Centralized Short-Term Thermal Energy Storage in Hybrid Heat Pump Building Systems

Dragi Antonijević[1](✉), Dimitrije Manić[1], and Mirko Komatina[2]

[1] Innovation Center of the Faculty of Mechanical Engineering, University of Belgrade, Beograd, Serbia
dantonijevic@mas.bg.ac.rs

[2] Faculty of Mechanical Engineering, University of Belgrade, Kr. Marije, 16 Belgrade, Serbia

Abstract. The impact of short-term thermal energy storage (TES) on heat pump–based systems in newly constructed multi-apartment buildings is evaluated for two emission concepts: a medium-temperature fan-coil system and a low-temperature radiant (floor/wall/ceiling) system. An optimized TES volume of 2.0 L/m^2, derived from parametric analysis, was applied to domestic hot water (DHW) and space heating. System-level considerations indicate that extending TES to cooling would provide only limited additional energy benefits while increasing investment and control complexity. TES integration achieves annual electricity savings of 10–14%, primarily through improved effective seasonal heat pump performance and winter peak load mitigation, with the largest gains observed for DHW operation. Although space cooling represents a small share of annual electricity demand, it governs installed system capacity, whereas TES reduces required heating capacity by smoothing coincident DHW and space-heating peaks. Low-temperature radiant systems achieve lower absolute electricity consumption, while TES provides comparable relative benefits across both emission technologies. Rooftop photovoltaic integration is proposed as a future upgrade toward a hybrid renewable configuration.

Keywords: Air-to-water heat pumps · Short-term thermal energy storage · Domestic hot water · Peak load reduction · Energy savings

1 Introduction

In the 21st century, energy challenges have become critical, with buildings playing a central role in reducing energy consumption and CO_2 emissions. Heating and cooling account for more than 50% of global final energy use and approximately 40% of CO_2 emissions, with space conditioning representing up to 80% of building energy demand in colder and hotter climates [1, 2]. Within Europe, heating and cooling in buildings comprise about half of total energy demand, over 60% of which is still supplied by fossil fuels [3]. When domestic hot water (DHW) is included, these end uses account for nearly 80% of direct CO_2 emissions from buildings [3], highlighting the need for improved heating technologies and further energy efficiency measures. While space-heating demand can

© The Author(s) 2026
L. Bragança et al. (Eds.): ReSBE 2026, LNCE 909, pp. 230–238, 2026.
https://doi.org/10.1007/978-3-032-35104-3_27

be decreased through enhanced envelope performance and reduced system operating temperatures, DHW consumption remains relatively constant. Consequently, its share of total building energy demand increases and is expected to grow further as building energy efficiency improves [4, 5].

In Serbia, households are the largest final energy consumers, accounting for approximately 40% of total final energy consumption. Space heating accounts for roughly 66%, and DHW preparation contributing around 12% [6, 7]. About 75% of households rely on individual heating systems, mainly using firewood, electricity, and natural gas, while the rest are connected to district heating networks. Although district heating is widespread in around 50 of the biggest cities and included in new multi-family buildings, household connections are growing slowly at about 0.4% per year [7], and many new buildings avoid it due to high costs, limited flexibility, and reliance on a single provider. As a result, heat pump (HP) based systems are starting to emerge, offering space heating, DHW, and cooling with greater energy efficiency, lower long-term costs, fewer emissions, and more independence.

In recent years, the dominant residential typology in Belgrade—and in a few other major Serbian cities—has been the mixed-use mid-rise building, typically realized as a single-core linear slab block with 6–10 above-ground storeys, ground-floor comercial spaces, underground parking, and a total heated floor area of approximately 1,200–2,500 m^2. These buildings are generally designed in accordance with the Serbian Rulebook on Energy Efficiency of Buildings [8] to achieve an annual heating energy demand of up to 60 kWh/m^2. Buildings with lower energy demands are less common and are typically found in higher-cost projects or in more desirable urban locations.

2 System Description and Calculation Method

In energy-efficient residential buildings with modest specific space-heating demand, the structure of final energy consumption changes significantly, and the share of energy used for DHW becomes proportionally larger than in conventional buildings. Under these conditions, thermal energy storage (TES) becomes increasingly important, particularly when HPs are used as the primary heat supply system. TES enables the decoupling of heat generation from heat demand, reducing compressor cycling, improving the seasonal coefficient of performance (SCOP), and allowing heat pumps to operate in more favorable thermodynamic regimes, such as lower supply temperatures and longer continuous operating periods.

