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Electrifying Residential Heating Systems toward Carbon-neutral Buildings: A Retrofitted Building Stock in Northern Italy

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Abstract. The electrification of residential heating systems is a key strategy for reducing fossil fuel use in existing urban building stocks. This study analyses monitored operational data from a set of residential building blocks in Milan, where gas-based boilers were replaced with ground water heat pumps as part of large retrofitting measures. Energy consumption data, collected before and after the activation of the heat pumps, were converted to primary energy and normalised using heating degree days to account for climatic variability of the considered periods. The analysis compares heating performance across building blocks by investigating how primary energy consumption responds to climatic demand and highlighting the potential impact of heating systems' electrification.

1 Introduction

The decarbonization of European buildings is a central goal of the latest Energy Performance of Buildings Directive [1], which aims at a zero-emission building stock by 2050 and the progressive phase-out of fossil-fuel boilers. Within the context of de-carbonising existing residential buildings, the replacement of gas-based boilers (GBs) with ground water heat pumps (GWHPs) is widely recognised as a key pathway to reduce dependence on fossil energy sources.

In recent years, research has examined the energy and economic impacts of re-placing boilers with heat pumps. Some studies have focused on analyses based on monitored operational data combined with digital twin models [2], while others have adopt-ed an aggregated perspective to assess the energy consumption and costs of multiple residential retrofit technologies at the national building stock level [3].

However, for Northern Italy, only a limited number of studies have analysed residential buildings based on long-term monitored energy consumption, typically focusing on specific social housing stocks or single districts. For instance, Ferrari et al. [4] analysed measured data from 227 social housing buildings in four northern Italian cities, and Biglia et al. [5]

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reported the monitored performance of GWHPs serving a residential district in Italy, while stressing that performance data from a large number of real GWHPs case studies are still hard to find.

Building heating energy demand is strongly influenced by climatic conditions. For this reason, heating degree days (HDD) normalisation is commonly applied to separate climate-driven variations from user behaviour that affects energy consumption [6]. Moreover, in cases where building envelope characteristics, occupancy patterns and system operation remain largely unchanged, HDD is often considered a suitable indicator for evaluating changes in heating systems performance [7].

Against this background, the present study investigates existing residential building blocks located in Milan, Italy, using monitored energy consumption data collected before and after the activation of the new GWHPs as part of large retrofitting interventions. Energy source consumption is consistently converted into primary energy, and HDD-based normalisation is applied to enable comparison across different heating periods. The analysis aims to assess the energy saving performance associated with the transition from gas-based heating systems to heat pump solutions under real operating conditions.

2 Case study and dataset

This study is based on a practical project involving six building blocks located in the northern urban area of Milan, Italy. The case study focuses on the assessment of the energy savings achieved by replacing existing GBs with GWHPs under real operating conditions.

2.1 Case study area: Milan residential blocks

The case study comprises forty-four buildings, representative of refurbished urban residential housing stock. The considered buildings built in the last century have been recently refurbished by insulating the building envelopes in line with the current updating requirements and by equipping the heating emitters (radiators) with thermo-static valves [8]. The buildings are grouped into blocks, each one served by the same central heating plant. As the last retrofit measure was the substitution of the GBs with GWHPs, during the first heating periods, once the other measures were already realised, the GBs remained activated.

Table 1 summarises the main geometric and construction characteristics of the se-lected residential blocks, including envelope surface, surface-to-volume ratio (S/V), and construction period. The S/V of the building stock is the average S/V value of the buildings in the selected block.

Table 1. Characteristics of selected building blocks

Stock name	Heated volume (m^3)	S/V	Construction decade
A	29,516	0.47	1970s
B	79,386	0.43	1970s
C	9,898	0.47	1960s
D	4,330	0.43	1960s
E	87,348	0.40	1930s
F	44,024	0.41	1960s

As shown in Table 1, the analysed blocks cover a wide range of heated volumes, while S/V ratios reveal similar building compactness levels, which are the most com-mon in the dense urban context. In addition, the variability of construction periods im-plies to consider the different technological solutions that can be found in most of the existing buildings in

Italy and in similar contexts [9]. These characteristics support the representativeness of the energy analysis referred to the case study.

2.2 Energy data sources and scope

The energy analysis is based on monitored data collected both before and after the activation of the GWHPs. Two main data sources were considered, reflecting the different heating technologies and monitoring approaches adopted during the study periods.

Before the GWHPs' activation, GBs consumption data were obtained from natural gas billing records provided by the building administrator. All gas-related data are available at a monthly time resolution and reflect aggregated energy use at the building block level.

