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Building value by decarbonizing the built environment

Uncovering how decarbonization can create unprecedented value

June 2023

McKinsey Sustainability
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Executive summary

Decarbonizing the built environment is possible and has the potential to generate significant value—but the industry must come together to scale solutions.

The built-environment ecosystem consists of real estate and infrastructure and touches all aspects of human life, from homes and offices to factories and highways. It is also responsible for about of a quarter of the world's greenhouse-gas (GHG) emissions.

To help industry players make progress toward decarbonization, this report assesses the most effective solutions available today. Our analysis shows that many levers not only have proven abatement potential but are also already cost-effective. In other words, companies across the built-environment ecosystem could derive value immediately from these lower-emitting technologies and solutions.

Further decarbonization levers would be cost-effective by 2030 if they are industrialized—that is, produced and implemented at scale with a focus on quality, cost, and time to market. Because today's value chains are often fragmented and localized, industrialization poses its own challenge. However, those that act now will likely be able to take advantage of powerful new business opportunities as global decarbonization gains traction. This report identifies 17 such opportunities that could prove particularly attractive for industry players.

Together, the 22 levers we highlight can potentially reduce overall emissions from the built environment by up to 75 percent if implemented at scale in the next five to ten years.

In these efforts, all companies in the ecosystem can have significant roles to play. By creating partnerships and focusing their efforts and investments, ecosystem players can find mutually beneficial ways forward while building a net-zero world.

About the analysis

To find the most effective solutions to reduce emissions, we analyzed more than 1,000 levers for their abatement potential, cost-effectiveness, and scalability. Out of these, we selected the most promising levers for more rigorous examination. This involved comparing their impact and technical applicability across six asset archetypes: single- and multifamily dwellings, commercial low- and high-rise buildings, industrial buildings, and infrastructure. These archetypes represent about three-quarters of the built environment.

For each archetype, the net cost of applicable levers was compared with the cost of traditional practices. Levers were considered both as they exist today and if they were to be applied at scale. Last, each lever was assessed across four geographies and two climate zones to determine if regionally specific factors, such as climate and regulatory differences, affected net cost.

Notably, we did not consider changes in regulatory and policy frameworks when assessing costs and business opportunities for given levers. Although regulatory incentives could create tailwinds for adoption, this report does not take the impact of these factors into account to emphasize that significant progress can be made solely through actions by ecosystem players today.

A serious challenge

Because the built environment encompasses the whole planet, the movement toward its decarbonization needs to be global in scope. The built environment accounts for 14.4 metric gigatons of CO_2 equivalent ($GtCO_2e$) of emissions around the world annually (Exhibit 1). Approximately 26 percent of all GHG emissions and 37 percent of combustion-related emissions come from the construction and operation of the built environment.

Emissions come from all phases of the construction process, from carbon-intensive material production processes and suboptimal technology choices to inefficient building designs, construction practices, and energy use after projects are completed. These emissions can be grouped into operational emissions (related to operating and maintaining buildings and structures) and embodied emissions (related to producing and transporting building materials and constructing buildings and structures).

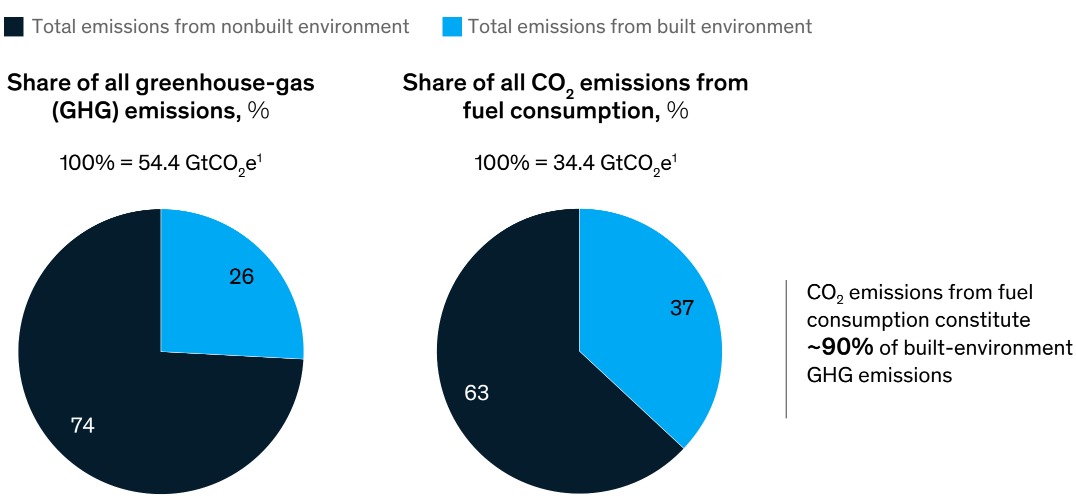
Although many solutions already exist to abate both operational and embodied emissions, the clock is ticking on their implementation. Operational emissions are constantly being released from already-built construction, and once embodied emissions are released, they can only be offset, not abated.

Industrializing solutions that work

All areas of the built environment can benefit from decarbonization, and some have particularly powerful abatement options. For example, on average, space heating and water heating emissions compose roughly three-quarters of operational emissions for residential buildings, making them an excellent target for decarbonization (Exhibit 2). According to our analysis, a single lever—heat

Exhibit 1

The built environment contributes a significant share of the world's emissions, particularly those related to fuel consumption.



Note: Our analysis was based on McKinsey research undertaken around decarbonization in construction and checked against the sources listed below.
[1]Metric gigatons of CO_2 equivalent.
Source: "Emissions Database for Global Atmospheric Research (EDGAR) v5.0 (1970-2015)," European Commission, November 2019; "Fuel share of CO2 emissions from fuel combustion, 2018," IEA, October 26, 2022; *Key world statistics 2020*, IEA, August 2020; OECD; Steel Construction Encyclopedia

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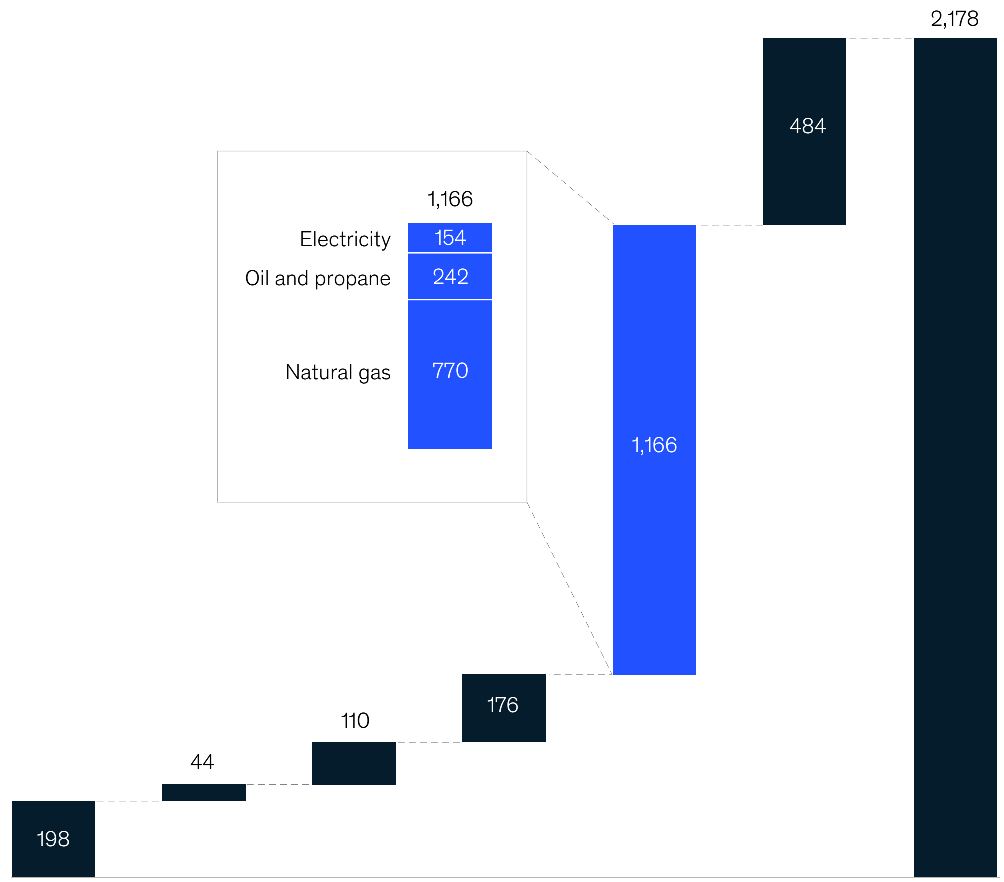
Exhibit 2

Most operational emissions in multifamily homes are caused by water and space heating.

Emissions breakdown, kg CO_2 per dwelling annually



Driver	Appliances	Cooking	Lighting	Space cooling	Space heating	Water heating	Total
Emissions, %	9	8	5	2	53	22	100

Note: Figures do not sum to 100%, because of rounding.
Source: McKinsey Real Estate Climate Action Platform

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pumps—can reduce these emissions by about 60 percent. This and many other effective levers are already cost-neutral relative to conventional solutions. Even more levers are expected to be cost-neutral or marginally more expensive by 2030 if they can be scaled.

In this report, we found that 22 levers had particularly strong potential due to their high abatement potential, cost-effectiveness, and applicability across archetypes and regions. These levers can reduce operational emissions by up to 90 percent and embodied emissions by up

Twenty-two levers can reduce operational emissions by up to 90 percent and embodied emissions by up to 60 percent for the built environment.

to 60 percent for most of the built environment.[1] However, a number of potentially effective levers face a central challenge: industrialization. No matter their abatement potential, if decarbonization levers and solutions cannot be produced and implemented at scale, ecosystem players will not be able to realize their full impact.

To industrialize decarbonization solutions, players will likely need to address challenges in the ecosystem that could deter their widespread adoption. The built environment may span the globe, but it varies widely at a local level and throughout the value chain. Players are often regional, overlapping, and varied in their objectives and business models. In addition, the established industry practices that do exist can be difficult to change. Because many of the solutions are relatively new or unconventional for the industry, industry players may be unaware of the abatement benefits and economic potential of certain levers, and financial institutions and insurers can be hesitant to support their deployment. Industry players may also face shortages of both labor and materials during the next five to ten years as value chains scale, though our analysis of the most impactful levers is not constrained by these potential shortages.

Despite these challenges, there are many incentives to industrialize decarbonization levers. Industrialization is likely to reduce input costs in several ways. For instance, by establishing procurement best practices, players can develop consistent supply chains and find efficiencies in transportation and in purchasing. An industrialized ecosystem can also enable technicians to gain skills and experience to drive process efficiencies. Increasing the number of units produced can reduce capital expenditures per unit, and the stable customer demand created by a steadier, cost-effective supply of sustainable options can decrease risk and financing costs.

How businesses can unlock value through decarbonization opportunities

Early movers that are able to lead industrialization and commercial adoption of decarbonization solutions are likely to create and capture value from this transition. Among the hundreds of possible business opportunities in decarbonizing the built environment, we have highlighted 17 that could deliver significant value for ecosystem players (Exhibit 3). Industry incumbents and disruptors could act upon these opportunities to accelerate adoption, application, and scaling of levers before 2030.

The value-generating potential of these levers extends across the entire built-environment ecosystem, from real estate owners and developers to investors, construction companies, material manufacturers, and design and engineering firms. Capturing these opportunities could require industry players to assess their existing capabilities, design future potential operating models, and build green businesses to develop new capabilities. For instance, engineering, procurement, and

[1] This emissions-reduction potential could be even greater if supported by policy drivers such as green premiums, incentives, or changes to existing certification practices. To fully reach net-zero emissions for the built environment, other solutions and technologies will likely be needed beyond 2030.

Exhibit 3

An ecosystem to decarbonize the built environment will offer a wide variety of solutions.

End users (developers and investors for infrastructure and real estate)

want → **Solution** (product or service) *made by* → **Solution provider** *which depends on* → **Solution enabler**

Solution (product or service)

- Low-carbon cement and concrete
- Green steel
- Low-carbon insulation
- Low-cost engineered wood
- Low-cost, high-efficiency heat pumps
- Energy upgrade solutions and installation services
- Green and cost-effective solution designs
- On-site equipment charging services
- Off-site modular construction solutions to minimize waste
- Validation of green assets and projects
- Certified green materials and solutions
- Green-solution professionals
- Energy optimization upgrades
- Transition financing
- Green insurance
- Transforming existing real estate and infrastructure to be more sustainable

Solution provider

- Cement and concrete producers
- Steel producers that deploy alternative energy, scrap metal, and CCUS[1]
- Insulation manufacturers that industrialize low-carbon insulation
- Engineered-wood providers that scale production
- Heat pumps and component manufacturers
- Consolidated services, which design and install energy optimization services
- D&E[2] firms, which create green-solution portfolios
- Logistics firms, which lease charging infrastructure and equipment
- D&E[2] and modular construction firms
- Audit, consulting, and engineering firms, which measure and track emissions
- Certification service providers which validate emissions abatement
- Training and vocational institutes which upskill green professionals and tech
- Financing entities which provide upfront capital expenditures for upgrades
- Financers and investor, which deploy new financing structures for solutions
- Insurers, which create foward-leaning underwriting for use of green solutions
- Investors, which design funding for green assets

Solution enabler

- EPC[3] firms, which design solutions; waste management, which collects and provides materials
- EPC[3] firms that design solutions
- Certification service providers that validate low-carbon insulation
- Certification service providers that validate use cases

Key

- Industrialize production of green materials
- Industrialize production of energy-efficient building tech
- Deliver efficient energy and electrification upgrades
- Design and engineer green and cost-effective structures
- Electrify on-site construction
- Minimize waste and maximize speed with off-site builds
- Validate and certify low-carbon actions and solutions
- Finance the green transition

[1]Carbon capture, utilization, and storage.
[2]Design and engineering.
[3]Engineering, procurement, and construction.

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construction (EPC) firms have an opportunity to design, develop, and implement carbon capture, utilization, and storage (CCUS) solutions for cement plants and high-emitting industrial clusters. And real estate developers, investors, and financiers can generate value by turning existing assets into green assets and setting specifications for green solutions and materials to drive offtake.

For many of these opportunities, players should consider acting together to realize maximum value. Collaboration across the value chain will likely be critical for success, even among competitors. For example, multiple real estate companies could collectively commit to procuring and installing low-carbon building materials, technologies, and services, thereby creating demand, increasing cost competitiveness through scale, and enabling investments thanks to reduced commercial risk.

In addition to horizontal collaboration, players in the built-environment ecosystem will likely need to create partnerships vertically throughout the value chain. Both new and incumbent manufacturers of materials and technologies (such as low-carbon insulation and engineered wood) can adopt best practices regarding process decarbonization and commercialization. They can also proactively approach and educate real estate developers to create demand. To support these decarbonization efforts, investors and financiers could identify high-potential suppliers and partner with forward-leaning real estate players to develop and provide competitive financing solutions.

The need to decarbonize the built environment is urgent, and significant progress can be made with technologies, materials, and solutions that are available today and are proved to have strong decarbonization potential. If ecosystem players can move quickly to assess which green businesses to build or fund, which business models could help create scale, and which partnerships would be beneficial, they are likely to capture economic benefits from opportunities that are executable in the near term.

Decarbonizing the built environment: A global challenge

Accelerating decarbonization in the built environment is essential for a sustainable future, but industry challenges need to be addressed for solutions to scale.

As one of the world's largest economic ecosystems, the built environment is also one of the world's highest emitters, releasing more greenhouse gases (GHGs) than either the transportation or industrial sectors. In total, the built environment is responsible for approximately 26 percent of all GHG emissions and approximately 37 percent of global CO_2 equivalent (CO_2e) emissions from fuel combustion (Exhibit 1). Given the volume of the built environment's emissions, it is crucial to decarbonize this industry to achieve global sustainability goals.

