

# Using UBEM to study decarbonisation strategies of urban neighbourhoods: a case study in Milan

Alessia Banfi<sup>1</sup>, Chiara Nardelli<sup>1</sup>, Martina Ferrando<sup>1</sup>, Xing Shi<sup>2</sup>, Francesco Causone<sup>1</sup>

<sup>1</sup> Department of Energy, Politecnico di Milano, Via Lambruschini 4, 20156 Milano, Italy

<sup>2</sup> College of Architecture and Urban Planning, Tongji University, No. 1239 Si Ping Road, Shanghai 200092, China;

\*Corresponding author's email: [alessia.banfi@polimi.it](mailto:alessia.banfi@polimi.it)

**Abstract.** Buildings are significant contributors to global energy consumption and CO<sub>2</sub> emissions, making it imperative to implement strategic intervention scenarios to reduce their energy and carbon footprint. Bottom-up physics-based Urban Building Energy Modelling (UBEM) tools are crucial for this goal. These tools provide quantifiable impacts of intervention scenarios on the building stock, supporting cities in developing roadmaps aligned with national and international environmental targets. This study simulates two intervention scenarios for a mixed-use district in Milan, Italy, using Urban Modeling Interface (umi). The first scenario focuses on renovating low-efficient buildings to meet the 2030 local regulation goals. The second envisions an operationally carbon-neutral district achieved through building envelope improvements and complete electrification of energy uses, aligning with the European Union's target for climate neutrality by 2050.

The impact of the proposed measures on heating energy use, primary energy, and operational CO<sub>2</sub> emissions is assessed and compared to the current performance of the buildings. An economic analysis, considering Net Present Value and Payback Time, explores the financial viability of the interventions. This study provides actionable insights into effective decarbonisation strategies, offering a practical framework for policymakers. The findings can guide compliance with regulatory directives, enhance urban energy efficiency, and promote sustainable development.

**Keywords:** Urban Building Energy Modelling (UBEM), Energy Efficiency, Building sector decarbonisation, Scenario Evaluation

## 1 INTRODUCTION

The building sector is a major contributor to global energy consumption and CO<sub>2</sub> emissions [1], accounting for a substantial share of the environmental impact associated with human activity. This reality has driven the establishment of ambitious decarbonisation goals at national and international levels aimed at reducing the energy uses and carbon footprint of buildings. For instance, the European Union's latest Energy Performance of Buildings Directive (EPBD) [1] directly underscores the critical role of the building sector in achieving these climate goals, targeting a highly energy-efficient and decarbonised building stock. While considerable progress has been made to improve the energy performance of new

buildings, achieving carbon neutrality on a broader scale requires a more holistic approach. As complex systems, cities demand integrated strategies that account for the existing building stock. Consequently, urban-scale energy interventions have emerged as a crucial component of climate action plans. In this context, Urban Building Energy Modelling (UBEM) has proven to be a pivotal approach [2]. By simulating and analysing the energy performance of entire building stocks, UBEM offers insights into the impacts of various intervention scenarios, enabling authorities and policymakers to develop effective strategies for urban decarbonisation. Among UBEM approaches, bottom-up physics-based models, calculating energy balances at the level of individual buildings, offer detailed and granular insights that can be aggregated to inform district- or city-wide decision-making [3].

This paper aims to present a methodological framework for designing, simulating, and comparing building renovation scenarios at the district level. By leveraging only open-source data, the study seeks to provide a replicable and accessible model for other researchers and practitioners. The methodology is applied to a mixed-use district in Milan, Italy, where two intervention scenarios are examined and simulated using a bottom-up physics-based UBEM tool to be finally compared to the current district performances. The first scenario focuses on upgrading the energy performance of low-efficiency buildings to meet local regulatory goals for 2030. The second scenario envisions an operationally carbon-neutral district achieved through comprehensive building envelope improvements and full electrification of energy uses, aligning with the European Union's 2050 climate neutrality targets.

The analysis evaluates the impact of these measures on heating energy use, primary energy, and operational CO<sub>2</sub> emissions, benchmarking them against the current buildings' performance of the district. Furthermore, an economic analysis is performed to explore the financial feasibility of these interventions. The findings of this study highlight decarbonisation strategies and provide policymakers with a practical framework to support compliance with regulatory directives. Ultimately, this research underscores the critical role of targeted urban energy policies and modelling tools in achieving environmental objectives.

