Building Archetypes Supporting the National Building Renovation Plan

Matteo Piro – Politecnico di Torino, Italy – matteo.piro@polito.it
Ilaria Ballarini – Politecnico di Torino, Italy – ilaria.ballarini@polito.it
Vincenzo Corrado – Politecnico di Torino, Italy – vincenzo.corrado@polito.it

Abstract

The national building renovation plan is a key element in the recently approved version of the Energy Performance of Buildings Directive. The plan will provide a comprehensive overview of the energy and environmental performance of both the residential and non-residential building stock. To achieve the objective of mapping the energy *status* of urban configurations, the exploitation of building typologies, representative of different climatic zones, building use categories, and construction periods, has shown to be a useful approach.

The huge data uncertainty related to the building archetype generation necessitates a deeper analysis of the variation of crucial inputs that have repercussions on the energy performance assessment of the building stock.

This work begins with the Urban Building Energy Model data classification aimed at identifying the fundamental inputs needed to run an urban large-scale energy analysis. Then, the paper proceeds with the review and categorisation of the existing Italian databases, exploitable to mitigate the high uncertainty related to the input data. Once the requisite information is collected and the databases classified, the application part progresses with the probabilistic building archetype schema generation from the energy performance certificates of the Aosta Valley Region, taken as a case study. A local large-scale sensitivity analysis, obtained varying one at a time the thermophysical parameters of the building fabric and the window-to-wall ratio of a residential stock located in Aosta, was carried out. The study highlights how variations in statistical ranges of inputs, particularly regarding the performance of opaque building envelope components, impact the assessment of building energy needs.

1. Introduction

1.1 Background Analysis

The implementation of the national building renovation plan (European Commission, 2024), to track the decarbonisation of the building stock, involves the development of Urban Building Energy Models (UBEMs). UBEM, a complex object using a bottom-up engineering model, aids urban planners, public administrations, energy agencies, and validation bodies to map the energy and environmental *status* of a block, a district, or a city. UBEMs require huge amount of information that is usually limited and lacks accuracy. The data restriction is influenced by privacy policies (Hosseini Haghighi et al., 2022; Johari et al., 2023) affecting the availability of building data at the city scale. Building energy consumptions are sensitive data, usually inaccessible for a portfolio of buildings. In large-scale energy models, a consequence of this issue is reported by Oraiopoulos & Howard (2022), who pointed out that just 9 % of UBEMs are validated. On the other hand, the inaccuracy of data is attributable to the non-interoperability between databases, the absence of controls to enhance data quality, and the lack of standardised format and harmonised procedures to collect data between local, regional, and national informative systems (Chen et al., 2019).

To bridge the data uncertainty at large-scale energy analysis, the collected data flow into the generation of the building archetypes (BAs). However, according to Swan and Ugursal (2009), the utilisation of archetypes is a possible approach but not the only one used in UBEMs. The BA approach is a trade-off to reduce complexity and enhance the model's accuracy in energy analysis. BAs, prototypes (Car-

Part of
Pernigotto, G., Ballarini, I., Patuzzi, F., Prada, A., Corrado, V., & Gasparella, A. (Eds.). 2025. Building simulation applications BSA 2024. bu,press.
https://doi.org/10.13124/9788860462022

nieletto et al., 2021), or building typologies (Dascalaki et al., 2011) are sets of geometric, in UBEMs directly extracted from GIS, and non-geometric properties that represent the heterogeneity of the building stock characteristics. Although a harmonised and shared methodology to generate BAs does not exist (Borges et al., 2022), archetyping is generally composed of two steps, i.e., the segmentation and the characterisation of the building stock (Pasichnyi et al., 2019). The segmentation phase refers to the taxonomy of similar buildings based on different criteria, such as climatic zone, building use category, construction periods, etc. The characterisation process corresponds to defining representative parameters that generalise the performance of the building stock. This aspect influences the structure of the BA dataset since archetypes may include deterministic or probabilistic parameters. From this perspective, Cerezo et al. (2017) investigated and compared simulation results for four groups of BAs, creating two with deterministic and two with probabilistic metrics. To discover the impact of different input parameters, Pernetti et al. (2021) applied different sensitivity analyses (SA) to rank the life cycle cost of eleven zero-energy buildings in Europe.

