieve the city's PED objectives.

A significant opportunity for improving the energy balance lies in harnessing the industrial waste heat within the Labore zone. Both high- and low-temperature waste heat streams can be captured and integrated into the DH network. To leverage this potential, the model scenarios include the adoption of heat pumps that can effectively upgrade lower-temperature waste heat to meet DH supply temperatures. Such an approach reduces natural gas consumption, lowers greenhouse gas emissions, and moves the district closer to becoming a net positive energy system.

In Table 1, the labels A–C denote three distinct industrial waste-heat sources in the Labore zone with different temperature levels and available thermal power. In the model, these sources are represented as exogenous heat streams that can be utilized in the DH supply via a waste-heat heat pump to upgrade low-temperature streams to the DH supply temperature. Where the waste-heat temperature is sufficiently high (e.g., location C), the model represents utilization through direct heat exchange with the DH network; otherwise, upgrading is required via the waste-heat heat pump. By contrast, the air-source heat pump (ASHP) is modeled as a separate technology option that uses ambient air as the heat source. In addition to its potential for waste heat utilization, the district also offers favorable conditions for the deployment of PV systems. The PED extends over approximately 740,000 m^2, and we assume that aggregating available rooftop surfaces across the district can provide up to 30,000 m^2 of PV area; this is implemented as the maximum PV area constraint in the model. This represents an optimistic upper-bound rooftop assumption (not a site-verified availability), and therefore, real-world deployment may be limited by roof suitability, shading, and competing rooftop uses. Moreover, two run-of-river hydropower plants located within the district supply a steady stream of renewable electricity; their surplus output can be used to operate the waste-heat heat pumps, further strengthening the local low-carbon energy mix.

4.2. Scenario descriptions

To assess how PED balance periods and building renovation shape the investment and supply mix of DH, we define six model scenarios (Table 2). All scenarios use identical technology, cost, and demand assumptions; only the PED balance horizon (none, yearly, seasonal) and the allowance for renovation vary. This design addresses two guiding questions: (1) Net primary energy exchange: How do different PED balance periods affect imports and exports? and (2) System adaptation: How does the model adjust generation, storage, renovation, and exports under these constraints?

With these scenarios in place and the key assumptions summarized in Appendix A, the next section presents and discusses the resulting technology portfolio, cost, and operational outcomes under the given constraints.

Table 1
Waste-heat potential at selected locations.

Location	Source T [°C]	ΔT [°C]	Medium flow [$kg\,s^{-1}$]	Power [kW]	Period
A	26	3.0	320	4,000	Year-round
B	55	25	4.2	500	Year-round
C	100	–	0.237	700	Year-round

Table 2
Scenarios combining PED targets and renovation options.

Scenario	PED targets applied	Balance period	Renovation	Short description
Scenario 1 (NNR)	no	–	no	No PED, no renovation
Scenario 2 (NR)	no	–	yes	No PED, with renovation
Scenario 3 (YNR)	yes	yearly	no	Yearly PED, no renovation
Scenario 4 (YR)	yes	yearly	yes	Yearly PED, with renovation
Scenario 5 (SNR)	yes	seasonal	no	Seasonal PED, no renovation
Scenario 6 (SR)	yes	seasonal	yes	Seasonal PED, with renovation

Table 3
Key performance indicators (KPIs) for scenarios.

Scenario	Net cost (M€)	LCOH (€/MWh)	CO_2 emissions (kt)	PV investment (MW)	Net primary energy balance (GWh)	Demand reduction (%)
Scenario 1 (NNR)	1.46	35.40	3.50	0.00	−20.50	0.00
Scenario 2 (NR)	1.46	35.40	3.50	0.00	−20.50	0.00
Scenario 3 (YNR)	1.60	38.60	2.40	5.87	0.00	0.00
Scenario 4 (YR)	1.60	38.60	2.40	5.87	0.00	0.00
Scenario 5 (SNR)	1.88	45.10	1.90	6.00	4.50	0.00
Scenario 6 (SR)	1.84	51.70	1.80	6.00	5.20	16.00

5. Results and discussion

This section presents the quantitative findings of the six scenarios, highlighting how PED constraints and building renovation affect the design and operation of the DH system.

Table 3 summarizes the key performance indicators (KPIs) across the six scenarios. All results are reported for the analyzed year 2024. Refurbishment is represented as an endogenous investment option that reduces the annual heat-demand in the analyzed year and is evaluated via annualized costs; the model does not capture the dynamic evolution of renovation uptake over multiple years. Notably, the paired scenarios without and with the renovation option yield identical results in the baseline (NNR = NR) and yearly PED cases (YNR = YR), as refurbishment is not cost-optimal under these constraints and is only selected in the seasonal PED case (SR). Imposing PED constraints changes the system outcome along three main dimensions. First, it reduces CO_2 emissions (from 3.5 kt in the baseline to 2.4 kt in yearly PED and 1.8–1.9 kt in seasonal PED). Note that CO_2 is counted only for energy imports (natural gas, grid electricity); electricity exported from PV (or CHP) is not given a CO_2 credit. Exports help the PED balance but do not reduce reported emissions, which is why the yearly (YNR, YR) and even the seasonal PED scenarios still show positive CO_2. Second, it shifts the net primary energy balance from a deficit (−20.5 GWh in baseline) to neutrality (0 GWh in yearly PED) and to a surplus (+4.5 to +5.2 GWh in seasonal PED). Third, it increases system costs (net cost from 1.46 M€ in baseline to 1.60 M€ in yearly PED and 1.84–1.88 M€ in seasonal PED), reflecting the additional investments required for local balancing and flexibility.

PV becomes relevant only once PED constraints are imposed, as it contributes to meeting the net primary energy balance through local renewable generation and export credits. Accordingly, no PV is selected in the baseline, whereas PV investment rises to 5.87 MW in the yearly PED cases and reaches the upper bound of 6 MW in the seasonal PED cases. Consistent with these additional requirements, the LCOH increases from 35.4 €/MWh in the baseline to 38.6 €/MWh under the yearly PED and to 45.1–51.7 €/MWh under the seasonal PED. In SR, the LCOH is higher despite a slightly lower net cost than SNR, because renovation reduces the delivered heat volume and therefore increases the cost per MWh of supplied heat.

The following subsections discuss these results in detail, first the technology portfolio shifts under PED constraints, then the cost and flexibility trade-off between the scenarios, and finally the comparison of economic, CO_2, and energy-performance trade-offs.

5.1. Technology portfolio shifts under PED constraints

The transition from a cost-optimized baseline to a PED necessitates a fundamental restructuring of the supply and demand-side technologies. This shift is illustrated in the generation mix (Fig. 2) and installed capacity (Fig. 3).

In the baseline scenarios (NNR and NR), where the objective is pure cost minimization without primary energy balance constraints, the system relies on industrial waste heat. The low-temperature source (26 °C) alone supplies 50.34% of the annual heat, which, combined with medium-temperature streams (55 °C, 5.46%) and high-temperature streams (100 °C, 14.29%), brings the total waste heat contribution to approximately 70%. Additionally, the air-source heat pump contributes 18.54%, indicating that at the assumed energy prices and with an average SCOP of 3.7, heat pump operation is competitive against part of the gas-based generation once the cheapest waste heat has been utilized. The remaining load is still met by natural-gas-based units (two boilers and two CHPs), which together provide about 11%–12% of the heat (around 1–1.5% from each boiler, 1.4% from the smaller CHP, and 7.5% from the larger CHP). These units primarily serve as flexible backup and peak providers when electricity prices are high.