## 2 METHODOLOGY

The methodology adopted is constituted by five subsequent activities (Figure 1). The process begins with collecting and preparing the data required to characterise the buildings in the model. This includes information on geometry, envelope characteristics, heating and cooling system specifications, domestic hot water (DHW) systems, lighting systems, equipment use, ventilation details, and occupant behaviour. Archetypes are introduced instead of independently defining each building to reduce computational effort and time. Typically, archetypes are defined for specific construction and building use types [4]. The data collected underwent cleaning to remove null, inconsistent, or erroneous values, and statistical techniques were applied to group buildings by construction age and use type to extract meaningful patterns, enabling the characterisation of the current state of the district (i.e.,

baseline). Once the data was prepared, it was transformed into the required format for use in the UBEM tool.

A 3D geometric representation of the buildings in the case study has been made, and each building was assigned a corresponding archetype. This step provided the foundation for defining the district's baseline energy performance. Following the baseline model creation, two renovation scenarios were designed to explore decarbonisation strategies. The first adopted a targeted approach, aligning with local regulation, which mandates that low-efficient buildings must be renovated and upgraded by 2030. A statistical analysis of the building stock of the Municipality of Milan identified targeted buildings in the case study based on their construction period and energy performance, and interventions were proposed accordingly. The second scenario focused on achieving operational carbon neutrality by implementing a district fully powered by electricity and upgrading building envelopes.

Once the definition of the baseline and the renovation scenarios were completed, simulations were performed to assess their energy performance to compare energy use, primary energy, and operational CO<sub>2</sub> emissions. Finally, an economic assessment was conducted to evaluate the financial feasibility of the proposed interventions. Two key indicators, Net Present Value (NPV) and Payback Time (PBT), were used to assess the economic efficacy of the investments over their lifecycle, ensuring the findings support informed decision-making for urban energy planning.



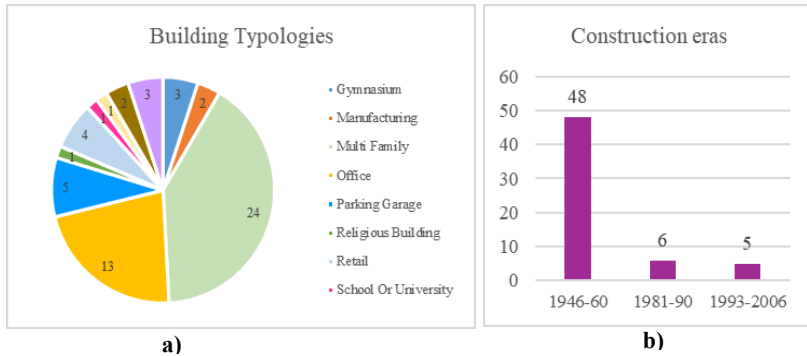
Fig. 1: Methodology workflow

## 3 RESULTS AND DISCUSSION

### 3.1 Data collection and creation of the baseline

The methodological framework was tested in a district in the northeast of Milan, Italy. The selected case study encompasses 59 buildings, predominantly residential and office typologies, with construction periods spanning from 1946 to 2006. Figure 2 illustrates the distribution of building use types and construction periods across the district, highlighting the diversity within the building stock.

A range of open-source datasets was employed to characterise the buildings comprehensively, ensuring that the data acquisition process remained adaptable and replicable. Geospatial data, including building footprints and geometry, were sourced from OpenStreetMap, while the Lombardy Region's Energy Performance Certificates (EPCs) repository (CEER database) [5] provided essential information about building envelope characteristics. A regional cadastre of heating, cooling, and DHW [6], was utilised to define the energy systems installed within the buildings. These datasets collectively provided a robust foundation for describing the district's building stock.



**Fig. 2.** a) Building typologies; b) Construction periods

A climatic file was generated using data collected from open-source meteorological stations near the case study area to accurately represent the local climate.

The archetypes of the case study were created by analysing the most common combinations of building types and their envelope and system characteristics. These archetypes were grouped based on construction periods and building types. Table 1 provides examples of the constructed archetypes.

