Cutting urban carbon emissions by retrofitting buildings

July 13 2023, by Nancy W. Stauffer

PhD candidate Zachary Berzolla SM ’21 (left), Professor Christoph Reinhart (right), and their colleagues have launched online simulation tools that enable urban policymakers to determine what building-retrofit incentives and other measures are needed to bring about a targeted reduction in their city’s carbon emissions. Credit: Gretchen Ertl

To support the worldwide struggle to reduce carbon emissions, many cities have made public pledges to cut their carbon emissions in half by 2030, and some have promised to be carbon neutral by 2050. Buildings can be responsible for more than half a municipality's carbon emissions. Today, new buildings are typically designed in ways that minimize energy use and carbon emissions. So attention focuses on cleaning up existing buildings.

A decade ago, leaders in some cities took the first step in that process: They quantified their problem. Based on data from their utilities on natural gas and electricity consumption and standard pollutant-emission rates, they calculated how much carbon came from their buildings. They then adopted policies to encourage retrofits, such as adding insulation, switching to double-glazed windows, or installing rooftop solar panels. But will those steps be enough to meet their pledges?

"In nearly all cases, cities have no clear plan for how they're going to reach their goal," says Christoph Reinhart, a professor in the Department of Architecture and director of the Building Technology Program. "That's where our work comes in. We aim to help them perform analyses so they can say, 'If we, as a community, do A, B, and C to buildings of a certain type within our jurisdiction, then we are going to get there.'"

To support those analyses, Reinhart and a team in the MIT Sustainable Design Lab (SDL)—Ph.D. candidate Zachary M. Berzolla SM '21; former doctoral student Yu Qian Ang Ph.D. '22, now a research collaborator at the SDL; and former postdoc Samuel Letellier-Duchesne, now a senior building performance analyst at the international building engineering and consulting firm Introba—launched a publicly accessible website providing a series of simulation tools and a process for using them to determine the impacts of planned steps on a specific building stock. Says Reinhart: "The takeaway can be a clear technology pathway—a combination of building upgrades, renewable energy deployments, and other measures that will enable a community to reach its carbon-reduction goals for their built environment."

Analyses performed in collaboration with policymakers from selected cities around the world yielded insights demonstrating that reaching current goals will require more effort than city representatives and—in a few cases—even the research team had anticipated.

Exploring carbon-reduction pathways

The researchers' approach builds on a physics-based "building energy model," or BEM, akin to those that architects use to design high-performance green buildings. In 2013, Reinhart and his team developed a method of extending that concept to analyze a cluster of buildings. Based on publicly available geographic information system (GIS) data, including each building's type, footprint, and year of construction, the method defines the neighborhood—including trees, parks, and so on—and then, using meteorological data, how the buildings will interact, the airflows among them, and their energy use. The result is an "urban building energy model," or UBEM, for a neighborhood or a whole city.

The website developed by the MIT team enables neighborhoods and cities to develop their own UBEM and to use it to calculate their current building energy use and resulting carbon emissions, and then how those outcomes would change assuming different retrofit programs or other measures being implemented or considered. "The website—UBEM.io—provides step-by-step instructions and all the simulation tools that a team will need to perform an analysis," says Reinhart.

The website starts by describing three roles required to perform an analysis: a local sustainability champion who is familiar with the municipality's carbon-reduction efforts; a GIS manager who has access to the municipality's urban datasets and maintains a digital model of the built environment; and an energy modeler—typically a hired consultant—who has a background in green building consulting and individual building energy modeling.

The team begins by defining "shallow" and "deep" building retrofit scenarios. To explain, Reinhart offers some examples: "'Shallow' refers to things that just happen, like when you replace your old, failing appliances with new, energy-efficient ones, or you install LED light bulbs and weatherstripping everywhere," he says. "'Deep' adds to that list things you might do only every 20 years, such as ripping out walls and putting in insulation or replacing your gas furnace with an electric heat pump."

Once those scenarios are defined, the GIS manager uploads to UBEM.io a dataset of information about the city's buildings, including their locations and attributes such as geometry, height, age, and use (e.g., commercial, retail, residential). The energy modeler then builds a UBEM to calculate the energy use and carbon emissions of the existing building stock. Once that baseline is established, the energy modeler can calculate how specific retrofit measures will change the outcomes.

Workshop to test-drive the method

Two years ago, the MIT team set up a three-day workshop to test the website with sample users. Participants included policymakers from eight cities and municipalities around the world: namely, Braga (Portugal), Cairo (Egypt), Dublin (Ireland), Florianopolis (Brazil), Kiel (Germany), Middlebury (Vermont, United States), Montreal (Canada), and Singapore. Taken together, the cities represent a wide range of climates, socioeconomic demographics, cultures, governing structures, and sizes.

