Supporting the EU mission “100-climate neutral cities”: using urban building energy modeling for zero-emission building retrofit scenarios at district scale

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Supporting the EU mission “100-climate neutral cities”: using urban building energy modeling for zero-emission building retrofit scenarios at district scale.

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Abstract

As a participant in the EU mission “100 climate-neutral cities by 2030”, Turin, Italy, must decarbonize by end of decade. This work supports transforming the building sector, quantifying savings from retrofits for 1,761 residential buildings in Turin using urban building energy modeling (UBEM). Past UBEM studies demonstrated retrofits reducing over 60% of energy use, with reductions of over 80% in net energy or carbon emissions when adding renewable energy in a few examples. The novelty of this study is to target retrofits using the zero-emissions building approach while emphasizing decision-making toward efficiency and constructability of retrofits. The results show a reduction of overall primary energy use of 56% to 71% in retrofit scenarios including envelope and mechanical system measures, and adding onsite PV energy generation reduces carbon emissions by 90% compared to baseline. The value of the study is to support Turin as one of the 100 climate-neutral cities, and offer lessons learned to other cities in the EU mission.

Highlights

- Novel workflow from GIS to UBEM containing 1,761 buildings and 2,132,124 m^2 gross floor area
- Decision-making analysis for building retrofits to maximize efficiency and constructability
- 90% CO$_2$ reduction across a district of 50,000 people, supporting EU’s “100 climate-neutral cities” mission

Introduction

While countries across Europe pledge to decarbonize by 2050, climate deadlines are even more rapidly approaching for cities participating in the EU mission “100 climate-neutral cities by 2030”. The 100 cities must eliminate all greenhouse gas (GHG) emissions by end of decade, in either the entire city or a district of minimum 50,000 people. The EU envisions the cities as innovation hubs, leading a systematic transformation in the bloc before the 2050 cutoff (EC 2020a). A key to success for this mission is the buildings sector, responsible for 40% of energy use and 36% of energy-related GHGs in the EU (EC 2020b). Improving buildings’ energy efficiency is of utmost importance, as 75% of buildings in Europe have poor energy performance (EC 2021).

One field of research supporting the EU mission is urban energy modeling. A specific sub-field, urban building energy modeling (UBEM), creates bottom-up, physics-based models for clusters of buildings, ranging in the tens to thousands. UBEM uses computational simulations of operational energy, while accounting for dynamics of individual buildings, inter-building effects, and microclimate (Reinhart & Davila 2016; Hong et al. 2020). Use cases of UBEM include urban planning and neighborhood design, building-to-grid integration, stock-level carbon reduction strategies, and building-level recommendations (Ang et al. 2020). The latter two cases typically model retrofits applied to some or all buildings in the cluster. Energy conservation measures (ECMs) at building level include retrofits to envelope, mechanical systems, or electrical and controls systems, as categorized in a recent literature review, while renewable energy systems (RES) and district energy systems (DES) can be applied at building or district level. When comparing pre- and post-retrofit scenarios, about half of the 26 reviewed studies measured reduction in heating energy use and half in overall energy use, and over 30% of these quantified CO$_2$ savings (Suppa & Ballarini, in press).

Examples applying building retrofits at district scale show 40% savings in overall energy in an academic campus (Napgal & Reinhart 2018); reductions of over 60% in heating energy in two residential neighborhoods (Teso et al. 2022; de Rubeis et al. 2021); and 69% lower overall energy use and CO$_2$ emissions in a residential district (Buckley et al. 2021b). Combining retrofits with RES and DES shows greater savings in energy and CO$_2$, with reductions of 93% and 100% in heating-related CO$_2$ emissions due to expansion of an existing DES and onsite PV generation, respectively (Nouvel et al. 2015; Hosseini Hashighi et al. 2022), or 80% in overall CO$_2$ emissions when expanding DES (Zivkovic et al. 2016).

A few district studies achieved net-zero energy (NZE), where energy produced equals energy consumed on an annual basis. One added off-site, ground-level photovoltaic (PV) panels plus envelope, mechanical, and electrical ECMs to attain NZE (Wang et al. 2022), while another reduced energy use by 88% with building-level retrofits, and the remaining energy required could be offset through PV energy generation on rooftops in the adjacent neighborhood (Buckley et al. 2021a). In addition to NZE, an essential concept for the proposed recast of the European Performance of Buildings Directive (EPBD) is the zero-emission building (ZEB), where a building pursues the “efficiency-first principle” leading to very high energy performance, with a low amount of energy generated on-site, from a renewable energy community, or renewable energy or waste heat from a DES (EC 2021).

