



ARTICLE

Assessing the Role of Aggregated Flexibility from Public Buildings in Enhancing Renewable Energy Integration

Franjo Pranjić^{1,*}, Doris Beljan², Primož Praper³, Matej Fike¹, Peter Vrtič¹, Antun Pfeifer² and Neven Duić^{2,4}

¹Faculty of Energy Technology, University of Maribor, Maribor, Slovenia

²Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Zagreb, Croatia

³EUTRIP, Celje, Slovenia

⁴School of Industrial Engineering, Pontificia Universidad Católica de Valparaíso, Valparaíso, Chile

*Corresponding Author: Franjo Pranjić. Email: franjo.pranjic@um.si

Received: 06 February 2026; Accepted: 08 May 2026; Published: 12 July 2026

ABSTRACT: This paper evaluates the role of aggregated demand-side flexibility from public buildings in supporting renewable energy integration and decarbonization of the Slovenian energy system. Using high-resolution monitoring data from over 100 public buildings and the H2RES energy system optimization model, two long-term scenarios are analyzed for the period 2020–2050: a reference scenario without public building flexibility and a flexibility scenario in which public building heat demand is electrified via heat pumps. The year 2020 is used as an internally consistent optimization reference for demand levels and technology availability, rather than as a statistical reconstruction of the observed national energy system. Reported CO₂ emissions represent modelled energy-system emissions within the covered sectors (power, heat, and industry) under exogenously imposed policy constraints and therefore may differ from national inventory totals. The results show that aggregated public building flexibility affects the temporal allocation of electricity demand and sectoral emission distribution, leading to moderate changes in renewable curtailment and heat-sector CO₂ emissions while maintaining identical renewable energy targets. The findings demonstrate that electrification and aggregation of public building demand can play a strategic role in supporting national climate objectives and system operation under high renewable penetration. It should be noted that the analyzed dataset, while based on high-resolution monitoring of more than 100 public buildings, is not statistically scaled to represent the full national building stock. The results should therefore be interpreted as indicative of system-level effects of aggregated flexibility rather than a direct national-scale quantification.

KEYWORDS: Demand-side flexibility; public buildings; renewable energy integration; energy system optimization; H2RES; decarbonization strategy; aggregated flexibility; energy transition

1 Introduction

Background and Motivation

The transition to sustainable energy systems is a pivotal challenge in today's global efforts to combat climate change and reduce greenhouse gas emissions. At the forefront of this transition is the integration of variable renewable energy sources (RES), which necessitates innovative strategies to support grid stability and enhance energy system resilience. As conventional power plants, such as Slovenia's TEŠ6 coal-fired unit, are to be decommissioned, demand-side flexibility emerges as a vital component in accommodating RES

and maintaining power system stability. Public buildings, with their substantial potential for aggregated flexibility, offer promising avenues for supporting this transition.

Current literature extensively explores the role of demand-side management and energy system optimization in achieving sustainable energy transitions. For instance, in [1,2], the authors emphasize the significance of integrating RES with flexible demand-side resources to accelerate renewable energy uptake and enhance system efficiency. The deployment of demand-side flexibility strategies, such as load shifting and demand response, is crucial in enabling the swift restoration of the power grid and optimizing the discharge of energy resources, as discussed in [3–5]. Furthermore, the role of public buildings in providing grid-responsive support through advanced monitoring and data analytics is highlighted in multiple studies, showcasing their potential to contribute significantly to grid balancing efforts [3,6].

In the realm of energy system optimization, tools like H2RES play a crucial role in simulating various scenarios and quantifying flexibility potential. This allows for strategic planning and enhanced integration of RES, particularly in the context of phasing out fossil-based balancing mechanisms. The application of H2RES in modelling the dynamics of energy systems at the local level, as seen in [7,8], underscores its utility in achieving national decarbonization goals and promoting energy system autonomy.

While extensive research has focused on the electrification of transport and its interaction with power systems, the potential of aggregated flexibility from public buildings is yet to be fully explored. Studies such as [9,10] illustrate the benefits of responsive loads and effective unit ramp management in enhancing system flexibility, yet the application of these strategies in the context of building energy systems requires further investigation. The integration of flexible strategies with renewable energy sources can significantly reduce reliance on fossil fuels, as evidenced by [11,12], thereby aligning with broader climate goals set forth by international agreements like the Paris Agreement [13].

Public buildings, through real-time monitoring and high-resolution data analysis, can play a crucial role in quantifying and leveraging flexibility potential. This is demonstrated by [14], which explore the economic viability of flexibility options in smart energy systems with high renewable energy penetration. The deployment of technologies like power-to-heat and power-to-vehicle strategies enhances system flexibility in urban energy districts, contributing to increased self-consumption and reduced reliance on fossil-based balancing mechanisms, as highlighted in [15,16].

Energy system optimization tools, such as EnergyPLAN, facilitate detailed simulations and analyses, supporting strategic decision-making for energy transitions. The MATLAB Toolbox for EnergyPLAN, introduced by [9], extends these capabilities by enabling the management of numerous simulations, providing insights into energy system operations.

The economic and environmental benefits of integrating RES and flexibility strategies are crucial considerations in energy planning. Studies indicate that these strategies can lead to significant cost reductions and environmental benefits [6,17], underscoring the need for comprehensive energy planning models that incorporate economic and environmental objectives [18–20].

A holistic approach to energy planning is increasingly recognized as essential for integrating energy systems and achieving sustainable transitions. This involves the coordination of policy, market, and community engagement to optimize energy use and infrastructure, as discussed in [21,22]. The RENERGY self-assessment methodology, for example, offers a structured framework for assessing regional energy systems and developing customized sustainable energy strategies [11]. Such integrated frameworks are vital for addressing the complexities of modern energy systems, ensuring long-term viability and resilience, supporting system stability under increasing shares of variable renewable energy, and enabling robust long-term planning decisions [23–25].