After the GWHPs' activation, electricity consumption data were extracted from the online digital energy monitoring and management platform. The dataset provides measured electricity consumption of the GWHP systems at a resolution of 5 minutes, expressed in kWh, covering the period from October 2024 to December 2025. The monitored electricity consumption includes the GWHP as well as circulation water pumps on the groundwater loop. To give a picture of operating condition, the Milan groundwater temperature is averagely at 15°C, and the supply temperature of the heat-carrier fluid in user side of considered blocks is around 50°C.

It should be noted that the availability of monthly energy data is not uniform across all building blocks and heating periods, because the activation of the online digi-tal platform was implemented progressively. In addition, during the initial commis-sioning and tuning phase of the heat pump systems, parts of the operational data were either not recorded successfully in the dataset or not suitable for the assessment. As a result, during the transition phase, energy consumption data are unavailable for some months in specific building blocks.

3 Methodology

This section describes the methodology of the study, with the focus placed on the variation in energy consumption observed before and after the activation of GWHPs.

Due to difference of energy carrier, temporal resolution, and system configura-tion, a consistent data processing approach was adopted to enable meaningful compari-sons between the analysed periods.

Energy data from different sources were converted to primary energy to enable a consistent comparison between GBs and GWHPs. HDD were applied to normalise en-ergy consumption, accounting for interannual climate changes. As for the gas data, which was collected by months, the electricity data of GWHP was aggregated to a monthly time step. Moreover, as heating plants serve multiple buildings, the analysis was conducted at the building block level.

3.1 Energy data sources and scope

As mentioned in Section 2.2, the monitored energy data should be processed and converted to primary energy in order to enable a consistent comparison between gas-based and electrically driven heating systems. The primary energy consumption Ep was derived from the monitored data based on the energy carrier and the measurement units. For GBs, primary energy was calculated by the gas volume. The gas volume was first converted to thermal energy using the lower heating value (*PCI*) and then converted to primary energy by the factor for natural gas $f_{p,\,gas}$, as shown in Equation (1).

$$E_p = V_{gas} * PCI * f_{p,\,gas} = E_{hp} * f_{p,\,e} \tag{1}$$

For GWHPs, the monitored electrical energy was converted by the primary energy factor associated with electricity supply $f_{p,e}$. The lower heating value of natural gas was set as 9.94 kWh/Sm³ [10]. The primary energy factor for natural gas was set to 1.05, while the primary energy factor for electricity was set to 2.42 [11].

The HDD approach is widely adopted in building energy studies to account for climatic influences on space heating demand. It is based on a given reference base temperature, which considers that internal heat gains and solar radiation partially compensate for heat losses through the building envelope and ventilation. When outdoor air temperature falls below this threshold, heating energy demand is considered proportional to the difference between the base temperature and the daily mean outdoor temperature.

As shown in Equation (2), $HDD_{monthly}$ represent the cumulative temperature difference over the month and provides a simplified indicator of heating demand that reflects the magnitude of cold conditions.

$$HDD_{monthly} = \Sigma\, max(0,\ \theta_{base} - \theta_{avg}) \quad (2)$$

- θ_{base}, the reference base temperature (θ_{base} = 20 °C) [12].
- θ_{avg}, the reference base temperature.

Outdoor air temperature data were obtained from a street meteorological weather station located in the same northern urban area of Milan. HDD are calculated within the heating season of Milan, that is, from October 15th to April 15th.

3.2 HDD-based primary energy normalisation

The primary energy consumption data were normalised as shown in Equation (3), a commonly adopted approach in building energy studies to account for climatic variability [13]. Based on this formulation, HDD normalisation has been extensively applied to residential buildings [14]. This normalisation approach characterises the primary energy performance of heating systems under comparable climatic conditions by relating the total primary energy consumption to the cumulative heating demand, expressed through HDD, and to the building heated volume.

$$E_{norm} = \Sigma E_p / (\Sigma HDD_{monthly} * V) \quad (3)$$

Due to non-contiguous monthly data availability across the analysed building blocks and heating seasons, a direct month-by-month comparison over a full and consistent heating season is not feasible. To address this issue, primary energy consumption was aggregated over the available heating months for GBs and GWHPs and subsequently divided by the corresponding sum of HDD over the same monthly period, be-fore being normalised by the heated volume.

This HDD-based primary energy normalisation enables a robust comparison of energy performance between GBs and GWHPs, thereby minimising biases caused by missing data.