This work seeks to demonstrate pathways to achieve the EU “100 cities” mission in the building sector. While the mission is defined broadly for multiple sectors and allows importing green electricity from outside the district, this study uses UBEM to evaluate building retrofits per the “efficiency-first” principle and applies on-site RES toward residual required energy. The aim is to achieve zero-emission buildings or at least drastically cut carbon emissions compared to baseline. The *Barriera di Milano* neighborhood in Turin, Italy, is used as a case study, which includes 50,377 inhabitants (City of Turin 2020). The article is structured beginning with a description of the novel workflow from GIS to UBEM, followed by an in-depth retrofit decision-making analysis, important to maximize efficiency and constructability of measures selected. Next, results are presented and discussed, and finally conclusions and future perspectives are provided. The value of the work is to support Turin in its candidacy as one of the 100 climate-neutral cities and offer lessons to other cities participating in the mission.

Methods

Figure 1 summarizes the UBEM workflow in several steps: (1) collecting and preparing data, plus classifying the building stock into archetypes using geographic information systems (GIS); (2) creating a digital template library, coding construction details for baseline and retrofit conditions; (3) defining a 3D model by importing 2D points, extruding to 3D using GIS metadata, and adding shading context; (4) assigning weather data; (5) coordinating and running the district-scale energy simulation, adding PV panels in the retrofit condition; and (6) analyzing and validating simulation results using heating values from the TABULA project (Corrado et al. 2014). In addition to UBEM development, retrofit decision-making is discussed in depth. The methodology is further detailed in the following sub-sections.

GIS database

The work begins with collecting and preparing GIS data, including building geometry and associated metadata using ArcGIS Pro 3.0[1]. As this methodology is applied to a case study in Turin, Italy, the full municipal GIS database was obtained (City of Turin 2022). The GIS input files contain metadata with geometric parameters such as building height and number of stories, used in later steps to model 3D building volumes. The metadata also include non-geometric parameters such as building use type and era of construction.

Both geometric and non-geometric parameters are used to classify the residential building stock according to Italian TABULA archetypes (Corrado et al. 2014), which include four residential types: single family (SF), terraced house (TH), multifamily (MF), and apartment block (AB). Archetypes can be applied to buildings in the GIS database by relating their geometric parameters to the mean, minimum, and maximum number of stories, building volumes, and surface-volume ratios within TABULA. Construction eras contained in the GIS database are based on the Italian statistics agency (ISTAT) and differ slightly from those in TABULA, so the eras were reconciled and applied as follows: era 2, 1918 and prior; era 3, 1919-1945; era 4, 1946-1960; era 5, 1961-1970; era 6, 1971-1990; era 7, 1991-2005; era 8, 2006 and after. TABULA era 1 (1900 and prior) is not included here as the GIS database does not distinguish between pre-1919 and pre-1900. Where the database notes an unknown construction era, the building is re-classified to match the era of the closest building, using the spatial join tool in ArcGIS.

Thus, archetypes are assigned accordingly, each of which is described with standard envelope construction and mechanical systems in TABULA, to be used in the next stage to define digital building templates. The top archetypes by gross floor area (GFA) in the case study are detailed in Table 3; a total of 1,791 residential buildings with 2,132,124 m^2 of GFA were classified in GIS and included in the urban model. As an example to interpret the coding used, “R6AB” refers to a residential (R) building built between 1971 and 1990 (era 6) with the sub-type apartment block (AB).