1.2 Aim of the Research

The data uncertainty for a single-building energy model grows significantly in large-scale energy analyses. The BA, which represents the mean characteristics of a building stock, helps mitigate this source of error. However, it is crucial to evaluate how variations in key inputs impact the overall energy performance of the building stock.

This work first explores UBEM data for large-scale analysis and then classifies sources to gather the required information. Next, considering a UBEM archetype-based approach, a local SA varying one relevant thermo-physical parameter at a time, included in the probabilistic BA schema, applied to a residential block located in the municipality of Aosta (Italy) was carried out. Using CitySim Pro (Robinson et al., 2009), this analysis emphasises the order of error in the building's energy need linked to the variability of significant input parameters within their confidence interval. It highlights the possible deviations in estimating energy needs of the building stock. The novelty of this study lies in addressing the high uncertainty levels in UBEM and identifying the information in the BA schema that requires greater accuracy.

2. Methods

The proposed methodology comprises: a) UBEM data classification, which provides a standardised overview of the required data to build a large-scale energy model, b) database cataloguing, including the listing and classification of recognised Italian local, regional, and national databases, c) definition of a probabilistic BA dataset (archetyping), and d) SA to assess the impact of relevant thermo-physical parameters in a non-validated UBEM scenario. The first three points of the proposed methodology fall into the "Urban Reference Buildings for Energy Modelling" (URBEM, 2024) project approach. The scope of URBEM—which is an Italian national research project financed under the PRIN 2020 Programme—is to create an Italian library of representative buildings to be used by UBEM tools.

2.1 UBEM Data Classification

UBEM is a bottom-up physical-based model (Reinhart & Cerezo Davila, 2016), aimed at determining the energy and environmental performance of the building stock.

The purpose of the simulation, the spatial and temporal granularity of data, and the calculation methodology integrated into the large-scale energy programs influence the UBEM input data needed. UBEM can be delineated into distinct layers: input data, mathematical model, and output data. The UBEM input data can be grouped into five different categories: geometrical information, properties of transparent and opaque building envelope components, occupancy data, technical building system characteristics, and climatic data. A detailed description about the simplifications and assumptions made in UBEM from the Building Energy Model (BEM) can be found in Piro et al. (2023).

However, the primary objective of the UBEM data classification is to distinctly identify basic and common input data, enabling a comprehensive evaluation of the energy performance of building stocks, regardless of the simulation tools used. The defined dataset is the minimum set of parameters to run a dynamic simulation on an hourly or sub-hourly basis.

2.2 Database Cataloguing

Data availability, data quality, and data accessibility at the city scale represent future challenges of our societies (Goy et al., 2020). Especially public administrations must face this difficult task since they are responsible for collecting the data. In this regard, achieving standardised data formats, harmonised procedures, and minimum data requirements between different Regions could reduce the efforts required to UBEM developers. In this context, the categorisation of the existing local, regional, and national information systems plays a pivotal role in contributing to informed decision-making and sustainable development.

The attribution of the BAs to the analysed building stock is typically accomplished using the following criteria: climatic zone, building use category, and construction period. The subdivision of climatic zones is conducted at the national level. In more challenging scenarios, the determination of the building use category may involve on-site inspection or rely on the modeller's expertise. However, the identification of the ages of buildings poses difficulties, particularly because open GIS maps and regional geographical databases seldom contain such information. To address this issue, Zagarella (2019) proposed a systematic procedure to determine the prevailing construction period of buildings depending on building-related parameters. Without such a method, attributing the BA to the analysed urban configuration becomes very complicated, making the building archetype-based approach less effective in mitigating data uncertainty. Furthermore, building energy consumption is sensitive data that is usually not released due to privacy issues. In UBEM, this information is indispensable for calibrating or validating energy models.

Once the UBEM data classification has been set, the necessity is to review, list, and organise the available existing Italian information systems to collect the relevant data to generate the BAs. In the URBEM project (URBEM, 2024), the databases were grouped into the following categories: i) "source type", which indicates the origin of the information, ii) "accessibility", which denotes the constraint levels of the informative systems, iii) "database digitalisation", connected to the presence of data either in digital online or offline form or in paper-based documents, and iv) "data granularity", associated to the measure of the level of detail of the information. In Fig. 1, the criteria for classifying local, regional, or national databases for each of the categories proposed are depicted.