In a purely cost-optimal scenario without PED constraints, the model does not invest in either PV capacity or building renovation. Under the assumed boundary conditions, local PV generation provides limited economic benefit relative to grid electricity when there is no primary energy balance constraint to incentivize exports. Similarly, the NR scenario reproduces exactly the same KPIs and technology mix as NNR, proving that demand-side renovation measures are not yet triggered by cost minimization alone; they only become attractive once additional constraints (seasonal PED balance) are introduced in the subsequent scenarios.

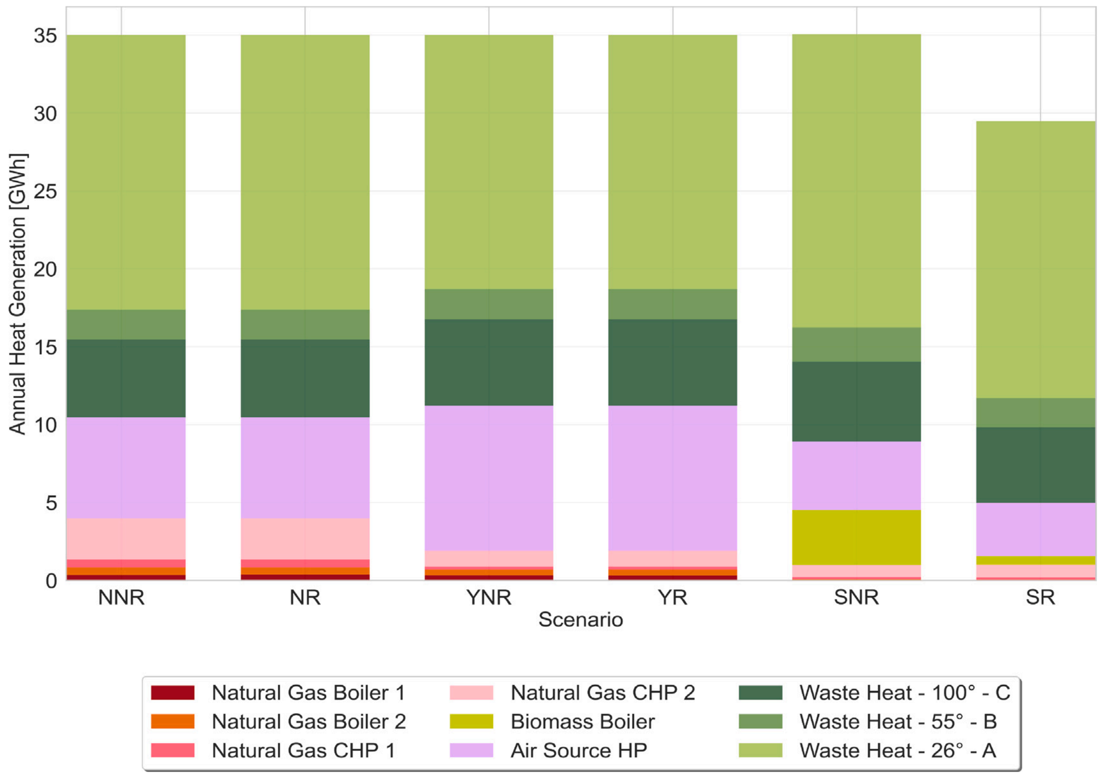


Fig. 2. Generation mix comparison across PED scenarios.

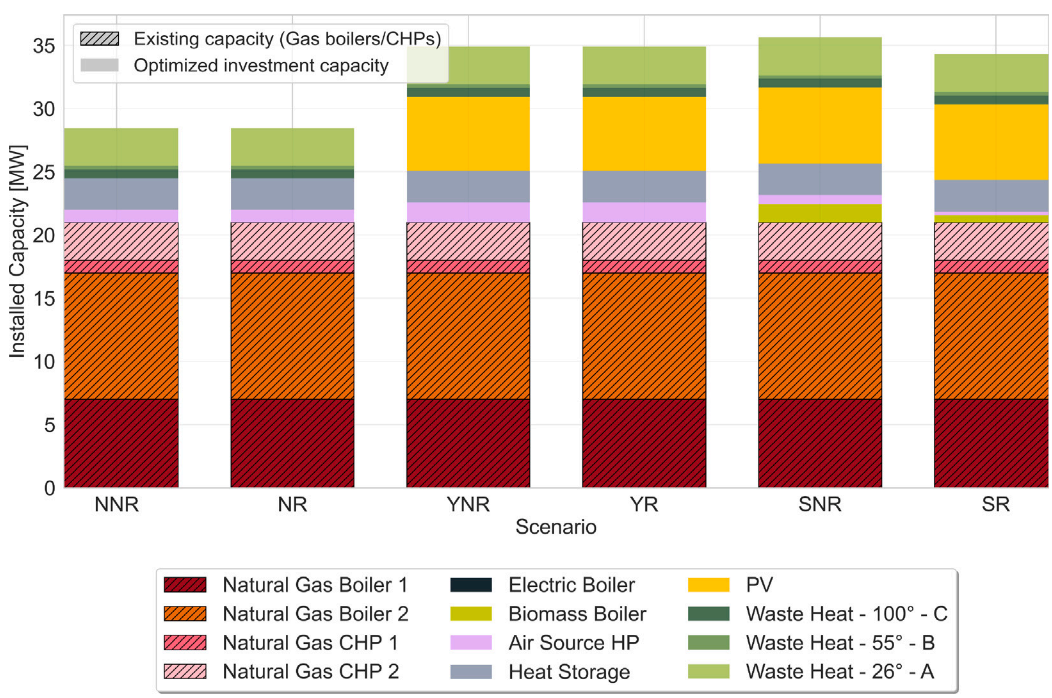


Fig. 3. Installed capacity comparison across PED scenarios.

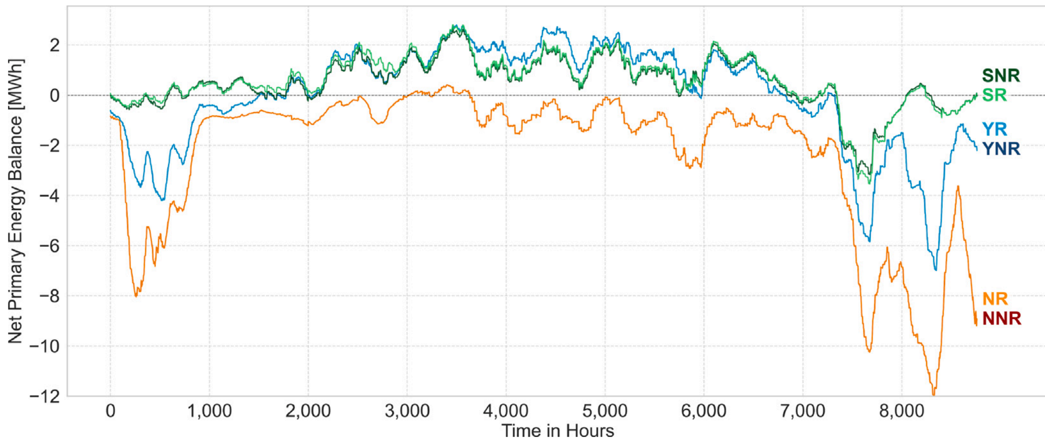


Fig. 4. 7-day rolling-average net primary energy balance.