The role of TES is even more pronounced when heat pumps provide both space heating and DHW, as DHW production requires higher temperatures and is characterized by short-term peak loads that do not coincide with average heating demand. TES tanks allow DHW to be produced outside peak demand periods—such as during off-peak electricity tariffs or times of higher renewable electricity availability—while hot water delivery is supplied from storage. This approach avoids oversizing the heat pump for DHW peak power, reduces installed capacity, improves overall energy and economic performance, and enhances operational flexibility, load management, and integration with renewable energy sources and smart grids.

In line with the above considerations, the analytical part of this study examines the optimal sizing of TES for a representative new residential building in Belgrade, taking

into account local climatic conditions and the structure of space-heating and DHW demand. A representative air-to-water heat pump system (Fig. 1) with radiant or fan-coil heat-emission systems is analyzed to quantify energy savings and evaluate the TES volume range that yields the greatest overall performance benefits.

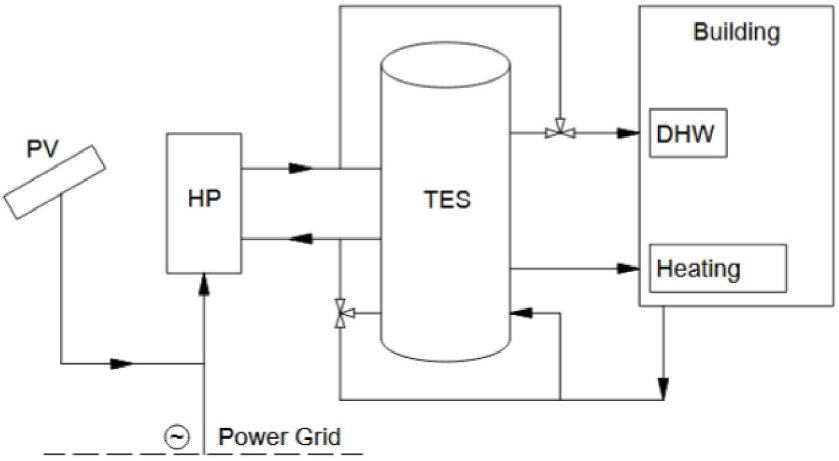


Fig. 1. TES connection scheme for DHW and heating mode.

Reliable estimation of DHW energy consumption in residential buildings remains challenging due to limited data availability and strong dependence on occupancy patterns, dwelling characteristics, user behavior, distribution losses, and the presence of non-residential functions. Based on a comprehensive synthesis conducted for the Budapest metropolitan region [5]—which is socio-technically comparable to urban areas in Serbia—an average DHW energy demand of 28.2 kWh/m^2·year is adopted in this study. A simplified seasonal DHW demand profile was assumed, with monthly demand during the summer period (June–August) taken as 20% lower than during the rest of the year due to higher cold-water inlet temperatures, the consequently reduced energy required for water heating, and reduced occupant presence during summer, resulting in monthly values of 1.98 and 2.47 kWh/m^2, respectively, while preserving the annual average demand.

Climate-based seasonal energy demand were derived from the multi-city dataset presented in Table 1 and used to disaggregate the annual specific energy demands for space heating, space cooling, and domestic hot water preparation into monthly values for Belgrade (Fig. 2). The dataset was compiled from multiple sources [9–14] and includes average January and July air temperatures, heating design temperature, heating and cooling degree days, average wind speed and relative humidity, day–night temperature differences in January and July, as well as 10-year averages of annual global insolation and average daily insolation in December and July for the selected cities. An annual specific space heating energy demand of 60 kWh/m^2 was distributed over the heating season (October–April) using monthly shares proportional to the heating degree days for Belgrade, with peak demand occurring in December and January.

The annual specific cooling energy demand was estimated by scaling the heating demand using the ratio of cooling to heating degree days for Belgrade and applying an empirical correction factor to account for typical solar and internal heat gains in residential buildings [15], resulting in an estimated cooling demand of approximately 18 kWh/m^2·year. This cooling demand was distributed over the cooling season (May–September) based on mean monthly outdoor temperatures for Belgrade, with peak demand occurring in July and August.

Table 1. Climate data for selected cities in Serbia and the region.