**Table 1.** Example of archetype – Residential buildings

Building Type		Residential			
<b>Heating</b>	Heating system	Efficiency	Fuel Type	Schedules	Internal loads
	Boiler	0.85	Natural gas	ISO 18523	ISO 18523
<b>Envelope</b>	Construction period	Window-to-wall-ratio [%]	Ext Wall U [W/m <sup>2</sup> K]	Roof U [W/m <sup>2</sup> K]	Ext Wind U [W/m <sup>2</sup> K]
	1946-60	13	1,35	1,4	3,8
	1981-90	14	1,11	0,98	3,3
	1993-2006	14	0,64	0,7	3,21

For aspects of building performance not directly available in the open-source datasets, supplementary information was adopted from ISO 18523 standard [7]. For instance, heating set points were 20°C for most buildings, except 18°C for gyms, manufacturing, and workshops. Ventilation was natural, with infiltration at 0.5 ACH for standard buildings and 1.5 ACH for retail, gyms, manufacturing, workshops, and religious buildings. Additionally, occupancy schedules, as well as heating, lighting, and equipment usage patterns, were defined in accordance with the standard. Cooling systems were excluded from the model due to the lack of available data on their presence in the building stock.

This comprehensive data collection and preparation process enabled the accurate definition of a baseline model representing the current state of the district. By using open-source data supplemented with standardised assumptions, the methodology demonstrated its adaptability to contexts where granular, detailed data might not be readily available. Having all

the information required, it was possible to create and characterise the 3D model of the district using Urban Modelling Interface (umi) [8], a well-known UBEM tool.

### 3.2 Creation of decarbonisation scenarios

Following the establishment of the baseline, two intervention scenarios were developed to explore decarbonisation strategies for the district. Each scenario reflects distinct objectives and approaches tailored to specific timeframes and regulatory targets.

The 2030 scenario adopts a pragmatic strategy, focusing on targeted interventions to improve the energy performance of the least efficient buildings in the district. This scenario assumes a renovation rate of 3% per year, implemented over a six-year period from 2024 to 2030. The interventions include enhancing the thermal performance of building envelopes and transitioning existing heating systems to electric solutions. Table 2 summarises the specific measures adopted in this scenario. Statistical analyses on the CEER database were exploited to identify which buildings needed renovation. This database provides detailed energy performance information for individual buildings or flats, including their energy efficiency class, determined by a performance index expressed in kWh/m<sup>2</sup>/year. This index represents the annual energy demand for heating, cooling, DHW, and lighting, with lower values corresponding to higher energy efficiency. Based on this analysis, the scenario prioritises renovation efforts for buildings classified in the two lowest energy efficiency classes, ensuring that these buildings are upgraded to meet the required standards. According to this procedure, a total of 7 buildings are selected to be renovated in the six-year period.

In contrast, the 2050 scenario is designed to achieve operational carbon neutrality across the district. This scenario envisions a fully electrified district powered exclusively by renewable energy sources. To reduce energy use, the plan incorporates comprehensive building envelope upgrades, including external wall insulation, roof insulation, and window replacements. The interventions for this scenario are summarised in Table 3.

**Table 2.** Intervention for 2030 scenario

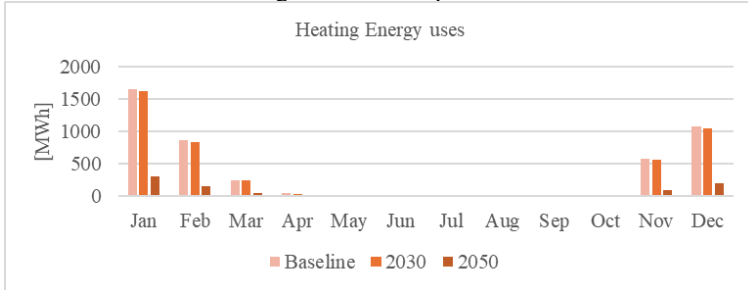
n° of Buildings	Ext.walls U [W/m <sup>2</sup> K]	Roof U [W/m <sup>2</sup> K]	Windows U [W/m <sup>2</sup> K]	Heating System
2	0,28	0,24	1,4	Standalone HPCOP 3,5
4	-	-	-	Standalone HP COP 2
1	0,28	0,24	1,4	Boiler

**Table 3.** Intervention for 2050 scenario

n° of Buildings	Ext. walls U [W/m <sup>2</sup> K]	Roof U [W/m <sup>2</sup> K]	Windows U [W/m <sup>2</sup> K]	Heating System
All buildings	0,28	0,24	1,4	If Centralized HPCOP 4 If Standalone HP COP 2