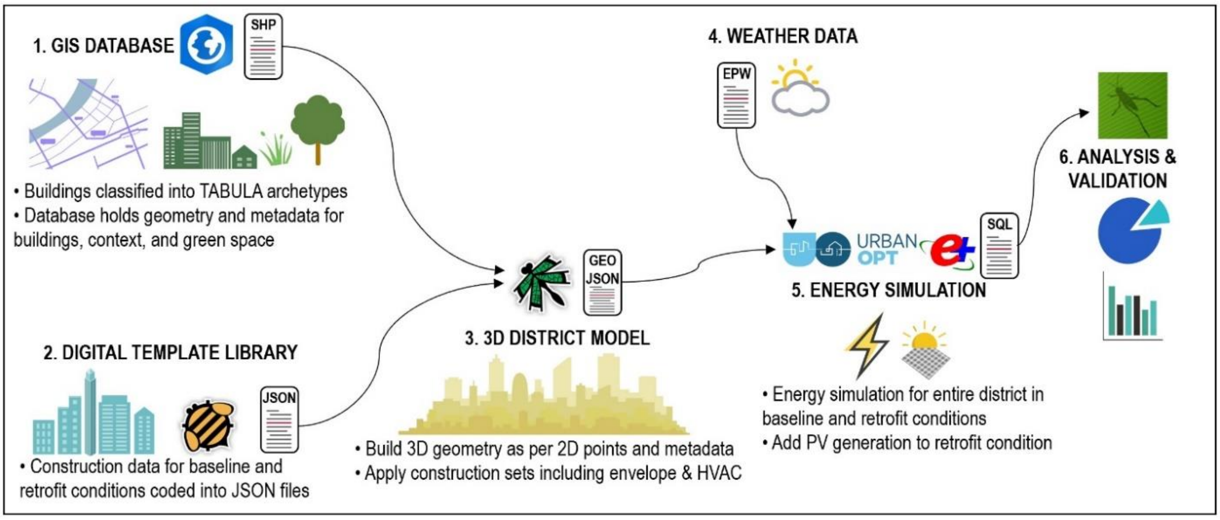

Figure 1: Overview of the UBEM methodology. Source: authors’ elaboration using images from www.fotor.com.

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[1] ArcGIS Pro 3.0; https://pro.arcgis.com

This classification approach has particularities to note. The data allows only GFA to be calculated; non-occupied spaces such as stairwells are not available and could not be subtracted. Cellars and unoccupied attics were not included in the GFA calculation. There are often multiple volumes contained within one building footprint to account for varying numbers of floors; for example, a building might have a 6-, 4-, and 2-story section due to terraces or step-backs. These volumes are always exported to the urban model with their correct height and story count, and thus for the 1,791 buildings, a total of 2,224 volumetric units were modeled.

The GIS database also includes context layers, such as non-residential buildings within the district. These context layers as well as the building archetypes are finally exported into separate Shapefiles (.shp) for use in creating the urban 3D model.

Digital template library

Next, the digital template library represents the baseline and retrofit conditions for each archetype building. Envelope construction and mechanical systems are programmed in the software Rhino[2], using its graphical algorithm editor Grasshopper[3]. Within this environment, the Honeybee[4] plug-in includes tools to select pre-defined construction sets or create custom sets. This work uses the latter approach, defining properties for each construction material (with appropriate thickness and sequence in an exterior wall, roof, or floor assembly) and mechanical system. This step culminates with the encoding of each construction set into a JSON file for the urban 3D model.

The baseline templates begin with envelope and mechanical values from TABULA for each archetype, which provides a material description for windows, exterior walls, roofs, and floors, as well as *U*-values. This work uses assemblies detailed in Italian technical report UNI/TR 11552 (UNI 2014) to match TABULA values, adjusting thicknesses as required, and programming these using Honeybee tools. For the retrofit condition, the baseline templates are copied and modified to reflect the envelope and mechanical ECMs selected in the study.

The digital template library also includes programs and schedules as per Table 1. Combining values from both Ferrando et al. (2022) and EN 16798-1 (CEN 2019) plus schedules for apartments and detached houses in the latter, a total of six programs were created using Honeybee/Dragonfly tools. These include apartments of pre-1971, 1971-1999, and post-1999 eras, associated with archetypes AB and MF for eras 2 to 5, 6 to 7, and 8, respectively. This pattern was similarly applied to the detached house schedules and values in EN 16798-1 for archetypes SF and TH of eras 2 to 5, 6 to 7, and 8.

Regarding the schedules and values, for DHW, EN 16798-1 Appendix A for Italian national criteria provides a formula for flow rate based on residence size. Since apartment size of archetypes AB and MF is not stated in the GIS database (only overall building sizes are present), the average size of all residential units in the *Barriera di Milano* district was calculated from the Piedmont Region EPC Database (Piedmont Region 2022), determined as 59.9 m^2. For SF and TH types, the average size of 209 m^2 was determined from the GIS database, and these values were used to calculate DHW flow rates. Ferrando et al. (2022) determined combined lighting and equipment values of 4, 5, and 6 W/ m^2 for Italian residences for the eras noted; these values are split 50%-50% toward lighting and equipment in this study. For infiltration, the categories of “high”, “medium”, and “low” are per the TABULA Webtool, respectively for archetype eras 2 to 5, 6 to 7, and 8 (Institute for Housing and Environment, 2017). The flow rates refer to building volume in m^3 and exterior façade area in m^2.

Table 1: Input schedules. *= Appendix A for Italian national criteria; **= apartment schedule – AB & MF types; ***= detached house schedule – SF & TH types.

