McKinsey & Company

Sustainability Practice

Net-zero steel in construction: The way forward

Rising demand for greener approaches creates an imperative for the industry to seize the moment, adopt new mindsets, and set standards for the transition to a greener future.

This report is a collaborative effort by Pedro Assunção, Brodie Boland, Trevor Burns, Emanuele D'Avolio, Alasdair Graham, Focko Imhorst, Ingrid Koester, Carl Kühl, Rory Sullivan, and Alex Ulanov, representing views from McKinsey's Metals & Mining and Sustainability Practices and the Energy Transitions Commission.

April 2022

From houses to bridges, hospitals, and skyscrapers, the construction industry is responsible for approximately 25 percent of global emissions,[1] about a third of which are associated with the construction process.[2] One reason for that heavyweight impact is that the industry is a voracious consumer of steel, accounting for more than 50 percent of global demand.[3] Steel is a carbon megaproducer due to the energy used in its production[4] and is responsible for about a quarter of emissions in the building construction process. Given these powerful impacts, there is an urgent need for decision makers in steel and construction to take stock, consider options for decarbonization, and plot a realistic path forward.

Under the Paris Agreement on climate change, governments pledged to keep global warming below 2°C above preindustrial levels, ideally below 1.5°C. To achieve that goal, net human emissions of greenhouse gas (GHG) must fall to zero by 2050. In the construction sector, massive changes are required to align with that pathway. However, a significant step forward would be to shift from high-CO_2 steel to near-zero-emissions steel.

Partial steel decarbonization is possible with modern furnace technologies—the most efficient of which are powered by natural gas and use comparably energy-efficient direct reduced iron or hot briquetted iron (NG DRI/HBI+EAF) to make steel. These emit much less GHG than coke-fueled blast furnaces or basic oxygen furnaces (BF/BOFs), which account for 73 percent of global production and are still dominant in Europe, China, and elsewhere.

Another route to lower-CO_2 steel would be to retrofit BF/BOFs for carbon capture and storage (CCS) or carbon capture and utilization (CCU). This technology can be a near-zero-emissions steel technology, contingent on a CO_2 capture rate of 90 percent, but the approach is not yet proven at scale and is significantly costly.

The "North Star" for decarbonization would be to scale hydrogen-reduced DRI/HBI EAF furnaces powered with renewable energy. With this combination, producers could make steel with a carbon intensity of less than 0.2 metric tons of CO_2 (tCO_2) per metric ton of steel. Still, the cost would be high. The steel produced in an EAF using hydrogen-reduced DRI would need to command a "green premium" of about 20 percent over 20 years to fund construction of the DRI plant and EAF (not including the capital expenditure for hydrogen production, transport, and storage).

To demonstrate the potential for construction to adopt greener steel, this paper presents an illustrative marginal-abatement cost curve for the materials and construction of an eight-story commercial office building.[5] In a business-as-usual scenario, total embodied carbon in the construction phase would be about 1,900 tCO_2, of which approximately 85 percent would be from materials.[6] Of that, some 25 percentage points would be associated with steel (and 37 percentage points with concrete).[7] The analysis shows it would be possible to reduce embodied carbon in the building by about 1,250 metric tons (or 70 percent), using alternative technologies, materials, and steel-production methods that will be widely commercially available by 2030. This would

1 "Call for action: Seizing the decarbonization opportunity in construction," McKinsey, July 14, 2021.
2 "Metals & Mining Insights," McKinsey, accessed in September 2021; "Real Estate Insights," McKinsey, accessed in September 2021. Based on 2017 emissions.
3 "Steel facts," World Steel Association, accessed January 26, 2022.
4 A significant portion of steel consumption in building and construction is from "long" products, which—in the United States—are most commonly produced through electric-arc furnaces (EAF) that have a lower CO_2 emissions intensity per metric ton of steel.
5 For illustrative purposes only. Regional differences and differences in the construction type of the building (for example, cast-in-place versus hybrid versus structural steel) have a significant impact on both overall emissions and on abatement potential of different levers.
6 Carbon emissions associated with buildings' whole-life materials and construction processes. Nonmaterial emissions include heavy equipment, transport, and small generators.
7 Mostly rebars used in reinforced concrete.

imply a relatively modest 5 percent real increase in the cost of building materials. A reduction of approximately 25 percent would be achievable with current technologies.

