# 70 kWh energy saving and emission reduction

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Cities run on energy. Since the industrial revolution, urban environments have dominated energy consumption patterns in countries around the world. Today, over 50% of the world"s population lives in urban areas, collectively generating over 75% of the global gross domestic product (GDP). Attracted by this wealth, urban dwellers are expected to double by 2050. At that point, the urban built-up area is projected to more than triple1, accounting for over 70% of global carbon emissions2.

We collaborated with representatives from eight cities and municipalities around the world--Braga (Portugal), Cairo (Egypt), Dublin (Ireland), Florianopolis (Brazil), Kiel (Germany), Middlebury (Vermont, United States), Montreal (Canada), and Singapore. The cities were selected based on public calls for participation on building/urban science mailing lists and via direct contacts in our networks. A requirement for participation was that teams had some expertise in building energy modeling as well as existing relationships with local city representatives. We also aimed for a diverse set of cities with different climates, socioeconomic demographics, cultures, governing structures, and sizes.

Our educational goal for the collaboration was to train city representatives to conduct an urban building energy analysis for parts/segments of their building stock that they could later independently expand to the whole jurisdiction. For each city, we followed a study framework that consisted of individual pre-workshop meetings with city representatives, a joint three-day remote workshop including goal-setting and technical working sessions, and another set of individual debriefs. The workshop took place in January 2021. During the opening session, city representatives were invited to share their carbon reduction objectives for existing buildings as well as what retrofitting measures they were considering for those buildings.

We then built eight seed urban building energy models (UBEM) ranging from 38 to 399 buildings in neighborhoods for which building footprints, heights, program (usage type), and year of construction were available (Fig. 1). An UBEM is a physics-based model of buildings that estimates hourly energy use for heating, cooling, hot water, lighting, and equipment for "as is" conditions and any combination of possible retrofit upgrades. Non-geometric building properties such as construction characteristics, building age, heating, ventilation, and air-conditioning system properties were compiled for each city before the workshop (see Methods).

The colour of each building indicates the relative energy use intensity compared to other buildings in the model. For example, in Singapore with two archetypes defined (viz. residential and commercial), we observe that the commercial building (in red) has a relatively higher energy use intensity than the residential buildings, which performed rather similarly, reflecting how all residential buildings in the region of interest are similar-type public housing apartment units.

The concept of a "seed" UBEM was introduced for this project. A seed UBEM is a scaled-down version of a full UBEM that covers a limited part of a jurisdiction. Working with seed UBEMs (and fewer buildings) in the workshop is useful for staying nimble and supporting on-the-spot analysis. A seed model should ideally represent the city"s overall building stock--i.e., covers building typologies that represent a significant fraction of all buildings--and extend over an area that will soon undergo substantial renovation efforts. If well chosen, the seed model simulation and analysis results are indicative of the entire stock model since--with more buildings--the difference introduced stems mainly from building geometry.

The regions for the seed models were selected in consultation with participating city representatives. Florianopolis and Montreal selected typical mixed-use neighborhoods, including residential, retail, and larger commercial buildings. Braga, Dublin, Kiel, and Middlebury selected aging residential neighborhoods that are representatives of many similar neighborhoods surrounding the city core and are slated to undergo energy retrofits soon. Cairo and Singapore focused on multi-story public housing complexes that comprise most of those cities" construction. For example, over 80% of Singaporeans live in public housing.

For each study area, we developed a baseline as well as shallow and deep retrofit scenarios based on input from the city representatives (see Results). Our research goals were to gauge the value city representatives would retain from using an UBEM-based model of their building stock and what specific building retrofit upgrades they were considering at the time from a list of possible options (see Methods). Although we provided some informal feedback at the end of the workshop to guide future development, we refrained from assuming the role of a "consultant" that provides custom-tailored, optimal solutions to each city.

In addition to building retrofits, we also predicted the maximum onsite electricity generation potential from PV assuming full rooftop utilization to provide an upper physical limit for onsite carbon emission reductions. To separate the emissions reduction contributions from building upgrades and grid decarbonization, future carbon emissions are shown as a range in the Results section, assuming current and projected future grid emissions, respectively.

This work contributes to urban-scale energy research and policy in multiple ways. Previous work on urban building energy modeling mainly focused on developing and validating simulation tools and identifying potential use cases for this new technology11,12. In select cases, the energy-saving potential from retrofitting existing buildings--for example, in San Francisco, CA13, and Venice, Italy14--was calculated. However, those studies do not report if and how the authors engaged with local governments. The LA10015 and Carbon Free

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Boston16 studies are notable exceptions where experts from a U.S. National Lab or university collaborated with the municipalities in Los Angeles and Boston to develop carbon reduction pathways using custom-built, fully integrated cross-sector models.

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