The scenario analyzed in this study aligns closely with Slovenia's National Energy and Climate Plan (NECP) [26] and the Long-Term Strategy for Building Renovation (DSEPS 2050) [27], which emphasize a decarbonization pathway integrating demand-side flexibility, digital monitoring, and local-level energy resilience. This approach corresponds to the most ambitious national scenario; wherein deep renovation of public buildings is combined with smart control technologies to actively support renewable energy integration and phase out fossil-based balancing mechanisms.

The Updated National Energy and Climate Plan of the Republic of Slovenia, adopted in December 2024 and covering the period up to 2030 with a 2040 outlook, highlights the critical importance of developing an efficient and competitive market to harness the full potential of power system flexibility and new technologies. As noted by the Energy Agency, maintaining active dialogue with electricity market stakeholders is essential for establishing a flexibility market that supports these goals. According to the updated NECP, the establishment of a power system flexibility market is a key policy element underpinning public building renovation, with a proactive role for the Energy Agency and market stakeholders.

Building upon this policy framework, this research aims to assess the aggregated flexibility potential from public buildings in Slovenia as a means to support power system stability and facilitate renewable energy source (RES) integration. By utilizing high-resolution datasets obtained through real-time monitoring of energy consumption patterns, this study quantifies flexibility potential and simulates various load-shifting and demand response scenarios using the H2RES energy system optimization tool. It is hypothesized that targeted flexibility strategies implemented at the local level can substantially contribute to grid balancing and enhance energy resilience at the community level. Through this approach, data-driven insights are provided into how public sector flexibility can be effectively mobilized, playing a vital role in accelerating national decarbonization efforts and ensuring a sustainable and just energy transition.

In the Slovenian context, the National Energy and Climate Plan (NECP) sets ambitious targets for renewable energy deployment, electrification of end-use sectors, and a complete phase-out of coal-based energy production by the mid-2030s. System-level analyses are therefore required to assess the feasibility and interaction of these targets under realistic operational constraints.

2 Methodology

2.1 Policy Context and Scenario Background

The scenario analyzed in this study aligns with Slovenia's National Energy and Climate Plan (NECP) and the Long-Term Strategy for Building Renovation (DSEPS 2050), which define a decarbonization pathway based on the electrification of end-use sectors, increasing shares of renewable energy sources (RES), and the gradual phase-out of fossil fuels. In particular, the NECP emphasizes the importance of demand-side flexibility, digital monitoring, and local-level energy resilience as key enablers for integrating high shares of variable renewable generation.

The updated National Energy and Climate Plan of the Republic of Slovenia highlights the development of an efficient and competitive electricity market capable of unlocking the full potential of power system flexibility and new technologies. The Energy Agency maintains an active dialogue with electricity market stakeholders to support the establishment of a flexibility market that can accommodate new forms of demand response and sector coupling [26]. Within this policy framework, public buildings are explicitly recognised as a priority segment for deep renovation, electrification of heating systems, and the deployment of smart control technologies.

Against this backdrop, the present study focuses on the empirical quantification of aggregated demand-side flexibility in public buildings and its role in supporting renewable energy integration and system

balancing. The analysis considers two system development pathways: a reference scenario without explicitly modelled flexibility from public buildings, and a flexibility scenario in which aggregated thermal demand from public buildings is assumed to be supplied by heat pumps and actively integrated into the power system.

2.2 Empirical Dataset: Public Buildings

The empirical analysis is based on a high-resolution dataset comprising more than 100 public buildings distributed across Slovenia. The dataset includes measured electrical and thermal energy consumption, collected at an hourly resolution through real-time monitoring systems. This level of temporal granularity enables a detailed characterization of daily and seasonal load patterns, which is essential for identifying demand-side flexibility potential.

The monitored building stock reflects a diverse typology of public buildings with different operational profiles and energy demands. The majority of facilities are educational buildings, including primary schools and kindergartens, followed by administrative buildings, healthcare and social infrastructure (health centres and elderly care homes), and a smaller share of cultural and sports facilities. This diversity allows for a comparative assessment of flexibility potential across building categories, as each group exhibits distinct thermal dynamics, occupancy patterns, and operating schedules.

A particularly relevant technological characteristic of the dataset is the widespread presence of heat pumps as the primary heating technology in most buildings, often complemented by auxiliary heating systems. This configuration enables the assessment of both direct electrical load shifting and indirect flexibility through thermal inertia and short-term heat storage. While the dataset does not explicitly include on-site renewable generation such as photovoltaic systems, the combined electrical and thermal consumption profiles provide a robust empirical basis for quantifying flexibility potential at the aggregated level.

For analytical purposes, buildings are classified according to their function (e.g., educational, healthcare, administrative) and technological configuration (presence of heat pumps and auxiliary systems). This classification supports the systematic aggregation of flexibility potential and provides the empirical foundation for scenario simulations within the energy system optimization framework.

Fig. 1 illustrates the typology of monitored public buildings included in the study.

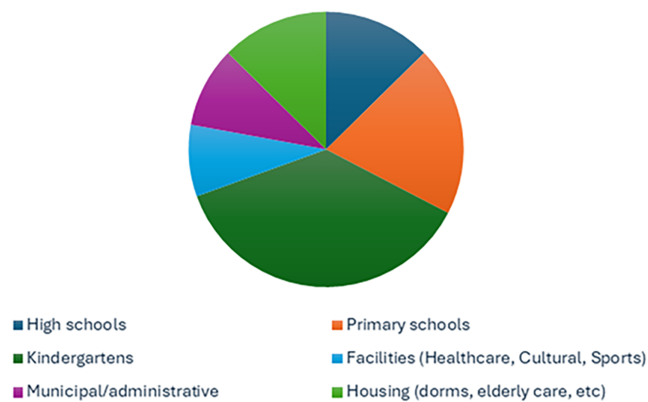


Figure 1: Typology of monitored public buildings included in the study.

2.3 Policy and Financial Incentives for Flexibility Technologies

To contextualize the technical flexibility potential of public buildings, the analysis accounts for the policy and financial frameworks that support the deployment of enabling technologies in Slovenia. Current

national policy instruments, as outlined in the NECP and implemented through public calls of the Eko Sklad (e.g., 119SUB LS24), provide substantial non-refundable subsidies for energy efficiency and electrification measures in public buildings.