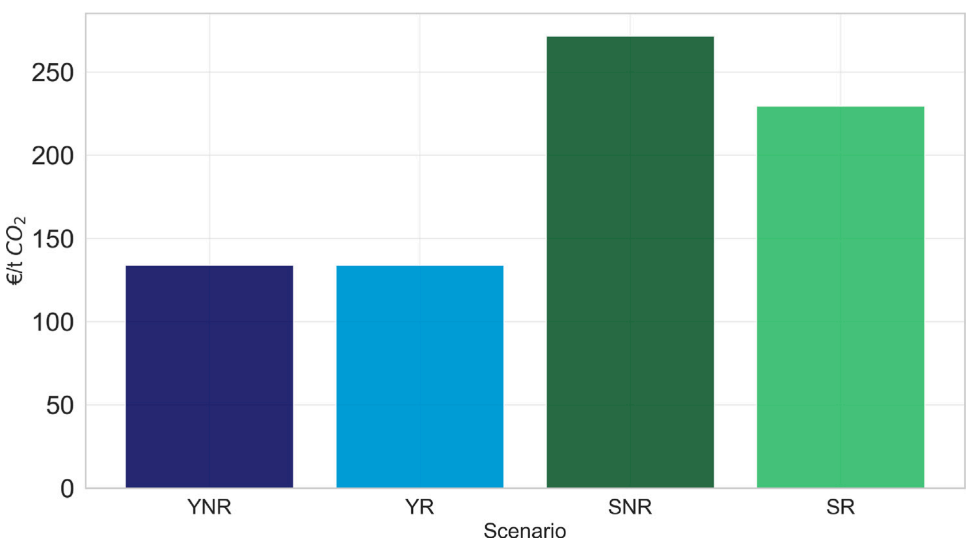


Fig. 5. Specific CO_2 mitigation cost compared to baseline NNR/NR.

The introduction of a Yearly PED constraint (YNR/YR) forces a move away from high-PEF natural gas. To compensate for the primary energy penalty of grid imports and fossil fuels, the model invests in 5.87 MW of PV capacity. The PEF serves as the accounting metric for this balance (values provided in Appendix A). By converting a high-level sustainability target into a strict balancing equation, the PED definition effectively forces the transition to sustainable technologies that would not be selected under pure cost optimization. On the thermal side, the share of industrial waste heat drops slightly to ~65% (44.50% from the 26 °C source, 5.23% from 55 °C, and 15.10% from 100 °C). The missing part is almost entirely taken over by the air-source heat pump, whose share rises significantly from 18.54% in the baseline to 30.00%. Natural gas technologies are pushed to the margin and together provide only about 5% of the annual heat.

Renovation remains unselected in the YR scenario. Since the yearly PED can already be met by a combination of waste heat, 30% heat pump operation, and 5.87 MW of PV, reducing the heat demand through building refurbishment does not bring an additional cost advantage. Therefore, YR replicates the same KPIs and technology mix as YNR.

The strict Seasonal PED constraint (SNR/SR) imposes a rigorous test on the system design, specifically addressing the critical mismatch between renewable generation and heating demand in winter. Since the system cannot rely on summer PV credits to offset winter deficits, it must achieve intraseasonal self-sufficiency. In the SNR scenario (no renovation), the model reaches the upper limit of feasible PV capacity (6.00 MW). Crucially, to bridge the gap during winter when PV is limited, and grid imports carry a high primary energy penalty, the system introduces a biomass boiler. Biomass is treated as a low-PEF dispatchable option ($PEF_{biomass} = 0$ in our PED accounting), assuming the biomass is sourced sustainably within the defined system boundary. While providing only 10.01% of annual heat, this unit acts as a critical low-PEF dispatchable resource essential for meeting peak loads during the heating season without incurring deficits.

However, when renovation is allowed (SR), the optimization logic shifts fundamentally. Renovation reduces total heat demand by 16%, essentially serving as a passive flexibility measure that lowers the winter peak. This demand reduction reshapes the supply stack: the system can now rely more heavily on the baseload industrial waste heat (whose share rises to ~83% relative to the reduced demand). Consequently, the need for expensive "gap-filling" technologies diminishes significantly: the air-source heat pump contribution stabilizes at 11.60%, and reliance on the biomass boiler drastically falls from 10.01% to a residual 1.85%. This demonstrates a pivotal finding: while renovation is not cost-efficient under baseline or yearly accounting, it becomes an essential, cost-optimal technology for achieving seasonal autonomy by mitigating the need for oversized generation infrastructure.

5.2. Yearly versus seasonal PED balance: cost–flexibility trade-off

The fundamental operational difference between the scenarios lies in the temporal resolution of the balancing constraint.

In the yearly PED scenarios (YNR/YR), the system operates as a "virtual battery", exporting excess renewable electricity from PV during the summer to mathematically offset the primary energy deficits incurred during the winter. This accounting mechanism allows the district to achieve a net-zero annual primary energy balance (0 GWh) without requiring strict physical self-sufficiency during the heating season. Consequently, the system eliminates the need for expensive, large seasonal storage or dispatchable low-carbon generation, instead relying on the grid to bridge the seasonal gap. In this configuration, thermal energy storage operates with a relatively flat profile, functioning primarily as a short-term buffer for daily/weekly optimization rather than for long-duration shifting. Detailed results on these storage capacities and seasonal level trajectories are provided in Appendix E.

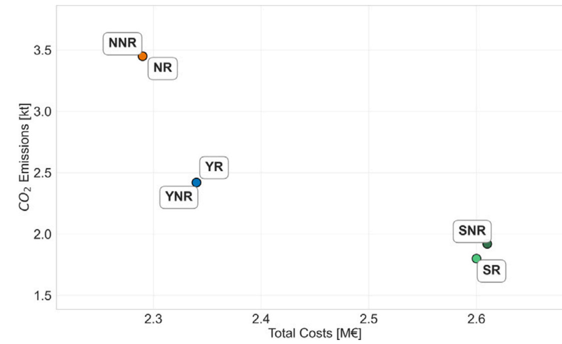
In contrast, the seasonal PED scenarios (SNR/SR) prohibit this annual buffering. As shown in Fig. 4, a net positive primary energy balance must be achieved within each three-month period. This eliminates the possibility of compensating winter deficits with summer surpluses. The removal of this buffer places a high premium on intraseasonal flexibility, making sector coupling essential. The model responds by maximizing the dispatch of large heat pumps to convert local renewable electricity into useful heat. Furthermore, the role of Thermal Energy Storage (TES) shifts fundamentally. The seasonal scenarios drive the model to invest in larger seasonal storage capacities and operate them over the season: charging over extended periods when heat is abundant and discharging during high-demand winter phases.

The economic implications of this flexibility requirement are substantial. As illustrated in Fig. 5, the specific cost of CO_2 mitigation doubles when moving from yearly to seasonal balancing. While the yearly PED targets can be met at a cost of roughly 127 €/tCO_2, achieving seasonal autonomy drives this cost up to 225–260 €/tCO_2. This cost difference represents the system's "willingness to pay" for temporal autonomy. Notably, the SR scenario (225 €/tCO_2) is cheaper than SNR (260 €/tCO_2), confirming that renovation acts as a cost-effective passive flexibility measure under these strict constraints.