Description	Schedule Reference	Value	Value Reference
Occupancy rate	EN 16798-1	28.3 m2/person** 42.5 m2/person***	EN 16798-1
Heating setpoint	EN 16798-1	20°C, occupied 16°C, unoccupied	EN 16798-1
Cooling setpoint	EN 16798-1	26°C, occupied 32°C, unoccupied	EN 16798-1
DHW flow rate	EN 16798-1*	0.0700 L/(m2·h)** 0.0498 L/(m2·h)***	EN 16798-1*
Lighting power density	EN 16798-1	2 W/m2, pre-1971 2.5 W/m2, 1971-1999 3 W/m2, post-1999	Ferrando et al. 2022
Equipment power density	EN 16798-1	2 W/m2, pre-1971 2.5 W/m2, 1971-1999 3 W/m2, post-1999	Ferrando et al. 2022
Ventilation flow rate	Constant	0.4 air changes per hour (ACH)	TABULA Webtool
Infiltration flow rate	Constant	0.006 m3/(s·m2), high 0.003 m3/(s·m2), med 0.001 m3/(s·m2), low	Default values in software

Retrofit decision-making

As a starting point for retrofit selection here, a recent literature review on retrofits in UBEM studies showed greatest energy savings for residential buildings in mixed climates (such as Turin) resulting from complete envelope retrofits (with window substitution, plus addition of insulation to exterior walls, roofs, and floor/basement), as well as upgrading mechanical systems to heat pumps (HPs). The review further showed that studies adding RES – typically onsite photovoltaic (PV) panels – reached the highest overall carbon savings. (Suppa & Ballarini, in press). Thus, this work applies ECMs as per Table 2.

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[2] Rhino 7; https://www.rhino3d.com/

[3] Grasshopper Build 1.0.0007; https://www.grasshopper3d.com/

[4] Honeybee 1.6.0; https://www.ladybug.tools/honeybee.html

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ECMs are applied in a cumulative manner, so that Scenario #1 contains ECM-1, Scenario #2 contains ECM-1 and -2, and Scenario #3 contains all three ECMs.

Table 2: Retrofits modeled in the study.

Code	Description	Values
ECM-1	Full envelope retrofit	U-values per element: Windows – 1.40 W/(m2K) Walls & Floors – 0.26 W/(m2K) Roofs – 0.22 W/(m2K)
ECM-2	Mechanical retrofit	COP: ASHP for space heating – 3.0 HP for DHW – 2.0
ECM-3	Photovoltaic panels	Eras 3 to 8: Applied to 50% of roof areas Panel efficiency of 15% Eras 2 to 3: Applied to 100% of roof areas Panel efficiency of 7.5%

The envelope ECMs are based on the nearly-zero energy standards of the Italian Interim-Ministerial Decree 26 June 2015 for the case study climate zone (Italian zone ‘E’) (Italian Republic 2015). Insulation retrofits to attain these values are often accompanied by overlapping and sealing joints in insulation or addition of air-vapor membranes to reduce building infiltration, which UBEM calibration studies have shown to be highly significant when modeling overall energy use (e.g. Wang et al. 2020). Thus, when applying ECM-1, the infiltration rates were reduced to the “low” default value in the UBEM software.

To ensure retrofit constructability, common materials such as mineral wool insulation, in commercially available thicknesses, are employed to meet or exceed values of Decree 26 June 2005. The oldest buildings in the case study have a higher probability of requiring historic protection; thus, this study follows precedents for historic districts in Teso et al. (2022) to avoid adding exterior insulation atop façades for eras 2 and 3. Instead, interior insulation ranging 10 to 12 cm plus gypsum board is modeled here. Installing 10 to 12 cm of building insulation plus gypsum board leads to a loss of interior space of 1 to 2%, assuming one side of the average 60m^2 apartment is exposed to the exterior.

To meet target wall *U*-values in buildings of eras 4 to 8, exterior mineral wool insulation ranging 8 to 12 cm plus exterior stucco was added, though only 3 cm insulation was required for the most recent era.

For roofs with an unheated attic, mineral fiber insulation can easily be sprayed at thicknesses required to meet target *U*-values, requiring 14 to 19 cm for older buildings and 6 cm for the most recent era. For pitched roofs with occupied attics, the existing roof tiles would have to be removed and reused/reinstalled (or replaced) on top of new, high-density mineral wool, ranging 10 to 12 cm in the older buildings and only 4 cm for era 8.