	Belgrade	Novi Sad	Niš	Prišti-na	Subotica	Vra-nje	Thess aloniki	Buda-pest
$T_{AV,\,Jan.}$ [°C]	0.8	0.8	−0.5	−0.6	0.5	−1.0	4.2	−0.5
$T_{AV,\,July}$ [°C]	24.3	23.7	23.4	21.5	23.3	26.4	27.4	22.1
$T_{Des.H.}$ [°C]	−12.1	−14.8	−14.5	−19.8	−14.8	−15.3	−6.0	−13.0
HDD_{18} [K day]	2550	2650	2450	2570	2750	2500	1850	2800
CDD_{22} [K day]	520	480	620	560	430	670	950	650
$w_{AV,\,Jan.}$ [km/h]	11.2	11.1	8.1	8.0	12.5	8.1	8.8	10.7
$w_{AV,\,July}$ [km/h]	8.6	8.7	9.0	8.5	12.4	11.7	8.2	10.3
$RH_{AV,\,Jan.}$ [%]	83	87	–	84	–	–	75	84
$RH_{AV,\,July}$ [%]	50	49	–	57	–	–	45	58
$\Delta T_{DN,\,AV,\,Jan.}$ [K]	4.0	4.4	5.0	5.0	4.5	6.5	5.0	5.5
$\Delta T_{DN,\,AV,\,July}$ [K]	11.0	11.0	13.5	13.0	11.0	14.5	11.0	12.5
$H_{y,AV10}$ [kWh/m^2]	1440	1390	1520	1570	1380	1540	1820	1410
$H_{d,AV,\,Dec.}$ [kWh/m^2]	1.2	1.1	1.4	1.5	1.1	1.4	1.7	1.1
$H_{d,AV,\,July}$ [kWh/m^2]	6.6	6.3	6.7	6.9	6.2	6.6	7.4	6.4

For a model residential building with a heated floor area of 2,000 m^2, air-to-water heat pumps without TES were sized to meet peak thermal loads based on representative specific design heat load values (W/m^2) for the Belgrade climate. This resulted in required capacities of approximately 145 kW for combined DHW production and space heating and 90 kW for space cooling with fan-coil systems, while low-temperature radiant systems required about 115 kW and 50 kW, respectively.

The introduction of TES for DHW and space heating significantly reduces peak heating capacity. A parametric Python-based analysis was performed for both fan-coil and radiant heating systems by varying the TES volume and evaluating the resulting peak load reduction and annual electricity consumption under identical boundary conditions. The analysis assumed climate-based seasonal demand profiles for space heating and DHW, while maintaining fixed annual heating and DHW energy demands (i.e., constant annual energy balances independent of TES configuration). The results indicate that the optimal TES volume lies within the range of 1.6–2.1 L/m^2. Beyond this range, only marginal reductions in annual electricity consumption were achieved, while storage costs and space requirements continued to increase.

For subsequent calculations, a representative value of 2.0 L/m^2 is adopted within the identified optimal range. Accordingly, the required installed heat pump capacity for DHW preparation and space heating is reduced to approximately 100 kW for fan-coil systems and 80 kW for radiant systems, whereas the required cooling capacity remains unchanged compared to systems without TES.

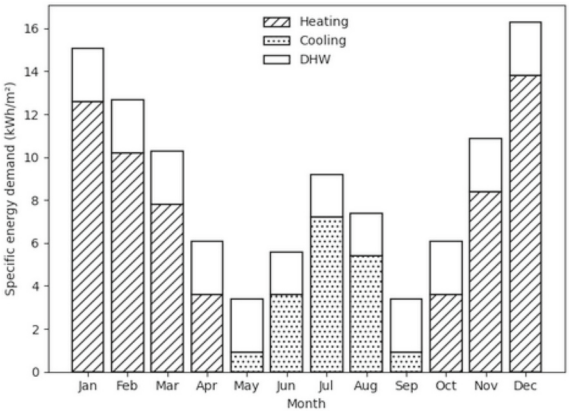


Fig. 2. Specific energy demand of the building.

Cooling loads are typically more continuous and evenly distributed than space heating and DHW demand, allowing modulating heat pumps to follow the load without intermediate storage. Fan-coil and radiant ceiling or wall systems have low water content and fast dynamic response, making direct operation straightforward. Therefore, cooling is handled directly by the heat pumps, without the use of TES.

An alternative configuration based on a single large heat pump covering heating, DHW, and cooling—with or without dedicated TES for cooling—was evaluated but rejected due to the need for complex hydraulic switching and priority management between operating modes, increased condensation risk, and higher operational vulnerability. Introducing TES specifically for cooling would further increase investment and complicate control, while providing only marginal energy benefits.

The system is therefore designed with two heat pumps operating in cascade, which improves part-load efficiency, reduces cycling, and enhances operational reliability. Under typical winter conditions, one unit satisfies the building's heating and DHW demand, while the second is activated only during extreme peak loads. In summer, the units operate in parallel, with one providing cooling and the other handling DHW production, enabling simultaneous operation without complex hydraulic switching or dedicated heat-recovery arrangements.