Working with the MIT team, the participants presented their goals, defined shallow- and deep-retrofit scenarios for their city, and selected a limited but representative area for analysis—an approach that would speed up analyses of different options while also generating results valid for the city as a whole.

They then performed analyses to quantify the impacts of their retrofit scenarios. Finally, they learned how best to present their findings—a critical part of the exercise. "When you do this analysis and bring it back to the people, you can say, 'This is our homework over the next 30 years. If we do this, we're going to get there,'" says Reinhart. "That makes you part of the community, so it's a joint goal."

Sample results

After the close of the workshop, Reinhart and his team confirmed their findings for each city and then added one more factor to the analyses: the state of the city's electric grid. Several cities in the study had pledged to make their grid carbon-neutral by 2050. Including the grid in the analysis was therefore critical: If a building becomes all-electric and purchases its electricity from a carbon-free grid, then that building will be carbon neutral—even with no on-site energy-saving retrofits.

The final analysis for each city therefore calculated the total kilograms of carbon dioxide equivalent emitted per square meter of floor space assuming the following scenarios: the baseline; shallow retrofit only; shallow retrofit plus a clean electricity grid; deep retrofit only; deep retrofit plus rooftop photovoltaic solar panels; and deep retrofit plus a clean electricity grid. (Note that "clean electricity grid" is based on the area's most ambitious decarbonization target for their power grid.)

The following paragraphs provide highlights of the analyses for three of the eight cities. Included are the city's setting, emission-reduction goals, current and proposed measures, and calculations of how implementation of those measures would affect their energy use and carbon emissions.

Singapore

Singapore is generally hot and humid, and its building energy use is largely in the form of electricity for cooling. The city is dominated by high-rise buildings, so there's not much space for rooftop solar installations to generate the needed electricity. Therefore, plans for decarbonizing the current building stock must involve retrofits. The shallow-retrofit scenario focuses on installing energy-efficient lighting and appliances. To those steps, the deep-retrofit scenario adds adopting a district cooling system. Singapore's stated goals are to cut the baseline carbon emissions by about a third by 2030 and to cut it in half by 2050.

The analysis shows that, with just the shallow retrofits, Singapore won't achieve its 2030 goal. But with the deep retrofits, it should come close. Notably, decarbonizing the electric grid would enable Singapore to meet and substantially exceed its 2050 target assuming either retrofit scenario.

Dublin

Dublin has a mild climate with relatively comfortable summers but cold, humid winters. As a result, the city's energy use is dominated by fossil fuels, in particular, natural gas for space heating and domestic hot water. The city presented just one target—a 40 percent reduction by 2030.

Dublin has many neighborhoods made up of Georgian row houses, and, at the time of the workshop, the city already had a program in place encouraging groups of owners to insulate their walls. The shallow-retrofit scenario therefore focuses on weatherization upgrades (adding weatherstripping to windows and doors, insulating crawlspaces, and so on). To that list, the deep-retrofit scenario adds insulating walls and installing upgraded windows. The participants didn't include electric heat pumps, as the city was then assessing the feasibility of expanding the existing district heating system.

Results of the analyses show that implementing the shallow-retrofit scenario won't enable Dublin to meet its 2030 target. But the deep-retrofit scenario will. However, like Singapore, Dublin could make major gains by decarbonizing its electric grid. The analysis shows that a decarbonized grid—with or without the addition of rooftop solar panels where possible—could more than halve the carbon emissions that remain in the deep-retrofit scenario. Indeed, a decarbonized grid plus electrification of the heating system by incorporating heat pumps could enable Dublin to meet a future net-zero target.

Middlebury

Middlebury, Vermont, has warm, wet summers and frigid winters. Like Dublin, its energy demand is dominated by natural gas for heating. But unlike Dublin, it already has a largely decarbonized electric grid with a high penetration of renewables.

For the analysis, the Middlebury team chose to focus on an aging residential neighborhood similar to many that surround the city core. The shallow-retrofit scenario calls for installing heat pumps for space heating, and the deep-retrofit scenario adds improvements in building envelopes (the façade, roof, and windows). The town's targets are a 40 percent reduction from the baseline by 2030 and net-zero carbon by 2050.

Results of the analyses showed that implementing the shallow-retrofit scenario won't achieve the 2030 target. The deep-retrofit scenario would get the city to the 2030 target but not to the 2050 target. Indeed, even with the deep retrofits, fossil fuel use remains high. The explanation? While both retrofit scenarios call for installing heat pumps for space heating, the city would continue to use natural gas to heat its hot water.

Lessons learned

For several policymakers, seeing the results of their analyses was a wake-up call. They learned that the strategies they had planned might not be sufficient to meet their stated goals—an outcome that could prove publicly embarrassing for them in the future.

Like the policymakers, the researchers learned from the experience. Reinhart notes three main takeaways.