For floors with unheated cellars, foil- or vinyl-faced mineral wool can be added to the underside of ground floor, ranging 10 to 12 cm in most buildings and only 4 cm for era 8. For buildings with no cellar, floor insulation on top of the slab on grade was not selected, assuming the cost of raising doors, stairs, and other elements would be prohibitive. In all of the above insulation works, the addition of air-vapor membranes is assumed, aiming to increase building tightness.

The upgraded windows are low-e, double-glazed windows, simulated with a solar heat gain coefficient (SHGC) of 0.35, to meet the minimum value for total g-value due to glazing and movable shades in Decree 26 June 2005. In reality, this could be achieved with a spectrally selective coating to glazing and still lead to a reasonable level of visible light transmission, or by adding shutters or other shading devices. Windows and exterior shutters can be replaced on historic buildings if the overall aesthetic remains unchanged.

The mechanical retrofits were selected to best replace the existing conditions, which currently consist of gas- or oil-fired hydronic boilers with heat distribution via radiators or radiant panels. Thus air-source heat pumps (ASHPs) can easily be exchanged, without the need to drill geothermal wells while still increasing the coefficient of performance (COP) to 3.0, compared to current gas-fired efficiencies ranging 0.71 to 0.94. DHW heating with HPs can also easily replace current centralized gas-fired DHW heating systems. These measures may allow for partial reuse of existing piping or distribution units, and thus in the energy calculations, distribution losses for each archetype building per TABULA are maintained in the retrofit scenarios. Such reuse decreases the energy efficiency of the mechanical systems but may increase the cost-effectiveness and practicality of the retrofits.

For PV, standard panels can be installed on most existing roofs, and 50% of roof area coverage is estimated to avoid installing panels in shaded areas or north-facing exposures. For eras 2 and 3 with a higher probability of historic restrictions, novel PV systems integrated into roof tiles are proposed. Such products have been installed on UNESCO world heritage sites including Pompei (Dyaqua 2023), and thus could be approved in historic cases in the district. It is assumed these roof tiles would be used on the entire historic roof surfaces, and thus efficiency assumptions are reduced by 50%. Three archetypes with occupied attics (R2SF, R2TH, and R3SF) require the removal and replacement of roof tiles to complete planned insulation work, based on their existing condition, thus installing the PV roof tiles has some cost efficiency for these building types when conducting a complete retrofit.

Urban 3D model

Here, Shapefiles are imported into the Rhino/Grasshopper environment using the plug-in Urbano[5]. The vertices of every polygon from the GIS database are imported, to be converted to polylines for building footprints in Grasshopper, as well as metadata for building height, number of stories, etc. This process is rapidly completed for each archetype and repeated, resulting in 3D extrusions of shoebox models of each building with Level

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[5] Urbano v1.4; https://urbano.io/

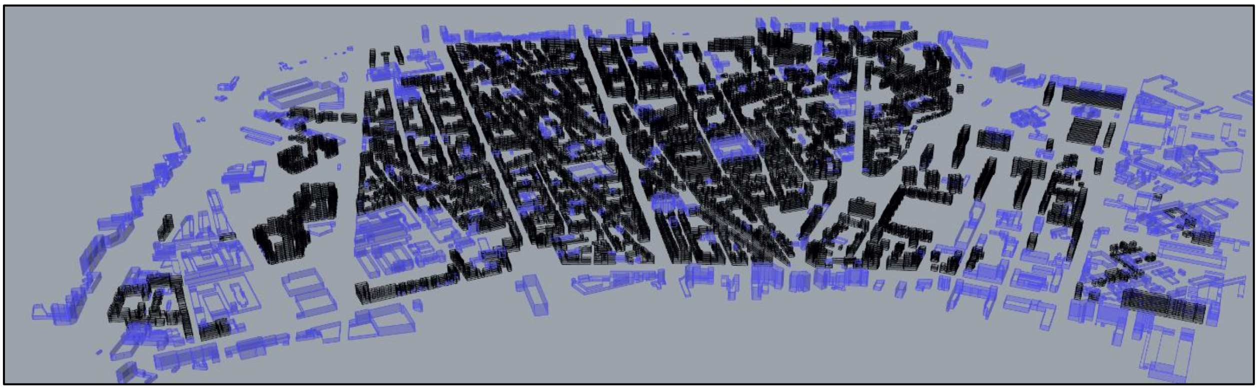

Figure 2: The urban 3D model of the Barriera di Milano neighborhood looking north. Residential buildings in the energy simulation are colored black, with non-residential structures used as shading context colored purple.

of Detail (LoD) 1. Building glazing is added per window-wall ratios (WWRs) in TABULA, ranging 10% to 20%.