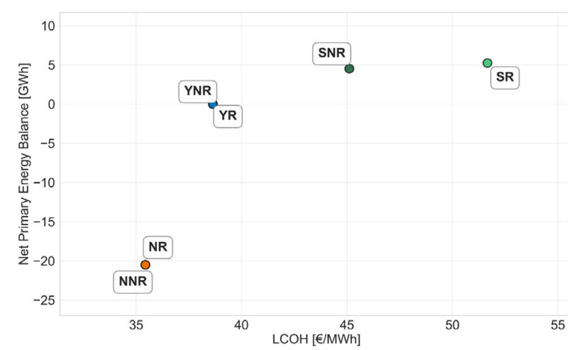
5.3. Cross-scenario analysis of techno-economic, CO_2 savings, and energy performance trade-offs

The trade-off plots (Fig. 6) provide a view of the relationships between economic, CO_2 savings, and energy performance across the six scenarios. A clear trade-off is visible between cost and environmental outcomes. As PED constraints become stricter, transitioning from the NNR scenario to the YR and SR scenarios, there is a steep and consistent reduction in CO_2 emissions, accompanied by a shift from being a net energy importer to a net exporter. However, this progress is achieved at the expense of rising LCOH and total system costs.

The scenarios that include renovation (here, only SR) occupy a slightly more favorable point on the trade-off curve: they achieved low emissions and a positive energy balance with a slightly lower total cost than their non-renovation counterpart, but at a higher LCOH because less heat is sold; therefore, one unit of energy is more expensive. This underlines the benefit of co-optimizing supply- and demand-side measures under PED constraints. Furthermore, the shape of the trade-off curves reveals the marginal cost of CO_2 reduction. The move from NNR/NR to YNR/YR yields a massive reduction in emissions (1.1 kt CO_2) for a moderate increase in net cost (0.14 M€). However, the subsequent step to SR yields a much smaller incremental emissions reduction (0.6 kt CO_2) for a larger incremental net cost increase (0.24 M€). This illustrates an economic principle of diminishing marginal returns on reduction: the final, most difficult step toward complete decarbonization and temporal autonomy is disproportionately more expensive than the initial steps.



(a) Economic vs environmental trade-off (Total costs vs CO_2 emissions).



(b) Economic vs energy performance trade-off (LCOH vs net primary energy balance).

Fig. 6. Economic, environmental, and energy performance trade-offs across scenarios.

Table A.4
PEF values used in the model.

Parameter	PEF
static_electricity_import	1.30
static_electricity_export	1.30
CHP_gas	2.00
fossil_fuel	2.00
natural_gas	1.70
waste_heat_26	0.00
waste_heat_55	0.00
waste_heat_100	0.00
wood_chips	0.00
wood_pellets	0.00

6. Conclusion

This study developed and applied an optimization framework that co-optimizes DH supply, operational dispatch, and building renovation under PED constraints. By applying this model to a waste-heat-dominated district in Kranj, Slovenia, the analysis proves that enforcing a net positive primary energy balance is a highly effective driver for decarbonization. The constraint forces a systemic shift from natural gas boilers toward a diversified portfolio centered on industrial waste heat recovery and large-scale electrification via heat pumps, confirming that well-defined sustainability targets can successfully steer investments toward low-carbon pathways.

The results highlight a fundamental trade-off between the temporal granularity of PED targets and system cost. While a Yearly PED offers a cost-effective entry point, it effectively treats the grid as a "virtual battery" to bridge winter deficits. In contrast, Seasonal PED targets reduce emissions further and ensure true autonomy but come at a higher cost due to the need for local storage and flexibility. Crucially, this stricter seasonal constraint highlights the synergistic value of demand-side measures: while building renovation was not cost-effective under baseline conditions and the annual target, it became a critical strategy for achieving seasonal targets. By lowering peak winter demand, renovation mitigates the need for expensive supply-side assets, proving that holistic planning must co-optimize supply and demand.

Although the specific technology mix is context-dependent, the underlying principles are generalizable. The model confirms that low-temperature sources (e.g., industrial waste heat, ambient heat, or shallow geothermal) can be effectively upgraded via heat pumps and distributed through DH networks, positioning DH as a key enabler for sector coupling in PEDs. The proposed framework can be adapted to other municipalities by redefining the spatial boundary and providing local inputs, specifically hourly demand profiles, supply potentials, and techno-economic parameters. From a policy perspective, our findings suggest that Seasonal PED definitions provide a necessary complement to annual accounting by incentivizing the low-carbon flexibility (e.g., storage and efficiency) required for grid-compatible climate neutrality.

The conclusions drawn in this paper are specific to the adopted DH-focused PED system boundary. Our PED accounting and optimization primarily assess the contribution of DH supply and renovation measures to achieving PED targets. If additional end-uses and generation were included (e.g., mobility, industrial process heat/electricity, or a detailed electricity supply portfolio with capacity constraints), the quantitative results and the cost-emissions trade-offs could change. Future research should address current limitations, particularly the static representation of refurbishment and the specific DH-focused boundary. This would imply extending the model to capture dynamic, multi-year renovation pathways and broader sector coupling (e.g., mobility and industrial processes). Furthermore, to move from modeling to implementation, research must integrate uncertainty analysis and focus on the non-technical governance mechanisms, such as tariffs and risk-sharing models, that ensure the transition to PEDs is not only technically viable but also socially just.

CRediT authorship contribution statement

Nirav Patel: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ali Kök:** Writing – review & editing, Writing – original draft, Methodology. **Sebastian Zwickl-Bernhard:** Writing – review & editing, Writing – original draft, Supervision, Methodology. **Lukas Kranzl:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition. **Hans Auer:** Writing – review & editing, Writing – original draft, Supervision.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT 5 in order to refine writing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Nirav Patel reports financial support was provided by Horizon Europe. Nirav Patel reports financial support was provided by Swiss State Secretariat for Education Research and Innovation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Input data

A.1. Hourly input profiles (electricity price, heat demand, PEF for electricity import/export, outdoor temperature, and electricity demand)

See Fig. A.7.

A.2. Marginal energy cost curve

See Fig. A.8.

A.3. PEF values

See Table A.4.

A.4. Technology cost data

See Table A.5.

A.5. Additional input data for all scenarios

See Table A.6.

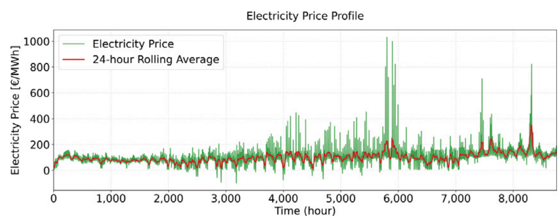
Appendix B. System boundary

Fig. B.9 summarizes the spatial system boundary and the PED accounting boundary adopted in this study. The spatial boundary follows the Planina district area in Kranj. All results, therefore, refer to this district-scale case study and the associated datasets for heat demand, electricity demand, and local renewable potentials.

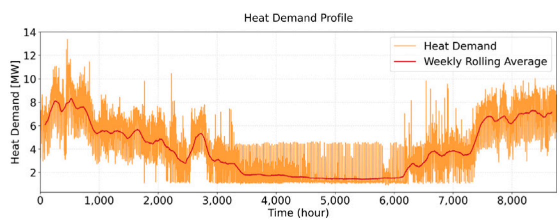
On the thermal side, the model represents the DH system supplying the aggregated heat demand of buildings within the Planina boundary. In the case study, approximately 95% of buildings in the district are connected to DH. Accordingly, the modeled heat demand corresponds to the connected building stock and reflects the DH-relevant final energy demand within the boundary, which encompasses approximately 4300 buildings. Decentralized heat supply and the connection decisions to the DH network are outside the scope of the present study. On the electricity side, the electricity demand corresponds to the total electricity consumption within Planina (i.e., not limited to residential use), consistent with the case-study dataset. To keep the analysis focused on the role of DH within a PED, the electricity sector is represented in a simplified manner: the district electricity demand is assumed to be fully supplied by locally available run-of-river hydropower. PV is treated as additional local renewable generation that can contribute

Table A.5
Investment cost, fixed/variable OPEX, and lifetime of technologies (Danish Energy Agency, 2025).

