# ARTIFICIAL INTELLIGENCE FOR CLIMATE CHANGE MITIGATION ROADMAP (SECOND EDITION)

## CHAPTER 8:

# BUILDINGS SECTOR

*Philippe Benoit & Alp Kucukelbir*

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Building operations generate about one quarter of global carbon dioxide ($CO_2$) emissions. Roughly 8% are direct emissions from buildings (Scope 1) and 18% are indirect emissions from electricity and heat consumed in buildings but produced elsewhere (Scope 2).[1] Embedded emissions related to the manufacture, construction and demolition of buildings are also significant, potentially representing over 50% of life-cycle carbon for new buildings.[2]

Artificial intelligence (AI) is already helping reduce the carbon footprint of the buildings sector, from design to demolition, with significant opportunities for improving operations and energy efficiency. In the future, AI could do much more. One recent study found that adopting AI could reduce energy consumption and $CO_2$ emissions from commercial buildings by 8–19% from business-as-usual forecasts in 2050.[3]

This chapter presents current trends and promising directions to deploy AI in residential and commercial buildings, including in heating, ventilation and air conditioning (HVAC) systems as well as elevators and other appliances and equipment. The chapter also touches on the interaction of the buildings sector with broader urban development elements, including transport. In particular, the placement of buildings in relation to other buildings and key infrastructure (such as roads and mass transit) will impact a region's carbon footprint.[a]

Significantly, most future building construction and urban expansion will take place in developing countries, driven by rising populations, incomes, migration and other forces. These countries present different challenges than developed countries for the deployment of AI solutions.

## A. AI for Reducing Building Emissions

AI can help reduce $CO_2$ emissions generated by a building in ways that cut across the three main stages of its lifecycle: design, construction & demolition, and operation. These reductions mostly involve increasing the impact of energy efficiency initiatives and other emission reduction activities, but they also include activities such as fuel switching and increasing the capacity of buildings to produce renewable energy.

### i. Design & materials

The design of a building and the materials used in constructing it can have significant impacts on the building's carbon footprint. (That footprint includes both the carbon emissions embedded in buildings and carbon emitted in their subsequent operations.) This section presents several of the many opportunities for AI to help in designing buildings and using such materials.

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[a] See Chapter 6 of this Roadmap (Road Transport).

- AI for lower-carbon and sustainable construction materials. AI can help reduce the carbon footprint of common construction materials such as steel and cement/concrete.[b] In addition, AI is being used to explore and encourage the use of sustainable construction materials, showing a strong potential to reduce the carbon footprint of industrial buildings.[5] AI is also being used to optimize the use of recycled concrete aggregate.[6]
- Optimizing the location of building siting. Identifying and quantifying the geophysical, ecological (including carbon) and economic properties of potential building sites involve integrating many disparate data sources and complex objectives. Explainable AI can help quickly process large amounts of data, identifying the properties of potential sites of interest, while also revealing new sites that may have been missed by traditional approaches.[7]
- Optimizing passive design of buildings. The shape, orientation, window-to-wall ratio and selection of construction materials are all factors in determining the carbon footprint of buildings. AI is being used to quickly and efficiently optimize these design parameters without adding costs or reducing comfort. One application in India reported a 46% reduction of energy consumption and 8% reduction in discomfort hours.[8]
- Optimizing ventilation properties of buildings. Indoor ventilation can also help reduce a building's carbon footprint. Designing windows to encourage pressure differences that drive natural ventilation typically involves computationally expensive simulations that are beyond the reach of all but the most sophisticated building design projects. AI is reducing the barrier

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[b] See Chapter 5 of this Roadmap (Manufacturing Sector), which explores opportunities for AI to reduce the carbon footprint of materials such as steel. Sixty percent of the steel used by the construction industry is used in buildings.[4] See also Chapter 13 of this Roadmap (Materials Innovation), which describes how AI could accelerate discovery of new materials, including those that could help reduce the carbon footprint of building construction.

to designing good indoor ventilation, with one example that optimizes rooms with one-sided windows showing a 10× speedup in design time over traditional techniques.[9]

- Modeling heating and cooling loads during design. Traditional modeling tools enable designers to simulate the energy their buildings would require to heat and cool through various HVAC systems. The complexity of these tools, along with their computational expense, makes it challenging for designers to optimize their designs for energy efficiency. AI has been reducing this barrier by offering fast and accurate approximations of heating and cooling loads, encouraging designers to adopt energy-efficient options early in the design process.[10]

## ii. Construction & demolition

AI offers opportunities to mitigate the climate impact of a building throughout its lifecycle. Once its design is finalized and decisions around what materials to use are made, its construction (and eventual demolition) offer additional avenues for carbon reduction. This is also an interactive process: construction opportunities can influence the choice of materials (e.g., weight of materials relative to distance to be transported to the construction site).