Table 2 summarises the temporal distribution of the available monthly data for each building block and heating system, together with the corresponding processed primary energy values and HDD, which form the input for the normalisation.

Table 2. Monthly primary energy consumption and HDD.

Heating system	Year	Month	Primary energy consumption of building blocks (MWh)						HDD (K• d)
			A	B	C	D	E	F	
GBs	2023	October	29.2	74.3	8.3	2.6	137.3	76.2	80.3
		November	106.4	307.6	30.2	10.2	339.9	162.7	302.9
		December		350.4	42.9	15.5	463.3	193.7	395.3
	2024	January		406.2	48.4		480.8	204.4	459.5
		February		308.4	28.3		380.5	153.2	288.3
		March		194.9	15.1		311.1	106.2	247.7
		April					182.4		50.6
		…	…	…	…	…	…	…	…
GW HPs	2024	October							58.8
		November		141.6		10.6	331.2	62.8	329.8
		December	111.0	168.8		13.2	439.6	69.4	438.9
	2025	January		186.2	51.1	15.4	427.3		438.2
		February		141.4	45.6	12.3	353.9	87.7	347.6
		March	91.1	116.6	35.9	9.7	280.1	89.5	255.5
		April	48.3	86.9	15.6	4.7	132.0	65.3	74.0
		…	…	…	…	…	…	…	…
		October	52.5	70.5	11.6	3.9	151.5	51.2	102.1
		November	102.5	123.2	32.1	9.4	298.7	106.1	317.3
		December	137.5	145.8	43.4	12.6	353.9	108.6	376.6

4 Results

Figure 1 compares the HDD-based normalised primary energy consumption of the analysed building blocks under GBs and GWHPs. For most building blocks, the transition from GBs to GWHPs results in a reduction in normalised primary energy consumption, indicating an overall improvement in heating energy efficiency following electrification. Notable reductions are observed for Blocks B and F, where GWHPs operation leads to primary energy savings exceeding 40% compared to the gas-based reference. Block B, in particular, exhibits the highest relative reduction, with a decrease of approximately 52%, suggesting a highly favourable interaction between the heat pump system and building-specific operating conditions. Primary energy reductions are also observed for Blocks A, D and E, with savings of approximately 2%, 6% and 18% respectively. These results indicate that electrification delivers consistent, though less pronounced, efficiency gains across different construction periods.

In contrast, Block C shows an energy increase in normalised primary energy consumption after electrification. This deviation indicates that the energy performance re-sponse to electrification is not uniform across the analysed blocks.

Given that the building envelopes and occupancy patterns remained unchanged, the opposite trend in Block C indicates that the operational management of the GWHP, including control logic and part-load operation that are still in tuning phase, may sig-nificantly influence the energy performance.

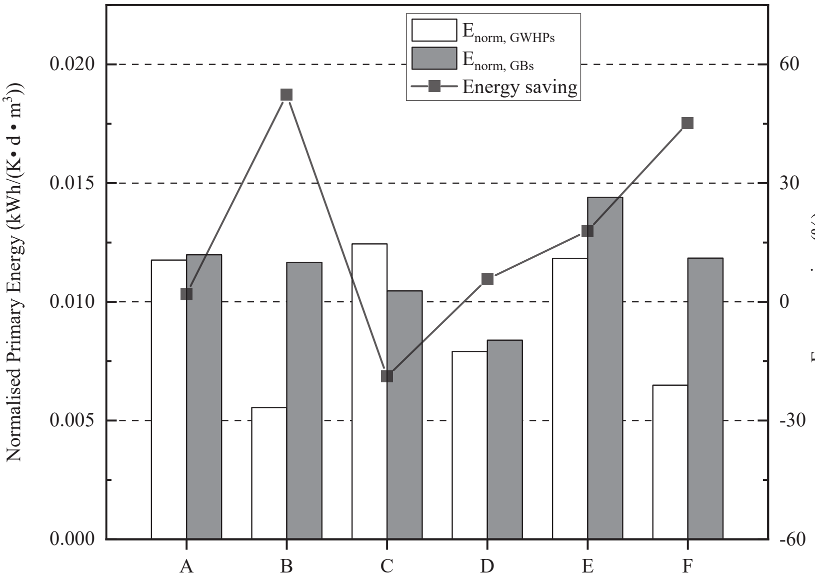

Fig. 1. Normalised primary energy consumption of the analysed building blocks under GBs and GWHPs.

To explore this aspect in greater detail, the relationship between monthly primary energy consumption and HDD was examined for each building block. This analysis, presented in Figure 2, allows the investigation of how primary energy demand scales with climate conditions with both GBs and GWHP.