### 3.3 Energy simulation

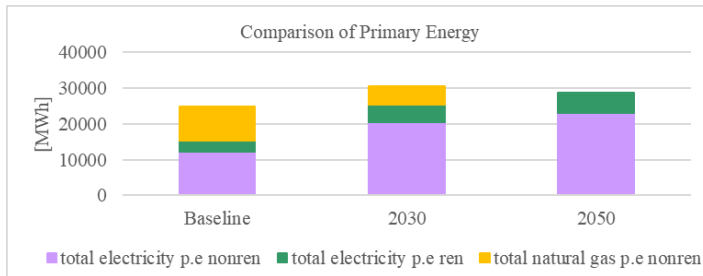
After establishing the baseline and defining the renovation scenarios, energy simulations were performed to evaluate the impact of the proposed interventions. The analysis focused on heating energy consumption, as lighting, equipment, and DHW systems were assumed to remain unchanged across the scenarios and cooling was not addressed due to the lack of data on current conditions. The climatic file used in the simulations reflects current weather conditions, without incorporating future weather projections. As a result, slightly different outcomes might be expected if the effects of climate change were considered. Figure 3 illustrates the heating energy use across the baseline, 2030, and 2050 scenarios. Significant reductions in heating energy use are observed when transitioning from the baseline to the intervention scenarios. Specifically, a modest reduction of 3% is achieved in the 2030 scenario due to the limited number of renovated buildings, while the 2050 scenario achieves a substantial 70% reduction, reflecting its more comprehensive intervention strategy.



**Fig. 3.** Heating energy uses comparison

Another critical aspect of the analysis involves primary energy use, as it provides a more comprehensive view of energy savings by accounting for the different energy carriers—natural gas and electricity—and their renewable energy potential. Final energy use was converted into primary energy use using the following coefficients: for primary energy conversion factors, natural gas has a non-renewable factor of 1.05, a renewable factor of 0, and a total factor of 1.05, while electricity has a non-renewable factor of 1.95, a renewable factor of 0.47, and a total factor of 2.42 [9]. Figure 4 presents the trends in total primary energy use associated with natural gas and electricity for the three scenarios. As expected, natural gas use decreases significantly in both the 2030 and 2050 scenarios due to the electrification of heating systems and reduced heating energy use from envelope improvements. Conversely, the total primary energy associated with electricity increases, with the highest value observed in the 2050 scenario. This underscores the need for further integration of renewable energy sources into the electricity grid to align with carbon-neutral goals.

The assessment also included the operational CO<sub>2</sub> emissions for the different scenarios, derived by applying conversion factors to the energy use data. For the baseline scenario, conversion factors were based on 2021 data, while future scenarios utilised factors interpolated from the Italian National Integrated Energy and Climate Plan projections of renewable energy penetration in the national electricity grid. Table 4 summarises the conversion factors used, reflecting renewable energy contributions of 65% for 2030 and 80% for 2050.



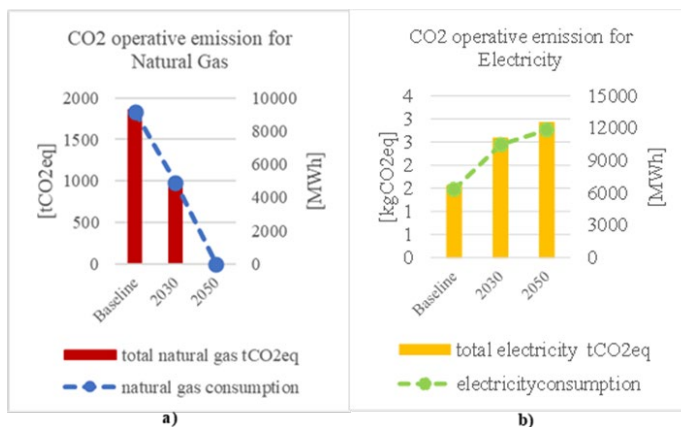
**Fig. 4.** Primary energy comparison

**Table 4.** Conversion factors for CO<sub>2</sub> operative emissions

Conversion factors	
Natural gas (metano) [KgCO <sub>2</sub> eq/GJ]	56,077
Electric energy 2023 (actual state) [KgCO <sub>2</sub> eq/kWh]	0,247
Electric energy 2030 [KgCO <sub>2</sub> eq/kWh]	0,156
Electric energy 2050 [KgCO <sub>2</sub> eq/kWh]	0,089

Figure 5a illustrates the CO<sub>2</sub> emissions associated with natural gas consumption, showing a steady decline as natural gas use decreases across the scenarios. In contrast, emissions related to electricity, shown in Figure 5b, exhibit an upward trend, driven by increased electricity demand, highlighting the need to boost renewable energy in electricity to counter emission increases.