- AI for traditional construction and waste management. Construction managers plan, direct and coordinate construction projects, ensuring compliance with building safety codes and other regulations. Construction technology and software vendors offer a variety of digital solutions that help detect defects during construction, perform root cause analysis of issues, and ensure workplace safety and compliance. New data sources at traditional construction sites, such as image and video data from drones, are creating opportunities for AI to help to better integrate and process such data streams, thereby creating opportunities to reduce operational emissions and waste.[11]
- Creating visibility into construction emissions. The carbon footprint of construction activities is hard to measure and quantify. A large component is created by heavy machinery, which are typically not equipped with direct emissions measurement mechanisms. AI offers a way to indirectly estimate the carbon footprint of on-site heavy equipment using accelerometer and gyroscope data, creating the visibility necessary to start optimizing operations to minimize emissions.[12]
- AI for accelerating prefabrication methods. Prefabricating buildings, which are manufactured off-site in a factory then installed on site, offers a promising pathway to reduce the carbon footprint of construction. AI-based robotics are particularly well suited for prefabrication facilities, as robots can be installed in the factory and AI can operate them efficiently with high throughput.[13] AI can also help optimize prefabrication techniques and scheduling,[14] while simultaneously matching designs to the specific capabilities of prefabrication manufacturers, thereby reducing construction times and material waste.[15]
- AI for reducing quantity and improving management of demolition waste. In South Korea, construction and demolition waste represent approximately 50% of total waste, including municipal solid waste and commercial and industrial waste.[16] AI can enable efficient categorization of construction waste from image data, which can increase identification,

segregation and reuse of materials in the circular material economy of recycled feed and fuel stocks.[c]

### iii. Operations

Building operations generate considerable Scope 1 emissions and even larger Scope 2 emissions. AI can assist with two strategies for reducing these emissions: lowering demand for heat and electricity (both on and off site) [d] and increasing on-site zero-carbon energy production.

- Optimizing HVAC and other building mechanical systems. Making HVAC, elevators and other building mechanical systems operate in a better, more efficient manner would reduce a buildings' carbon footprint. This includes understanding where people are and where they are not (e.g., in a commercial building) at different times of the day and adjusting heating and cooling accordingly. AI can monitor and enhance HVAC operations at increasing scales, incorporating all factors mentioned above.[18] But nobody uses systems they do not trust, which drives a recent focus to make such AI systems interpretable.[19]
- Minimizing the energy requirements of appliances and office equipment. Appliances are major drivers of energy use in buildings. Governments run a variety of appliance efficiency programs, including those that "nudge" consumers to buy energy efficient products (such as Japan's Top Runner and US Energy Star programs). AI can help to make operation of these products even more efficient.[20] It can also increase information flows through digitalization (including in appliances) which can improve the efficiency of buildings. This includes communication between appliances and the power system to lower demand from individual appliances at times of peak demand that would potentially call on the need for deployment of fossil fuel–based power generation. These systems already exist (e.g., refrigerators), and AI can improve their design and operation.[21] One of the expanding sources of demand from within buildings is for the servers they contain to power AI and other computational functions. This is an emerging issue of concern in efforts to reduce emissions and will require increasing attention as the use of AI increases.[22]
- Raising knowledge regarding existing space usage. AI is enabling building owners, developers and investors to better understand and adapt their existing assets to shifting usage and market demands. By leveraging data from wireless networks and other sensors, building usage can be analyzed and visualized in a way that allows owners to make better decisions for lowering their

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c See Chapter 5 of this Roadmap (Manufacturing Sector)

d Measures that reduce the amount of energy required to maintain an adequate level of comfort and other emissions-related actions should also generate other important co-benefits, such as reducing energy poverty by reducing the need of poorer families to consume energy to heat their homes. (See, e.g., US DOE 2024[17]).