This step culminates by importing context geometry from GIS for shading context in the energy simulation, including non-residential structures within the district, and structures in a buffer of 50 meters outside the district. Figure 2 depicts the full urban model including 1,761 residential buildings and all shading objects.

Energy Simulation

In the final step, the 3D model is converted to a GeoJSON file and sent to the URBANopt[6] module. URBANopt coordinates simulations using the EnergyPlus[7] dynamic engine, completed in parallel using separate CPUs. Here, the weather (.epw) file for Turin Caselle Airport (DoE 2023) is incorporated into the simulation. The model is geolocated setting the latitude and longitude of a known point in the geometry. Simulations are run using a timestep of every 15 minutes over one full year. The model also permits the addition of OpenStudio measures from the Building Component Library (NREL 2023). Such a measure is used to model addition of PV panels.

In addition to parallel computing, other features save computational effort. This includes simulation using multipliers: for example, in a 6-story building, only three floors with different boundary conditions are simulated, namely, the first floor, with a ground condition; the top floor, with sky condition; and the second floor, which is simulated and then multiplied for typical floors in between. The model also limits shading context to include only objects within a 50-meter band around buildings.

The dynamic simulation measures energy need for heating, cooling, and DHW, as well as energy use for lighting and equipment (appliance/plug loads). In the baseline and Scenario #1, energy need for heating and DHW from the simulation is converted to energy use by dividing by the percentage efficiencies of the gas-fired appliances as per TABULA. These values are then normalized by GFA and values for standby losses or auxiliary power per TABULA are added. In Scenario #2, the energy need is met for heating with ASHPs and DHW HPs, and thus the values for energy need are divided by COP of 3.0 and 2.0, respectively. Heating distribution losses per TABULA are maintained in Scenarios #2 and #3 to reflect the notion that piping and distributors are partially maintained in the retrofit condition. In all scenarios, existing cooling systems are assumed to have an energy efficiency ratio (EER) of 2.5, and thus cooling energy need is divided by this EER for cooling energy use. No cooling upgrades are applied in the study.

Results and discussion

Simulation duration was 11.5 to 12.5 hours for the district, using a 14-core laptop computer. The baseline simulation result for normalized heating energy need was validated against values in TABULA, as summarized in Table 3. The table includes only archetypes with at least 1% of the district GFA; 13 archetypes with less than 1% of GFA are not indicated but are included in total and overall values.

Table 3: Heating energy need compared to TABULA.

Archetype	% of GFA in district	No.	TABULA [kWh/m2]	Simulation [kWh/m2]	PE
R2AB	4.7%	75	194	190.2	-2.0%
R2MF	1.5%	41	199	205.7	3.4%
R3AB	12.7%	236	162	162.4	0.2%
R3MF	2.4%	100	200	219.6	9.8%
R4AB	26.6%	394	157	151.4	-3.6%
R4MF	3.0%	126	170	235.1	38.3%
R4TH	1.4%	134	173	360.2	31.0%
R5AB	27.4%	259	134	132.1	-1.4%
R6AB	7.5%	59	67.6	87.1	28.8%
R7AB	6.0%	51	62.9	89.7	42.7%
R8AB	3.9%	16	36	49.9	38.7%
District	100%	1,761			10.7%

The heating energy need noted for TABULA and the simulation results is limited to October 15th to April 15th, reflecting local laws. The overall percent error (PE) of 10.7% for the district considers the absolute value of PE for each archetype, weighted by GFA, such that individual negative values do not reduce the overall PE.

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[6] URBANopt CLI 0.9.0; https://docs.urbanopt.net/