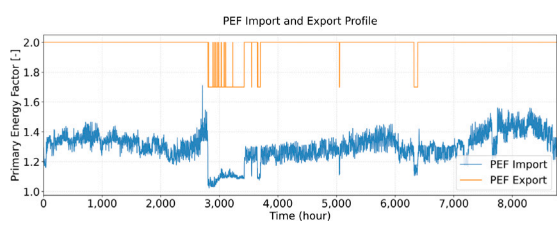
Technology	Investment (€/MW)	$OPEX_{fix}$ (€/MW)	$OPEX_{var}$ (€/MWh)	Lifetime (yr)
Natural gas boiler (1 & 2)	65,303.00	2,482.00	1.31	25.00
Electric boiler	182,849.00	1,332.00	1.31	25.00
Natural gas CHP (1 & 2)	1,175,460.00	12,146.00	6.66	25.00
Waste heat 26 °C	992,610.00	2,612.00	10.00	25.00
Waste heat 55 °C	1,488,916.00	2,612.00	15.00	25.00
Waste heat 100 °C	491,292.00	2,997.00	20.00	25.00
Wood-pellet boiler	979,550.00	41,141.00	4.48	25.00
Air-source heat pump	1,123,217.00	2,612.00	3.28	25.00
Photovoltaics (PV)	900,000.00	0.00	0.00	20.00



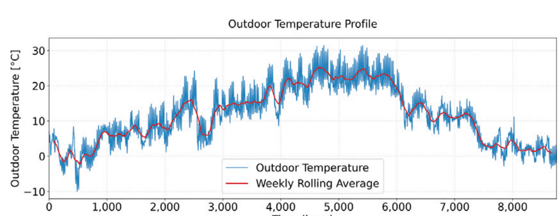
(a) Electricity-price profile



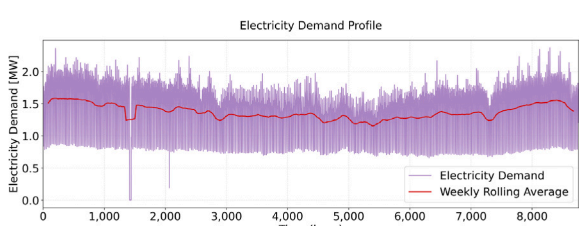
(b) Heat-demand profile



(c) PEF for electricity import/export



(d) Outdoor-temperature profile



(e) Electricity-demand profile

Fig. A.7. Summary of hourly input profiles.

Table A.6
Key assumptions for the model scenarios.

Parameter	Unit	Value	Source/Note
Demand			
Annual heating demand	MWh/yr	$\sim 35,000$	Model input
Peak heat demand	MW	13.44	Model input
Energy prices/tariffs			
Gas price	EUR/MWh	75	Market data
Biomass price (pellets)	EUR/MWh	50	Market data
Renovation			
Renovation interest rate	%	4	Hummel et al. (2020)
Renovation lifetime	%	40	Hummel et al. (2020)

to the PED balance via renewable electricity exports and associated avoided primary energy, consistent with the adopted PED accounting.

The PED accounting follows the JPI Urban Europe definition, emphasizing net-zero greenhouse gas (GHG) emissions and the management of a local renewable energy surplus (JPI Urban Europe, 2025). In practice, this means that (i) CO_2 emissions are quantified based on the modeled fuel consumption and relevant emission factors within the boundary, and (ii) the net primary energy exchange is calculated using time-dependent PEFs for electricity imports/exports. PV generation contributes to the PED balance through reduced imports and/or credited renewable exports, and is evaluated consistently against the defined final energy demand within the adopted system boundary.

Appendix C. Symbols, parameters, and decision variables

See Table C.7.

Appendix D. List of abbreviations

See Table D.8.

Appendix E. Additional results

E.1. Daily primary energy flow

See Fig. E.10.

E.2. Hourly heat generation

See Fig. E.11.

E.3. Hourly COP

Heat-pump efficiencies (COP) are pre-computed as time-varying parameters from the hourly source temperature (ambient air or waste-heat stream) and the assumed DH supply/return temperatures; thus, the COP profiles in Fig. E.12 mainly follow seasonal temperature patterns. The air-source HP exhibits the largest variability because its source temperature is the outdoor air, while the waste-heat HPs show more stable COPs due to their comparatively steady source temperatures

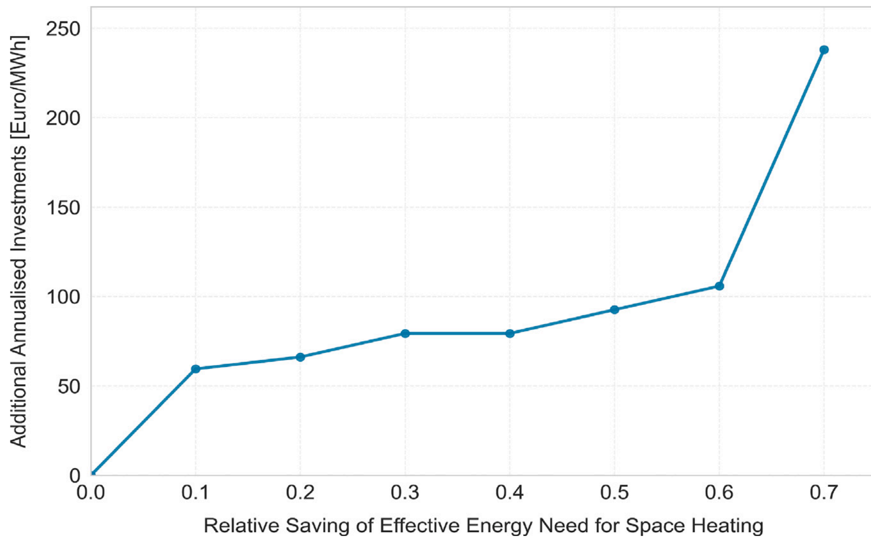


Fig. A.8. Marginal Energy Saving Cost (MESC) curve from Hummel et al. (2020).