In absolute terms, the built environment contributes up to 14.4 metric gigatons (Gt) of CO_2e to the atmosphere annually. Assuming limited changes to how building stock is managed, operated, and constructed, this number could rise by 10 to 15 percent in total by 2030.

The typical 30- to 130-year lifetime of a building means that of the building stock expected to exist in 2050, 80 percent has already been built,[1] which points to two imperatives. First, decisions made today will have consequences for decades to come. Therefore, it is critical to design and build energy-efficient buildings to avoid increasing stock that will require energy upgrades in the future and to use low-emissions materials to avoid up-front embodied emissions that can never be recovered.

Second, it is important to improve the energy efficiency of most existing buildings (see sidebar, "Buildings and energy demand"). Both imperatives can be addressed by identifying green products and materials that lower or eliminate emissions footprints and by retrofitting energy-efficient solutions that reduce operational emissions.

Given the scale of the economic transition required to decarbonize, companies that lead

Buildings and energy demand

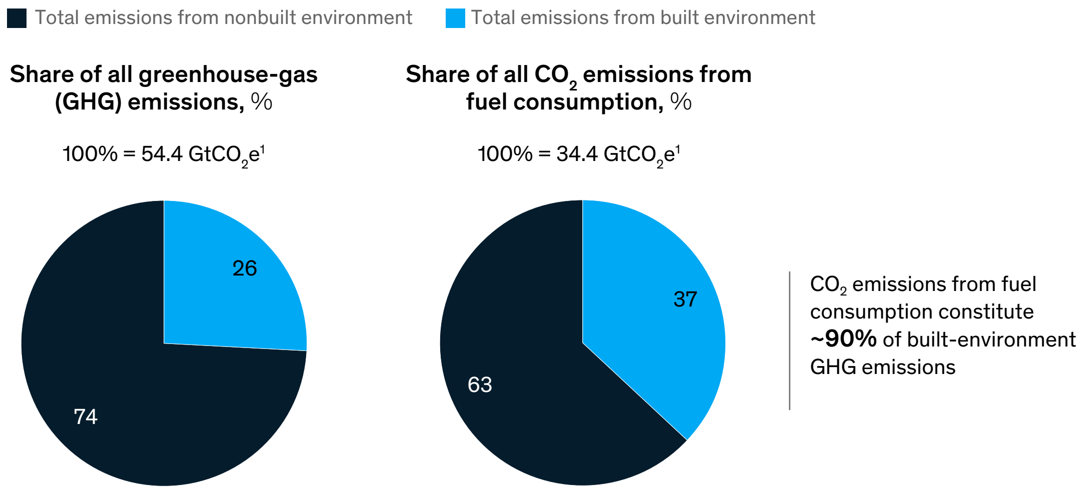
In a decarbonized world, power grids will have the burden of serving the needs of the built environment as well as fully electric automotive fleets. This will require enormous increases in renewable capacity, energy storage, and transmission and distribution infrastructure.

This poses a challenge for the built-environment ecosystem. To eliminate emissions for a given building, electrifying assets such as gas furnaces is an excellent option. However, as adoption of electric assets grows, electric grids will be put under increasing stress. Therefore, companies in the built-environment ecosystem have a strong incentive to not only increase project electrification but also reduce energy consumption. Both of these goals can be achieved by upgrading inefficient processes and technology to options that are more energy efficient.

[1] "Call for action: Seizing the decarbonization opportunity in construction," McKinsey, July 14, 2021.

Exhibit 1

The built environment contributes a significant share of the world's emissions, particularly those related to fuel consumption.



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in sustainability are likely to succeed. Capital markets are expecting companies to take prompt action on decarbonization, and players in the built environment are increasingly setting aggressive targets. There is also significant pressure to decarbonize because of factors such as regulatory requirements, employee needs, and customer demands for environmentally sustainable solutions.

Despite these strong incentives, progress in decarbonizing the built environment has been limited for a variety of reasons. The built environment is complex and fragmented, with different players and business models at every step in the value chain. It is also highly local, with varying standards, building codes, and decision makers—often with partially conflicting objectives. Arrangements are typically project-based, with temporary, nonstandardized agreements. Companies also often operate on small margins and have a limited ability to take risks by investing in new businesses and solutions. And though many levers to decarbonize the built environment are proved, there is a lack of transparency and knowledge about which of these levers are cost-effective today or could be if industrialized.[2]

In light of this urgency and these challenges, finding solutions that meet both abatement and cost requirements is imperative. Many of these solutions and technologies already exist and can drive significant improvements at low (or even negative) net costs.

[2] We define "industrialize" as "to produce and implement a lever at scale with a focus on quality, cost, and time to market."

Finding the solutions that work

Our analysis shows there are many levers available to decarbonize the built environment in a cost-effective manner and meet global emissions targets.

Achieving net-zero emissions for the built environment is a bold endeavor and will require significant investment. While a sizable challenge, there are many pathways with proven technologies and solutions that can get the industry there. A number of these are already cost-effective today.

Emissions baseline and initial lever pool

To assess how effective levers were at abating emissions, we compared them to a global emissions baseline. Of the approximately 14.4 Gt of global emissions contributed by the built environment, approximately two-thirds are operational (related to the daily operations of a building, such as electricity consumption) and one-third are embodied (related to the materials used to build the structure) (Exhibit 2). Roughly three-quarters of operational emissions are attributable solely to residential buildings, while the remaining quarter comes from commercial buildings. Infrastructure contributes little to no operational emissions once constructed. By contrast, embodied emissions are shared roughly equally between residential buildings, commercial buildings, and infrastructure.

Our goal was to identify the levers that could best accelerate near-term decarbonization in the built environment, accounting for their abatement potential, cost-effectiveness, and potential to be industrialized. For our analysis, we focused on proven levers with demonstrated use cases, known or tested abatement potential, and the potential to be applied at scale.

There may be other disruptive solutions with greater abatement potential in development that will be available in the near future. At the time of this report's publication, however, these solutions either did not have established and industry-accepted use cases or had not demonstrated potential to be applied at scale. Therefore, we did not consider them in our analysis. In any case, similarly to the levers we touch on, these solutions would also benefit from investments and resources in the near term to have the potential to scale.

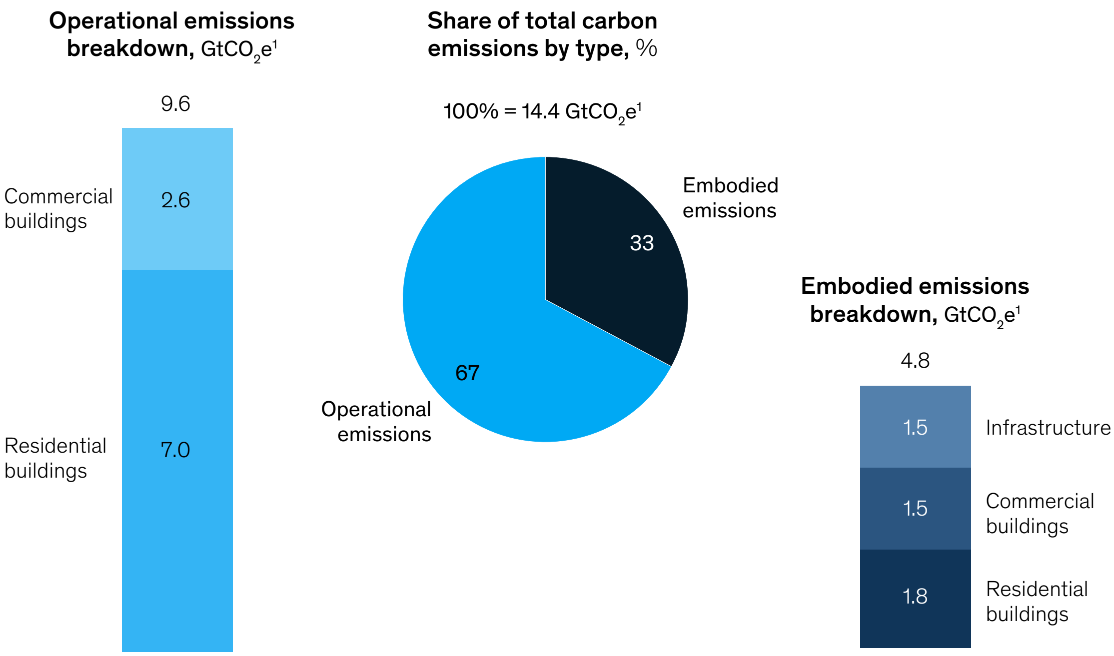
Identifying carbon- and cost-effective levers

Through academic research and input from McKinsey experts and industry leaders, we identified and mapped more than 1,000 decarbonization levers applicable to the built environment. These levers were compared with emissions baselines and systematically analyzed across three main attributes: abatement potential, net cost change today, and net cost change by 2030.

— *Abatement potential* is defined as the potential reduction in emissions for each lever relative

Exhibit 2

Residential buildings, commercial buildings, and infrastructure each contribute to the built environment's emissions.



[1]Metric gigatons of CO_2 equivalent.
Source: "Emissions Database for Global Atmospheric Research (EDGAR) v5.0 (1970-2015)," European Commission, November 2019; "Fuel share of CO2 emissions from fuel combustion, 2018," IEA, October 26, 2022; *Key world statistics 2020*, IEA, August 2020; OECD; Steel Construction Encyclopedia

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to the corresponding emissions baseline. For example, using biomass as an alternative fuel can reduce overall emissions[3] during cement production by up to 40 percent, as compared with an emissions baseline of using a conventional fuel such as coal or petroleum coke.

— *Net cost change today* indicates the estimated cost increase or decrease associated with applying a given lever relative to the cost of the existing or conventional practice that the lever is intended to replace. The net cost comparison considers both capital and operations and maintenance (O&M) costs, including savings from reduced energy consumption.

— *Net cost change based on expected costs in 2030* estimates the cost in 2030 if the lever is produced and installed at scale. Industrialization will reduce input costs through implementing procurement best practices, enabling technicians to gain experience and drive process efficiencies, reducing the capital expenditures per unit by increasing the number of units produced, and decreasing the risk and financing cost because of stable customer demand.

Using these criteria, we narrowed down the list of levers for analysis to around 150 based on impact potential and technological and commercial feasibility. These levers were then classified into

[3] Considering net emissions potentially created from the use of biomass.

four main categories based on their net cost of application:

— *Cost-effective today.* These levers are technically and commercially viable and are cost-neutral or cost-positive today relative to conventional solutions. Assessed on a net cost basis (capital and O&M), these levers are either equal to or less expensive than existing practices. Any up-front additional costs can be recuperated through subsequent savings on O&M, including efficiency savings and utility costs. Many of the operational levers are compared based on total costs as well as on their potential return (such as lower energy costs due to increased energy efficiency). Levers in this category are therefore assessed to be ROI positive.

— *Cost-effective by 2030 or earlier, if industrialized.* These levers are currently technically proved but more expensive than conventional alternatives today. If industrialized, these levers are expected to be commercially viable. Industrialization results in increased scale and process efficiencies, which in turn results in lower unit costs. Therefore, the net expected cost of applying these levers in 2030 could be lower than the expected cost of conventional practices in 2030.

— *Marginally more expensive by 2030, if industrialized.* In this category, levers are technically proved to have a significant impact on emissions but would still be marginally more expensive after industrialization than conventional alternatives. In this case, we define "marginally more expensive" as a net cost increase of up to 5 percent for the given lever based on expected costs by 2030.

— *Significantly more expensive by 2030 or not technically viable.* These levers are either expected to be significantly more expensive than conventional practices in 2030, even if industrialized, or are not expected to be viable for industrialization by 2030 without a significant technological breakthrough. Here, we considered a net cost increase of more than 5 percent for the given lever based on expected costs in 2030.

To be conservative, the net cost analysis does not consider incentives, carbon price changes, or green premiums. We use today's average prices for conventional solutions or commodities, such as steel and cement, and do not factor in significant or unexpected price changes by 2030. If jurisdiction-specific incentives and green premiums are applied, it is possible that several of the marginally or significantly more expensive levers will also be cost-effective by 2030.

Sorting levers for embodied and abated emissions

Once effective levers were identified, they were sorted for ease of analysis and clarity of purpose in the overall construction process.

For embodied emissions, the top levers were categorized into four groups aligned with different phases of the construction process. This allowed for them to be applied sequentially and considered in conjunction with one another, capturing the overall abatement potential of the entire process.

— *Design optimization levers* are applied at the design stage, prior to on-site construction. As the first levers, these have the most cascading effects and can be used to reduce the archetype's overall emissions baseline while reducing costs and schedule extensions. These levers enable simplification of building design due to standardization and efficiency improvements. As a result, smaller quantities of materials are needed, and overall embodied emissions are reduced, both through incorporating green components or processes and through efficiencies resulting from using fewer materials and resources. Design decisions can also affect operational efficiencies of archetypes and can help lower operational emissions.

For embodied emissions, the top levers were categorized into four groups aligned with different phases of the construction process.

- *Material substitution levers* are applied at the preconstruction stage. These levers reduce emissions by replacing traditional materials used in manufacturing or end-products with low-carbon alternatives. By choosing materials that emit less during production or are more locally available, embodied emissions can be avoided. For instance, reducing or replacing clinkers in cement with low-carbon alternatives, often referred to as supplementary cementitious materials (SCMs), has potential to abate emissions.

- *On-site improvement levers* are applied once construction has begun and can reduce emissions stemming from the construction process. For instance, fuel or materials used in the construction process can be substituted with alternative fuels or clean power sources, enabling a reduction in the emissions footprint at this stage.

- *Process decarbonization levers* broaden to encompass the entire construction value chain. They are applied at the material-manufacturing stage and address remaining emissions from conventional materials with larger emissions footprints. Steel and cement, for example, have conventional manufacturing processes that are highly emissive due to the use of fuels such as coal, petroleum coke, and natural gas. Replacing these with proven renewable and low-carbon fuels such as hydrogen and biomass will enable a significantly lower emissions footprint during manufacturing.

Top operational levers were similarly categorized into four groups:

- *Space heating and cooling levers* are ways to more efficiently heat or cool a space with fewer emissions, with the heater either within the space or external to it.

- *Water heating levers* use low-carbon methods to heat water for residential buildings.

- *Cooking levers* enable users to shift from traditional gas cooking appliances to more efficient cooking methods.

- *Appliances and lighting levers* include using more-energy-efficient home appliances and light sources.

Unlike embodied levers, which are typically applied sequentially, operational levers can be applied simultaneously, in some cases to capture additional abatement from synergies between levers. For example, installing energy efficiency measures first can reduce the overall required heat pump capacity and cost. If strategically implemented, the economics of each lever can be improved in this manner.

Applying levers to global archetypes

Finally, to pressure test the levers with the highest impact and demonstrate their applicability, abatement efficacy, and cost-efficiency, we applied them to six common archetypes that we believe represent about three-quarters of the built environment ecosystem: single- and multifamily dwellings, commercial low- and high-rise buildings, industrial buildings (such as manufacturing plants), and infrastructure builds (such as roads and highways).

These chosen archetypes were modeled to span four regions (China, Europe, India, and North America) and three climate zones (cold, warm, and temperate) to capture variations in building codes and standards and in construction and operational practices.[4] For each archetype, we identified the embodied and operational abatement levers that were most impactful and relevant to the archetype.

From our initial pool, we identified 22 levers that could have a particularly strong impact on decarbonization due to their high abatement potential, cost-effectiveness, and applicability across archetypes and regions. To illustrate how we determined which levers were most effective and to offer some examples of selected levers, we provide two case studies in the next chapter.