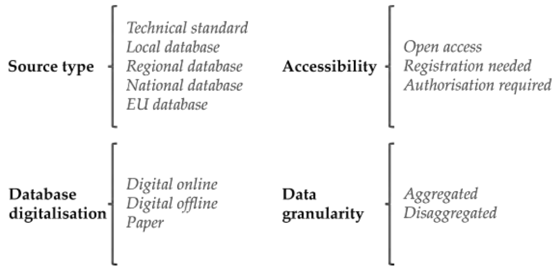

Fig. 1 – Database cataloguing criteria adopted in URBEM (2024)

2.3 Archetyping and Sensitivity Analysis

The BAs embed the most common and typical technologies shared by a group of similar buildings. A significant research advancement in this field can be attributed to the well-recognised and pioneering TABULA project (TABULA, 2009-2012), which harmonised the building typology approach across numerous EU countries.

The BA encapsulates both geometric and non-geometric data that summarise the building's stock energy performance. The data integrated into the BA schema can be presented from either a deterministic or probabilistic standpoint. However, the association of the confidence interval to the data included in the BA schema contemplates and manifests the high uncertainty related to UBEM development.

To emphasise the importance of having a statistical range to guide the UBEM modeller's decisions, conducting a SA becomes imperative. This approach enables observations of how variations in crucial input data influence the model's output, particularly in terms of the building's energy need.

3. Application

The probabilistic BAs simulated in CitySim Pro were generated using data extracted from the energy performance certificate (EPC) database of the Aosta Valley Region. This Italian Region was chosen within the framework of the URBEM project. Then, a local large-scale sensitivity energy analysis was conducted on a residential block located in the municipality of Aosta, highlighting the significant impact of key UBEM inputs on the overall performance of the building stock.

3.1 CitySim Pro

CitySim Pro—developed by the Solar Energy and Building Physics Laboratory of EPFL (L'École Polytechnique Fédérale de Lausanne)—is one of the most recognised and used UBEM tool (Robinson et al., 2009). The calculation engine of the software is CitySim Solver (CitySim Solver, 2024) on which the KAEMCO company developed a graphical user interface. CitySim Pro is a dynamic hourly energy model with a Resistive-Capacitive system that discretises the building envelope components into nodes of temperature, thermal resistances, and heat capacities (Emmanuel and Kämpf, 2015).

3.2 Case Study

The case study examines a real residential block situated in the municipality of Aosta (583 m a.s.l.). This city block consists of twenty-one buildings, five of which are single-family houses (SFHs), while the others are apartment blocks (ABs). The construction period range of these buildings was determined based on the findings of D'Alonzo et al. (2020). Fig. 2 presents the residential building stock analysed, including details such as the building code, size and shape, construction period range, and compactness ratio.

The Level of Detail (LOD) of the urban geometry scene was improved through a series of steps. Initially, the building footprint (LOD0) was established using data from the OpenStreetMap database. Then, the objects were extruded (LOD1), capturing the slopes of the roofs (LOD2). Additionally, further adjustments were made to enhance the accuracy of the assessed objects, such as converting incorrect volumes into shading elements (see Fig. 3).

Fig. 2 – Satellite view of the city block (source GoogleMaps)

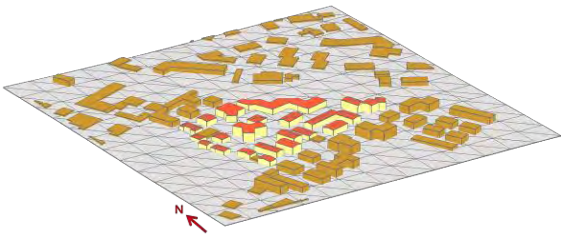

Fig. 3 – Urban scene imported in CitySim Pro

The interquartile ranges of the building fabric performance parameters, encompassing thermal transmittance of walls (U_{wl}), floors (U_{lf}), roofs (U_{uf}), and windows (U_{w}), and the *WWR* were calculated from the data included in the EPC database of the Aosta Valley Region. The EPCs were categorised considering the different climatic zones, building use categories, construction periods, and size and shape for residential buildings (e.g., SFHs and ABs). Following the determination of the first (Q_1), second (Q_2), and third (Q_3) quartiles of thermal transmittances, the layers of the building components and thermal characteristics of the materials were extracted from UNI/TR 11552 (UNI, 2014). To propose an example, Table 1 presents the thermal transmittances of the walls per building construction types, quartiles, and construction period ranges.