3 Results and Discussion

Scenario A. The fan-coil–based emission system was analyzed under continental climate conditions using seasonal performance factors typical of medium-temperature air-to-water heat pump operation. SCOP values of 3.4 (space heating) and 3.0 (DHW), and

a SEER of 4.0 (space cooling) were adopted, consistent with literature values for similar systems [16, 17] under part-load operation in continental climates.

With TES implemented, the total annual electricity consumption amounts to 31.5 kWh/m^2, with space heating, DHW preparation, and space cooling accounting for approximately 56%, 30%, and 14% of the total demand, respectively. In the absence of TES, electricity consumption increases to 35.8 kWh/m^2 due to reduced effective seasonal performance during peak heating and DHW operation. The integration of TES results in annual electricity savings of 13.7% for heating and DHW, corresponding to 12.9% when space cooling is included in the total electricity balance.

Scenario B. The low-temperature radiant (floor, wall, or ceiling) emission system was evaluated assuming improved seasonal performance due to lower supply temperatures in heating mode and higher chilled-water temperatures in cooling mode, with SCOP values of 4.0 for space heating and 3.1 for DHW preparation, and a SEER of 4.5 for space cooling, consistent with literature values for similar low-temperature systems.

When TES is applied, total annual electricity consumption is reduced to 28.1 kWh/m^2, with approximately 53% attributed to space heating, 32% to DHW preparation, and 15% to space cooling. Without TES, annual electricity consumption increases to 31.5 kWh/m^2, primarily due to reduced seasonal efficiency during simultaneous heating and DHW operation. The resulting electricity savings amount to 12.4% for heating and DHW, or 10.8% when cooling is included in the overall electricity demand (Fig. 3).

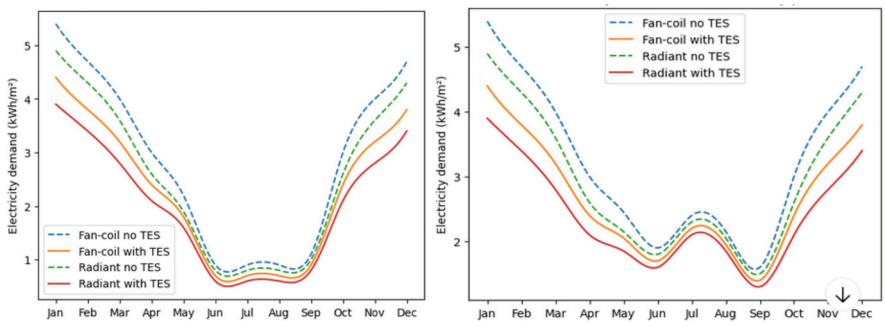


Fig. 3. Seasonal electricity demand profiles for (a) space heating and DHW and (b) space heating, DHW, and cooling, for fan-coil and radiant systems with and without TES.
Interpolated from monthly values using a third-order spline.

The radiant emission system exhibits lower absolute electricity consumption in both configurations, reflecting improved heat pump efficiency under low-temperature operating conditions. However, the relative impact of TES is comparable in both systems, indicating that its effectiveness is not limited to a specific heat-emission technology. TES was primarily dimensioned to support DHW preparation, as DHW demand is characterized by high supply temperature requirements, pronounced short-term peak loads, and a strongly intermittent daily consumption profile. By decoupling heat production from consumption, TES enables longer and more stable operation, resulting in improved effective seasonal performance, particularly for DHW preparation. Additional benefits

are observed for space heating through peak load shaving during cold periods. This reduction in coincident peak demand directly influences heat pump sizing by lowering the required design heating capacity and mitigating oversizing driven by simultaneous DHW and space heating loads, thereby enabling more balanced and efficient operation. In both scenarios, space cooling represents a relatively small share of annual electricity consumption but remains the determining factor for installed cooling capacity, while the benefits of TES are primarily associated with improved winter operation.

4 Conclusions

This study assessed the impact of short-term thermal energy storage on the electricity consumption and operational performance of HP systems coupled with fan-coil and low-temperature radiant emission systems. The integration of relatively small-volume TES—requiring limited additional space and no cooling storage—leads to significant reductions in annual electricity consumption, reaching 13.7% (12.9% including cooling) for the fan-coil system and 12.4% (10.8% including cooling) for the radiant system. These results confirm the effectiveness of TES across different heat-emission technologies while maintaining a simple heat pump configuration.