[4] These regional variations are not the focus of this report, although for some levers, we do address their impact.

Two case studies in decarbonization

Of our six archetype analyses, two illustrative case studies—a multifamily dwelling in North America and a large infrastructure project in Europe—were chosen to provide a detailed view of our approach and demonstrate the range of applicability of decarbonization levers to both buildings and infrastructure.

Multifamily dwellings are common throughout the world and have material compositions that are close to single-family dwellings and commercial buildings. Therefore, the majority of the top operational- and embodied-emission abatement levers applied to this archetype are also applicable to other archetypes.

As for large infrastructure projects and upgrades, they are similarly relevant around the world and will be increasingly important sites of investment and development as populations grow. These two archetypes represent common use cases across the built environment, and, barring regional and jurisdictional differences, results for these can be reasonably scaled and applied across the broader ecosystem.

Archetype 1: Multifamily dwelling in North America in a cold climate

A multifamily dwelling refers to a residential building that houses multiple families, such as an apartment complex. An example of this archetype might be a 5,500-square-meter, five-story building in a cold climate in North America. On average, such a building has an embodied emissions baseline of about 4,000 metric tons, estimated from a material composition and weight baseline of about 13,000 metric tons. Though the cost and abatement potential for specific levers are based on a North American structure, the results and levers we recommend are reasonably applicable to other geographies and climates, with some region-specific nuances.

Top levers to abate embodied emissions

For multifamily residential dwellings, most embodied emissions—about 2,000 metric tons or 50 percent—are driven by concrete, followed by steel, with about 900 metric tons or 22 percent (Exhibit 3).

Of the 1,000 levers assessed, we determined that approximately 50 were relevant to this archetype. Out of these, the top nine alone can abate roughly 81 percent of embodied emissions relative to the current baseline (Exhibit 4).

Top embodied levers for this archetype were classified into the four categories—design optimization, on-site improvements, material substitution, and process decarbonization—and applied sequentially.

Design optimization levers

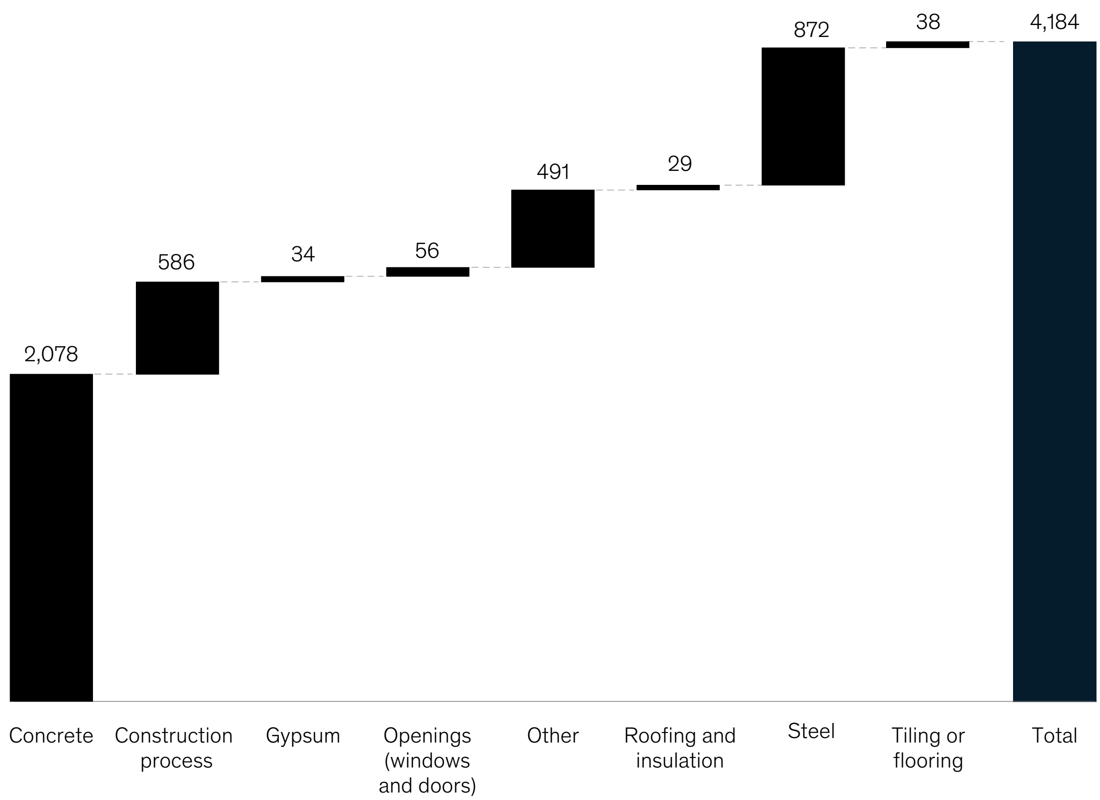
In the design phase, one lever stood out as particularly effective in decreasing embodied emissions:

Increase adoption of design for manufacturing and assembly (DFMA) and off-site construction. This lever explores the manufacturing, planning, design, fabrication, and assembly of building elements at an off-site location, such as a factory or plant.

Exhibit 3

Concrete and steel are the main drivers of embodied emissions for multifamily residential dwellings.

Drivers of emissions breakdown, metric tons



Source: Tsz Kuen Ma and Qingshi Tu, "Bill of materials (BoM) and archetype information for buildings in Canada," UBC Research Data; July 25, 2021; McKinsey analysis

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This enables the speeding up of on-site construction through standardized design. As a result, lower net waste is generated. This has an abatement potential of up to 40 percent of the emissions released during on-site construction due to reduced waste from saving up to 30 percent of construction material as well as fewer truckloads needed to transport building materials to the construction site. Applying this lever for this archetype is expected to save up to 2 percent of total material costs in 2023, making it cost-effective today.[5]

Off-site construction is already widely used in both Europe and Asia but struggles to gain a foothold in North America because of a variety of potential factors, such as increased desire for customization in structures and a reluctance to use a single supplier to provide for all building needs.

[5] Off-site processes (prefab, automated production to create precision pieces) can also help bring down costs of airtight envelope solutions that seal places where heating or cooling may leak from a building. These solutions can retroactively improve energy efficiency of existing structures but are currently expensive.

Exhibit 4

Nine levers can abate most embodied emissions for multifamily residential buildings.

Design optimization | Material substitution | On-site improvements | Process decarbonization

Scenario	Lever	Estimated abatement potential as share of baseline emissions		Total embodied emissions abated, %
Cost effective today	Increase use of DFMA[1] and offsite construction	40%	of equipment and transport emissions	5
	Replace cement with fly ash	30%	of concrete emissions for fly ash	14
	Scale up use of low-carbon insulation	90%	of emissions for insulation	1
Cost effective by 2030 or earlier, if industrialized	Electrify on-site heavy equipment and small generators	90%	of heavy-equipment and small-generator emissions	5
	Electrify production of recycled construction steel	50%	of steel emissions by switch to DRI-EAF[4]	6
Marginally more expensive by 2030, if industrialized	Replace cement with GGBFS[2]	50%	of concrete emissions for GGBFS[2]	2[5]
	Use biomass as alternative fuel	20%	of concrete emissions	6
	Electrify production of recycled construction steel	45%	of steel emissions by using scrap and switching to renewable energy	3
	Augment concrete and steel use with engineered wood	40%	of concrete and steel emissions	30
Significantly more expensive by 2030, if industrialized	Carbon capture in cement production	90%	of concrete emissions	9
			Total	**81%**

[1]Design for manufacturing and assembly.
[2]Ground-granulated blast-furnace slag.
[3]Assuming 25% max addressable baseline by 2030.
[4]Direct reduced iron–electric arc furnace.
[5]Actual GGBFS is 16% but is listed as less the reduction already achieved by fly ash.
Source: "Emissions Database for Global Atmospheric Research (EDGAR) v5.0 (1970-2015)," European Commission, November 2019; "Fuel share of CO2 emissions from fuel combustion, 2018," IEA, October 26, 2022; Key world statistics 2020, IEA, August 2020; OECD; Steel Construction Encyclopedia; Tsz Kuen Ma and Qingshi Tu, "Bill of materials (BoM) and archetype information for buildings in Canada," UBC Research Data; July 25, 2021; McKinsey analysis

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Material substitution levers

Companies can make effective material substitutions by replacing cement with SCMs, scaling up use of low-carbon insulation, and augmenting concrete and steel use with engineered wood.

Replace cement with fly ash. SCMs are used to substitute portland cement in concrete or clinker in cement to make concrete mixtures more economical, reduce permeability, increase strength, and reduce embodied emissions. Examples of SCMs include fly ash, ground-granulated blast-furnace slag (GGBFS), calcined clay, and recycled concrete. For instance, fly ash can be used to substitute up to 30 percent of ordinary portland cement (OPC) in concrete manufacturing. This has an abatement potential of up to 30 percent of overall emissions associated with concrete and is also cost-effective. For a multifamily dwelling, the cost of replacing cement with SCMs is expected to remain consistent with the cost of OPC in most locations, making this lever cost-effective today. By contrast, contractors intending to use fly ash must be careful because it retains moisture longer than OPC and therefore takes longer to dry. Expenditures on equipment and energy used to dry the material (as opposed to drying naturally) could negatively affect cost-savings and abatement potential.

Replace cement with GGBFS. GGBFS, another SCM, is a by-product in ironmaking and can be used to substitute up to 50 percent of OPC cement in concrete or clinker in cement manufacturing. While using GGBFS has an abatement potential of up to 50 percent of overall emissions associated with concrete, its application is expected to increase costs by up to 3 percent of total material costs by 2030.[6]

Because both fly ash and GGBFS are by-products of using coal, the supply of these materials will likely dwindle as coal is phased out. Therefore, other SCMs, such as calcined clay-blended cement and fine-limestone filler, will have an increasingly large role to play in producing green cement.

There are other innovative solutions in the market to produce low-carbon concrete: one example is replacing carbon-intensive cement with lower-carbon industrial waste or other materials; another is CO_2 mineralization to abate approximately 70 to 100 percent of emissions associated with concrete production. Although these solutions are not yet commercially mature, they are likely to be widely available by 2030.

Scale the use of low-carbon insulation. Insulations are used in both home and commercial applications and can be made from conventional materials (such as stone mineral wool, glass mineral wool, or polystyrene), bio-based sources (such as wood fibers, hemp fibers, or cotton fibers), or recycled paper products (such as newspaper or cardboard). Conventional insulation typically has energy-intensive manufacturing processes that can result in a relatively high emissions footprint depending on the technology used.

First, low-carbon conventional insulation can be developed by using an increased proportion of recycled materials in its composition as well as by improving manufacturing processes through electrification, renewable energy, process improvements, and so on to lower fossil-fuel and energy use. This can abate emissions associated with the production of conventional insulation by up to 90 percent and can be relatively cost-neutral. Second, using recycled paper–based insulation (such as blown-in cellulose) has the potential to abate emissions associated with the production process by up to 90 percent. Applying this lever for this archetype is expected to be cost comparable to conventional insulation, making it cost-effective today. And third, using natural-fiber insulation can also abate emissions associated with the production process by up to 90 percent, though the cost of materials is likely too high today for this to be feasibly scaled in the near future. If industrialized, however, natural-fiber insulation could present a financially attractive opportunity, reducing overall costs to be comparable to the costs of conventional insulation, making it cost-effective by 2030.

While reducing embodied emissions for insulation is important, it is only one aspect of how insulation affects the environment. Most insulation, regardless of what material is used, can reduce the operational emissions of a building by reducing energy use for heating and cooling. Therefore, it is critical to consider the full life cycle of emissions for insulation materials when making choices about their design, material, and production to avoid suboptimal outcomes such as shorter life cycles and inadequate thermal performance, among other potential negative effects.

Augment concrete and steel use with engineered wood. Though most of the concrete used in foundations and infrastructure cannot be

[6] The cost of GGBFS and fly ash is highly dependent on regional availability. Where both materials are plentiful, they are often similar in price. As use of coal continues to dwindle in steel manufacturing and power plants, both materials will likely become difficult to source. However, there is a large quantity of fly ash that is already produced and stored, which should keep prices lower for longer.

replaced, there are proven designs for residential and commercial buildings that enable replacing a significant portion of concrete and steel in construction with engineered wood. An example of engineered wood that can be used is cross-laminated timber (CLT), which is a large-scale, prefabricated, solid-engineered wood panel that is both lightweight and strong. Another example of engineered wood is glue-laminated timber (glulam), which consists of layers of dimensional lumber bound together with durable, moisture-resistant structural adhesives.

These and other products, such as laminated veneer lumber (LVL) and mass ply panel (MPP), have many different applications in the engineered-wood space. Innovations in material use and production continue to progress, and new products are made available each year. Each of these can be evaluated for their sustainable sourcing strategy, performance attributes, and waste created during production.

By reducing the use of concrete and steel and substituting it with engineered wood in this archetype, it is possible to abate the embodied emissions associated with these materials. Given the existing emissions baseline for steel and concrete, use of engineered wood has an abatement potential of up to 40 percent but is currently limited by resource availability. Applying this lever for this archetype is expected to increase costs by up to 1 percent of total material costs by 2030, making it marginally more expensive by 2030, if industrialized.

On-site improvement levers

Once construction moves on-site, multifamily dwellings can substantially decarbonize with the following lever:

Electrify on-site heavy equipment and small generators. Using electric construction equipment instead of internal-combustion-engine (ICE) equipment has an abatement potential of up to 90 percent for heavy-equipment emissions, assuming the use of renewable electric sources. The abatement this lever achieves is a result of reducing fossil-fuel usage. Applying this lever for this archetype is expected to be cost-neutral by 2030—that is, not contributing any material cost. As such, this lever could be cost-effective by 2030, if industrialized.

Primary process decarbonization levers

Among the process decarbonization levers that were successfully applied to this archetype, three stood out: utilizing biomass[7] as alternative fuel; upgrading and electrifying production of recycled construction steel; and carbon capture, utilization, and storage (CCUS) in cement production.

Utilize biomass as alternative fuel. Replacing coal used in cement production with biomass as the primary fuel can enable abatement of up to 20 percent of emissions during cement production. Applying this lever for this archetype is expected to increase costs by up to 1 percent of total material costs by 2030, making it marginally more expensive by 2030, if industrialized. Biomass is already widely used in many parts of the world but has struggled to gain a foothold in North America. Easy access to relatively inexpensive natural gas likely limits the appetite to fully explore biomass as an alternative fuel source in this geography.

Upgrade and electrify production of recycled construction steel. The original method of modern steel production is to use blast furnaces, which heat purified coal, limestone, and iron ore. The mixture is then injected with oxygen to diminish the carbon content and remove impurities before finished steel is produced. Arc furnaces, on the other hand, produce steel using mainly recycled steel and electricity. Switching to an arc furnace has an abatement potential of up to 50 percent of overall steel emissions for blast furnace–basic oxygen furnace (BF-BOF) producers. Additional actions, such as primarily using scrap steel and switching to a renewable energy source to operate the arc furnace can reduce emissions by an additional 45 percent, for a total of 95 percent reduced emissions. Applying this lever for this archetype is expected

[7] Waste that is derived from organic plant or animal sources.

Using the levers that are expected to be cost-effective by 2030 could abate nearly one-third of embodied emissions for this archetype.

to be cost-neutral by 2030 for BF-BOF producers, with increased efficiencies from the furnace offsetting higher costs in energy.

For producers already using direct reduced iron–electric arc furnace (DRI-EAF) technology, using scrap steel as the primary input and switching to a renewable energy source has an abatement potential of up to 45 percent of overall steel emissions. Applying this lever for this archetype is expected to increase costs by up to 3 percent of total material costs by 2030 for DRI-EAF producers. As such, this could be marginally more expensive by 2030, if industrialized.