Eligible measures include the installation of heat pumps, thermal storage tanks, advanced building energy management systems, and comprehensive renovation of building envelopes. Subsidy rates typically reach up to 40% of eligible investment costs, significantly improving the economic feasibility of technologies that enable demand-side flexibility.

[Table 1](#) summarizes the key measures and corresponding subsidy levels that directly support flexibility provision and renewable energy integration in public buildings [28].

Table 1: Eligible measures and subsidy levels supporting demand-side flexibility in public buildings.

Measures/Technologies	Area	Subsidy Rate	Funding Source/Call	Notes
Heat pump for central heating	Heating	up to 40%	119SUB LS24 (Eko Sklad, 2024)	Applies to public buildings owned by municipalities
Thermal storage tank (water)	Heat storage	up to 40%	119SUB LS24	Condition: only with HP or RES system
Photovoltaic system	Electricity	up to 25%–30%	NECP + Eko Sklad + EU funds	Usually combined with renovation or HP
Advanced control/BMS	Energy management	up to 30%	Various EU calls + local tenders	System must be connected to HP/heating
Ventilation system with heat recovery	Air quality & efficiency	up to 40%	119SUB LS24	Often part of a comprehensive energy renovation
Insulation of façade, roof, building envelope	Passive measures	Passive measures	Passive measures	Passive measures

These incentives are financed through a combination of national funds, European cohesion policy instruments, and dedicated NECP support schemes. In several cases, the implementation of flexibility-enabling technologies (e.g., thermal storage or advanced control systems) is conditional on their integration with primary heating or renewable energy systems, reinforcing the coupling between electrification and flexibility provision.

2.4 Energy System Modelling Framework

To assess the system-level impacts of aggregated flexibility from public buildings, the H2RES energy system optimization model is applied. H2RES is designed to support short- to long-term energy system planning and optimizes both capacity investments and hourly operation across the full modelling horizon. Unlike models based on aggregated time slices, H2RES operates at an hourly resolution, allowing for a detailed representation of variable renewable generation, demand patterns, and flexibility options [8].

Reported CO₂ emissions represent direct energy-system emissions within the modeled system boundary, including electricity generation, heat supply, and the explicitly modeled industrial energy use. Upstream emissions related to fuel extraction and processing, non-energy process emissions, land-use-related emissions, and sectors not represented in the H2RES framework are excluded. Consequently, modeled emission values are not directly comparable to national greenhouse gas inventories, which follow different accounting conventions and cover a broader set of sectors.

A general schematic representation of the H2RES model is shown in Fig. 2. The model comprises three main modules. The first module represents electricity generation, including conventional power plants and variable renewable energy sources. The second module covers energy transformation technologies, such as power-to-hydrogen, power-to-heat, fuel cells, and different forms of energy storage (hydrogen, hydro, thermal, and electric vehicle storage). The third module represents end-use demand sectors, including transport, buildings, commercial activities, and industry.

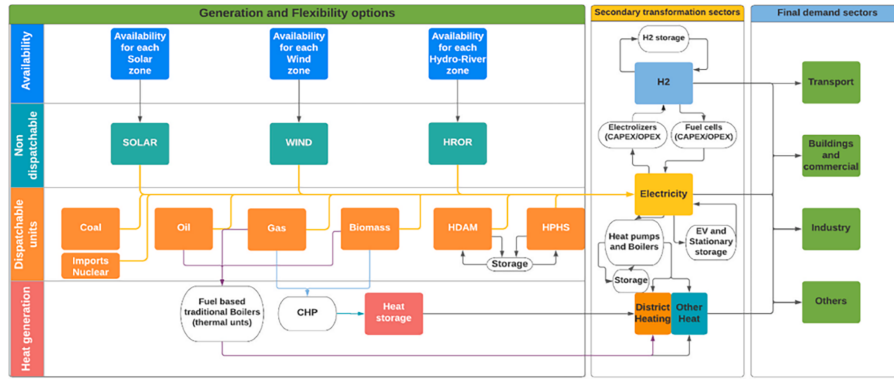


Figure 2: Schematic representation of the H2RES model.

For clarity, the electricity balance is presented in a simplified schematic form, highlighting the main energy flows rather than a full formal mathematical representation of all model constraints.

The objective function of the model minimizes the total annualized system cost over the planning horizon. This includes fuel and non-fuel operational costs, capital investment costs for new technologies, ramping costs, electricity import costs, and the cost of CO₂ emissions. The optimization problem is formulated as shown in Eq. (1), where all cost components are discounted over time using year-specific discount factors.

$$\min Z = \sum_y \sum_p \sum_t df_y (C_{t,p,y} D_{t,p,y} + TC_{t,y} K_t Inv_{t,y} + R_{t,p,y} Ramp_{t,p,y} + I_{t,p} Inp_{p,y} + CO_2 Price_y CO_2 level_{t,p,y}) \quad (1)$$

The first term represents fuel and non-fuel operating costs associated with technology dispatch. The second term accounts for capital investment costs. The third term represents ramping-related operational costs. The fourth term corresponds to electricity import costs, while the fifth term accounts for CO₂ emission costs.

2.5 Scenario Definition and System Constraints

Two system development scenarios are analyzed in this study. The first represents a reference pathway consistent with national strategic documents, without explicitly modelled aggregated flexibility from public

buildings. The second scenario incorporates aggregated flexibility from public buildings by introducing an additional thermal demand category representing heat supplied by heat pumps in public buildings. This category reflects the real, measured heat demand of public buildings and represents the potential contribution of public-sector electrification to system flexibility.

The reference year 2020 is not intended to reproduce observed national generation mixes or emission totals. Instead, it serves as an internally consistent optimization baseline under historical demand levels, available technologies, and imposed policy constraints. Deviations from official statistics therefore reflect endogenous optimization outcomes rather than data inconsistencies.