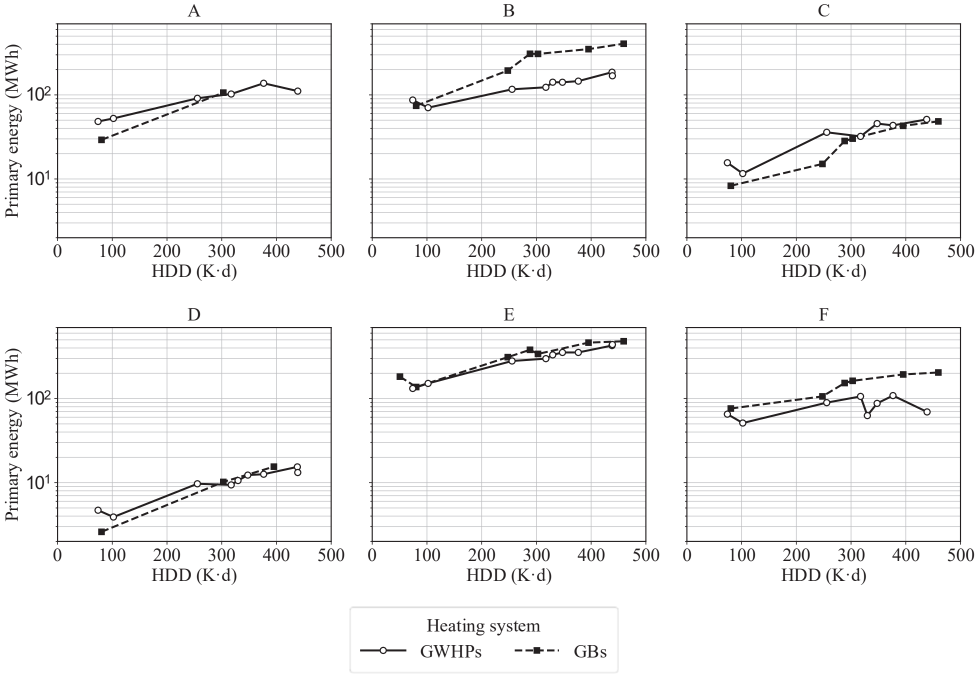

Fig. 2. Normalised primary energy consumption of the analysed building blocks under GBs and GWHPs.

According to Figure 2, in most cases, an approximately linear relationship is observed, indicating that primary energy consumption increases proportionally with heating demand. This behaviour suggests a stable system response, where the heat pump operation effectively tracks heating requirements as outdoor temperatures decrease.

Building blocks such as Block B and F, which exhibited the largest reductions in HDD-normalised primary energy in Figure 1, also show a consistent energy reduction in Figure 2. It indicates that the observed energy savings are not the result of specific periods but a stable performance of the GWHP systems across different climate conditions. This is supported by the consistent linear relationship between primary energy consumption and HDD across the entire observed range, rather than being driven by isolated months.

Blocks A, D and F exhibit a more nuanced behaviour. In both cases, the primary energy–HDD relationship under GWHP operation shows a reduction in slope compared to the GB, particularly in the higher HDD range. This indicates that, under colder climatic conditions, the GWHPs in these blocks can deliver heat with a lower primary energy demand per HDD, reflecting a theoretical energy saving potential.

Overall, the combined analysis of Figures 1 and 2 highlights that the transition from GBs to GWHPs generally leads to a reduction in primary energy consumption across the analysed residential blocks. However, the results also demonstrate that electrification alone does not guarantee energy savings. The effectiveness of GWHP systems is strongly influenced by their operational characteristics, and inappropriate control or system configuration can significantly undermine their theoretical efficiency benefits.

These results highlight the need to move beyond equipment substitution toward an effective system operation. In this context, further research focusing on advanced and adaptive control solutions appears essential to fully realise the energy-saving potential of GWHPs in retrofitting existing residential building stock.

5 Conclusions

This study assessed the primary energy impact of replacing GBs with GWHPs in a set of retrofitted residential building blocks in Milan, using monitored operational data and HDD-based normalisation.

The results indicate that, generally speaking, electrification leads to a reduction in primary energy consumption, confirming the potential of GWHPs to improve heating energy performance of existing residential buildings. However, the observed performance varies significantly across building blocks. While several cases show consistent energy savings, others exhibit limited or even negative overall improvements.