Capture carbon in cement production. This lever relies on capturing and absorbing the CO_2 created in the cement production process using a chemical solvent, which is typically amine-based, such as compounds of ethanolamine. Other technologies include solid ab- or adsorption, membrane ab- or adsorption, and oxyfuel combustion. If optimally implemented, carbon capture has an abatement potential of up to 90 percent[8] of emissions associated with cement production. However, applying this lever for this archetype is expected to increase costs by up to 15 percent of total material costs by 2030, making it significantly more expensive by 2030.

Based on our analysis, using the levers that are either cost-effective today or expected to be cost-effective by 2030 could abate nearly one-third of embodied emissions for the multifamily residential archetype (Exhibit 5).

Top levers to abate operational emissions

Total operational emissions for an average multifamily residential building in North America are approximately 2.2 metric tons of CO_2 annually, with most emissions being driven by space heating (approximately 1.1 metric tons or 50 percent) and water heating (approximately 0.5 metric tons or 22 percent) (Exhibit 6).

Of the 1,000 levers assessed, 11 levers were found to be most relevant in this specific case (Exhibit 7). Applying these levers to the multifamily residential archetype, we see that the top 11 levers can enable abatement of up to 90 percent of operational emissions relative to its current baseline, given 100 percent renewable electricity from off- and on-site sources.

Nine of these levers are explored below. Top operational levers for this archetype were categorized into four groups: space heating and cooling, water heating, cooking, and appliances and lighting.

Space heating and cooling levers

In the space heating and cooling category, technologies such as heat pumps,[9] smart thermostats, and high-efficiency insulation can effectively decrease operational emissions. We expand on five of these levers below:

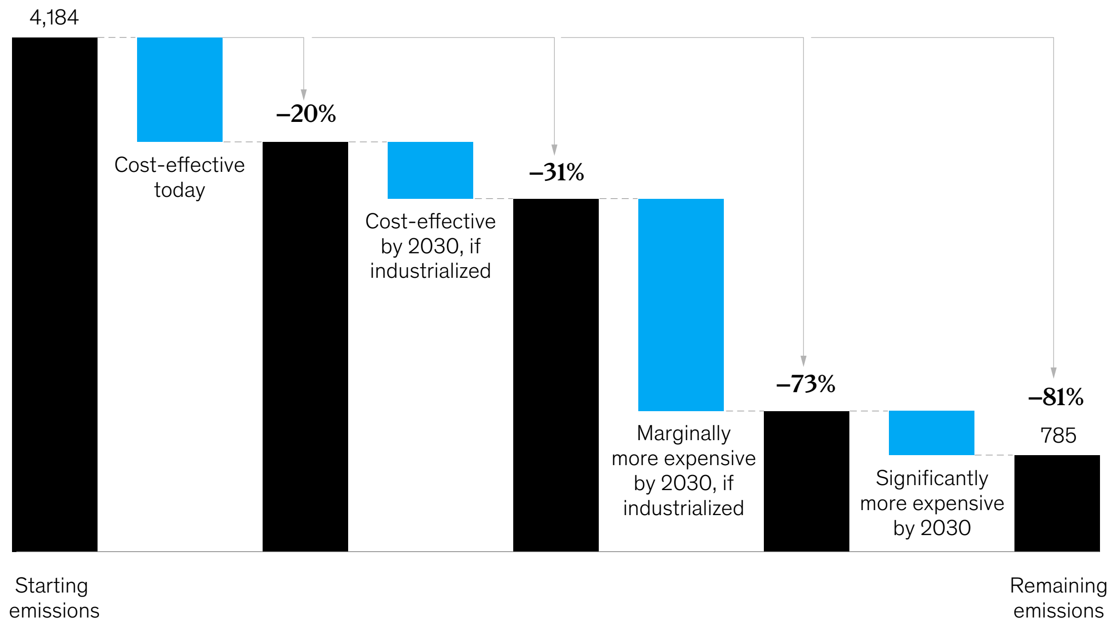
[8] Referring to a baseline of all direct emissions (Scope 1) in cement production, such as those that arise from chemical reactions as well as fuel combustion.

[9] Although we do not explore the embodied emissions associated with the production of heat pumps, it is important to discuss the use of refrigerants. Natural refrigerants (CO_2, ammonium, and ammonia) and hydrofluoroolefins (HFO) are associated with greatly reduced emissions, compared with hydrofluorocarbons, the most used type of refrigerant, and should be used whenever safe design allows. Proper installation and observation of operational best practices should also help prevent leakage of refrigerants and unintended emissions. In addition, existent heat pumps containing more emissive refrigerants could be retrofitted or replaced with less emissive refrigerants.

Exhibit 5

Embodied emissions for multifamily residential dwellings could be reduced by roughly 30 percent just by using levers that are cost-effective.

Embodied carbon abatement potential (at scale), metric tons of CO_2e[1]



Note: Figures do not sum to 100%, because of rounding.
[1]CO_2 equivalent.
Source: "Fuel share of CO_2 emissions from fuel combustion, 2018," IEA, October 26, 2022; *Key world statistics 2020*, IEA, August 2020; OECD; Steel Construction Encyclopedia; "Emissions Database for Global Atmospheric Research (EDGAR) v5.0 (1970-2015)," European Commission, November 2019; Tsz Kuen Ma and Qingshi Tu, "Bill of materials (BoM) and archetype information for buildings in Canada," UBC Research Data; July 25, 2021; McKinsey analysis

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Use heat pumps for heating. As previously mentioned, heat pumps use refrigerant and electricity to transfer heat from outdoor air or the ground to the inside of a building, even in colder temperatures.[10] According to prior research by McKinsey, today's models are 2.2 to 4.5 times more efficient than gas furnaces.[11] Applying this lever to this archetype has the potential to abate up to 60 percent of emissions associated with space heating. This lever is ROI positive today.

Use heat pumps for cooling. Heat pumps can similarly be used for cooling purposes. They are built with reversing valves which makes it possible to change the direction of heat transfer. Applying this lever to this archetype has the potential to abate up to 10 percent of emissions associated with space cooling. This lever is ROI positive today.

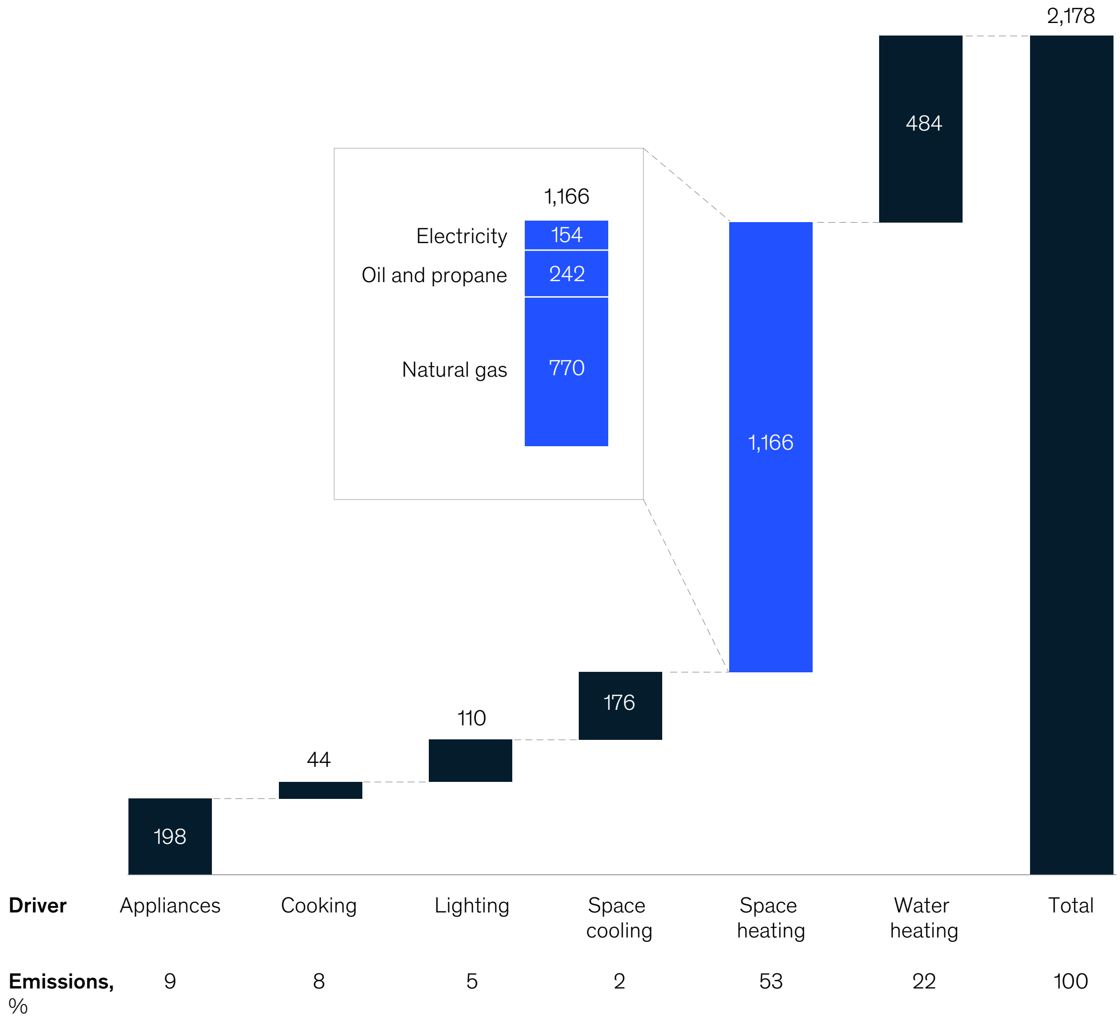
Use smart thermostats. Smart thermostats are part of a building's energy-management system. Using heat pumps in combination with smart thermostats can help lower GHG emissions

[10] "Building decarbonization: How electric heat pumps could help reduce emissions today and going forward," McKinsey, July 25, 2022.
[11] Tom Hellstern, Kimberly Henderson, Sean Kane, and Matt Rogers, "Innovating to net zero: An executive's guide to climate technology," McKinsey, October 28, 2021.

Exhibit 6

Most operational emissions in multifamily homes are caused by water and space heating.

Emissions breakdown, kg CO_2 per dwelling annually



Note: Figures do not sum to 100%, because of rounding.
Source: McKinsey Real Estate Climate Action Platform

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significantly, saving on heating and cooling costs. Applying this lever to this archetype has the potential to abate up to 10 percent of overall space heating and cooling emissions. This lever is ROI positive today.

Improve buildings with high-efficiency insulation. High-efficiency insulation, regardless of the type of material used (conventional or natural-fiber), can improve building energy efficiency. Operational emissions abated over the lifetime of this archetype through the use of high-efficiency

Exhibit 7

Eleven levers have the potential to abate 90 percent of total operational emissions in multifamily homes.

Space heating | Water heating | Cooking | Appliances and lighting

Scenario	Lever	Estimated abatement potential as share of baseline emissions[1]
ROI positive today and by 2030	Use heat pumps for heating	60% of space heating emissions
	Use heat pumps for cooling	10% of space cooling emissions
	Improve buildings with high-efficiency insulation	30% of space heating and cooling emissions
	Utilize smart thermostats	10% of space heating and cooling emissions
	Heat water using heat pumps	60% of water heating emissions
	Use induction cooking	30% of cooking emissions
	Use high efficiency appliances	20% of appliance emissions
	Use refrigerators with ENERGY STAR ratings	20% of appliance emissions
	Use LED and smart lights	90% of lighting emissions
Marginally more expensive by 2030, if industrialized	Use high-efficiency heat pumps for cold climate	40% of space heating emissions
Significantly more expensive by 2030, if industrialized	Install new district heating facilities	100%[2] of concrete and steel emissions

[1]Assuming 2019 US grid. Heat pumps, water heaters, induction cooking, high-efficiency appliances, and LED and smart lights would abate 100% if the US grid became 100% renewable-based. Abatement potentials assume no interaction with other levers. Applying a combination of levers in parallel or in sequence will affect the abatement calculations.
[2]Assumes 100% clean steam generation at high capital expenses. Abatement potential may vary based on regional fuel mix of steam generation heat.
Source: McKinsey Real Estate Climate Action Platform

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insulation can often outweigh the emissions footprint associated with the production of conventional insulation. Lowering a building's embodied emissions with low-carbon, high-efficiency insulation also increases operational effectiveness through reduced use of energy and a lower emissions footprint. Some types of conventional insulation materials also tend to have better thermal performance relative to natural-fiber insulation. Applying this lever to this archetype has the potential to abate up to 30 percent of remaining space heating emissions. This lever is ROI positive today.

Install new district heating facilities. District systems reduce greenhouse emissions by heating multiple buildings with hot water from a central plant. Applying this lever to this archetype can abate up to 100 percent of remaining space heating emissions. However, given the realities of current urban planning in North America, it is unlikely this efficiency can be captured. For countries in the Middle East and for Singapore, however, this is a lever that can be considered.

Emissions from water heating can be most effectively abated by using alternative heating technologies, particularly heat pumps.

Water heating levers
Emissions from water heating can be most effectively abated by using alternative heating technologies, particularly heat pumps:

Heat water using heat pumps. Heat pumps can be used to heat water, either as a stand-alone water heating system or as a combination water heating and space conditioning system. Applying this lever to this archetype has the potential to abate up to 60 percent of overall water heating emissions (with an annual baseline of 0.5 metric tons of CO_2e). These are the emissions that arise from using traditional water heating methods. This lever is ROI positive today.

Cooking levers
For cooking, replacing gas stoves with induction cooktops can reduce a sizeable proportion of emissions:

Use induction cooking. This is a method of cooking that uses a copper coil underneath the cooking surface to generate electromagnetic energy. Thus, instead of burning methane gas and emitting GHGs such as CO_2, induction stoves run on electricity, which can be generated from clean, emission-free sources. Applying this lever to this archetype has the potential to abate up to 30 percent of overall cooking emissions. This lever is ROI positive today.

Appliances and lighting levers
Many types of readily available technology can significantly reduce emissions in this category. Below, we explore two such levers:

Use LED and smart lights. Replacing traditional light bulbs with more-efficient LEDs plus smart capability has significant potential to reduce emissions. In a given application, LEDs normally use less power compared to traditional light sources such as halogen and fluorescent. Because the overall kilowatt-per-hour consumption is less, this helps reduce overall CO_2 emissions. Applying this lever to this archetype has an abatement potential of up to 90 percent of overall lighting emissions. This lever is ROI positive today.

Use refrigerators with ENERGY STAR ratings. Replacing traditional refrigerators with ones that have earned the ENERGY STAR label has the potential to reduce CO_2 emissions by more than four metric tons[12] over the lifetime of the product. Applying this lever to this archetype has an abatement potential of up to 20 percent of overall refrigeration emissions. This lever is ROI positive today.

Using only the levers across the four categories that are ROI positive today and expected to be ROI positive by 2030 if industrialized, it is possible to

[12] ENERGY STAR is a program run by the US Environmental Protection Agency and US Department of Energy to promote energy efficiency. It is used in the United States, Canada, Japan, Taiwan, and Switzerland. Other geographies may have similar regionally-specific programs. For more, see Energystar.gov.

abate roughly 70 percent of operational emissions for the multifamily residential archetype (Exhibit 8). Thus, multifamily residential buildings and other similar archetypes can get most of the way to net-zero emissions while generating a positive ROI.