The simulations show both scenarios reduce energy use and CO<sub>2</sub>, with 2050 achieving greater cuts. Increased electricity reliance highlights the need to boost grid renewables for sustainability and carbon neutrality. This dual focus on reducing final use and greening the energy supply is essential to achieving long-term sustainability and carbon neutrality goals.



**Fig. 5.** Operative CO<sub>2</sub> emissions for a) natural gas and b) electricity

### 3.4 Economic assessment

While the ambition to renew the entire building stock is commendable, the associated costs demand careful consideration to ensure that priorities are balanced effectively.

The costs associated with the interventions were estimated using values established by the National Ministerial decree [10]. For cash flow calculations, several assumptions were adopted: operational and maintenance costs were considered to be 1% of the total cost of heating and DHW system replacements, with an upfront payment in the first year of the investment lifecycle, equal to 60% of the total renovation cost. Financing was modelled as a 10-year loan with an interest rate of 3%, and a tax relief of 75% over 10 years was applied. Energy costs were determined using rates provided by ARERA, set at 0.50 €/m<sup>3</sup> for natural gas and 0.31 €/kWh for electricity.

The results of the economic analysis for the two scenarios are presented in Figures 7 and 8. For the 2030 scenario, the PT is relatively short, at 7 years, with an NPV of around 620000 € after 20 years and 773000 € after 25 years. Upgrading low-efficiency buildings offers a cost-effective way to reduce energy use and emissions in the medium time. Moderate renovation costs and immediate energy savings drive favourable economic outcomes. This targeted approach ensures efficient resource use for impactful results. In contrast, the 2050 scenario presents a significantly different financial profile. The PT is 31 years, with an NPV of almost – 3500000 € after 20 years and – 1800000 € after 31 years. These negative NPVs reflect the high initial investment required for the comprehensive electrification and envelope requalification measures, coupled with the extended timeline for realising economic returns. While the 2050 scenario achieves dramatic energy and emissions reductions, its financial feasibility is challenged by the substantial upfront costs and the relatively long horizon needed to recover these investments.

The two scenarios reveal trade-offs in urban decarbonisation. The 2030 scenario shows the economic advantages of targeting inefficient buildings first, reducing risks while delivering short-term benefits. In contrast, the 2050 scenario highlights the challenges of ambitious strategies requiring high investment and longer payback periods.

These findings underscore the importance of integrating financial considerations into urban energy planning. While strategies like the 2050 scenario are essential to meeting long-term climate goals, they must be accompanied by supportive measures such as incentives, subsidies, and financing mechanisms to mitigate the economic burden on stakeholders.

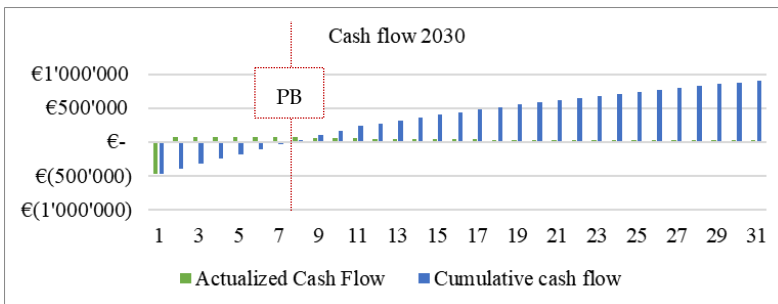
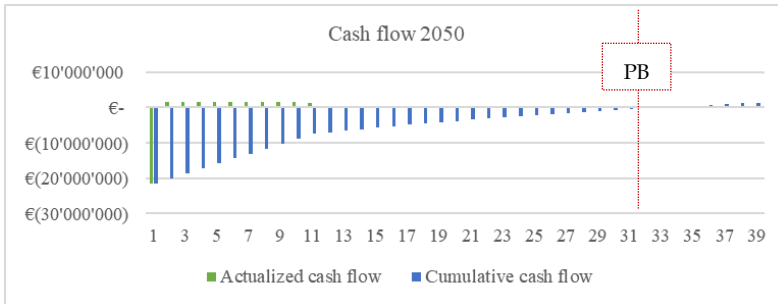


Fig. 7. Cashflow 2030 scenario



**Fig. 8.** Cashflow 2050 scenario

## 4 CONCLUSION

This study demonstrates the potential of UBEM in designing and evaluating decarbonisation strategies for urban districts. Two intervention scenarios were analysed: one targeting compliance with 2030 goals and another with operational carbon neutrality by 2050.