To ensure consistency with European climate policy and national decarbonization targets, explicit CO₂ emission constraints are implemented in the optimization model. Emission limits follow a gradual reduction pathway towards climate neutrality by 2050, in line with the European Green Deal and the Slovenian National Energy and Climate Plan.

In addition to emission constraints, a Critical Excess Electricity Production (CEEP) limit is introduced. The CEEP constraint restricts the share of curtailed electricity relative to total generation, preventing unrealistic overcapacity of variable renewable energy sources and enforcing system-feasible deployment levels. This constraint incentivizes the utilization of flexibility options, including energy storage, sector coupling, and hydrogen production, rather than excessive curtailment of renewable generation.

By combining high-resolution empirical demand data, policy-consistent assumptions, and a detailed energy system optimization model, the methodological framework ensures that the analyzed scenarios reflect both technical feasibility and realistic institutional conditions.

Definition of the Flexibility Scenario (HP_Public)

In this study, HP_Public denotes an explicit, separate heat-demand category representing the aggregated hourly thermal demand of public buildings, derived from measured monitoring data. To ensure methodological consistency, this demand is removed from the corresponding aggregated building heat demand in the reference load and is introduced as a dedicated demand node in the model.

In the Flexibility (HP_Public) scenario, HP_Public demand is constrained to be supplied exclusively by electricity-driven heat pumps and electric boilers (i.e., technologies representing electrified public-building heating). The operational flexibility is implemented by allowing temporal shifting of electricity consumption for HP_Public heating within the model's hourly balance constraints, thereby enabling demand-side interaction with variable renewable generation.

The Reference scenario excludes HP_Public entirely and therefore represents a system evolution pathway without explicitly activated aggregated flexibility from public buildings. Throughout the paper, "Flexibility scenario" and "HP_Public scenario" are used interchangeably.

Implementation note. The flexibility reported in this paper refers to explicitly modelled flexibility of the HP_Public electrified heating segment (heat pumps and electric boilers supplying the separated HP_Public demand). Flexibility results should therefore be interpreted as system-level impacts of this dedicated electrified public-building heating load, rather than as a generic flexibility attribute of the entire building sector.

Electricity cross-border exchange is represented as net hourly trade. Imports and exports may occur simultaneously within the same hour; reported values therefore reflect the net balance (imports minus exports) rather than gross physical flows. This accounting approach ensures consistency of the hourly system balance and avoids double counting of cross-border electricity exchanges.

3 Results

For clarity, throughout the [Section 3](#), the term “Flexibility scenario” refers to the scenario including HP_Public, i.e., aggregated public building heat demand supplied by electricity-driven heat pumps and modelled as flexible demand. The term “Reference scenario” refers to the system configuration without HP_Public and without explicitly activated demand-side flexibility from public buildings.

3.1 Renewable Energy Deployment and Capacity Investments

The evolution of renewable energy capacity investments under both analyzed scenarios is summarized in [Table 2](#). The results indicate that both scenarios follow a similar long-term trajectory towards high shares of renewable electricity generation, in line with national policy targets. However, notable differences emerge in the composition and timing of capacity investments.

Table 2: Installed renewable electricity capacity in the reference and flexibility scenarios.

Year	Scenario	Solar PV (MW)	Wind (MW)
2030	Reference	2443.34	0
2030	Flexibility	2443.58	0
2040	Reference	1562.62	972.23
2040	Flexibility	1563.30	971.91
2050	Reference	2713.60	1462.18
2050	Flexibility	2713.62	1462.34

Installed capacities are reported for selected milestone years (2030, 2040, 2050), which correspond to policy-relevant planning horizons and capture the structural system configuration emerging from the long-term optimization.

Aggregated flexibility from public buildings leads to marginal differences in optimal wind capacity in the flexibility scenario, while also affecting the timing and magnitude of solar photovoltaic deployment due to system-wide cost optimization under binding policy constraints.

Installed capacities are continuous optimization outputs and therefore not restricted to integer values, reflecting cost-optimal system configurations rather than discrete project-level investments.

The achieved renewable electricity shares under both scenarios are summarized in [Table 3](#).

Table 3: Renewable electricity share in the reference and flexibility scenarios (%).

Year	Reference	Flexibility
2020	30.00	30.00
2025	32.00	32.00
2030	50.00	50.00
2035	70.00	70.00
2040	80.00	80.00
2045	90.00	90.00
2050	95.00	95.00

In the reference scenario without aggregated public building flexibility, higher investments in wind power capacity are observed, particularly after 2035. Wind capacity reaches approximately 1.11 GW by 2040 and continues to increase towards 2050. In both scenarios, wind capacity reaches approximately 1.0 GW by 2040, with only negligible differences between reference and flexibility cases. These differences reflect system-wide cost optimization effects under identical policy constraints, with aggregated flexibility influencing capacity deployment only marginally.

Solar photovoltaic investments differ between scenarios, particularly in the timing and intermediate deployment levels. While long-term photovoltaic capacity is constrained by policy targets and reaches similar upper bounds by 2040–2050, the flexibility scenario exhibits a different deployment pathway, reflecting system-wide optimization effects and interactions with electrified heat demand from public buildings.

Overall, differences between scenarios remain moderate due to binding renewable energy and emission constraints, highlighting that aggregated flexibility primarily affects system efficiency rather than target attainment. The resulting electricity generation mix of the optimized reference system is illustrated in Fig. 3, providing a contextual overview of the technology composition underlying the capacity and renewable share results.

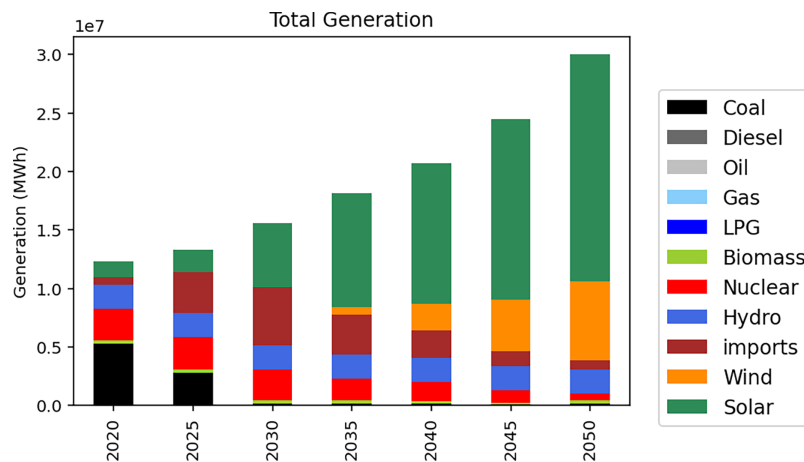


Figure 3: Optimized electricity generation mix in the reference scenario, illustrating the internally consistent model solution for the reference year and selected future years.