Archetype 2: Large infrastructure project in Europe in a cold climate

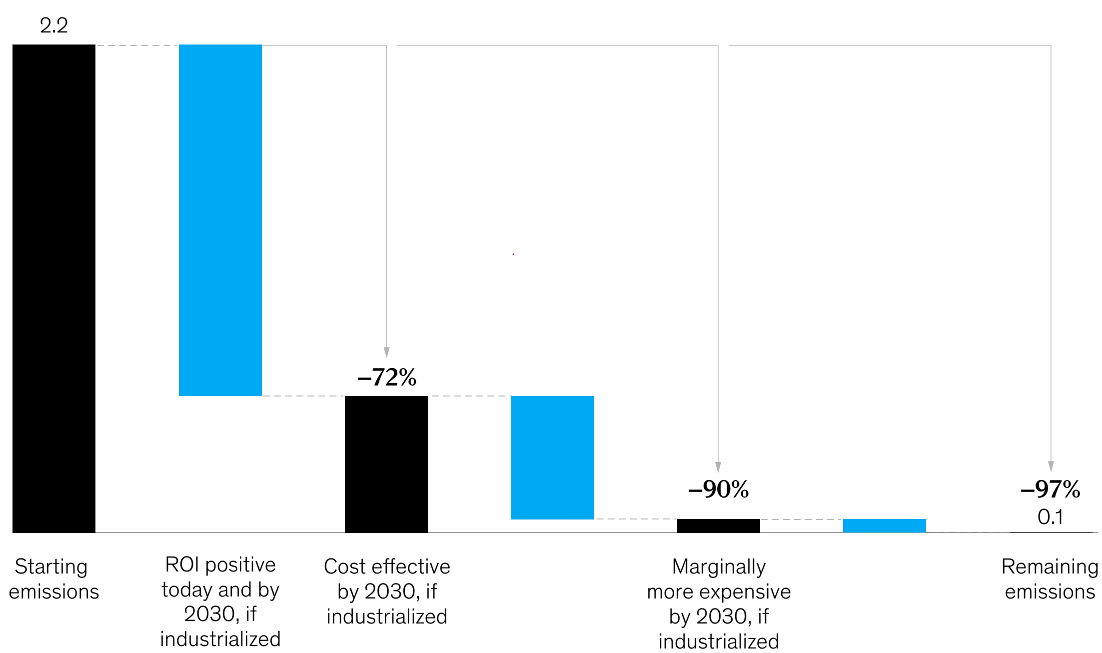
Large infrastructure projects are typically related to infrastructure assets such as roads, bridges, or ports. For this analysis, we considered a road network project in Europe as our baseline. This infrastructure project was estimated to have an embodied emissions baseline of approximately 1.2 million to 1.5 million metric tons, estimated from a material composition and weight baseline of about 7.0 million metric tons. Maintenance and repair of infrastructure typically constitutes a relatively small portion of overall emissions and is included in the baseline for this archetype.

Though the cost and abatement potential for the levers applied are based on a European infrastructure project, the results are mostly valid for other regions, with some nuances. Therefore, the recommended levers are reasonably applicable for infrastructure archetypes in other geographies and climates.

Exhibit 8

For multifamily dwellings, the expected abatement of operational emissions against today's baseline is up to 97 percent across the four cost scenarios.

Operational (Scope 1) carbon abatement potential for an average multifamily dwelling, kg CO_2 per year



Note: Figures may not sum, because of rounding.
Source: McKinsey Real Estate Climate Action Platform

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To assess the composition of the archetype, we developed an emissions baseline rooted in the project's embodied emissions. Since operational emissions directly associated with this infrastructure archetype would be low or negligible (other than the transportation-related emissions from vehicles using the roads), these were not considered for evaluating abatement potential. In addition, there are many potential levers for the transportation industry to use to decarbonize emissions related to the use of infrastructure (such as transitioning fuel-operated fleets to electric vehicles [EVs]). However, because these emissions are not considered to be part the built environment, the corresponding decarbonization levers are not the focus of this report.

Top levers to abate embodied emissions

The embodied emissions baseline for a large infrastructure project was estimated to be about 1.2 million to 1.5 million metric tons of CO_2, with most emissions driven by steel (about 30 percent) and concrete (about 25 percent) (Exhibit 9).

We assessed more than 70 levers and classified them into the same four categories as the previous archetype: design optimization, on-site improvements, material substitution, and process decarbonization (Exhibit 10). Applying these levers to the infrastructure archetype, we see that the top nine levers can enable abatement of up to 55 percent of embodied emissions relative to its current baseline.

Design optimization levers

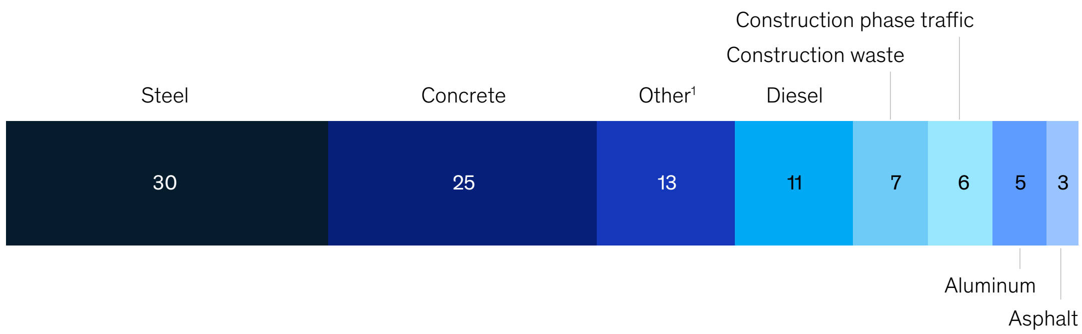
For large infrastructure projects, value engineering can reduce demand for both concrete and steel in the following ways:

Value engineering to decrease concrete demand. Concrete manufacturing is the second-largest contributor of embodied emissions for this archetype, contributing about 300,000 metric tons of CO_2e to overall emissions during construction of a structure that weighs approximately seven million metric tons. Value engineering, such as better structural design, has been proved to

Exhibit 9

Most emissions in an average large infrastructure project are driven by materials and fuel; the rest come from construction and logistics.

CO_2 emissions breakdown by driver, %



[1]Includes soil and fill, additional materials for risk mitigation, and other costs associated with construction.
Source: "Emissions Database for Global Atmospheric Research (EDGAR) v5.0 (1970-2015)," European Commission, November 2019; "Fuel share of CO2 emissions from fuel combustion, 2018," IEA, October 26, 2022; *Key world statistics 2020*, IEA, August 2020; OECD; Steel Construction Encyclopedia; McKinsey analysis

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Exhibit 10

More than 50 percent of embodied emissions in an average large infrastructure project can be abated with nine levers.

Design optimization | Material substitution | On-site improvements | Process decarbonization

Scenario	Lever	Estimated abatement potential as share of baseline emissions		Total embodied emissions abated, %
Cost effective today	Value engineering to decrease concrete demand	2%	of all concrete emissions	1
	Value engineering to decrease steel demand	2%	of all steel emissions	2
	Replace aggregate in asphalt with recycled concrete aggregate and replace bitumen in asphalt with lignin	40%	of all asphalt emissions	1
	Electrify heavy equipment	7%	of all heavy-equipment emissions	1
Cost effective by 2030 or earlier, if industrialized	Use inert anode to reduce emissions from anode breakdown and switch to green electricity in aluminum smelter	30%	of all aluminum emissions[1]	4
Marginally more expensive by 2030, if industrialized	Use renewable natural gas as fuel for heavy equipment	23%	of all heavy-equipment emissions	3
	Use biomass as alternative fuel	20%	of concrete emissions[1]	6
	Upgrade and electrify production of recycled construction steel	50%	of steel emissions by switch to DRI-EAF[2]	26
		45%	of steel emissions by using scrap and switching to renewable energy	
Significantly more expensive by 2030, if industrialized	Carbon capture in cement production	90%	of concrete and steel emissions	11
			Total	55%

[1]Assuming 25% max addressable baseline by 2030.
[2]Direct-reduced iron electric-arc furnace.
[3]Assuming 25% max addressable baseline by 2030.
Source: "Emissions Database for Global Atmospheric Research (EDGAR) v5.0 (1970-2015)," European Commission, November 2019; "Fuel share of CO2 emissions from fuel combustion, 2018," IEA, October 26, 2022; *Key world statistics 2020*, IEA, August 2020; OECD; Steel Construction Encyclopedia; McKinsey analysis

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result in significant concrete savings through lean construction. Lean construction refers to the process of designing production systems in a construction environment with the goal of decreasing material waste. It is estimated that up to 5 percent of concrete can be saved through value engineering, specifically by single-shell tunnel construction methods, which effectively minimize the use of concrete. It is expected to reduce costs by up to 1 percent of total material costs, making this lever cost-effective today.

Value engineering to decrease steel demand. Steel manufacturing is the largest contributor of embodied emissions for this archetype, contributing approximately 30 percent of overall emissions during construction. Better structural design through lean construction can result in significant steel savings that can lower emissions. According to research published by McKinsey,[13] prioritizing efficiency in construction materials and design is a no-regret move that would lower both material and construction costs. By implementing single-shell construction methods, we estimate that 5 percent of steel can be saved. Similarly to value engineering to decrease concrete demand, this lever is expected to reduce material costs by up to 1 percent and is cost-effective today.

Material substitution levers

Infrastructure projects can be decarbonized by using less-emission-intensive materials, as in the following levers:

Replace aggregate in asphalt with recycled concrete aggregate, and replace bitumen in asphalt with lignin. Asphalt production is a significant driver of embodied emissions, contributing 35,000 to 40,000 metric tons of overall emissions during construction of an average large infrastructure project. By recycling concrete and using the resulting aggregate—recycled concrete aggregate, or RCA—in asphalt, producers can reduce their GHG emissions, among other environmental benefits. Replacing bitumen, the traditional binder in asphalt, with lignin can also lower GHG emissions. Lignin can be produced at much lower temperatures than bitumen, so much less energy is required in its manufacturing process. By applying this lever, it is possible to abate up to 40 percent of overall emissions associated with asphalt production. Applying this lever for this archetype is expected to save up to 1 percent of total material costs, making this lever cost-effective today.

On-site improvements levers

Two levers for on-site improvements prove particularly effective for this archetype:

Electrify heavy equipment. The use of electrified equipment will necessitate the additional installation of mobile-charging infrastructure, but with this lever, it is possible to abate up to 7 percent of all heavy-equipment emissions. This lever is applicable to one-third of crawler cranes, 1,000-metric-ton cranes, piling rigs, and continuous flight auger (CFA) crawler-mounted rigs. Although leasing electrified heavy equipment from vendors can result in an increase of 10 percent in lease prices, the price of fuel consumption can decrease by up to 60 percent. Combined, these factors result in an expected reduction in material costs of up to 1 percent, making this lever cost-effective today.

Use renewable natural gas as fuel for heavy equipment. Renewable natural gas (RNG), or biogas, is produced by anaerobically decomposing organic material. Leasing liquefied natural gas– and RNG-capable equipment from vendors can lead to an estimated 20 percent increase in lease price and a 50 percent increase in fuel consumption price. At the same time, applying this lever can abate an additional 23 percent of all heavy-equipment emissions when it is applied with the previous lever, for a combined total of 30 percent of heavy-equipment emissions. This lever is applicable to all equipment. Applying this lever for this archetype is expected to increase costs by up to 3 percent of total material costs by 2030. Thus, we categorize this lever as marginally more expensive by 2030, if industrialized.

[13] "Net-zero steel in building and construction: The way forward," McKinsey, April 28, 2022.

Both archetypes have significant embodied emissions, but the potential to abate embodied emissions varies between them.

Primary process decarbonization levers
Among effective process decarbonization levers, one is uniquely applicable to this archetype:

Use inert anodes to reduce emissions from anode breakdown and switch to green electricity in aluminum smelter. Aluminum production is a significant driver of embodied emissions, contributing roughly 5 percent of CO_2 to overall emissions during infrastructure construction. The smelting of aluminum during production is a highly energy-intensive electrolytic process that relies on passing electric energy through an anode that is dipped into an iron vessel containing aluminum oxide. This releases molten aluminum that can be further processed. By replacing standard carbon anodes with inert, nonconsumable materials, such as ceramics or alloys, emissions from this smelting process can be reduced by preventing the formation of CO_2 and only releasing pure oxygen as a by-product. Applying this lever to this archetype has an abatement potential of up to 30 percent of overall emissions associated with aluminum. However, it is also expected to increase costs by up to 0.5 percent of total material costs by 2030, making it marginally more expensive by 2030, if industrialized.

In addition, three other process decarbonization levers are as effective in the large infrastructure archetype as they are in the multifamily dwelling archetype: utilizing biomass as alternative fuel, upgrading and electrifying production of recycled construction steel, and using carbon capture in cement production.

Using only the levers that are cost-effective today and expected to be cost-effective by 2030 if industrialized across the four categories, it is possible to abate roughly 10 percent of embodied emissions for this archetype (Exhibit 11).

Overall takeaways
By comparing these two archetypes, we can see a number of important findings.

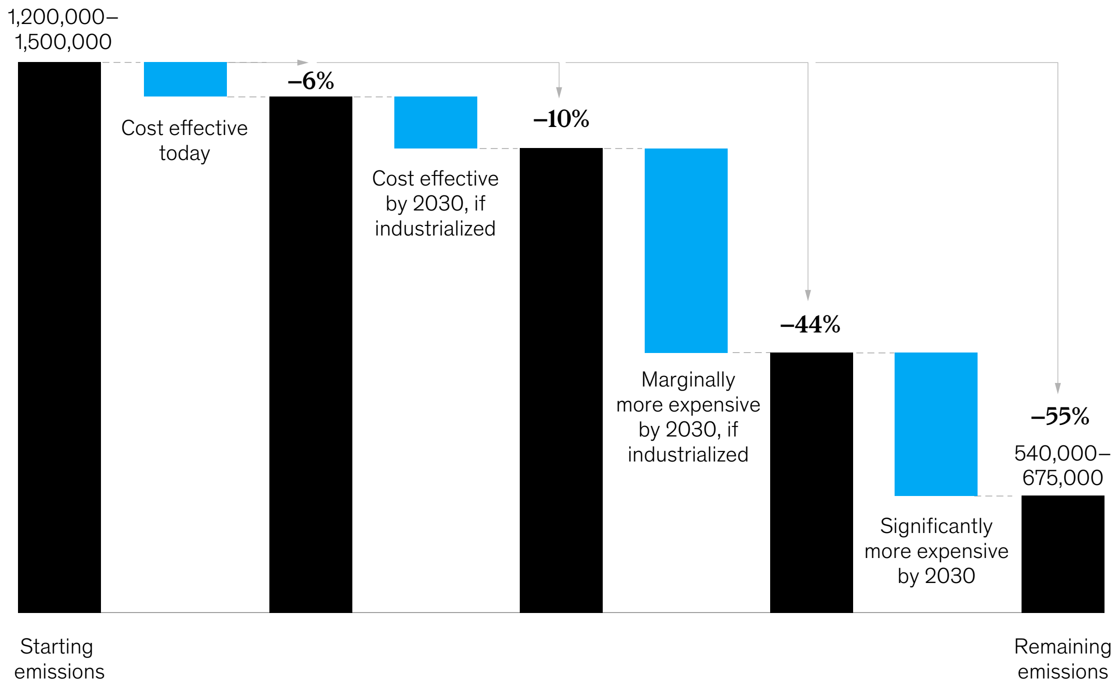
Both the multifamily dwelling archetype and the large infrastructure project archetype have significant embodied emissions, but the potential to abate embodied emissions varies between them. For the multifamily dwelling, it is possible to abate about one-third of all embodied emissions by using levers that are cost-effective today and expected to be cost-effective by 2030. On the other hand, for the large infrastructure project, it is possible to abate approximately 10 percent of all embodied emissions by applying similar levers. This is primarily due to the different material makeup and scale of these archetypes: the infrastructure project has a greater composition of materials (such as cement and steel) that are much more challenging to abate, and it requires substantially larger and more emissive machinery during construction.