TES primarily enhances winter operation by reducing peak loads and improving the seasonal performance factor of the HP, with the most pronounced benefits for domestic hot water preparation due to its high-temperature requirements and intermittent demand profile. Although space cooling accounts for a minor share of annual electricity consumption, it governs installed cooling capacity, whereas TES benefits are mainly associated with heating and DHW operations. Additional improvements may also be achieved through the integration of rooftop photovoltaic systems, which align well with cooling demand and could further reduce grid electricity use while enabling a hybrid renewable-based HP system without modifying the core system architecture.

Due to the simplified monthly approach and Belgrade-specific conditions, the quantitative results may vary for other climates and building typologies, although the overall trends remain broadly applicable. Future work should therefore address dynamic validation, techno-economic feasibility, and implementation constraints to further substantiate the practical deployment potential of the proposed configurations.

Acknowledgement. This research was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia under Contract No. 451-03-33/2026-03/200213 dated February 5, 2026, and by the Science Fund of the Republic of Serbia, Project No. 4344, Grant No. TF C1389YF: Forward Looking Framework for Accelerating Households Green Energy Transition – FF GreEN.

References

1. Zhou, J., et al.: Thermal energy storage–coupled heat pump systems: review of configurations and modelling approaches. Renew. Sust. Energ. Rev. **226**, 116226 (2026)

2. Li, Y., et al.: Electrification of residential heating, cooling and hot water: load smoothing using onsite photovoltaics, heat pump and thermal batteries. J. Energy Storage. **56**, 105873 (2022)
3. Testasecca, T., et al.: Energy assessment of thermal solar-powered district heating and cooling networks for a cluster of buildings in Mediterranean climate. Renew. Energy. **251**, 123397 (2025)
4. Pomianowski, M.Z., et al.: Sustainable and energy-efficient domestic hot water systems: a review. Renew. Sust. Energ. Rev. **128**, 109900 (2020)
5. Vamos, V., Horvath, M.: Residential domestic hot water consumption analysis for multifamily buildings supplied by district heating. Therm. Sci. **26**(2B), 1267–1276 (2022)
6. Pavlović, B., Ivezić, D., Živković, M.: Transition pathways of household heating in Serbia: analysis based on an agent-based model. Renew. Sust. Energ. Rev. **163**, 112506 (2022)
7. Pavlović, B., Živković, M., Ivezić, D.: Integrated energy planning approach for accelerating energy transition of households. Energy Rep. **10**, 4641–4650 (2023)
8. Ministry of Construction, Transport and Infrastructure: Rulebook on Energy Efficiency of Buildings [Pravilnik o energetskoj efikasnosti zgrada]. Official Gazette of the Republic of Serbia: 61/2011 (2011)
9. Eurostat: Heating degree days – metadata. https://ec.europa.eu/eurostat/cache/metadata/en/nrg_chdd_esms.htm?utm_source=chatgpt.com (2023), last accessed 2026/1/22
10. European Commission JRC: PVGIS (SARAH2/ERA5): Global horizontal irradiation monthly averages for 2014–2023. https://re.jrc.ec.europa.eu/pvgis/, last accessed 2026/1/21
11. Janković, V., Podraščanin, Z., Đurđević, V.: Future climate change impacts on residential heating and cooling degree days in Serbia. IDOJARAS Q J. Hungar. Meteorol. Serv. **123**(3), 351–370 (2019)
12. Spinoni, J., Vogt, J., Barbosa, P.: European degree-day climatologies and trends for the period 1951-2011. Int. J. Climatol. **35**, 25–36 (2015)
13. Papakostas, K., Martinopoulos, G., Tsimpoukis, A.: Estimating heating and cooling degree days through an urban environment using publicly available sensors. Appl. Mech. Mater. **659**, 411–416 (2014)
14. NOAA NCEI: Global Climate Station Summaries. https://catalog.data.gov/dataset/global-climate-station-summaries (2025), last accessed 2025/12/9
15. De Rosa, M., et al.: Heating and cooling building energy demand evaluation; a simplified model and a modified degree days approach. Appl. Energy. **128**, 217–229 (2014)
16. EU Committee for Standardization: EN14825:2022 Air Conditioners, Liquid Chilling Packages and Heat Pumps, with Electrically Driven Compressors, for Space Heating and Cooling - Testing and Rating at Part Load Conditions and Calculation of Seasonal Performance. CEN, Brussels (2022)
17. Dongellini, M., Naldi, C., Morini, G.L.: Seasonal performance evaluation of electric air-to-water heat pump systems. Appl. Therm. Eng. **90**, 1072–1081 (2015)

Open Access This chapter is licensed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (http://creativecommons.org/licenses/by-nc-nd/4.0/), which permits any noncommercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if you modified the licensed material. You do not have permission under this license to share adapted material derived from this chapter or parts of it.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

