PhD thesis: Climate-neutral Turin – evaluating energy, emissions, and life cycle costs in district-scale building retrofit scenarios

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Abstract

While most G20 nations pledge decarbonization 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, including Turin, Italy, must eliminate all territorial greenhouse gas emissions by end of decade, in the entire city or within a district of minimum 50,000 people. Key to success are retrofit strategies to reduce energy demand in the buildings sector, which accounts for 40% of energy use and 36% of energy-related emissions across the EU.

A recent review of the climate-neutral cities concept shows how research can support cities to develop and evaluate action plans, advance innovative solutions, and increase stakeholder collaboration. This doctoral thesis, which unfolds over four scientific articles, aims to support cities striving for climate neutrality by providing evaluation tools in the fields of urban building energy modeling (UBEM) and life cycle costing (LCC) for building retrofit scenarios.

Article #1, a review of UBEM studies that model retrofits, focuses on energy and environmental performance, financial cost, and decision-making in retrofit selection and study design. The review shows that deep envelope retrofits and switching to heat pumps lead to the greatest energy and emissions savings among tested scenarios, in several contexts in Europe and North America with mixed to cold climates.

Article #2 creates a UBEM of 1,761 residential buildings in a district in Turin, Italy, showing that cumulative addition of deep envelope retrofits, heat pumps, and photovoltaic panels leads to a 90% reduction in emissions compared to baseline. Regarding retrofit selection, the study also analyzes constructability of retrofits given the existing building conditions according to TABULA archetypes. Energy model parameters, UBEM design, and retrofit decision-making in Article #2 also inform research design of Article #4.

Article #3 enhances level of detail (LOD) for 3D city models using an automatic detection workflow for window-to-wall ratio (WWR). According to the literature, WWR and glazing efficiency have strong links to both building energy performance and retrofit cost outcomes, and hence increasing accuracy in how windows are modeled at urban scale could increase accuracy in both energy and cost modeling. The methodology first extracts street view imagery (SVI) in constituent tiles and stitches them to form an image dataset. The images are annotated using a custom tool developed within Rhino 3D software, which aids the location of occluded glazing. The annotated images are used to train and validate a YOLOv9 deep learning model which predicts windows, walls, and garage doors in unseen images, resulting in accuracy of ±5% for 94% of images, based on the difference in WWR between detected and

ground truth images. Finally, an automatic algorithm classifies building faces as street-facing fronts and non-street-facing sides and rears, allowing estimation of WWR at sides and rears that are not visible by SVI, and providing detailed WWR data for urban-scale energy and cost analysis.

Finally, Article #4 further enhances LOD to create a LCC model at LOD3. The method calculates pitched roof areas using LiDAR data and distinguishes exterior walls from shared party walls in adjoining buildings using an existing tool in Rhino. The objective is to automatically compute areas to be insulated, and by combining the window detections from Article #3, investment costs for all envelope retrofits can be accurately calculated. Energy use in pre- and post-retrofit scenarios is determined by UBEM, with each building simulated using URBANopt. A total of 80 scenarios are modeled, including 10 retrofit packages under two scenarios for roof renovation (with and without occupied attics), and four deployment scenarios to modulate retrofit rates and emissions factors in the electricity supply. The research shows complex outcomes arising from multiple scenarios, though packages with envelope retrofits plus heat pumps consistently lead to the lowest CO_2 emissions and lowest cumulative discounted cash flow per CO_2 emissions saved.

The PhD thesis fills gaps in the literature in several aspects. First, while there are several existing UBEM reviews, Article #1 is the first review to focus solely on UBEM studies conducting retrofits and compare such studies for retrofit decision-making, performance, and cost. Second, Article #2 provides a digital building library by tying together the Italian implementation of the TABULA project and UNI technical report UNI/TR 11552, which is used in the remainder of the thesis and made openly available for other UBEM researchers. Third, while a small number of precedent studies demonstrated deep learning methods to detect WWR, some of which were based on street view imagery, all of these studies focused only on visible façades. Article #3 uniquely develops an automatic algorithm to classify building façades and use urban planning regulations and observations of the case district to assign WWRs for non-street-facing rears and sides. Finally, previous studies have combined urban-scale energy and LCC analysis, mostly at LOD 1, although one recent precedent used LOD2 data for urban-scale LCC. The work of Article #4 demonstrates how advanced urban sensing and machine learning techniques can fill data gaps and enrich urban-scale energy and LCC models.

Combining energy, emissions, and cost analysis for district-scale retrofit scenarios using UBEM and LCC, the value of the overall PhD dissertation is to demonstrate, firstly, how advanced urban sensing and machine learning techniques can be used to fill data gaps for UBEM and LCC, and secondly, to support decision-making for policymakers guiding the rapid transition to climate neutrality.

Keywords

Climate-neutral cities; urban building energy modeling (UBEM); life cycle costing (LCC); building retrofit scenario analysis; automatic envelope detection workflows.