Still, the levers outlined above represent a real opportunity to lower the overall embodied emissions of the built environment. Recall that embodied emissions represent close to one-third of all built-environment emissions. Given that infrastructure represents about one-third of all embodied emissions, with the other two-thirds coming from residential and commercial buildings, this would indicate that (using a weighted average) it is possible to abate close to 10 percent of overall emissions associated with the built environment by applying embodied-emissions levers that are cost-effective today or expected to be cost-effective by 2030.

Exhibit 11

Approximately 10 percent of emissions from large infrastructure projects can be abated with levers that are ROI positive today or expected to be by 2030.

Embodied carbon abatement potential (at scale), metric tons of CO_2e[1]



[1] CO_2 equivalent.

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Operational emissions provide another informative point of comparison between these two archetypes. As noted above, large infrastructure projects are considered to not have operational emissions, whereas about two-thirds of the total emissions of the multifamily dwelling are operational. It is possible to abate roughly 70 percent of all operational emissions for the multifamily dwelling by using levers that are ROI positive today and expected to be ROI positive by 2030. These figures can be extrapolated to other residential and commercial building archetypes. Considering that operational emissions represent about two-thirds of all built-environment emissions and that residential and commercial buildings represent close to 90 percent of all those emissions, there is significant opportunity to abate close to 40 percent of overall emissions associated with the built environment by applying operational-emissions levers that are ROI positive today or expected to be ROI positive by 2030.

Our analysis draws attention to many of the most impactful levers to decarbonize the built environment. However, there are other mechanisms and solutions with potential to increase the impact of these levers but that are either cost-prohibitive or face barriers to industrialization. One such mechanism is circularity in the materials value chain—that is, redesigning, reducing, and repurposing structures and materials to increase decarbonization. Such circular technologies include alternative fuels, carbon curing, and more. If these technologies are scaled, they could help to decarbonize roughly 80 percent of cement and concrete emissions by 2050.[14] Based on our estimates and expected carbon prices, each of these technologies is expected to be value-positive by 2050 but face challenges in scaling and industrializing in the near to medium term.

[14] "The circular cement value chain: Sustainable and profitable," McKinsey, March 6, 2023.

Business opportunities with a potential to generate significant value

Unlocking barriers and accelerating the adoption of abatement technology can potentially fuel hundreds of billions of dollars' worth of business opportunities across the value chain.

There are multiple pathways to cost-effective decarbonization for the built environment. The world could abate up to half of total emissions at no net cost and without any green premiums or other incentives. Many levers discussed in the previous chapter, such as heat pumps and smart thermostats, are economically and technically viable today. However, some levers, such as utilizing biomass as an alternative fuel, need industrialization to achieve no net cost. By scaling levers that are not yet cost-effective through industrialization, an even larger share of total emissions could be abated in the following years—up to 80 percent.

The push for deep renovations of existing buildings in the European Union gives a sense of the size of the opportunities. The European Union's Fit for 55 targets for deep renovation encourage individuals and organizations to improve heating and cooling efficiency, which could be done by updating windows and walls, roofs, and basement insulation, for instance.[15] To reach these goals, the Buildings Performance Institute Europe (BPIE), a not-for-profit organization, estimates that the rate of renovations may need to increase 15 times the current average of 0.2 percent.[16] This could increase the insulation service sector to about 1.5 million workers and to a total potential market size in the European Union of $175 billion by 2030.

Accelerating adoption and removing current barriers to adoption can fuel hundreds of billions of dollars' worth of business opportunities across the value chain in producing, distributing, or building with these materials and technologies. Large-scale adoption of these levers would require unlocking structural, geographic, value chain, and skill barriers, as well as specific barriers such as investment flow and technology advancement.

Creating a more collaborative ecosystem

For most opportunities to be fully realized, collaboration among ecosystem players will likely be critical. First, established or existing players could expand their offerings to produce new materials, technologies, or services. We call such companies solution providers. Second, solution providers could benefit from real estate owners and investors, developers, construction companies, or other users committing to adopting their products and services at a significant scale. Third, financiers would likely have to invest in scaling production, deployment, and adoption, such as by financing asset owners to pay for retrofits and new technology. Together, this ecosystem can serve as the driving force to get new green materials, technologies, and services operational and cost-effective.

Although creating this ecosystem may appear daunting, the demand, capital, and producers exist

[15] "'Fit for 55': Council agrees on stricter rules for energy performance of buildings," European Council, October 25, 2022.
[16] "Refurbishing Europe: Igniting opportunities in the built environment," McKinsey, February 28, 2023.

today. As we have already discussed, many levers are cost-effective today or could be soon, making them ideal targets for launching and scaling.

Ecosystem players have an opportunity to generate value and, at the same time, contribute to the net-zero transition. While some of these opportunities can be captured in isolation, most are likely to require new ways of collaboration. Moreover, industrialization is not a zero-sum game; partnerships across the value chain, even among competitors, stand to benefit the entire ecosystem. To accelerate production of new technology and materials in today's fragmented ecosystem, partnerships can enable scale to achieve financial viability and make unit costs commercially comparable to conventional solutions. Partners can also share the burden of testing and evaluating new solutions across peers while simultaneously reducing the individual risk for peers adopting industry-wide solutions requiring significant investments.

In these promising times, players have the opportunity to act to accelerate what is cost-effective now and industrialize what will be cost-effective by 2030. Out of all the business opportunities we have analyzed across every archetype, we focus on the largest 17 discrete opportunities, each of which could have significant value potential (Exhibit 12). The business opportunities we examine are by no means exhaustive, but by focusing on these 17, ecosystem players would be likely to make the most impact on lowering emissions and decarbonizing the built environment.

1. Industrialize production of green materials

Existing production processes for construction materials, such as cement and steel, are highly emissive. Opportunities in this space include decarbonizing production processes for existing materials and increasing the production of new green-material alternatives, such as low-carbon insulation and engineered wood.

Produce low-carbon cement with new or retrofitted cement plants

There are several decarbonization business opportunities for cement manufacturers, the first of which has to do with the cement production process. Fossil-fuel combustion (primarily coal) is used to fuel the precalciners and kilns in cement plants. This represents approximately 40 percent of cement production emissions.[17]

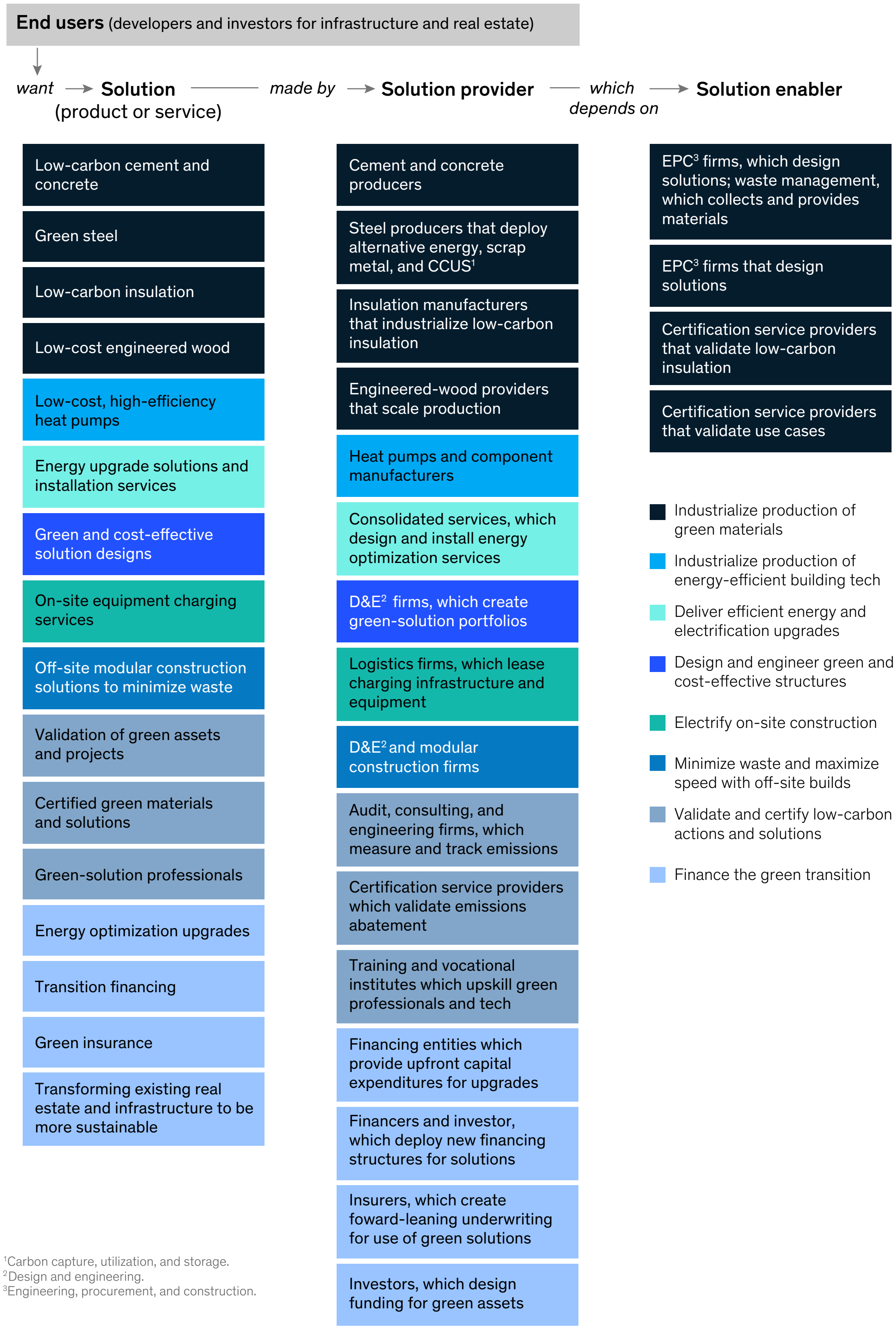
Fortunately, at no or little cost, biomass and waste can be substituted for coal to begin decarbonizing the cement production process. Some cement kilns already operate using more than 90 percent alternative fuels.[18] In the European Union, large cement manufacturers have committed to reducing their emissions per metric ton of cement by 20 percent from a 2020 baseline through thermal-energy efficiency, fuel switching, and clinker substitution.[19] According to S&P, this can be done at a reasonable cost.[20]

As a result, there is an opportunity for large, comprehensive waste-management firms to collect and source biomass for cement production, particularly in certain regions. Biomass is the main source of renewable energy in the European Union[21] but contributes less than 5 percent of renewable energy in the United States.[22] This less-mature biomass market and others like it are open to

[17] Sebastian Reiter, "Transition to net zero: Cement," *McKinsey Quarterly*, August 1, 2022.
[18] "Decarbonizing cement: How EU cement-makers are reducing emissions while building business resilience," S&P Global, October 27, 2022.
[19] *Concrete future: The GCCA 2050 cement and concrete industry roadmap for net zero concrete*, Global Cement and Concrete Association, October 12, 2021.
[20] "Decarbonizing cement," October 27, 2022.
[21] "Biomass," European Commission, accessed May 26, 2023.
[22] "Table 3.1.B. Net generation from renewable sources: Total (all sectors), 2011 – 2021," US Energy Information Administration, accessed May 26, 2023.

Exhibit 12

An ecosystem to decarbonize the built environment will offer a wide variety of solutions.



[1]Carbon capture, utilization, and storage.
[2]Design and engineering.
[3]Engineering, procurement, and construction.

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cement producers and waste management looking to form mutually beneficial offtake agreements.

Another decarbonization opportunity comes from retrofitting cement production plants with CCUS and from upgrading older cement plants with the latest, most efficient capabilities. CCUS technologies are rapidly advancing across industries, and several pilot studies have proved the technical viability of CCUS in cement plants. For example, the world's first CO_2-capture facility at a cement plant, Heidelberg's facility in Brevik, Norway, is projected to be fully operational in 2024.[23]

The average cement production plant in North America is approximately 50 percent older than that of Asia–Pacific,[24] meaning there are many opportunities in the region to retrofit or replace older plants with CCUS and the latest conventional and commercially proven technologies. These retrofits might involve replacing outdated wet-process kilns with dry-process kilns (including staged preheaters and precalciners) and efficient grinding equipment, which could greatly improve energy and thermal efficiencies.[25] This would increase the cement produced per unit of energy, thereby reducing both emissions and the cost per unit of cement. As a result, such retrofitting could provide a cost-effective opportunity to decarbonize cement production.

Scale up low-carbon concrete production

Beyond technological advancements to improve the cement production process, cement producers can also reduce emissions by using more environmentally friendly SCMs such as fly ash and GGBFS to make concrete. Given that the availability of these two SCMs is likely to decline going forward in many regions, producers may need to increase their adoption of other techniques. One option is using calcined clay-blended cement, which is a cost-effective SCM that requires production scaling.

Fine-limestone filler is another SCM option that has been extensively quarried, and therefore, supply is expected to be stable in several regions. Cement and concrete firms could set up or expand concrete-mixing businesses that maximize the amount of low-carbon cement and clinkers that are allowed, cost-feasible, and technically sound.

Modern grinding technologies allow much more precise separation of waste concrete components than in the past. This makes upcycling waste concrete as a filler or SCM a promising opportunity for concrete producers, given the scale of materials available. Cement manufacturers can also use upcycled concrete as clinker raw material. The European Union is expected to allow using recycled concrete as the main component in cement in 2023.[26] Given the carbon tax on CO_2 emissions from cement, the European Union could be an attractive market for upcycled concrete waste in cement production.

To accelerate the opportunity from waste concrete, waste management firms could play a role in the supply chain by sourcing and distributing clinker substitutes, such as fly ash and GGBFS, from steel and coal-fired power plants and recycled concrete from demolition sites. In addition, suppliers could develop partnerships and offtake agreements with cement producers to guarantee material use.

Concrete could be further decarbonized at no additional cost with carbon curing. In carbon curing, CO_2 is added before the concrete cures to reduce the amount of cement needed without compromising structural strength. The CO_2 used in the process could even be captured from earlier phases of cement production with carbon capture technologies. These opportunities could help concrete producers meet increasing demand for low-carbon concrete from developers, real estate investors, construction companies, and builders seeking to reduce their carbon footprints.

[23] "Brevik CCS—World's first CO_2-capture facility at a cement plant," Heidelberg Materials, accessed May 26, 2023.
[24] "Age profile of global production capacity for the cement sector (kilns)," International Energy Agency, updated October 26, 2022.
[25] David Hodgson, Paul Hugues, and Tiffany Vass, "Cement," International Energy Agency, September 2022.
[26] *State of the art cement manufacturing: Current technologies and their future developmen*t, European Cement Research Academy (ECRA), 2022.

Produce green construction steel

A number of levers exist for steel producers to lower their emissions while making construction steel. First, steel producers can significantly reduce emissions by shifting to DRI-EAF steel production and using scrap feedstock, which has proved to be both technically and commercially viable. Second, existing DRI-EAF plants can be optimized using renewable energy sources, such as green hydrogen, instead of natural gas. While the high cost of green hydrogen currently acts as a barrier, rising carbon costs and the anticipated decrease in green-hydrogen costs in the future would help facilitate the transition. Third, steel producers and smelters can look into integrating CCUS technology throughout their processes. For example, a carbon capture pilot for smelters is now connected to a steel plant in Mo i Rana, Norway.[27]

The opportunity for steel producers to retrofit construction steel plants to produce green steel could tactically be achieved through partnerships between steel producers; alternative-fuel providers; and engineering, procurement, and construction (EPC) firms specializing in developing leading green technologies. These partnerships could be particularly beneficial for EPC firms, given that steel plants moving to low-emissions production could require $164 billion dollars in annual capital spending by 2030.[28]

As an example of one type of partnership, cement and steel producers could partner across the value chain with alternative-fuel providers to set price and quantity offtake agreements to ensure continuous markets for each other's products. This type of agreement is common in industries looking to decarbonize fuel usage.