[7] EnergyPlus 22.2.0; https://energyplus.net/

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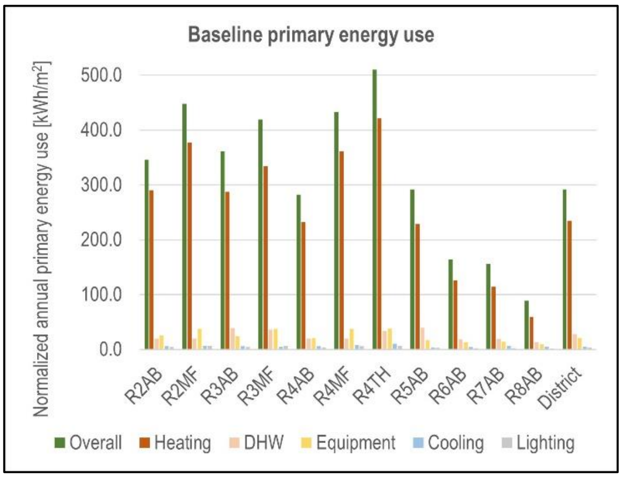
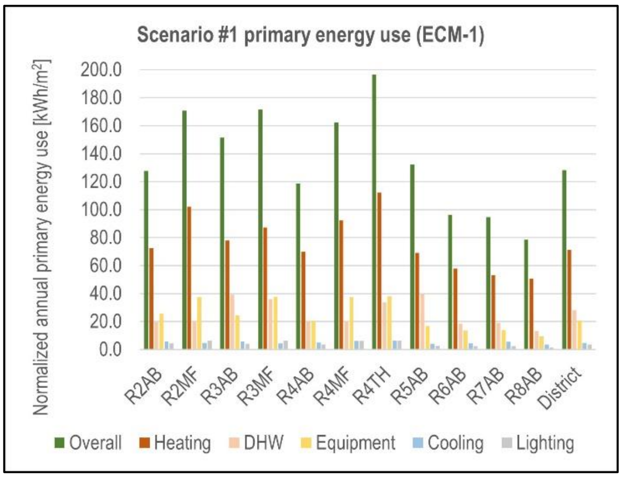
The overall PE can be considered acceptable, driven by low individual error rates (-3.6% to 0.2%) for archetypes AB from eras 2 to 5, representing over 70% of district GFA. However, some archetypes had an unacceptably high PE, with several values over 20% error compared to TABULA, with the highest error rates in newer eras or SF and TH types, and must be further investigated.

Simulated values for energy need (heating, cooling, and DHW) and site energy use (lighting and equipment) were converted to total primary energy use using factors of 1.05 and 2.42 for natural gas and Italian grid electricity, respectively (Noussan 2018). Primary energy values for baseline and Scenarios #1 and #2 are depicted in Figure 3, highlighting archetypes with the greatest GFA as well as the district total for all buildings in the study. One sees that heating energy use predominates the baseline, at 80% of overall primary energy use, followed by DHW at 10%, equipment at 7%, and cooling and lighting at less than 2% each. With no retrofits to equipment or lighting, these energy services increase slightly relative to overall energy use in Scenarios #1 and #2.

Figure 4 shows changes in primary energy use from baseline to Scenarios #1 and #2. One sees an overall energy reduction of 56% and 71% in Scenario #1 and #2, respectively. Reductions in heating energy use are more significant, with a 70% and 83% reduction in Scenario #1 and #2. No DHW reductions are present in Scenario #1, which addresses envelope only, whereas a reduction of 44% is observed in Scenario #2 when DHW heating is switched to heat pumps. Cooling primary energy use also decreased in the simulation. While cooling use might actually increase after some envelope retrofits, as added insulation can better retain internal gains and absorbed solar radiation while reducing the ability to garner free cooling at night, this was not observed. Instead, cooling decreased by 8% after ECM-1, perhaps explained by a large reduction in SHGC, from values ranging 0.67 to 0.85 in baseline condition, to 0.35 in Scenarios #1 and 2.





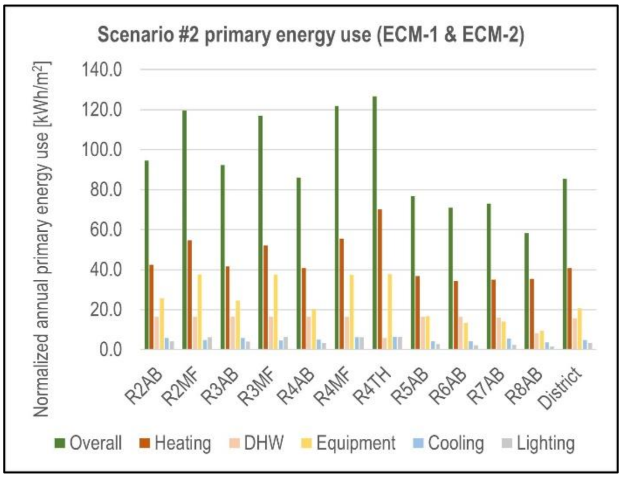


Figure 3. Normalized annual energy use for baseline condition, Scenario #1, and Scenario #2.