Interpretation of the “Biomass” category and base-year results. In the model outputs, the label “Biomass” represents an aggregated dispatchable renewable category (e.g., biomass-based generation, biogas, and waste-to-energy where applicable in the input data), used to provide firm renewable supply in the optimization. Consequently, the modelled 2020 generation mix should be interpreted as an optimized reference system configuration consistent with the imposed constraints and input costs, and not as a direct reproduction of official statistical generation shares. This is particularly important when comparing modelled biomass shares against national electricity statistics.

Imports are represented as net hourly exchanges. When simultaneous imports and export occur within the same hour, the reported value corresponds to the net balance, which may reduce the apparent magnitude of gross cross-border flows in annual summaries.

In addition, the total annualized system cost differs only marginally between the analyzed scenarios. This is consistent with the near-identical capacity investments, renewable shares, and emission trajectories

observed across scenarios, indicating that aggregated public-building flexibility primarily affects system operation and sectoral allocation rather than overall system cost.

3.2 Renewable Energy Share and CO₂ Emissions

Sectoral CO₂ emissions and the achieved renewable electricity share under binding policy constraints are summarized in Table 4. Both scenarios achieve the same renewable electricity shares over time, reaching approximately 95% renewable electricity by 2050. This outcome reflects the binding Renewable Portfolio Standard and CO₂ constraints imposed in the optimization model.

Table 4: Sectoral CO₂ emissions in the reference and flexibility scenarios (kt CO₂/year).

Year	Scenario	CO ₂ Power	CO ₂ Heat	CO ₂ Industry	Total CO ₂
2020	Reference	5623.54	1507.55	201.43	7332.52
2020	Flexibility	5624.15	1507.71	201.43	7333.29
2025	Reference	3035.53	1438.66	223.93	4698.12
2025	Flexibility	3038.24	1439.12	223.93	4701.29
2030	Reference	221.59	1390.30	226.37	1838.26
2030	Flexibility	221.59	1389.88	226.37	1837.84
2035	Reference	209.47	1179.28	216.50	1605.25
2035	Flexibility	209.48	1179.60	216.49	1605.57
2040	Reference	196.91	1089.74	182.29	1468.94
2040	Flexibility	196.92	1090.15	182.28	1469.35
2045	Reference	113.37	1045.88	157.54	1316.79
2045	Flexibility	113.44	1045.57	158.42	1317.43
2050	Reference	184.83	897.95	118.02	1200.80
2050	Flexibility	173.24	901.65	118.61	1193.50

Note: Values represent modelled CO₂ emissions within the H2RES system boundary (power generation, heat supply, and modelled industrial energy use). In the flexibility scenario, public-building heat demand is modelled as a separate category that can be supplied exclusively by flexible technologies, while total heat demand remains unchanged compared to the reference scenario. Differences in heat-sector and total CO₂ emissions therefore reflect changes in the allocation of heat supply technologies and sectoral energy flows rather than additional energy demand. Both scenarios follow identical renewable energy targets and long-term decarbonization pathways.

Reported values represent modelled direct energy-system CO₂ emissions within the H2RES system boundary, including power generation, heat supply, and modelled industrial energy use. These values are not directly comparable to national greenhouse gas inventories, which cover additional sectors and apply different accounting conventions. Consequently, emission levels in the reference year should be interpreted as model-internal benchmarks rather than as reconstructions of national emission statistics.

Aggregated flexibility from public buildings primarily affects the sectoral distribution of emissions rather than total system-wide emission levels. In the flexibility scenario, a share of public-building heat demand is electrified and supplied by flexible technologies, modifying the allocation of emissions between the power and heat sectors while leaving total heat demand unchanged. As a result, heat-sector CO₂ emissions are lower in several intermediate years compared to the reference scenario, whereas total modelled system emissions remain similar across scenarios due to binding emission constraints.

Across both scenarios, CO₂ emissions follow a long-term downward trajectory consistent with national decarbonization pathways. Differences between scenarios are most pronounced at the sectoral level and

reflect changes in energy carrier use and technology allocation rather than differences in overall mitigation ambition.

CO₂ emissions from the power sector exhibit only marginal differences between scenarios, as electricity generation is already largely decarbonized under both pathways. Industrial CO₂ emissions decline substantially toward mid-century in both cases due to increasing hydrogen uptake, indicating that public building flexibility primarily influences the heat sector and does not materially alter industrial decarbonization pathways.

3.3 Critical Excess Electricity Production (CEEP)

The Critical Excess Electricity Production (CEEP) is used as a system-level indicator of renewable integration feasibility under high renewable penetration, and it is summarized in [Table 5](#).

Table 5: Critical excess electricity production (CEEP) in reference and flexibility scenarios.

Year	Reference CEEP (GWh)	Reference (%)	Flexibility CEEP (GWh)	Flexibility (%)	Δ CEEP (Flex–Ref) (GWh)
2020	0.000	0.00	0.000	0.00	0.000
2025	0.000	0.00	0.000	0.00	0.000
2030	0.365	0.00	0.401	0.00	+0.036
2035	455.182	2.34	455.263	2.34	+0.081
2040	819.284	3.75	819.788	3.75	+0.504
2045	1317.594	5.00	1317.554	5.00	−0.040
2050	1844.598	5.00	1844.519	5.00	−0.078

CEEP denotes electricity generation that cannot be absorbed by demand, storage, or export within the model and is therefore curtailed. Percentages refer to the share of total annual electricity generation.