operational carbon footprint and encourage them to consider alternative uses for their existing spaces.[23]

- Automating sustainability reporting. AI-powered cloud-based reporting can help construction companies and building operators automatically track their performance and adjust as needed, making it easier to measure and transparently report their environmental impact and make adjustments to lower impacts, which in turn they can also track.[24]

## B. Buildings as Clean Energy Producers

Reducing the emissions impact of buildings involves looking not only at the demand-side aspects, but also the capacity of buildings to generate low-carbon energy for use by the building or even potentially other offsite consumers. Crafting buildings to produce low-carbon energy can be integrated into the various aspects regarding buildings enumerated in the previous subsection, including notably their design, as well as the operation of onsite solar and other clean energy production capacity.

AI can integrate additional layers of information (including dynamic hourly data regarding solar radiation and the placement of other structures) to build systems that optimize available solar and other resources (including wind, geothermal and other).

In addition, AI can help to better match demand and supply at the building level. Adding the energy production dimension to the consumption of buildings increases operational complexity. AI can help buildings adapt to dynamic load and demand, optimally allocating clean energy production to building demand[25] and tightly coupling the specific energy requirements of a building with the power it generates and consumes.[26]

# FROM BUILDINGS TO TOWNS AND CITIES

Individual buildings do not exist in isolation but are built and operate within a larger environment that includes other buildings, infrastructure (such as roads, bridges and mass transit) and natural terrain. The areas around a building can affect its energy usage and emissions. For example, the location of nearby buildings will affect the amount of solar radiation a building will receive (e.g., by casting shadows). So, in designing a building at a specific site, the surrounding built environment is also a factor—one that injects additional complexity.

This is also true when designing a new block of buildings, such as a townhouse development or a commercial building complex. This adds additional levels of complexity. And this complexity is further increased when extending it to the construction of new neighborhoods (or efforts to redesign existing ones), let alone new cities. Moreover, cities themselves produce higher temperatures than surrounding areas, at times up to 4° C higher.[27] This increases the demand for electricity for cooling, an anticipated major driver of future emissions, as well as presenting the challenge of using materials and urban design technique specifically to reduce the extent of this “heat island” phenomenon.

The computational power of just several years ago provided the ability to address the interaction of these larger sets of variables but to a degree that was substantially more limited than what AI can provide today. Areas where AI can help when thinking beyond the single building to a block or a broader city include the following:

- Placement and design of a series of buildings (both residential and commercial).
- Structure of utility services, including electricity, water and sewage.
- Design and placement of residential versus commercial and retail services.
- Design of urban transport systems, including bus routes and commuter rail systems, as well as bike routes (invoking the framework of avoid/shift/improve).
- Operation of heating and other systems, including beyond the single building unit, such as district heating and district cooling systems.
- Interaction of all the above: the design of new neighborhoods or even entire new cities (e.g., in Egypt and Indonesia) provide an opportunity to deploy AI technologies to reduce emissions and improve sustainability.[28]

The data-driven insights that AI potentially provides can help make environmental strategies more effective, leading to better, more sustainable urban environments. Bibri et al. (2024)[29] highlight AI’s applications to energy and water conservation, sustainable transportation management, waste management and environmental monitoring.

## C. Barriers

- Geography. Significantly, most new construction is projected to take place in emerging economies and other developing countries. The IEA posits that building floor–area equivalent to that of the city of Paris will be added every week globally between 2020 and 2030,[30] 80% of which will be in emerging market and developing economies (See page 58, IEA's *Energy Efficiency 2022*[31]). Opportunities to apply AI would be squandered if geography is not considered in this construction, including adapting solutions to the on-the-ground realities in these countries, such as capacity and financial constraints that typically differ from those in advanced economies.
- Low digital penetration. The degree of familiarity with digitalization and AI techniques within the building sector (like in many others) will constrain the ability to fully exploit theoretical opportunities. Closing the gap between the potential and the actual will require raising the degree of expertise, either in house or alternatively through the use of specialized outside suppliers. To date, both areas are immature, especially as the potential of AI has, naturally, outpaced the rate of change in the industry. Digitalization and application of AI techniques specifically require governments, designers and developers to build, hire or outsource personnel with expertise. Developing such talent in house involves training internal domain experts with data literacy, storage and manipulation skills. Hiring for digital talent often involves recruiting data scientists and data engineers to enhance the work of existing staff in this field. Some entities within the building sector may prefer to outsource such activities to consulting groups and other companies that provide such services.
- Rapid pace of urbanization. One of the barriers to deploying innovative AI solutions is the rapid pace at which urbanization is taking place. The pressure of numerous real-world forces driving increased urbanization are not leaving city planners with the time to adopt new technologies to optimize emissions. This pressure is compounded by the fact that many of these expanding urban populations are in countries with limited technical and other capacities, notably in some of the largest cities in the developing world. This limits time and opportunity required to develop, vet and deploy AI-based solutions, particularly on construction sites.