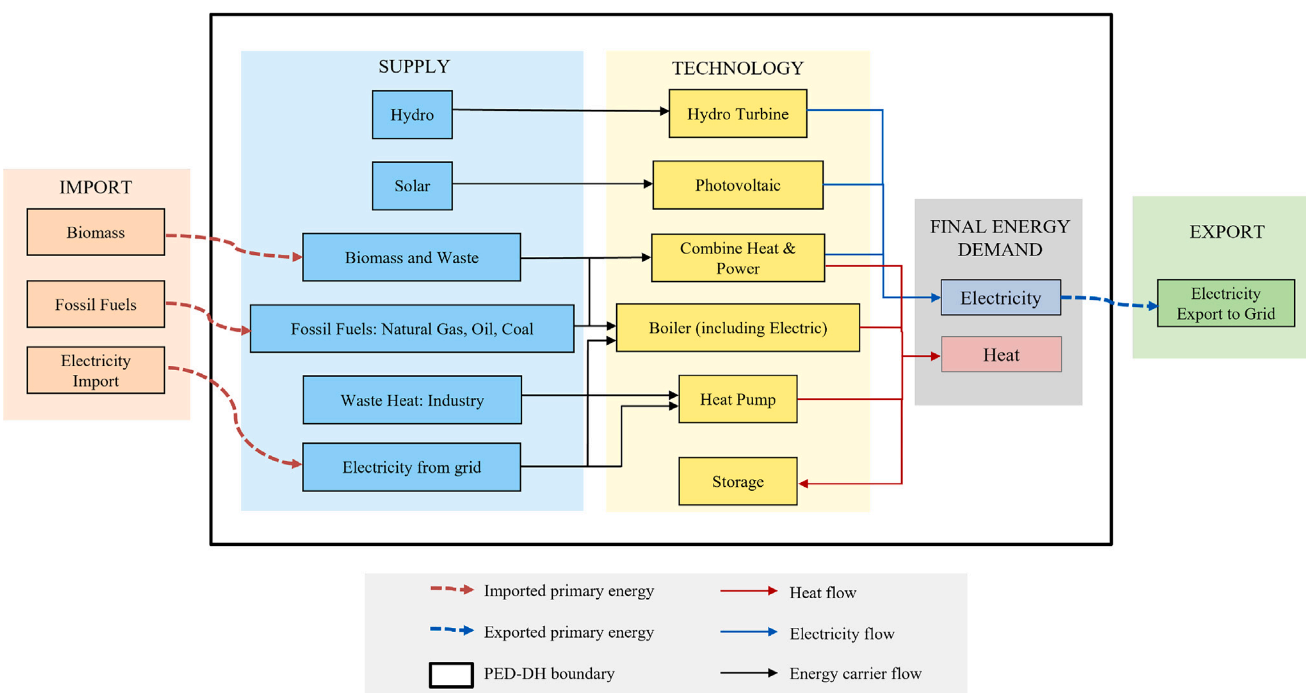


Fig. B.9. System boundary for DH supply optimization for PEDs.

(26 °C and 55 °C). Across scenarios, the COP curves are identical for paired cases (NNR=NR and YNR=YR) because these pairs select the same operating conditions and do not differ in the endogenous choice of refurbishment. Differences in dispatch across scenarios are instead driven by economics: although the waste-heat HPs often achieve higher COP, they incur source-specific variable costs (10 €/MWh_{th} for the 26 °C stream and 15 €/MWh_{th} for the 55 °C stream), whereas the air-source HP has no purchased heat-source cost; consequently, the optimizer may still run the air-source HP in hours when the cost advantage from a higher waste-heat COP is outweighed by the additional waste-heat OPEX.

E.4. Storage level

Thermal energy storage (TES) is represented as a district-level heat storage technology that can be installed and operated by optimization. TES is primarily used to provide seasonal flexibility, but its role differs significantly depending on the system configuration. In the Seasonal PED case, the model invests in a substantially larger storage and operates it with a pronounced seasonal pattern, charging over extended periods when heat is relatively abundant/low-cost and discharging during high-demand phases, so that TES becomes a key balancing asset for shifting heat across months. In contrast, the No-PED and Yearly PED cases lead to smaller storage investments and flatter storage trajectories, indicating that the value of long-duration shifting is lower and that balancing is achieved more through direct hourly dispatch of supply technologies rather than through large seasonal charging/discharging cycles (see Fig. E.13).

E.5. Share of heat supply by generator

See Table E.9.

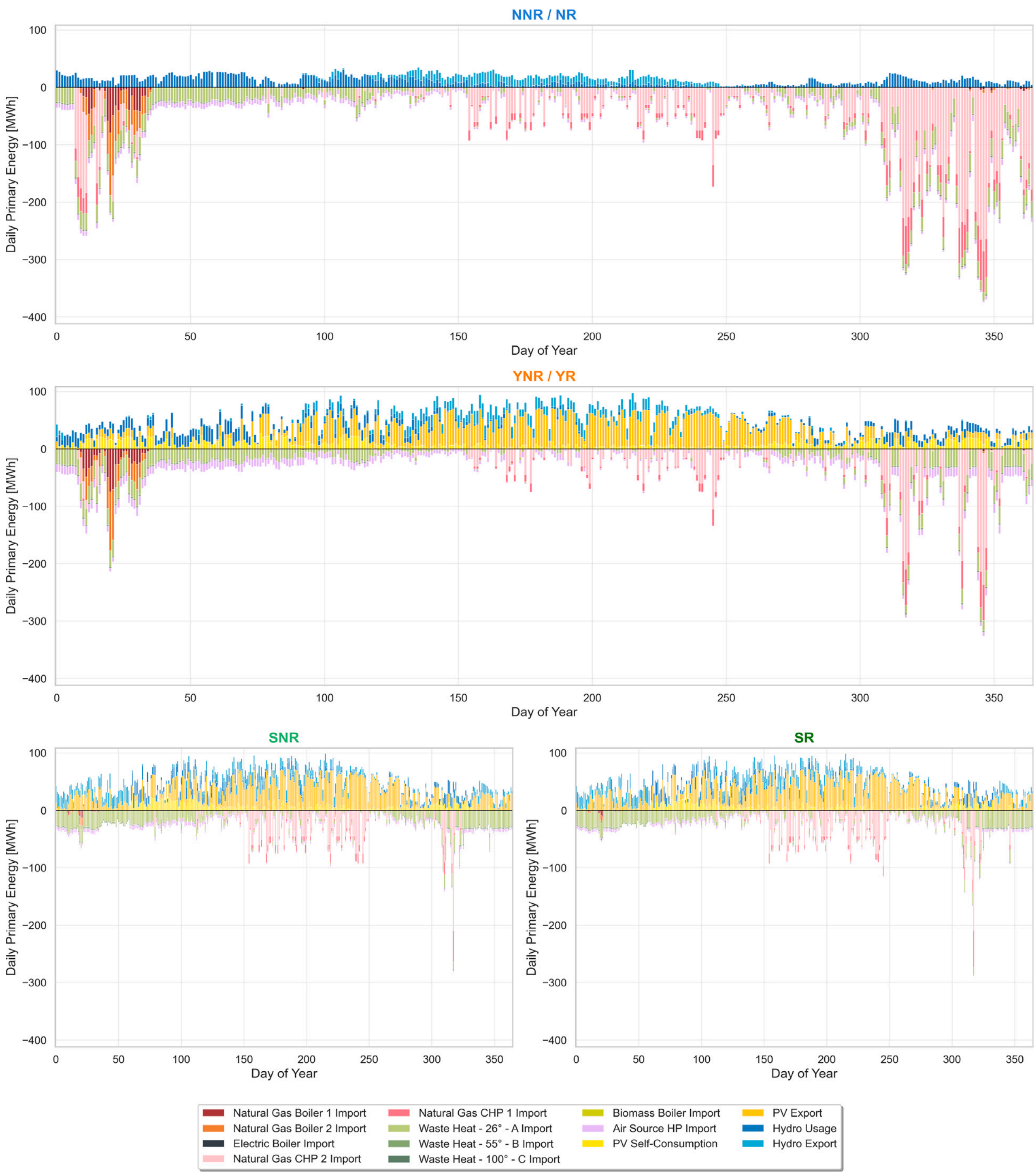


Fig. E.10. Daily Primary energy flows across scenarios (Note: NNR and NR are identical, as are YNR and YR).