The building construction type was assigned to the building based on the statistical prevalence derived from the EPCs of each specific cluster. Before 1945, load-bearing stone masonry was the predominant type, transitioning to reinforced concrete structures with brick walls and load-bearing brick masonry thereafter. SFHs were assumed to have floors adjacent to the ground, while the thermal transmittance of the floors facing unconditioned spaces was considered for ABs. The floors of the ABs D1 and F2 are elevated *pilotis* storeys. Additionally, the roofs are differentiated whether the upper floor is flat or sloped.

Table 1 – Thermal transmittances of the walls per building construction type and construction period (a)

U_{wl} ($W \cdot m^{-2} \cdot K^{-1}$)	1919-45			1946-61			1962-71		
	Q_1	Q_2	Q_3	Q_1	Q_2	Q_3	Q_1	Q_2	Q_3
S (*)	1.01	1.64	2.01	0.70	1.57	2.10			
C	0.66	1.02	1.30	0.80	1.10	1.23	0.85	1.10	1.22
B	0.64	1.18	1.43	0.77	1.10	1.34	0.76	1.13	1.27

(*) S = load-bearing stone masonry; C = reinforced concrete skeleton with brick walls; B = load-bearing brick masonry

Table 2 – Thermal transmittances of the walls per building construction type and construction period (b)

U_{wl} ($W \cdot m^{-2} \cdot K^{-1}$)	1972-81			1982-91		
	Q_1	Q_2	Q_3	Q_1	Q_2	Q_3
C	0.82	1.10	1.23	0.51	0.88	1.08

For the various construction period ranges, the *WWR* is differentiated between SFHs and ABs. The calculated window-to-wall ratio was assumed to be the same for every building orientation. The *WWR* extracted from the EPCs issued for single building units was used for the whole apartment blocks. The median values representing the glazing ratio are between 9 % and 18 %, with the *WWR* of SFHs generally lower than those of ABs.

The window glazing type was used to cluster the U_w values. An example is depicted in Fig. 4 for different construction periods. The total solar energy transmittance of glazing was derived from a technical standard (CTI, 2021), depending on the glazing types adopted.

The Typical Meteorological Year file elaborated by the Italian Thermo-technical Committee (CTI, 2024) was used in the simulation. Moreover, the schedules and intensities of the internal heat gains (occupants, appliances, and lighting) were derived from the draft of the Italian National Annex of UNI EN 16798-1 (CTI, 2022). An infiltration rate equal to 0.30 h^{-1} was assumed for every building.

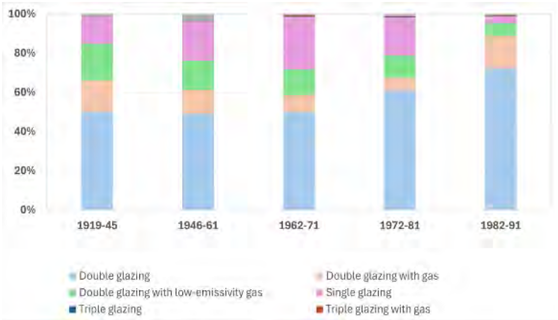

Fig. 4 – Glazing type share per construction period

3.3 Sensitivity Analysis

A local large-scale SA was performed by varying one at a time different features of the building envelope, such as the thermal transmittance of opaque walls, floors, roofs, and windows, as well as the *WWR*, within their respective interquartile ranges.

Three groups of simulations (OP_, W_, and WWR_) were conducted. These groups evaluate the variation of the performance of the opaque (U_{wl}, U_{lf}, and U_{uf}) and transparent (U_w) building envelope components, as well as different *WWR* values. Each group comprises two scenarios, defined based on the values of the first quartile (Q_1) in the first case and the third quartile (Q_3) in the second for each considered parameter. These scenarios were compared with the baseline, which was determined by assuming the median values for each parameter.

4. Results and Discussion

The Aosta municipality experiences a climate dominated by space heating. Therefore, only the variation in the building's energy need for space heating ($EP_{H;nd}$) for the different configurations has been evaluated, thus excluding the cooling need.