CEEP remains negligible through 2025 in both scenarios but increases from 2035 onwards under high renewable penetration. Differences between the reference and flexibility scenarios remain small and are primarily observed in selected high-renewable periods, indicating that aggregated public building flexibility has a limited influence on the magnitude of excess electricity generation.

While absolute differences in CEEP are moderate, they occur predominantly during periods of high surplus generation, when additional demand-side flexibility can affect system operation. Aggregated flexibility from public buildings therefore modifies the temporal handling of surplus electricity rather than eliminating excess generation or materially altering renewable energy targets.

3.4 Heat Sector Transformation

3.4.1 District Heating

In the flexibility scenario, HP_Public represents an aggregated public-sector heat pump load, as defined in the model input data, which is introduced progressively after 2035 as a dedicated category of heat demand that can be supplied exclusively by flexible technologies.

[Fig. 4](#) presents heat generation in district heating systems by technology. In both scenarios, electrification of district heating increases after 2035, with electricity-driven heat pumps gradually replacing fossil-based heat supply technologies. In the flexibility scenario (HP_Public), aggregated public-sector heat

demand is supplied by dedicated heat pumps, modifying the allocation of heat supply technologies within the district heating system rather than accelerating or delaying the overall decarbonization trajectory.

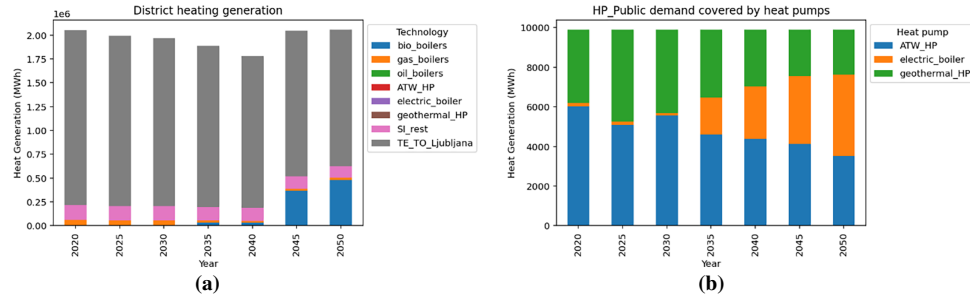


Figure 4: Heat supply by technology in (a) district heating systems and (b) aggregated public-building heat demand (HP_Public).

By mid-century, public-sector heat pumps supply a substantial share of district heating demand in the flexibility scenario. This highlights the role of aggregated public-sector heat demand in shaping the technological composition and operational characteristics of district heating systems under identical decarbonization constraints.

3.4.2 Individual Heating

Heat generation for individual heating systems is shown in Fig. 5. In the reference scenario, electrification of individual heating is achieved primarily through the widespread deployment of individual heat pumps, resulting in a steady increase in electricity demand for heating toward mid-century.

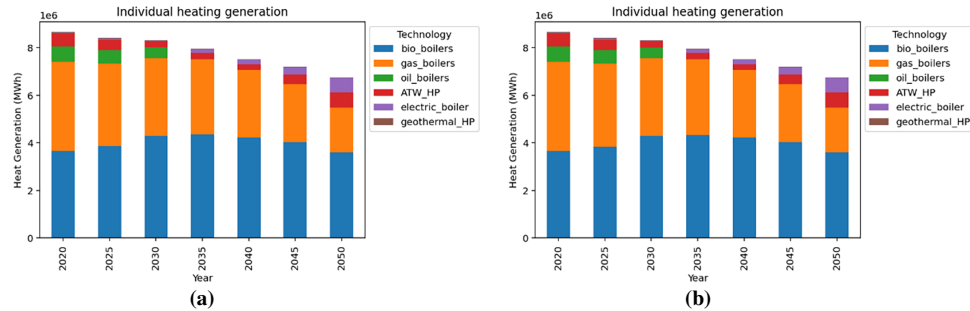


Figure 5: Individual heating generation: (a) Reference scenario, (b) Flexibility (HP_Public) scenario.

In the flexibility scenario, a share of public-building heat demand is modelled separately and supplied by dedicated flexible technologies. As a result, the deployment of individual heat pumps is lower compared to the reference case, reflecting a redistribution of heat pump deployment between individual and public-building heating categories rather than a reduction in overall electrification of the heat sector.

3.5 Hydrogen Production and Sector Coupling

Hydrogen production, storage, and utilization are summarized in Fig. 6 and Table 6. In both scenarios, hydrogen production increases after 2030, reflecting its role as a long-term decarbonization option and a cross-sectoral energy carrier. Hydrogen production levels remain very similar between the reference

and flexibility scenarios, indicating that the introduction of aggregated public building flexibility does not materially alter long-term hydrogen deployment.