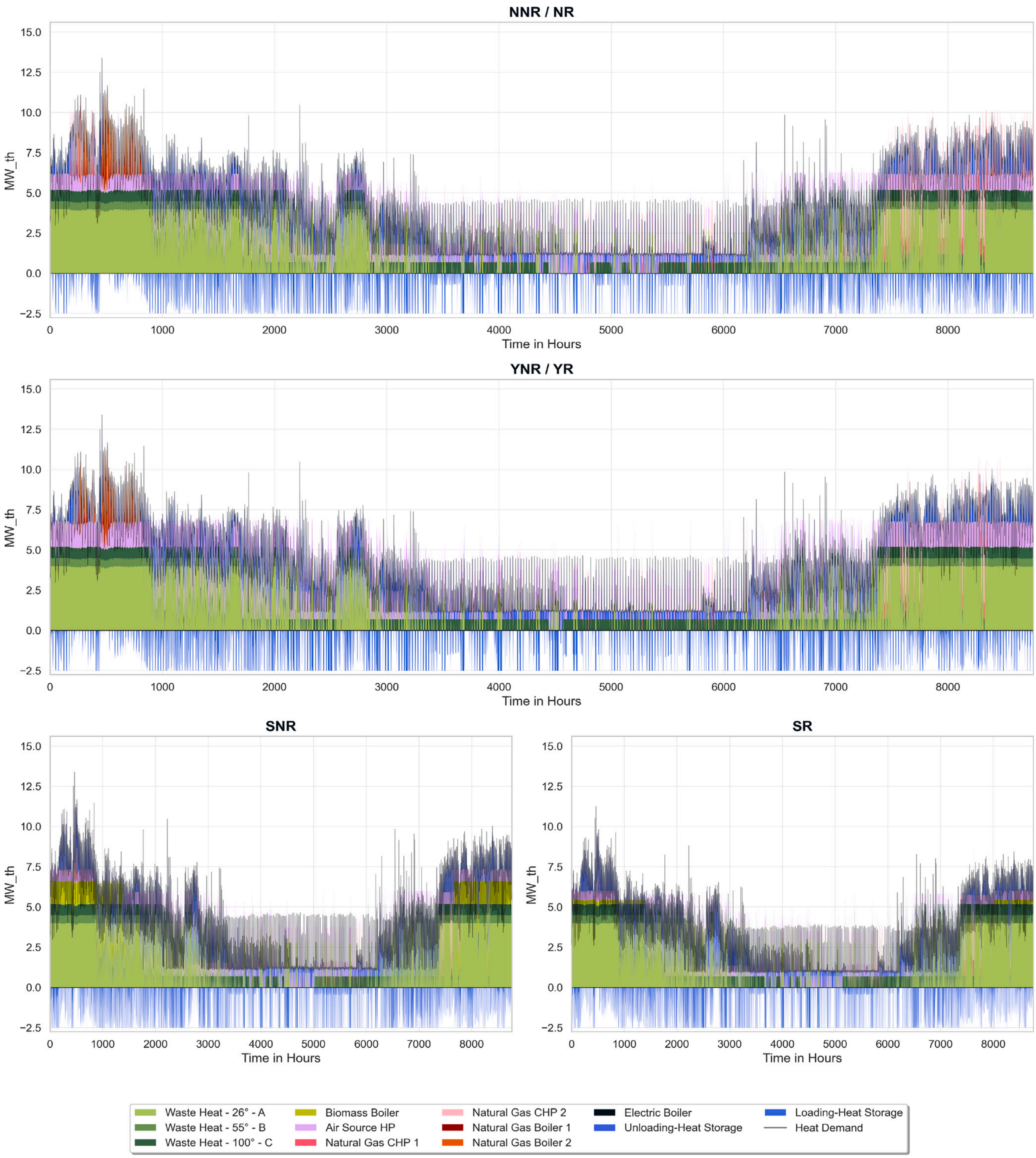


Fig. E.11. Hourly heat generation across scenarios (Note: NNR and NR are identical, as are YNR and YR).

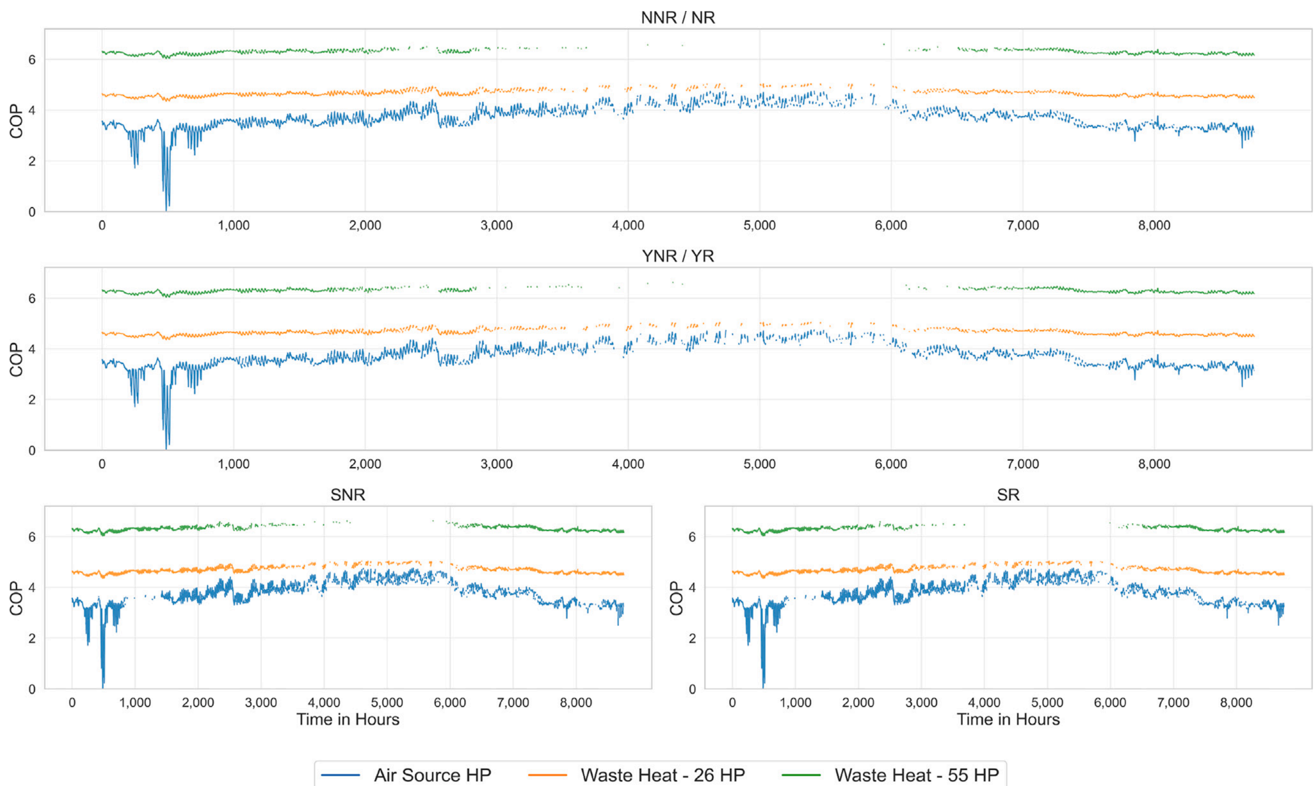


Fig. E.12. HP hourly COP across scenarios (Note: NNR and NR are identical, as are YNR and YR).