In **Error! Reference source not found.**, the outcomes of the three model configurations, each with two scenarios—considering Q_1 and Q_3 values, respectively—are compared with the outcomes of the simulation carried out with the median values applied. The opaque building fabric's performance reveals to be the most impactful factor influencing the variation of the $EP_{H;nd}$, with percentage fluctuation between – 33 % and 37 %. Across various buildings, the trend remains consistent: as the thermal transmittance of the building envelope components decreases, the thermal energy need decreases (OP_Q1), whereas the opposite pattern is observed in OP_Q3.

A similar trend is observed when analysing the thermal performance of different windows (W_Q1 and W_Q3), but the percentage impact (between – 6 % and 3 %) is an order of magnitude lower compared to the previous case, due to limited *WWR* compared to the opaque fraction.

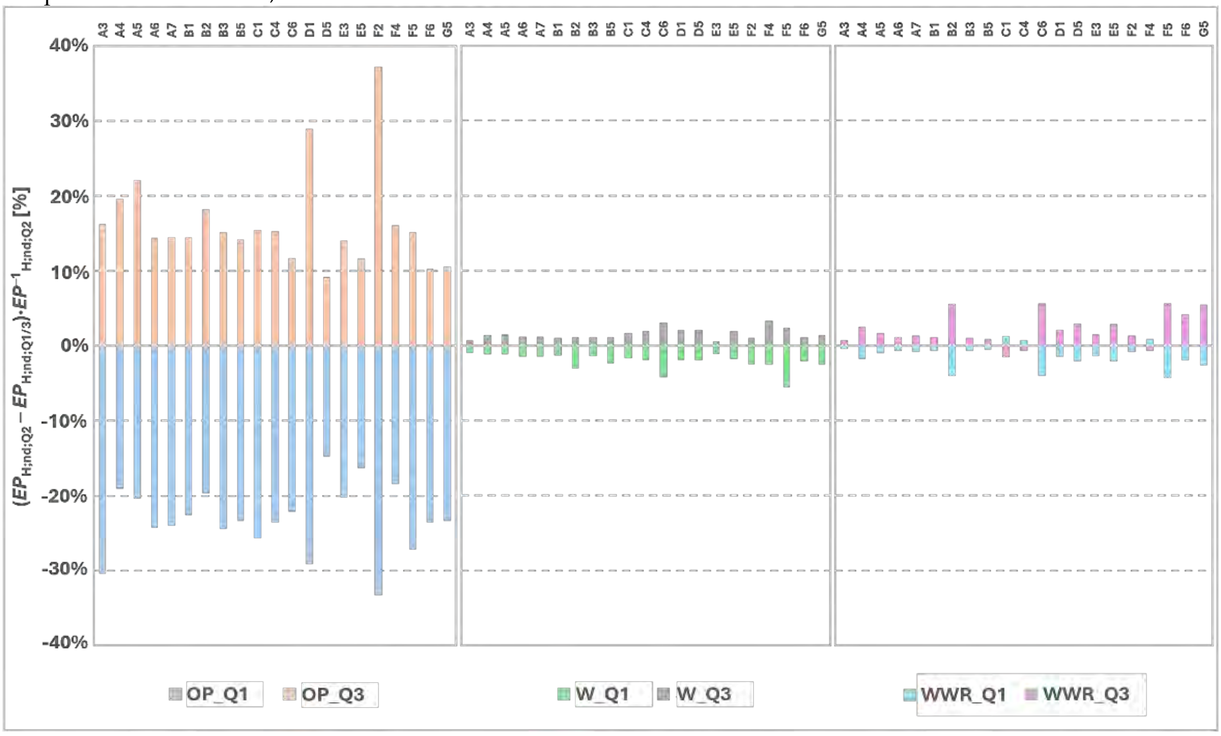

Fig. 5 – Results of the SA. Space heating variation of the city block for different scenarios of the building envelope parameters

In the SA for the *WWR*, reducing the glazing fraction (WWR_Q1) decreases the heat transfer through transmission, thereby reducing the $EP_{H;nd}$. Conversely, increasing *WWR* in configuration WWR_Q3 leads to the opposite trend. Notably, a reverse pattern can be observed for well-sun-exposed buildings C1, C4, and F4, where the solar heat gains compensate for and exceed the heat losses through transmission. Globally, the percentage variation of WWR_Q1 and WWR_Q3 scenarios is between – 4 % and 6 %. The incidence of *WWR* accounts more during the summer season since the energy need for space cooling decreases reducing the *WWR*, and vice versa.