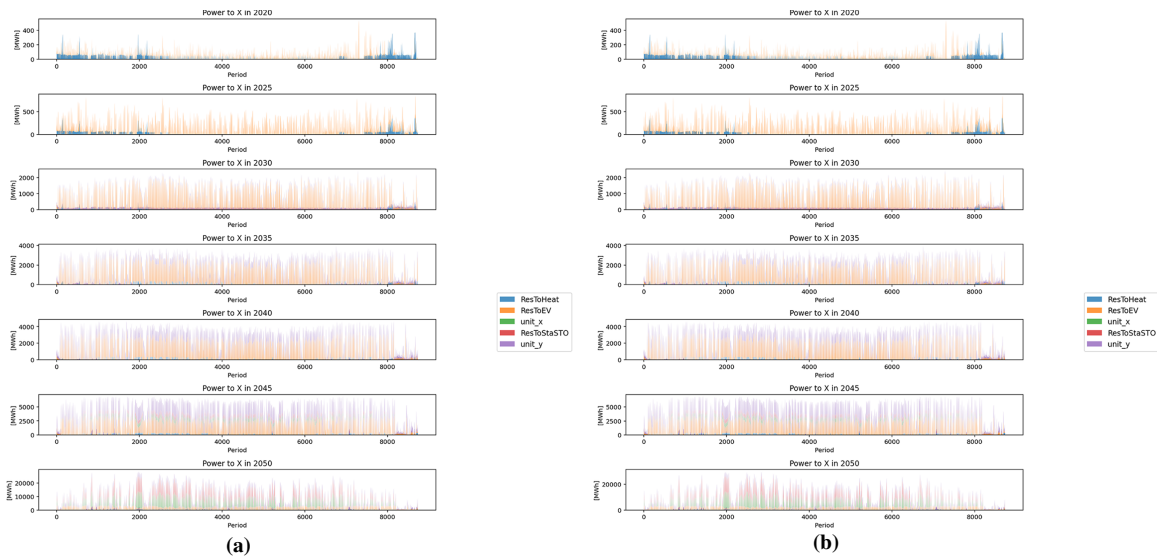


Figure 6: Hydrogen production & storage: (a) Reference scenario, (b) Flexibility (HP_Public) scenario.

Table 6: Hydrogen production (GWh/year).

Year	Reference	Flexibility
2030	74.20	75.62
2040	395.91	432.70
2050	668.42	684.77

Fig. 6 illustrates that the temporal profiles and magnitudes of hydrogen production remain closely aligned across scenarios, with only minor deviations. This indicates that aggregated public-building flexibility has a limited impact on long-term hydrogen deployment and primarily affects short-term operational allocation.

In the flexibility scenario, a share of surplus electricity is supplied to public building heat pumps, modifying the allocation of electricity use between heat production and other conversion pathways. However, hydrogen remains essential for industrial decarbonization and long-term energy storage in both scenarios, with only marginal differences in production levels.

These results indicate that aggregated public building flexibility affects the operational allocation of electricity in the short term, while hydrogen continues to play a central role in long-term storage and industrial decarbonization under both scenarios.

4 Discussion

From a system perspective, public buildings provide an intermediate flexibility layer between short-term operational balancing and long-term hydrogen-based sector coupling. While the National Energy and Climate Plan primarily focuses on supply-side decarbonization and sector coupling through hydrogen,

this study shows that demand-side electrification of public buildings affects system operation under high renewable penetration without altering renewable energy targets.

Public buildings provide an intermediate flexibility layer between short-term balancing and long-term hydrogen storage. Their contribution becomes particularly relevant in high-renewable scenarios after 2040, when curtailment levels increase sharply. In this context, demand-side flexibility complements rather than replaces hydrogen-based balancing, reinforcing the need for an integrated policy approach combining electrification, flexibility markets, and sector coupling.

5 Conclusions

This study assessed the role of aggregated demand-side flexibility from public buildings in supporting renewable energy integration and decarbonization of the Slovenian energy system. Using high-resolution monitoring data and the H2RES energy system optimization model, two long-term scenarios were analyzed: a reference scenario without public building flexibility and a flexibility scenario including heat pump-based public building demand.

The results show that public buildings, when aggregated and electrified via heat pumps, provide flexible demand that:

- moderately affects the optimal deployment and timing of variable renewable generation,
- moderately affects critical excess electricity production,
- modifies the distribution of CO₂ emissions within the heat sector,
- complements hydrogen-based sector coupling.

While overall renewable targets remain unchanged, the flexibility scenario achieves these targets more efficiently and with reduced system stress. These findings highlight the strategic value of public buildings as early adopters of electrified heating and as a scalable source of aggregated flexibility.

The results support national policy priorities and demonstrate that targeted activation of public building flexibility can contribute meaningfully to a resilient, low-carbon energy system. Future research should extend the analysis to include spatial constraints, market-based flexibility mechanisms, and interactions with other flexible demand sectors.

A key limitation of this study is the representativeness of the empirical dataset. Although based on detailed monitoring of more than 100 public buildings, the sample is not statistically scaled to the full national building stock. Consequently, the results should be interpreted as indicative of system-level trends and relative impacts rather than precise national-level estimates.

Acknowledgement: Not applicable.

Funding Statement: The authors received no specific funding for this study.

Author Contributions: Conceptualization, Franjo Pranjić, Doris Beljan, Antun Pfeifer and Neven Duić; methodology, Franjo Pranjić, Doris Beljan and Antun Pfeifer; software, Franjo Pranjić; validation, Franjo Pranjić, Primož Praper and Matej Fike; formal analysis, Franjo Pranjić and Matej Fike; investigation, Franjo Pranjić, Doris Beljan and Peter Vrtič; data curation, Franjo Pranjić; writing—original draft preparation, Franjo Pranjić; writing—review and editing, Doris Beljan, Primož Praper, Matej Fike, Peter Vrtič, Antun Pfeifer and Neven Duić; visualization, Franjo Pranjić; supervision, Antun Pfeifer and Neven Duić. All authors reviewed and approved the final version of the manuscript.