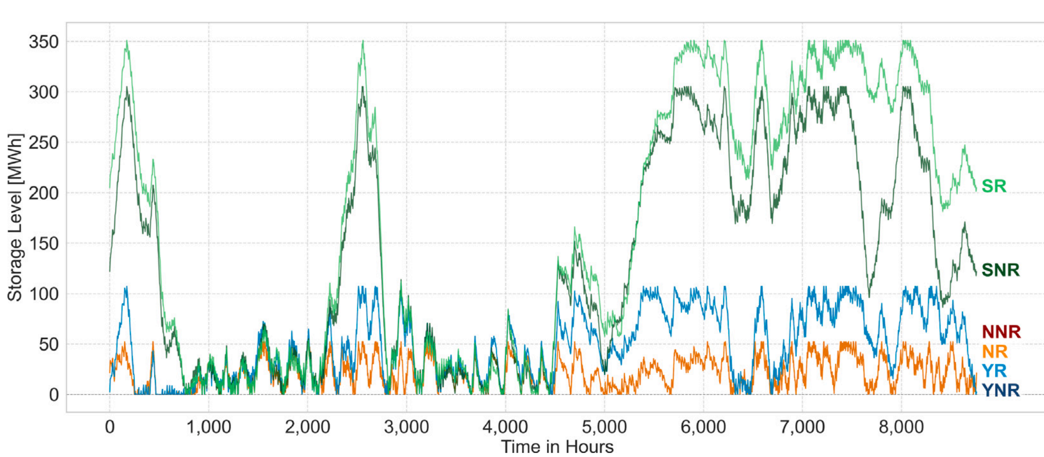


Fig. E.13. Hourly storage level (Note: NNR and NR are identical, as are YNR and YR).

Table C.7
Symbols, parameters, and decision variables used in the optimization model.

Symbol	Description	Unit
c_{total}	Total DH system cost (original model)	EUR
c^*_{total}	Total cost including refurbishment	EUR
rev_{total}	Total revenue from electricity (original model)	EUR
rev^*_{total}	Total revenue from exported electricity (extended)	EUR
IC	Annual total investment cost (incl. RES)	EUR
$OPEX_{fix}$	Annual total operational fixed costs	EUR
$OPEX_{var}$	Annual total operational variable costs	EUR
c_{cold}	Annual total cold-start costs	EUR
c_{ramp}	Annual total Ramping costs	EUR
c_{refurb}	Annual total refurbishment costs	EUR
$R_{CHP}, R_{PV}, R_{Hydro}$	Revenue components	EUR
$x_{th,j,t}$	Thermal output of unit j at t	MWh_{th}
$x_{el,j,t}$	Electric output of unit j at t	MWh_{el}
$x_{unload,hs,t}$	Storage discharge from hs at t	MWh_{th}
$x_{load,hs,t}$	Storage charge into hs at t	MWh_{th}
$demand_{th,t}$	Thermal demand at t	MWh_{th}
$p_{s,el,j,t}$	Electricity sale price for unit j at t	EUR/MWh_{el}
$p_{s,t}$	Market electricity sale price at t	EUR/MWh_{el}
$E_{export,el,t}$	Electricity exported at t	MWh_{el}
$E_{import,electricity,t}$	Imported electricity at t	MWh_{el}
$\eta_{th,j,t}$	Thermal efficiency of unit j at t	–
$COP_{nom,j}$	Nominal COP of heat pump j	–
$\upsilon_{s,j,t}, \upsilon_{f,j,t}, \upsilon_{r,j,t}$	Source, flow, return temperatures (actual)	°C
$\upsilon_{s,nom,j}, \upsilon_{f,nom,j}, \upsilon_{r,nom,j}$	Source, flow, return temperatures (nominal)	°C
$s_{COP,source}, s_{COP,flow}, s_{COP,return}$	COP sensitivity factors	1/°C
PV_{cap}	Installed PV capacity	MW
PV_{PR}	PV performance ratio	–
$radiation_t$	Solar irradiance at t	W/m^2
$PV_{gen,t}$	PV electricity generation at t	MWh_{el}
PV^{used}_t	On-site PV used at t	MWh_{el}
PV^{export}_t	PV exported at t	MWh_{el}
$PV^{used}_{j,t}$	PV used by device j at t	MWh_{el}
x_i	Decision variable: share of refurbishment block i	–
f	Total savings fraction of space heating demand	–
D	Annual total thermal demand	MWh_{th}/a
P	Share of space heating in total demand (0.8)	–
E	Annual total energy saved	MWh_{th}/a
c_i	Marginal energy saving cost for block i	EUR/MWh_{th}
c_{refurb}	Annualized refurbishment cost	EUR/a
d_t	Original hourly heat demand	MWh_{th}
d^r_t	Post-refurbishment hourly heat demand	MWh_{th}
$PE_{import,t}$	Imported primary energy at t	MWh_{prim}
$PE_{export,t}$	Exported primary energy at t	MWh_{prim}
PEF_j	PEF of fuel for unit j	–
$PEF_{import,electricity,t}$	PEF of imported electricity at t	–
$PEF_{export,RE,t}$	PEF credited to exported electricity	–
$E_{export,t}$	Exported energy (PED balance)	MWh
$E_{import,t}$	Imported energy (PED balance)	MWh

Table D.8
Abbreviations used in the paper.

Abbreviation	Full term
4GDH	4th Generation District Heating
5GDHC	5th Generation District Heating and Cooling
COP	Coefficient of Performance
BIPV	Building-Integrated Photovoltaics
CHP	Combined Heat and Power
DH	District Heating
DHN(s)	District Heating Network(s)
GHG	Greenhouse Gas
HTHP	High-Temperature Heat Pump
LCA	Life-Cycle Assessment
LCC(s)	Life-Cycle Cost(s)
LTDH	Low-Temperature District Heating
MILP	Mixed-Integer Linear Program
NPV	Net Present Value
NZEB	Net-Zero Energy Building
OPEX	Operating Expenditure
ORC	Organic Rankine Cycle
PEB(s)	Positive Energy Block(s)
PED(s)	Positive Energy District(s)
PEF	Primary Energy Factor
PV	Photovoltaics
RES	Renewable Energy Sources
SCOP	Seasonal Coefficient of Performance
SSR	Self-Sufficiency Ratio
TES	Thermal Energy Storage
TRL	Technology Readiness Level

Table E.9
Share of heat supply by generator for each scenario (%).

Heat Generator	NNR	NR	YNR	YR	SNR	SR
Natural Gas Boiler 1	0.98	1.09	0.86	0.82	0.09	0.06
Natural Gas Boiler 2	1.43	1.32	1.00	1.04	0.11	0.07
Natural Gas CHP 2	7.54	7.54	2.78	2.78	2.24	2.80
Natural Gas CHP 1	1.41	1.41	0.55	0.55	0.43	0.48
Waste Heat 26 °C (A)	50.34	50.34	44.50	44.50	53.73	60.27
Waste Heat 55 °C (B)	5.46	5.46	5.23	5.23	6.22	6.41
Waste Heat 100 °C (C)	14.29	14.29	15.10	15.10	14.60	16.45
Biomass Boiler	–	–	–	–	10.00	1.85
Air-Source HP	18.54	18.54	30.00	30.00	12.58	11.60

Data availability

The authors do not have permission to share data.

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