The combined analysis of normalised indicators and primary energy–HDD relationships demonstrates that electrification alone does not guarantee proper energy savings. System operation, control strategies and load conditions play a critical role in determining actual performance and may offset the theoretical efficiency advantages of GWHPs.

These findings highlight the need to complement heating systems electrification with improved operational and control approaches to optimise energy saving in existing residential building stock.

Symbology

Symbol	**Meaning**
E_p	Primary energy consumption, kWh
E_{norm}	HDD-normalised primary energy consumption, kWh/(K• d • m^3)
E_{gas}	Thermal energy from gas combustion, kWh
V_{gas}	Natural gas volume at standard conditions, Sm³

E_{hp}	Electricity of heat pump systems, kWh
PCI	Lower heating value of natural gas, kWh • Sm^{-3}
$f_{p,\ gas}$	Primary energy factor for natural gas, ND
$f_{p,\ e}$	Primary energy factor for electricity, ND
$HDD_{monthly}$	Monthly heating degree days, K• d
V	Heated volume of building blocks, m^3
θ_{base}	Reference base temperature for HDD calculation, °C
θ_{avg}	Daily average outdoor air temperature, °C

References

1. European Parliament. Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings. Official Jour-nal of the European Union. (2024)
2. D. R. Bayer, M. Pruckner, Data-driven heat pump retrofit analysis in residential buildings: Carbon emission re-ductions and economic viability. Appl. Energy **373**, 123823 (2024) https://doi.org/10.1016/j.apenergy.2024.123823
3. B. Coyne, E. Denny, Retrofit effectiveness: Evidence from a nationwide residential energy efficiency pro-gramme. Energy Policy **159**, 112576 (2021) https://doi.org/10.1016/j.enpol.2021.112576
4. S. Ferrari, T. Blázquez, G. Dall'O', Energy performance indexes based on monitored data of social housing buildings in Northern Italy. Appl. Energy **298**, 117264 (2021) https://doi.org/10.1016/j.apenergy.2021.117264
5. A. Biglia, M. Ferrara, E. Fabrizio, On the real performance of groundwater heat pumps: Experimental evidence from a residential district. Appl. Therm. Eng. **192**, 116887 (2021) https://doi.org/10.1016/j.applthermaleng.2021.116887
6. P. Hernandez-Cruz, C. Giraldo-Soto, C. Escudero-Revilla, J. M. Hidalgo-Betanzos, I. Flores-Abascal, Energy efficiency and energy performance gap in centralized social housing buildings of the Basque Country. Energy Build. **298**, 113534 (2023) https://doi.org/10.1016/j.enbuild.2023.113534
7. E. Wang, Z. Shen, N. Alp, N. Barry, Benchmarking energy performance of residential buildings using two-stage multifactor data envelopment analysis with degree-day based simple-normalization approach. Energy Convers. Manag. **106**, 530 (2015) https://doi.org/10.1016/j.enconman.2015.09.072
8. S. Ferrari, M. Zoghi, R. Cardelli, G. Dall'O', A monitoring campaign introducing the indoor driving temperature to assess the build-ing envelope performance. Appl. Energy **377**, 124650 (2025) https://doi.org/10.1016/j.apenergy.2024.124650
9. S. Ferrari, F. Zagarella, P. Caputo, G. Dall'O', Mapping Buildings' Energy-Related Features at Urban Level toward Energy Planning. Buildings **11**, (2021) https://doi.org/10.3390/buildings11080322
10. UNI. Energy performance of buildings. UNI/TS 11300-2:2019 Standard. Milan: Ente Italiano di Normazione. (2019)
11. DM. Application of minimum energy performance requirements for buildings. DM 26-06-2015. Rome: Ministero dello Sviluppo Economico. (2015)
12. A. D'Amico, G. Ciulla, D. Panno, S. Ferrari, Building energy demand assessment through heating degree days: The importance of a climatic dataset. Appl. Energy **242**, 1285 (2019) https://doi.org/10.1016/j.apenergy.2019.03.167
13. K. H. Andersen, A. R. Hansen, A. Marszal-Pomianowska, H. N. Knudsen, D. Leiria, P. K. Heiselberg, A mixed-method approach to understand energy-related occupant

behavior and every-day practices in multi-story residential buildings. Energy Build. **337**, 115650 (2025) https://doi.org/10.1016/j.enbuild.2025.115650

14. S. Wang, C. Yan, F. Xiao, Quantitative energy performance assessment methods for existing buildings. Energy Build. **55**, 873 (2012) https://doi.org/10.1016/j.enbuild.2012.08.037