A number of companies in the space have already taken steps to form partnerships. Hygenco India has signed a green hydrogen offtake agreement with Jindal Stainless. The deal will see Hygenco build, own, and operate a multimegawatt green-hydrogen facility for 20 years,[29] which will help Jindal Stainless reduce its carbon emissions by 2,700 metric tons annually. Vertex Hydrogen, a part of the Essar Group, has signed a "heads of terms" offtake agreement for more than 200 megawatts of low-carbon hydrogen with Tata Chemicals Europe.[30] And Neste has an offtake agreement to supply 320,000 metric tons of hydroprocessed esters and fatty acids (HEFA) biojet fuel to DHL over the next five years.[31]

Another tactic to increase the ease and efficiency of decarbonizing would be to develop hydrogen and CCUS hubs. Clustering steel, cement, and other high-emitting industries into these hubs could unlock and accelerate the deployment of hydrogen and CCUS. It allows organizations to share specialized expertise, services, resources, suppliers, and infrastructure. It could also decrease the risks inherent in deploying and scaling these technologies and could spread high up-front capital expenditures across peers and other high-emitting industries. For example, HyNet North West UK, an industrial cluster project, includes Hanson Padeswood Cement Works as part of its hydrogen and carbon capture and storage cluster.[32]

Clustering industries is already common practice. The European Union has 1,500 industrial clusters, accounting for almost a quarter of total EU employment.[33] Since the founding of the 2021 World Economic Forum initiative Transitioning Industrial Clusters towards Net Zero, which seeks to help industries reduce emissions, 17 industrial clusters from around the globe have joined.[34]

Governments are taking steps to cluster industries further. For instance, the US Bipartisan Infrastructure Law set aside $7 billion for regional

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[27] "World's first carbon capture pilot for smelters inaugurated at Elkem in Rana, Norway," Aker Carbon Capture, January 20, 2023.
[28] Steve Vercammen, "Transition to net zero: Steel," *McKinsey Quarterly*, August 1, 2022.
[29] "Hygengo enters into green hydrogen agreement with Jindal Stainless," *Construction World*, August 19, 2022.
[30] "Tata Chemicals Europe, Vertex sign low-carbon hydrogen offtake agreement," *Business Standard*, January 26, 2023.
[31] "Neste and DHL Express announce one of the largest ever sustainable aviation fuel deals," Neste, March 21, 2022.
[32] "HyNet North West: Carbon capture and storage: A UK first at a cement plant," Hanson, accessed May 26, 2023; "Government sets out next steps for CCUS clusters," Carbon Capture and Storage Assocation, March 30, 2023.
[33] "Cluster policy," European Commission, accessed May 26, 2023.
[34] "Decarbonization of Industrial Clusters initiative gains global momentum," Accenture, January 19, 2023.

clean-hydrogen hubs, including clustering industrial production.[35] The European Commission approved €5.2 billion for the hydrogen Hy2Use project.[36] It includes 35 projects at 29 firms to build infrastructure for producing, storing, and transporting hydrogen and developing hydrogen applications for high-emissive industries such as steel and cement.

Scale manufacturing of low-carbon insulation
As producers of traditional construction materials start to decarbonize their processes, there are options for builders looking to immediately lower their emissions—in this case, using materials that are inherently less emissions-intensive. For example, using natural-fiber insulation or conventional low-carbon insulation, made using a greater proportion of recycled materials, can abate a significant portion of embodied carbon emissions associated with conventional insulation at a reduced cost.

Insulation manufacturers could scale production of high-efficiency conventional insulations that use a greater proportion of recycled materials in their composition. They could also improve production measures, such as by optimizing equipment use, using renewable energy sources, and implementing process improvements. Together, these actions can help lower fossil-fuel and energy use and thereby reduce their emissions footprint.

Natural-fiber insulation has the potential to abate almost all emissions associated with the production process. However, the limited supply of raw inputs and the high price for natural-fiber insulation compared to conventional insulation are significant constraints that currently prevent widespread adoption. By establishing agreements with farmers and foresters to procure the required amounts of raw materials and by industrializing production processes to lower costs by 2030, producers could potentially increase their manufacturing capacity of natural-fiber insulation offerings and become cost-competitive with traditional insulation producers.

Scale manufacturing of low-cost engineered wood
For many applications, engineered wood is a viable alternative to concrete and steel. Thus, developers can choose to use engineered wood to reduce emissions from steel and concrete while benefiting from the natural carbon sequestration of trees.

For manufacturers, there is significant opportunity in ramping up the production of engineered wood (such as CLT, LVL, and MPP) by automating finger joining, layup and gluing, pressing, and other production processes. Given that many regions have limits on deforestation and the supply of verified, sustainable timber is limited, producers who can secure robust offtake agreements with verified sustainable-lumber producers and foresters will likely realize benefits. In the long term, leveraging smart and sustainable forestry practices can improve supply constraints. Producers will likely need to leverage multisourcing or vertical integration to diversify and ensure their supplier base. The final key to unlocking this market is access to the construction market via partnerships. Design and engineering (D&E) firms can establish standards for use, and developers can commit to offtake agreements to show demand, which could help derisk the investment by engineered-wood producers. While currently expensive, assurances over offtake of engineered wood can allow necessary investments to industrialize production and the supply chain to drive down the price barrier.

2. Industrialize production of energy-efficient building technology

The majority of built-environment emissions come from space cooling, space heating, and water heating. The principal lever for decarbonizing these forms of emissions is heat pumps, which can abate up to 60 percent of heating and cooling emissions for most building types. However, as of 2023, the heat pump supply chain is currently experiencing—and may continue to experience—manufacturing and supply chain bottlenecks.

[35] "Regional clean hydrogen hubs," Office of Clean Energy Demonstrations, accessed May 26, 2023.
[36] Caterina Tani, "Commission approves €5.2B in state aid for hydrogen technologies," Science|Business, September 22, 2022.

Scale manufacturing of low-cost and high-efficiency heat pumps

There is opportunity to scale the production of heat pumps and related components by industrializing manufacturing, strengthening supply chains, and implementing operational excellence best practices. For the European Union to grow from 15 million heat pumps in 2021 to RePowerEU's target of 54 million heat pumps by 2030, McKinsey estimates it would require 132 new assembly factories, each producing 100,000 heat pumps annually.[37]

Large appliance and commercial manufacturers, especially those seeking to invest in a high-growth market, can benefit from this opportunity. Actionable measures include standardizing and optimizing designs, diversifying the supplier base, and vertically integrating the supply chain for large-scale heat pump subcomponents. Expanding design-to-value (DTV) techniques can also help reduce material usage, identify lower-cost materials, and increase recycling. Residential heat pumps require 15 times more copper and brass than condensing gas boiler equivalents.[38] Using aluminum alternatives to copper for key components and increased recycling of copper, aluminum, iron, and components from scrapped HVAC equipment could alleviate supply chain bottlenecks while reducing costs and decarbonizing the supply chain because raw metals will not have to be mined.[39] Using alternative refrigerants, such as low-emission ammonia or captured CO_2, could further decarbonize and diversify the supply chain. Procuring and supplying these alternative components to heat pumps and related component manufacturers provides a unique opportunity that can be derisked by securing offtake agreements with major heat pump manufacturers and component suppliers.

3. Deliver efficient energy and electrification upgrades

Energy upgrade services are likely too fragmented and of insufficient scale to meet the hundreds of billions of dollars of annual demand required for decarbonization.[40] Fragmentation across trades in the built environment can result in complex and time-consuming handovers. As a result, the responsibility of coordinating different trades, procurement, and administration often falls on building owners. Given how nascent some of the proposed energy optimization solutions are, creating a comprehensive energy upgrade service could generate significant value.

Develop and offer energy upgrade installation services

There is opportunity for stakeholders to consolidate services to create integrated packages of key decarbonization solutions to ease the transaction costs of decarbonization upgrades. Operators of consolidated services could generate value by providing customers with a combination of energy audits, procurement plans to outline which green materials to use, installation services, and administrative support to navigate region-specific tax incentives to help customers maximize the energy cost savings of their buildings. After projects are complete, consortiums could manage construction waste material removal. Coordination of these services will likely vary by region but can save time and reduce costs across the board. The cost of net-zero consumables could be reduced by up to 30 percent through centralized digital procurement and other best practices, and the global market for potential retrofits could reach almost $1 trillion annually by 2035.[41]

[37] "Refurbishing Europe," February 28, 2023.
[38] "The future of heat pumps," International Energy Agency, updated December 2022.
[39] Ibid.
[40] "Accelerating green growth in the built environment," McKinsey, November 2, 2022.
[41] "Accelerating green growth," November 2, 2022.

4. Design and engineer both green and cost-effective structures

Conventional bespoke designs create costly material waste and rely on highly emissive materials such as cement and steel. Real estate and infrastructure owners, investors, and developers often rely on advice from D&E firms when they commission projects, but many D&E firms currently do not focus on optimizing designs for minimal emissions. As a result, there is opportunity for these firms to recommend innovative solutions and systematically evaluate the cost implications of alternative choices.

Expand green and cost-effective design and engineering capabilities

Builders can only implement green solutions if plans actually use low-carbon materials and technologies and are carefully scrutinized to minimize material use. Therefore, D&E firms will likely play an important role in driving decarbonization within the built environment by expanding their service offerings and cultivating their design capabilities to leverage green technologies. By creating a core design portfolio that incorporates green solutions, firms can help facilitate and spearhead the implementation of off-site construction via DFMA, engineered wood, green materials, and more. DFMA could enable firms to develop a database of prefabricated building components, limiting customization and enhancing modularity at the design stage.

There are three tangible actions that D&E firms can take if they are keen on this opportunity. First, firms can develop and enhance the accuracy of their cost estimation tools to enable cleansheet designs using green materials (for example, by digitization). For instance, firms could create full and standard market-transparency tools to calculate lifetime emissions and cost implications of design decisions. Many designers don't design buildings with lower operating emissions because buyers often do not incorporate that factor into how they value buildings and may not be willing to pay the premium on specifications. D&E firms can guide customers in the cost trade-offs between different designs and encourage customers to try the less well-beaten—and lower-emissions—pathways.

Second, firms can create a portfolio of optimized designs, possibly employing generative design, that minimizes waste, cost, and emissions by leveraging green solutions. This could equip builders with the tools to meet evolving client demands, such as net-zero operational homes.

Last, firms could deploy generative design AI to enhance the transition, given that it could allow builders to decarbonize their projects based on a specific set of criteria (costs, aesthetics, materials, and so on). Increased use of generative design and digitization may require changing the business model of some D&E firms from charging hourly rates to project-based fees because these technologies require up-front investment to implement (in other words, increased fixed costs). Companies, particularly developers, looking to decarbonize their construction projects could benefit from using these technologies.

5. Electrify on-site construction

Emissions from on-site construction equipment only contribute a small portion of built-environment emissions. Still, electrification of construction equipment can be cost-effective by 2030 if industrialized, and major construction-equipment manufacturers continue to expand their offerings of electric construction equipment. For example, Volvo committed to level-set the price of electric machines with diesel by the mid-2020s,[42] and

[42] "It's time to launch our electric construction machines," Volvo, accessed May 26, 2023.

Caterpillar even demonstrated a battery-powered large mining truck.[43]

Build and scale electrified offerings and on-site charging infrastructure for equipment
OEMs have first-mover and scale advantages in developing electric construction equipment and improving existing battery technology. Many customers today could be willing to switch to this electric construction equipment but are tied to ICE equipment because of a lack of charging options in their operation locations. As a result, there is an opportunity in electrification logistics to build the charging infrastructure—particularly high-speed mobile charging stations—needed to support these electrified technologies.

To build out the infrastructure more quickly, partnerships will likely be essential to expand the reach of charging-station services. These partnerships would potentially benefit both manufacturers of electric construction equipment and charging station companies, which could establish a steady stream of customers even in locations with low EV penetration while growing the market of construction companies, which are able to use EVs.

6. Minimize waste and maximize speed with off-site builds

Conventional on-site bespoke construction can create large amounts of waste materials since builders typically order most materials with an extra margin to avoid the risk of standing still. These margins can also make the process more costly and time intensive. By constructing buildings off-site, companies can reduce the size of this extra margin of materials since, in a factory setting, inventory can be made available across projects.

Develop off-site (modular) solutions
Modular construction can be restricted by limited customization capacity and use cases, making it difficult to deploy in bespoke conventional construction projects. However, residential and commercial builders and investors with time- and cost-sensitive projects could take advantage of many of the benefits modular construction offers, such as more-efficient and automated processes that lead to shorter construction times and lower financial and labor costs. In fact, we estimate that off-site construction could help reduce construction time by approximately 20 percent[44] and that modular construction in European and US markets can potentially create $22 billion in annual savings.[45]

These incentives create exciting opportunities for companies looking to unlock the barriers to the large-scale deployment of modular construction solutions. Modular construction firms can industrialize processes for constructing modules, and D&E firms can develop a suite of modular solutions for developers focused on reducing waste and cost while increasing speed. To accelerate the adoption of these technologies, large real estate developers and builders could partner with D&E firms to identify optimized low-waste modular design principles that could help reduce cost, timelines, waste, and emissions through standardization and design, such as by standardizing window and facade panels. For certain applications, parametric design can enable customization while standardizing modules. Offtake agreements and coordination with modular design firms could allow all parties to create use cases and determine how best to balance customization with efficiency.

Scaling modular businesses would require a strong manufacturing skill set and a deep knowledge of regional differences. Players would likely have to navigate region-specific resource scarcity as well as complexities and remote conditions that can create

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[43] "Caterpillar successfully demonstrates first battery electric large mining truck and invests in sustainable proving ground," Caterpillar, November 22, 2022.
[44] Depending on project scope, type, geography, and other characteristics, some projects have reported an almost 50 percent reduction in construction times.
[45] "Modular construction: From projects to products," McKinsey, June 18, 2019.

challenges for on-site construction. However, if these challenges can be addressed, modular solutions are projected to have highly cost-effective use cases.

7. Validate and certify low-carbon actions and solutions

Establishing trustworthy and verifiable green credentials is crucial to scaling green solutions. Consumers of these solutions will need confidence in their efficacy and abatement potential to create demand or, in some cases, to pay a premium for these solutions. Verified credentials will likely create a stable demand scenario that could empower investors and entrepreneurs to scale these solutions confidently. Additionally, these credentials could provide opportunities to lower financing costs for these solutions thanks to the demand for green financial instruments and reduced risk from stranded assets.

Accurately verify and track emissions in the built environment

Today, taxes on carbon emissions and related programs, such as compliance and voluntary carbon markets, are in place in Europe, some US states, and Canada, with more expected. Of the 2,000 largest global public companies, about 700 have made net-zero commitments.[46] Many large real estate portfolio holders have net-zero targets, as well. To leverage these carbon taxes and credits and adhere to net-zero targets and commitments, players in the built environment ecosystem would have to reputably and defensibly account for the carbon emissions in their structures, products, operations, materials, and projects.