First, he and his team were surprised to find how much of a building's energy use and carbon emissions can be traced to domestic hot water. With Middlebury, for example, even switching from natural gas to heat pumps for space heating didn't yield the expected effect: On the bar graphs generated by their analyses, the gray bars indicating carbon from fossil fuel use remained. As Reinhart recalls, "I kept saying, 'What's all this gray?'" While the policymakers talked about using heat pumps, they were still going to use natural gas to heat their hot water. "It's just stunning that hot water is such a big-ticket item. It's huge," says Reinhart.

Second, the results demonstrate the importance of including the state of the local electric grid in this type of analysis. "Looking at the results, it's clear that if we want to have a successful energy transition, the building sector and the electric grid sector both have to do their homework," notes Reinhart. Moreover, in many cases, reaching carbon neutrality by 2050 would require not only a carbon-free grid but also all-electric buildings.

Third, Reinhart was struck by how different the bar graphs presenting results for the eight cities look. "This really celebrates the uniqueness of different parts of the world," he says. "The physics used in the analysis is the same everywhere, but differences in the climate, the building stock, construction practices, electric grids, and other factors make the consequences of making the same change vary widely."

In addition, says Reinhart, "there are sometimes deeply ingrained conflicts of interest and cultural norms, which is why you cannot just say everybody should do this and do this." For instance, in one case, the city owned both the utility and the natural gas it burned. As a result, the policymakers didn't consider putting in heat pumps because "the natural gas was a significant source of municipal income, and they didn't want to give that up," explains Reinhart.

Finally, the analyses quantified two other important measures: energy use and "peak load," which is the maximum electricity demanded from the grid over a specific time period. Reinhart says that energy use "is probably mostly a plausibility check. Does this make sense?" And peak load is important because the utilities need to keep a stable grid.

Middlebury's analysis provides an interesting look at how certain measures could influence peak electricity demand. There, the introduction of electric heat pumps for space heating more than doubles the peak demand from buildings, suggesting that substantial additional capacity would have to be added to the grid in that region. But when heat pumps are combined with other retrofitting measures, the peak demand drops to levels lower than the starting baseline.

The aftermath: An update

Reinhart stresses that the specific results from the workshop provide just a snapshot in time; that is, where the cities were at the time of the workshop. "This is not the fate of the city," he says. "If we were to do the same exercise today, we'd no doubt see a change in thinking, and the outcomes would be different."

For example, heat pumps are now familiar technology and have demonstrated their ability to handle even bitterly cold climates. And in some regions, they've become economically attractive, as the war in Ukraine has made natural gas both scarce and expensive. Also, there's now awareness of the need to deal with hot water production.

Reinhart notes that performing the analyses at the workshop did have the intended impact: It brought about change. Two years after the project had ended, most of the cities reported that they had implemented new policy measures or had expanded their analysis across their entire building stock. "That's exactly what we want," comments Reinhart. "This is not an academic exercise. It's meant to change what people focus on and what they do."

Designing policies with socioeconomics in mind

Reinhart notes a key limitation of the UBEM.io approach: It looks only at technical feasibility. But will the building owners be willing and able to make the energy-saving retrofits? Data show that—even with today's incentive programs and subsidies—current adoption rates are only about 1 percent. "That's way too low to enable a city to achieve its emission-reduction goals in 30 years," says Reinhart. "We need to take into account the socioeconomic realities of the residents to design policies that are both effective and equitable."

To that end, the MIT team extended their UBEM.io approach to create a socio-techno-economic analysis framework that can predict the rate of retrofit adoption throughout a city. Based on census data, the framework creates a UBEM that includes demographics for the specific types of buildings in a city. Accounting for the cost of making a specific retrofit plus financial benefits from policy incentives and future energy savings, the model determines the economic viability of the retrofit package for representative households.

Sample analyses for two Boston neighborhoods suggest that high-income households are largely ineligible for need-based incentives or the incentives are insufficient to prompt action. Lower-income households are eligible and could benefit financially over time, but they don't act, perhaps due to limited access to information, a lack of time or capital, or a variety of other reasons.

Reinhart notes that their work thus far "is mainly looking at technical feasibility. Next steps are to better understand occupants' willingness to pay, and then to determine what set of federal and local incentive programs will trigger households across the demographic spectrum to retrofit their apartments and houses, helping the worldwide effort to reduce carbon emissions."

More information: Yu Qian Ang et al, Carbon reduction technology pathways for existing buildings in eight cities, *Nature Communications* (2023). DOI: 10.1038/s41467-023-37131-6

Yael Nidam et al, Census-based urban building energy modeling to evaluate the effectiveness of retrofit programs, *Environment and Planning B: Urban Analytics and City Science* (2023). DOI: 10.1177/23998083231154576