## D. Risks

- Rebound effect. One of the main challenges in using AI to reduce emissions related to the built environment is the possibility of a rebound effect, namely that the improved efficiency afforded by AI will lead to greater consumption that negates the emissions gains generated by AI.
- Distracting from other decarbonization strategies. AI is a "high-end" approach that has the possibility to distract from less sophisticated but more attainable approaches. AI is good but not if you deprioritize more accessible technological solutions (such as improved insulation, etc.) that can generate, in practice, a stronger impact (particularly in developing countries and settings with some of the capacity issues described above).

- AI in energy production brings operational risks. AI dependent systems present operational risks. While HVAC, appliances and other systems can generate important emissions savings, they are also exposed to software and internet-based operational, safety and security risks.
- AI can justify decisions that are worse than alternatives. AI can be used to "optimize" a solution of a particular input that results in a larger life-cycle carbon footprint for the building than an alternative. For example, AI can be used to marginally reduce the carbon footprint of using a particular construction material (e.g., cement) while an alternative material (with or without the use of AI) would have led to a lower overall carbon footprint (e.g., one that involves lower transport emissions). Failing to move toward lifecycle approaches can result in AI being misapplied to produce the mirage of emissions gains (an issue that also affects non-AI interventions).

## E. Recommendations

1. *Governments at all levels working with the private sector should identify and pilot AI-supported technological improvements in design, materials, construction and demolition that reduce the embedded carbon in buildings.*

2. *National governments should develop research and development programs for AI improvements in emissions efficiency of building operations (including HVAC systems, lighting, elevators and other mechanical systems). Municipalities should explore more restrictive commercial-building energy use and emissions standards (including for Scope 2 emissions) that become attainable through AI. These efforts should combine a "pull" strategy of government support paired with a "push" effort of more restrictive norms.*

3. *Public and private construction organizations should engage government research agencies, academia and the nonprofit community in providing support for developing and deploying AI. Sharing data, encouraging the development of standards and best practices, and creating venues for dissemination and discussion of these results can help accelerate development and deployment of AI in this sector. In particular, using AI to build more sophisticated life-cycle analytic tools can help optimize AI's impact and reduce the possibility of its misapplication.*

4. *Governments, the private sector and professional associations should develop a platform to disseminate best practices regarding improving digitalization and other data collection to support the deployment of AI to reduce building energy use and emissions (including Scope 2). This platform should be tied into the areas of action for AI identified under recommendations 1, 2 and 3. These groups should also work with suppliers to increase the availability and improve the affordability of related sensors and other equipment.*

5. *Multilateral development banks, national/bilateral organizations and other donor agencies should develop a program of technical assistance and funding to increase the capacity of stakeholders both (1) to develop domestic AI innovation programs for the buildings sector in urban areas and (2) to implement AI-enhancements, whether designed locally or abroad. AI in the buildings sector should be adapted to the opportunities and constraints presented by developing economies, including designing and deploying technology-appropriate solutions (such as low-tech approaches where country conditions present constraints), as well as encouraging data gathering in those geographies.*

6. *Governments, in association with city associations and academia, and supported by international development agencies, should identify and develop one or more urban development pilot programs to explore using AI to lower embedded carbon and operational emissions. The new cities being built in emerging economies (such as Indonesia's new capital, Nusantara) provide a possible opportunity for targeted cooperation between donor agencies, such as the World Bank and Japan's JBIC, together with developing-country national and municipal authorities (e.g., Egypt's new administrative capital).*

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