Partnerships between auditing, environmental, and engineering firms could create offerings to measure emissions transparently and accurately over the life cycle of a given asset, while environmental and engineering professionals' expertise will be needed to measure emissions. Audit professionals could provide the framework to create structures to comply with relevant regulations, standards, and best transparency and reporting practices. The rigor and accountability of adhering to generally accepted accounting principles (GAAP) and International Financial Reporting Standards (IFRS) will likely be required for the new emissions frameworks (such as the Task Force on Climate-Related Financial Disclosures), regardless of the framework.

One way to facilitate these transparency services would be to provide reliable and detailed design libraries of carbon footprints of all materials and technologies in a structure. These standardized details would make it easier for developers to apply for net-zero and green building and structure certifications. This "carbon passport" would promote the use of new materials and technologies and could help small- and medium-size real estate investors and developers validate their decarbonization credentials. This could enable them to sell their assets at a premium to real estate investors decarbonizing their portfolios, get better loan rates from financial institutions decarbonizing their loan portfolios, and receive higher rent for commercial office spaces. Already, more-limited versions of sustainability ratings have been shown to increase rent by up to 6 percent.[47]

Certify green materials and solutions

To be deployed, conventional construction materials and processes must meet quality standards that are transparent and accountable, and green materials are no different. Because green materials are novel in many cases, they often require enhanced assurances, given that historical use and tolerance precedents are not well established.

Verifying sustainable material sourcing—for example, verifying that mass timber falls within the regulation limits for sustainable forestry—and corresponding abatement potentials provides credibility for pursuing carbon incentives and credits, green premiums, and large-scale adoption of green materials. These opportunities are

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[46] John Goddard, "Why companies aren't living up to their climate pledges," *Harvard Business Review*, August 11, 2022.
[47] Lucy Bishop, "Office buildings with sustainability certifications command a 6% rental premium, new CBRE analysis finds," CBRE, November 29, 2022.

good for both the environment and the economy because green products can have margins that are 15 to 150 percent higher than their conventional counterparts.[48]

To facilitate the verification process, new entrants and disruptors could create services to certify green materials. This could enable D&E firms to deploy materials in designs, insurers to insure green structures and projects, and developers to finance projects that use green materials.

Train and certify green-solution providers

The IEA estimates that the demand for heat pump installers is expected to quadruple by 2030 to more than 850,000 and that 170,000 more workers need to be trained to maintain and service the additional heat pumps.[49] This demand is not confined to heat pump installation: upskilled D&E professionals will likely be needed throughout the built-environment ecosystem to deploy green solutions.

To fill the labor and skills gap, there is opportunity to establish and expand training academies and vocational institutes to upskill D&E professionals and technicians such as HVAC installers, plumbers, electricians, and contractors in new green materials, products, and solutions deployment (heat pump installations, modular construction, green steel, cement, and so on). Upskilling D&E professionals and certifying tradespeople could accelerate lever adoption, since these skilled professionals would be more available to install abatement levers such as heat pumps, modular construction, and CLT.

Partnerships between green-job training academies and companies that need this talent are already common. Companies are eager to fill the talent pipeline and, in some cases, are willing to provide sponsorship. ARS, one of the United States' largest providers of residential HVAC services, is sponsoring candidates to earn credentials as HVAC technicians via paid eight-week training camps and will offer jobs to those who complete the program.[50] Columbus State Community College is leading the development of a novel statewide strategy to fill the 2,000 nondegreed jobs for Intel's $20 billion facility (the first new fabrication plant associated with the CHIPS Act) with a one-year certificate program for upskilling existing workers.[51]

8. Finance the green transition

Financing the transition would require new approaches. The two likely primary barriers to financing are high capital expenditures and limited insurance offerings. First, high capital expenditures stem from the technology installations or retrofits needed to decarbonize existing or new assets. Premiums for these green materials and products come from increased capital expenditures or operational expenditures to produce materials, as well as from additional planning and designing considerations. Second, insuring, underwriting, and investing in green projects is difficult because agencies would have to value assets that do not have historical precedents and that are not standardized or widely accepted across stakeholders. This can lead to excessive insurance prices or a lack of proper coverage for green projects.

Offer energy-as-a-service financing

Energy optimization solutions such as heat pumps often require high up-front capital expenditures, discouraging end users from upgrading. This barrier could be overcome by OEMs partnering with financing entities to deliver energy as a service in conjunction with the energy upgrade service (installation). Existing utilities could potentially provide these services in conjunction with financing entities.

The business model for such services can possibly be subscription-based: the service operator would

[48] "Playing offense to create value in the net-zero transition," *McKinsey Quarterly*, April 13, 2022.
[49] "The future of heat pumps," updated December 2022.
[50] Stewart Curet, "Partnership to offer paid HVAC training to Dallas workers to help fill shortage," *Dallas Morning News*, updated September 12, 2022.
[51] Lavea Brachman, Mark Muro, and Yang You, "With high-tech manufacturing plants promising good jobs in Ohio, workforce developers race to get ready," Brookings, January 24, 2023.

provide the capital needed to finance the energy optimization upgrades up front and recoup their investment by collecting monthly payments from the customer. This structure could help alleviate high up-front costs for customers for upgrades to their heating, cooling, distributed power, cooking, and lighting (among other appliances). It could also enable customers to benefit from lower total cost of ownership—the expenses associated with purchasing, deploying, using, and retiring a product throughout its lifetime—inherent in many green technologies.

The financing for this business model could provide a bankable, energy-saving asset with predictable, reliable, and steady cash flows. Pricing could even be structured so that monthly payments are less than end users would otherwise pay in utility bills, making it a cost-beneficial solution. Offering performance-based contracts based on achieving mutually agreed-upon performance cost goals could ensure the symbiotic relationship of these contracts.

In addition to partnerships between OEMs and financial entities, partnerships can be made across the energy solution value chain. To share the risks and benefits, optimization planners, installers, OEMs (such as heat pumps and insulation manufacturers), green-material procurement companies, financiers, and administrative services can come together to provide turnkey commercial and residential energy upgrade services to ensure that those upstream have a market and that those downstream have the necessary materials, products, and services to execute energy optimization plans and navigate tax subsidies and incentives. For example, Apollo, an asset manager, and Johnson Controls, a heat pump manufacturer and energy optimization solutions planner, partnered to create a turnkey performance-based energy efficiency and smart buildings service for commercial buildings at no up-front cost.[52]

Energy as a service would not be limited to site-specific energy upgrades. District heating, community solar, and microgrids could be financed similarly. A 100 percent renewable energy source would allow 100 percent abatement for all electric levers.[53] These power solutions could be financed by securing purchasing power agreements (PPAs) from real estate investors and holders. The PPAs could then collateralize the loan for the power solution to secure favorable funding from banks or capital markets.

Develop project financing for green solutions

New technologies and processes associated with decarbonization will likely require a modification in cost structure and ROI calculations. For example, this might involve higher up-front capital expenditures for products such as heat pumps that have long-term cost savings. Another example might be increasing up-front design and engineering for off-site prefabrication to shorten project durations. These new technologies and processes would allow developers to obtain financing and investors and financial intermediaries to provide it. This is particularly relevant for financiers as financial institutions seek to decarbonize their portfolios for their net-zero targets. (More than 40 percent of global banking assets are committed to net-zero targets.[54])

Financial entities and developers stand to benefit from a number of financial levers related to decarbonizing the built environment. Financial barriers can be unlocked by financial intermediaries and investors by modifying time horizons (to account for long-term energy efficiency savings) for cash flows and other existing financing structures and products. Modifying these products and instruments could allow financial institutions and other parties to effectively compare the ROI of conventional and green investments, since green projects tend to have higher up-front costs than conventional projects but realize more savings in the long term. Furthermore, developers and

[52] "Johnson Controls and Apollo Infrastructure join forces to pursue innovative sustainability and energy efficiency services for commercial buildings," Johnson Controls, accessed May 26, 2023.
[53] It should be noted that distributed generation may not count toward decarbonizing a building in most jurisdictions.
[54] "Net-Zero Banking Alliance," UN Environment Programme, accessed May 26, 2023.

financiers can benefit from financial incentives offered for green solutions, such as premiums from green bonds and better discount rates from fewer stranded existing assets.

Scale offerings of green insurance underwriting

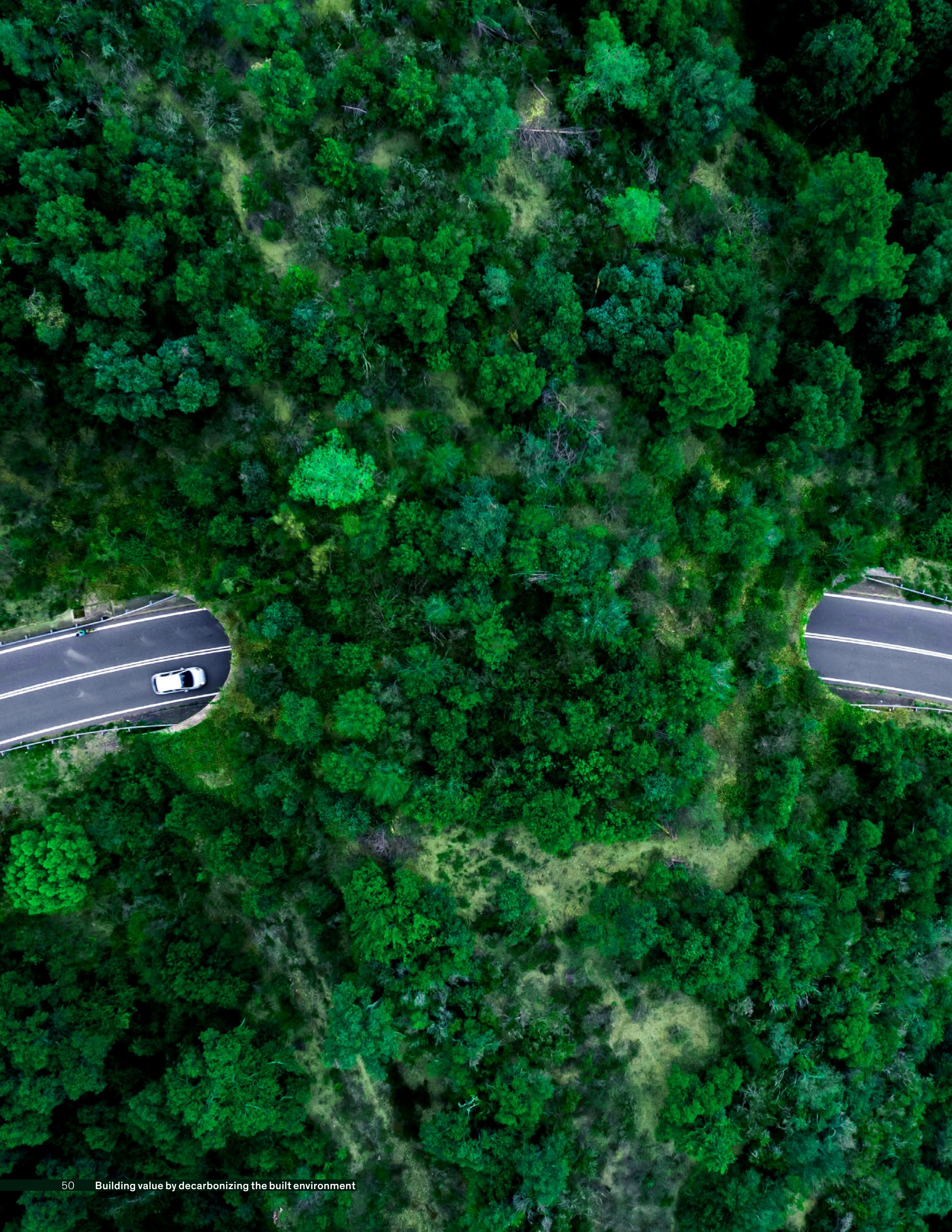
Conventional insurers can find it difficult to assess the risks of green building materials and processes. Whereas conventional materials and technologies have been used for 30 or more years across many types of buildings and infrastructure, new green materials lack this proven track record. However, green buildings and infrastructure would still require insuring, so it is essential that the insurance industry finds ways to facilitate this transition. Insurance companies specializing in green buildings and infrastructure could be the early players to take potentially higher risks (at the right premium). Built-environment expertise will aid in insuring retrofits because retrofits are often an uncertainty for underwriters. Expertise will allow insurers to answer questions such as whether the asset should be insured as a new green asset or as its original build and erection date.

Insurers have the opportunity to facilitate insurance for projects and structures by creating forward-leaning real estate underwriting capabilities for structures made with green technologies. With a green premium, insurers can also guarantee that assets being rebuilt after loss will use green materials, technologies, and processes, regardless of the original build. Partnerships between D&E firms specializing in green solutions and insurers could also accelerate the adoption through information sharing of acceptable deployment methods for green solutions in the projects and structures these insurers are being asked to underwrite.

Deploy investments to make existing real estate and infrastructure green

Financing can provide investment opportunities to turn the existing built environment into green investments. By 2030, the global retrofit potential market is forecast to grow to hundreds of billions of dollars annually.[55] Investors could capture above-market returns by transforming existing real estate and infrastructure assets into green assets through decarbonization solutions focused on cost-effectiveness. This excess return could be captured by improving efficiency (energy reduction and design improvement cost savings), as well as from green investment and rental premiums from documented emissions reductions, government incentives, carbon credits, reduced risk from stranded existing assets, and optimized carbon taxes.

[55] "Accelerating green growth," November 2, 2022.



Where to go from here

Each company in the built environment and adjacent industries can consider new green businesses it could build and companies with which it could partner to create and realize value.

Decarbonizing the built environment is a significant challenge with the potential for equally significant value creation. Despite the size of this task, there are clear actions that each player can take today to reduce the ecosystem's carbon footprint and capture value from new business opportunities. Players hoping to benefit from these opportunities could do the following:

— Assess existing business and operating models, and identify changes critical to succeed in the future industry ecosystem.

— Identify which opportunity areas they can play in and what core capabilities would be required to launch and scale the new business opportunities.

— Channel investments and efforts toward building new green businesses and developing solutions and offerings.

The opportunities are not limited to large ecosystem players; most companies in the ecosystem can potentially find value in building businesses to industrialize green solutions. Newer players can focus on trends that could disrupt the industry. For instance, disruptors in their early stages of development have even shown the potential to reduce their carbon footprint in concrete by up to 100 percent by replacing cement with industrial waste or biological materials and by carbon-curing concrete for permanent mineralization. In this way, small players can help prove the potential of promising solutions and highlight them as good sites for investments to scale by 2030.

For the entire ecosystem, companies of all sizes and maturity can seek partners to enable the upscaling of new green solutions. By working together, companies can gain access to new markets and channels and share any potential risks associated with industrializing solutions. Smaller manufacturers can partner with investors and larger, more-established players to industrialize their solutions and create offtake agreements to ensure steadier, less risky demand. This could be supported by downstream efforts from real estate investors, which could review what materials and technologies will be most critical to reach net-zero emissions and work with corresponding manufacturers, service providers, developers, and EPC firms to implement and scale these solutions. Investors and financiers also could identify high-potential manufacturers, suppliers, and disruptors and partner with forward-leaning real estate companies to develop and provide competitive financing solutions.

To support industrialization, players can also take steps within their own businesses to secure the supply and demand for green solutions. For example, to support the deployment of low-emissions technologies, real estate companies could set ambitious specifications for green solutions. This could create demand and ensure offtake for materials such as low-carbon cement, as well as for green technologies and services. Contractors and distributors could also build sourcing expertise in new green solutions and help aggregate demand and secure supply.

Significant efforts are still needed today to pave the way for decarbonizing the built environment, but many of the transformative technologies required in the long term are already viable today or, with the right focus and investments, could be soon. Players positioned to swiftly move and act upon these opportunities, in part by collaborating with others in the ecosystem, are likely to realize value and play a vital part in building a net-zero world.

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