5. Conclusion

The variation in heating energy need was assessed ranging one at a time the key input indicators within their confidence intervals. The BA workflow from the generation to the exploitation phase was evaluated to support the development of a national building renovation plan in a UBEM environment. The UBEM data classification, which involves cataloguing the required input data, was carried out. Then, the review and organisation of existing Italian local, regional, and national databases to derive the thermal properties of the building envelope, the technical building system characteristics, the building occupancy, and the climatic data were identified. Next, considering a UBEM archetype-based approach, the effect of the variation of the building fabric performance and *WWR* within the confidence interval of their BA schema was explored for a case study located in the northern part of Italy. The SA showed the major impact on the output resulting from the different characterisation of the thermal performance of the opaque building envelope components. This aspect suggests the need for precise determination of the thermal transmittances of walls, roofs, and floors. However, the limitations of this work are related to the limited information available in the EPCs.

The spread in the distribution of the outcomes for the analysed city block highlights the need for more reliable and representative statistical samples to define the BA schema. The validation of BAs is of foremost importance above all when low-quality input data are used in the analysis.

The future steps of the work will focus on implementing and validating the created BAs to be used in UBEMs. Then, according to the methodology proposed in this work, a future implementation will be focused on detailed SA obtained by combining the variation of different parameters in a single simulation to assess if the discrepancies would be increased or compensated.

Acknowledgement

The study was developed within the framework of the project URBEM (PRIN, code: 2020ZWKXKE), which has received funding from the Italian Ministry of University and Research (MUR).

Nomenclature

Symbols

EP	energy performance ($kWh \cdot m^{-2}$)
U	thermal transmittance ($W \cdot m^{-2} \cdot K^{-1}$)
WWR	window-to-wall ratio (%)

Subscripts

H	heating	uf	upper floor
lf	lower floor	w	window
nd	need	wl	wall

References

Borges, P., Travesset-Baro, O., and Pages-Ramon, A. 2022. "Hybrid approach to representative building archetypes development for urban models – A case study in Andorra". *Building and Environment* 215. https://doi.org/10.1016/j.buildenv.2022.108958.

Carnieletto, L., Ferrando, M., Teso, L., Sun, K., Zhang, W., Causone, F., et al. 2021. "Italian prototype building models for urban scale building performance simulation". *Building and Environment* 192. https://doi.org/10.1016/j.buildenv.2021.107590.

Cerezo, C., Sokol, J., AlKhaled, S., Reinhart, C., Al-Mumin, A., and Hajiah, A. 2017. "Comparison of four building archetype characterization methods in urban building energy modeling (UBEM): A residential case study in Kuwait City". *Energy and Buildings* 154: 321-334. https://doi.org/10.1016/j.enbuild.2017.08.029.

Chen, Y., Hong, T., Luo, X., and Hooper, B. 2019. "Development of city buildings dataset for urban building energy modeling". *Energy and Buildings* 183: 252-265. https://doi.org/10.1016/j.enbuild.2018.11.008.

CitySim Solver. 2024. "CitySim Solver Official Code web-site". Accessed March 24, 2024. https://github.com/kaemco/CitySim-Solver.

D'Alonzo, V., Novelli, A., Vaccaro, R., Vettorato, D., Albatici, R., Diamantini, C., et al. 2020 "A bottom-up spatially explicit methodology to estimate the space heating demand of the building stock at regional scale". *Energy and Buildings* 206. https://doi.org/10.1016/j.enbuild.2019.109581.

Dascalaki, E. G., Droutsa, K. G., Balaras, C. A., and Kontoyiannidis, S. 2011. "Building typologies as a tool for assessing the energy performance of residential buildings – A case study for the Hellenic building stock". *Energy and Buildings* 43 (12): 3400-3409. https://doi.org/10.1016/j.enbuild.2011.09.002.

Emmanuel, W., and Kämpf, J. H. 2015. "A verification of CitySim results using the BESTEST and monitored consumption values". In *Proceedings of Building Simulation Application*

2015: 2nd Conference of IBPSA-Italy. Bozen, Italy, 4-6 February 2015.