Availability of Data and Materials: Data available on request from the authors.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Prina MG, Lionetti M, Manzolini G, Sparber W, Moser D. Transition pathways optimization methodology through EnergyPLAN software for long-term energy planning. *Appl Energy*. 2019;235:356–68. doi:10.1016/j.apenergy.2018.10.099.
2. Luo Z, Peng J, Cao J, Yin R, Zou B, Tan Y, et al. Demand flexibility of residential buildings: definitions, flexible loads, and quantification methods. *Engineering*. 2022;16(4):123–40. doi:10.1016/j.eng.2022.01.010.
3. Chen Y, Chen Z, Xu P, Li W, Sha H, Yang Z, et al. Quantification of electricity flexibility in demand response: office building case study. *Energy*. 2019;188:116054. doi:10.1016/j.energy.2019.116054.
4. Koričan M, Herc L, Pfeifer A, Vladimir N, Duić N. Long-term influence of the gradual naval fleets decarbonization on the flexibility of an integrated energy system. *Sustain Energy Technol Assess*. 2024;72:104041. doi:10.1016/j.seta.2024.104041.
5. Tronchin L, Manfren M, Nastasi B. Energy efficiency, demand side management and energy storage technologies—a critical analysis of possible paths of integration in the built environment. *Renew Sustain Energy Rev*. 2018;95:341–53. doi:10.1016/j.rser.2018.06.060.
6. Pfeifer A, Herc L, Batas Bjelić I, Duić N. Flexibility index and decreasing the costs in energy systems with high share of renewable energy. *Energy Convers Manag*. 2021;240(5):114258. doi:10.1016/j.enconman.2021.114258.
7. Pastore LM. Combining power-to-heat and power-to-vehicle strategies to provide system flexibility in smart urban energy districts. *Sustain Cities Soc*. 2023;94(7):104548. doi:10.1016/j.scs.2023.104548.
8. Feijoo F, Pfeifer A, Herc L, Groppi D, Duić N. A long-term capacity investment and operational energy planning model with power-to-X and flexibility technologies. *Renew Sustain Energy Rev*. 2022;167(1):112781. doi:10.1016/j.rser.2022.112781.
9. Cabrera P, Lund H, Thellufsen JZ, Sorknæs P. The MATLAB Toolbox for EnergyPLAN: a tool to extend energy planning studies. *Sci Comput Program*. 2020;191:102405. doi:10.1016/j.scico.2020.102405.
10. Bakhtavar E, Prabatha T, Karunathilake H, Sadiq R, Hewage K. Assessment of renewable energy-based strategies for net-zero energy communities: a planning model using multi-objective goal programming. *J Clean Prod*. 2020;272(18):122886. doi:10.1016/j.jclepro.2020.122886.
11. Cosmi C, Dvarionienė J, Marques I, Di Leo S, Gecevičius G, Gurauskienė I, et al. A holistic approach to sustainable energy development at regional level: the RENERGY self-assessment methodology. *Renew Sustain Energy Rev*. 2015;49:693–707. doi:10.1016/j.rser.2015.04.094.
12. Hung F, Ghaffari A, Ethan Yang YC, Dillingham G. An investment behavioral modeling framework for advancing power system transformation toward renewable energy integration. *Energy Clim Change*. 2024;5:100127. doi:10.1016/j.egycc.2024.100127.
13. Zhu X, Zhang X, Gong P, Li Y. A review of distributed energy system optimization for building decarbonization. *J Build Eng*. 2023;73(2):106735. doi:10.1016/j.job.2023.106735.
14. Farghali M, Osman AI, Mohamed IMA, Chen Z, Chen L, Ihara I, et al. Strategies to save energy in the context of the energy crisis: a review. *Environ Chem Lett*. 2023;21(4):2003–39. doi:10.1007/s10311-023-01591-5.
15. Tundo A, Capezzuto P, Blaso L, Marinucci P, Mutani G. Holistic approach for sustainable cities and communities: best practices in living labs. In: *Innovation in urban and regional planning*. Cham, Switzerland: Springer Nature Switzerland; 2024. p. 301–12.
16. Tayyab M, Hauer I, Helm S. Holistic approach for microgrid planning for e-mobility infrastructure under consideration of long-term uncertainty. *Sustain Energy Grids Netw*. 2023;34(214):101073. doi:10.1016/j.segan.2023.101073.
17. Thiam FB, Slegers J, Nash J, Nguyen T, Tackett M, Reddoch J, et al. MISO's regional long range transmission planning: a proactive and holistic planning approach. In: *Proceedings of the 2023 IEEE Power & Energy Society General Meeting (PESGM)*; 2023 Jul 16–20; Orlando, FL, USA. p. 1–5.

18. Mussawar O, Mayyas A, Azar E. Built form and function as determinants of urban energy performance: an integrated agent-based modeling approach and case study. *Sustain Cities Soc.* 2023;96(1):104660. doi:10.1016/j.scs.2023.104660.
19. Maïzi N, Mazauric V, Assoumou E, Bouckaert S, Krakowski V, Li X, et al. Maximizing intermittency in 100% renewable and reliable power systems: a holistic approach applied to Reunion Island in 2030. *Appl Energy.* 2018;227(1):332–41. doi:10.1016/j.apenergy.2017.08.058.
20. Njoka GM, Mogaka L, Wangai A. Impact of variable renewable energy sources on the power system frequency stability and system inertia. *Energy Rep.* 2024;12(1):4983–97. doi:10.1016/j.egyr.2024.10.057.
21. Noran O, Bernus P. An evolution-based approach towards next-gen defence HQ and energy strategy integration. In: *Proceedings of the 23rd International Conference on Enterprise Information Systems*; 2021 Apr 26–28; Online.
22. Al-Mohannadi DM, Linke P. Optimal utilization of natural gas in processing clusters with reduced CO₂ emissions through material and energy integration. *Energy Technol.* 2020;8(8):1901381. doi:10.1002/ente.201901381.
23. Lei Y, Wang D, Jia H, Chen J, Li J, Song Y, et al. Multi-objective stochastic expansion planning based on multi-dimensional correlation scenario generation method for regional integrated energy system integrated renewable energy. *Appl Energy.* 2020;276(3):115395. doi:10.1016/j.apenergy.2020.115395.
24. Deng X, Lv T. Power system planning with increasing variable renewable energy: a review of optimization models. *J Clean Prod.* 2020;246:118962. doi:10.1016/j.jclepro.2019.118962.
25. Integrated national energy and climate plan of the republic of Slovenia. [cited 2025 Jan 1]. Available from: [si_final_necp_main_en_0.pdf](#).
26. Slovenia's national energy and climate plan (NECP). [cited 2025 Jan 1]. Available from: National energy and climate plans, https://commission.europa.eu/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en.
27. Long-Term Strategy for Building Renovation (DSEPS 2050). National building renovation plans. [cited 2025 Jan 1]. Available from: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/national-building-renovation-plans_en.
28. Public Call 119SUB-LS24: non-repayable financial incentives for local communities for new investments in greater energy efficiency and the use of renewable energy sources in buildings. [cited 2025 Jan 1]. Available from: <https://rra-koroska.si/en/updates/tenders/public-call-119sub-ls24-non-refundable-financial-incentives-to-local-communities-for-new-in-greater>.