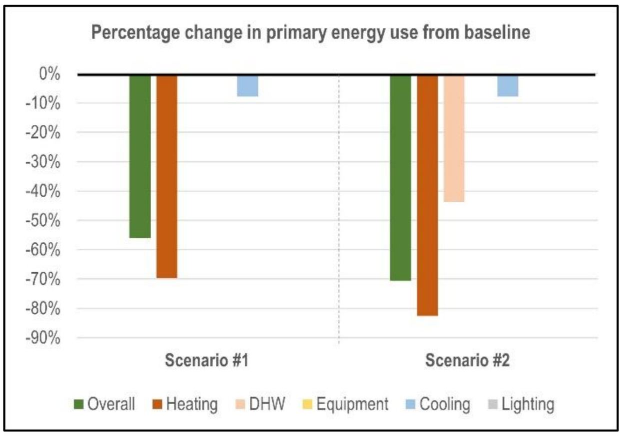


Figure 4. Percentage change in energy use in Scenario #1 and #2 compared to baseline. Percent change for equipment and lighting is zero in both cases.

Values for site energy use were converted to gas and electricity consumption, assuming heating and DHW are fueled by natural gas in the baseline and Scenario #1, with other energy services using electricity. In Scenarios #2 and #3, all services are powered by electricity. Site energy use is converted to CO_2 emissions using factors of 0.2085 and 0.2663 kg/kWh for gas and grid electricity, respectively (ISPRA 2022; ISPRA 2021). As Figure 5 shows, Scenario #1 leads to a 59% reduction in carbon emissions, as gas consumption is vastly reduced due to envelope efficiency gained in ECM-1. In Scenario #2, gas is eliminated entirely, as ECM-2 electrifies all heating and DHW systems. The combined effect of ECM-1 and ECM-

2 in this scenario leads to an 83% CO_2 reduction. Finally, Scenario #3 adds PV generation of electricity, reducing net electricity consumption, and leading to a 90% reduction in carbon emissions on an average annual basis.

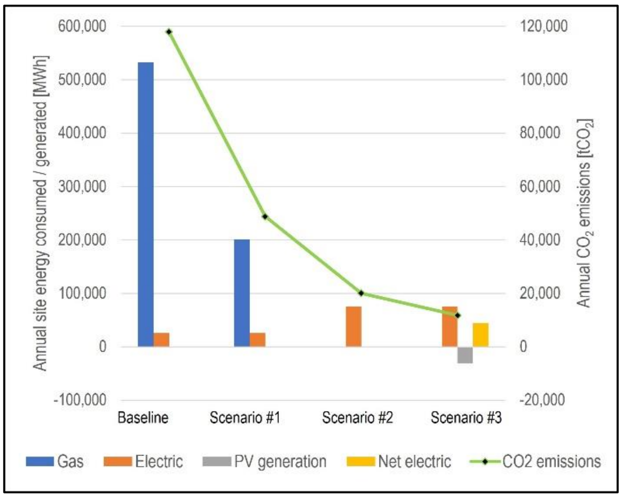


Figure 5. Annual energy consumed and produced, and annual CO_2 emissions.

While Scenario #3 sees a low value of annual net energy – only 44.5 MWh in site energy use – a finer time resolution is instructive. On the day of lowest annual PV generation, January 17th, the electrified buildings of Scenario #3 consume nearly 375 MWh, yet only 8 MWh of PV energy is generated – a difference of over 45-fold. Meanwhile, during maximum PV production on July 4th, the district uses 99 MWh and generates 182 MWh, nearly double its consumption. Such a seasonal mismatch is an obstacle to achieving climate-neutral districts, a challenge for future research to address.

Conclusion and future perspectives

This study created a UBEM for 1,761 buildings with 2,132,124 m^2 of GFA in Turin, Italy, applying retrofits to support the EU mission “100 climate-neutral cities by 2030”. The results show a reduction of primary energy use of 56% to 71% in different retrofit scenarios including envelope and mechanical system measures, following the “efficiency-first” principle of the new EPBD. Shifting the focus to carbon emissions, a third scenario generating on-site energy provides even greater reductions – a decrease of 90% in CO_2 compared to baseline when cumulatively adding PV to envelope and mechanical measures.

Importantly, this study analyzed retrofit decision-making to ensure that efficient and constructible measures are selected given the existing conditions in the district. As a next step in this research, quantities from the 3D model will be combined with a pricing database to determine investment costs, as well as financial returns due to energy savings. Providing a cost and savings perspective might reveal financial barriers for policymakers to address, perhaps leading to incentives or other policies for certain building types or retrofit measures. Another future step will include stakeholder collaboration to determine stakeholder preferences, better understand historic protection requirements, and further validate the practicality of the retrofits proposed.

As a limitation of the study, the validation was conducted only on an archetype-by-archetype basis compared to the TABULA project, as utility data was unavailable at the time of writing. In the future, it will be important to further validate the simulation results using gas and electricity consumption data for the district, leading to greater assurance of result accuracy.

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