The results highlight the effectiveness of both approaches in reducing energy use, primary energy demand, and CO<sub>2</sub> emissions. The 2030 scenario offers a pragmatic and economically viable strategy, prioritising renovations for the least efficient buildings to achieve immediate energy savings and regulatory compliance. In contrast, the 2050 scenario provides a more ambitious vision of full electrification and comprehensive envelope requalification, achieving significant environmental benefits but at a higher economic cost and with a longer payback period.

The economic analysis underscores the importance of balancing ambition with financial feasibility. While transformative strategies are essential to meet long-term climate neutrality goals, they must be supported by incentives, subsidies, and policies that reduce the financial burden on stakeholders. Incremental approaches, such as those outlined in the 2030 scenario, demonstrate the potential for achieving near-term progress with manageable investments.

Ultimately, this research underscores the value of leveraging open-source data and UBEM tools to develop adaptable, replicable methodologies for urban energy planning. By providing actionable insights into the trade-offs between environmental benefits and economic viability, the findings contribute to the development of sustainable and effective decarbonisation roadmaps for urban areas. The results emphasise the need for integrated strategies that combine energy efficiency improvements, renewable energy adoption, and supportive financial mechanisms to achieve long-term sustainability goals.

## REFERENCES

- [1] P. Office of the European Union L-, L. Luxembourg, DIRECTIVE (EU) 2024/1275 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 24 April 2024 on the energy performance of buildings n.d. <http://data.europa.eu/eli/dir/2024/1275/oj>.
- [2] M. Ferrando, F. Causone, An overview of urban building energy modelling (UBEM) tools, in: *Building Simulation Conference Proceedings*, 2019: pp. 3452–3459.
- [3] A. Banfi, M. Ferrando, P. Li, X. Shi, F. Causone, Integrating Occupant Behaviour into Urban-Building Energy Modelling: A Review of Current Practices and Challenges, *Energies* 17 (2024). .
- [4] L. Carnieletto, M. Ferrando, L. Teso, K. Sun, W. Zhang, F. Causone, P. Romagnoni, A. Zarrella, T. Hong, Italian prototype building models for urban scale building performance simulation, *Build Environ* 192 (2021). <https://doi.org/10.1016/j.buildenv.2021.107590>.
- [5] ARIA, CENED: Certificazione ENergetica degli EDifici, (n.d.). <https://www.cened.it/dati-cened> (accessed January 14, 2025).
- [6] ARIA, CURIT: Catasto Unico Regionale Impianti Termici , (n.d.). <https://www.curit.it/opendata> (accessed January 14, 2025).
- [7] Energy performance of buildings-Schedule and condition of building, zone and space usage for energy calculation BSI Standards Publication, 2017.
- [8] C.F. Reinhart, T. Dogan, J.A. Jakubiec, T. Rakha, A. Sang, UMI - An urban simulation environment for building energy use, daylighting and walkability, *Proceedings 13th Conference of the International Building Performance Simulation Association*, 2013: pp. 476–483.
- [9] Italian Ministry of Economic Development, Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici, 2015.
- [10] Italian Ministry of Ecological Transition, DECRETO 14 febbraio 2022 Definizione dei costi massimi specifici agevolabili, per alcune tipologie di beni, nell’ambito delle detrazioni fiscali per gli edifici., *Gazzetta Ufficiale* (2022).

## ACKNOWLEDGMENTS

The study was developed partially within the framework of the project URBEM (PRIN, code: 2020ZWKXKE), funded by the Italian Ministry of University and Research (MUR); and partially under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3 - Call for tender No.1561 of 11.10.2022 of Ministero dell’Università e della Ricerca (MUR); funded by the European Union –NextGenerationEU. Award Number: Project code PE0000021, Concession Decree No.1561 of 11.10.2022 adopted by Ministero dell’Università e della Ricerca (MUR), CUPC93C22005230007, according to attachment E of Decree No.1561/2022, Project title“Network 4 Energy Sustainable Transition – NEST”.

We wish to acknowledge AMAT for collaborating on this study.