European Commission. 2024. “Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the Energy performance of buildings (recast)”, *Official Journal of the European Union*, 24 April 2024.

Goy, S., Maréchal, F., and Finn, D. 2020. “Data for Urban Scale Building Energy Modelling: Assessing Impacts and Overcoming Availability Challenges”. *Energies* 13 (16). https://doi.org/10.3390/en13164244.

HosseiniHaghighi, S., de Uribarri, P. M. Á., Padsala, R., and Eicker, U. 2022. “Characterizing and structuring urban GIS data for housing stock energy modelling and retrofitting”. *Energy and Buildings* 256. https://doi.org/10.1016/j.enbuild.2021.111706.

Italian Organisation for Stardardisation (UNI). 2014. *Opaque envelope components of buildings – Thermophysical parameters (UNI/TR 11552)*. In Italian. UNI: Milan, Italy.

Italian Thermo-technical Committee (CTI). 2021. *Draft of the Italian National Annex to UNI EN ISO 52016-1 (document no. 020200134)*. Restricted document. CTI: Milan, Italy.

Italian Thermo-technical Committee (CTI). 2022. *Draft of the Italian National Annex to EN 16798-1 (document no. 024100360)*. Restricted document. CTI: Milan, Italy.

Italian Thermo-technical Committee (CTI). 2024. “Typical Metereological Year (2015)”. Accessed March 24, 2024. https://try.cti2000.it.

Johari, F., Shadram, F., and Widén, J. 2023. "Urban building energy modeling from geo-referenced energy performance certificate data: Development, calibration, and validation". *Sustainable Cities and Society* 96. https://doi.org/10.1016/j.scs.2023.104664.

Oraiopoulos, A., and Howard, B. 2022. “On the accuracy of Urban Building Energy Modelling”. *Renewable and Sustainable Energy Reviews* 158. https://doi.org/10.1016/j.rser.2021.111976.

Pasichnyi, O., Wallin, J., and Kordas, O. 2019. "Data-driven building archetypes for urban building energy modelling". *Energy* 181: 360-377. https://doi.org/10.1016/j.energy.2019.04.197.

Pernetti, R., Garzia, F., and Oberegger, U. F. 2021. "Sensitivity analysis as support for reliable life cycle cost evaluation applied to eleven nearly zero-energy buildings in Europe". *Sustainable Cities and Society* 74. https://doi.org/10.1016/j.scs.2021.103139.

Piro, M., Ballarini, I., and Corrado, V. 2023. “From Building Energy Models (BEM) to Urban Building Energy Models (UBEM): input data and modelling approaches”. In *Proceedings of Building Simulation 2023*: 18th Conference of IBPSA. Shanghai, China, 4-6 September 2023.

Reinhart, C. F., and Cerezo Davila, C. 2016. "Urban building energy modeling – A review of a nascent field". *Building and Environment* 97: 196-202. https://doi.org/10.1016/j.buildenv.2015.12.001.

Robinson, D., Haldi, F., Kämpf, J., Leroux, P., Perez, D., Rasheed, A., et al. 2009. “CITYSIM: Comprehensive Micro-Simulation of Resources Flows for Sustainable Urban Planning”. In *Proceedings of Building Simulation 2009*: 11th Conference of IBPSA. Glasgow Scotland, 27-30 July 2009.

Swan, L. G., and Ugursal, V. I. 2009. "Modeling of end-use energy consumption in the residential sector: A review of modeling techniques". *Renewable and Sustainable Energy Reviews* 13 (8): 1819-1835. https://doi.org/10.1016/j.rser.2008.09.033.

Typology Approach for Building Stock Energy Assessment (TABULA). 2009-2012. “Typology Approach for Building Stock Energy Assessment web-site”. Accessed March 24, 2024. https://episcope.eu/iee-project/tabula/.

Urban Reference Buildings for Energy Modelling (URBEM). 2024. “Urban Reference Buildings for Energy Modelling web-site”. Accessed March 24, 2024. https://www.urbem.polimi.it/en/.

Zagarella, F. 2019. *Estimating the buildings hourly energy demand for smart energy district planning*. Ph.D. thesis, Politecnico di Milano (Italy).