Still, technical and economic feasibility is only half the battle. The other half is implementation, adoption, and scaling. Here we set out five actions the public and private sector must take to drive the green-steel agenda: agree to common standards and promote transparency; encourage participation by fostering visibility; unlock end-user demand (for example, through a buyers' club for near-zero-emissions steel); tilt capital formation toward near-zero-emissions steel; and promote learning and disseminate knowledge. In a fast-changing demand landscape, these actions would accelerate the decarbonization of the construction sector, with greener steel playing a leading role.

Steel, construction, and carbon: The state of play

Globally, there are two dominant modes of steel production. The first is based on BF/BOF technology, which blows currents of air to turn iron ore, mixed with coal and smelting agents such as limestone, into molten metal. The second dominant mode is electric-arc furnace (EAF) technology. EAFs use electricity passed through giant electrodes to create a fiery arc in which the temperature reaches 3,000°C. The furnaces often process recycled scrap metal and scrap substitutes including pig iron and DRI, which is made using natural gas, to produce steel. Today, BF/BOFs emit around 2.5 tCO_2 per metric ton of steel, while NG DRI/HBI+EAFs emit 0.5 tCO_2 per metric ton or less, depending on the share of scrap and energy source.[8]

Steel CO_2 emissions intensity is due to three process steps: raw-material preparation, ironmaking, and steelmaking. Raw-material preparation requires heating metallurgical or coking coal to 1,100°C to create coke and an agglomeration of iron fines, either producing sinter or pellets. Ironmaking can be in either BF or DRI furnaces. In BF, coke and iron ore sinter or pellets are combined, whereas in DRI, iron ore pellets are directly reduced to purer iron using natural gas. Subsequent steelmaking from iron can be through either combining the iron ore with a small amount of carbon in a basic oxygen furnace or combining DRI-based iron, pig iron, or both with scrap in a cleaner electric-arc furnace. Modern versions of BF/BOF technology account for about 73 percent of global steel production, with significant variations by geography. More energy-efficient EAFs account for about 27 percent of production.

Construction companies are not operating in a vacuum. Indeed, they face rising pressure to decarbonize from end buyers, investors, and regulators. In addition, some governments have passed legislation to drive the change agenda. Measures include Denmark's limit of 12 kilograms of carbon-dioxide equivalent emitted per square meter (CO_2e/m2) per year for new buildings larger than 1,000 square meters[9] and California's Buy Clean California Act (BCCA), which sets limits on global-warming potential for structural steel, concrete-reinforcing steel, flat glass, and mineral wool board insulation.[10] Amid increased focus on Scope 3 emissions, institutional investors are also engaged as they seek to cut emissions from their portfolios.

Against this background, what is preventing the construction sector from moving to green—or greener—steel? The reality is that, despite tailwinds, companies face significant commercial, structural, and regulatory barriers. The sector's generally low margins are a limiting factor, dampening steel producers' appetites for investing in green technologies.[11] Established approaches produce

[8] *Steeling demand: Mobilising buyers to bring net-zero steel to market before 2030*, Material Economics and the Energy Transitions Commission, June 2021.
[9] *National strategy for sustainable construction*, Danish Ministry of the Interior and Housing, April 2021.
[10] "Buy Clean California Act," California Department of General Services, accessed January 20, 2022.
[11] LEED-certified buildings typically command a higher rent than non-LEED-certified buildings, but this is generally insufficient to offset the additional costs of using green steel. "LEED" stands for Leadership in Energy and Environmental Design.

steel for approximately $400 to $500 per metric ton at the slab level. Near-zero-emissions steel is more expensive, with significant variations based on technology, location, and project.

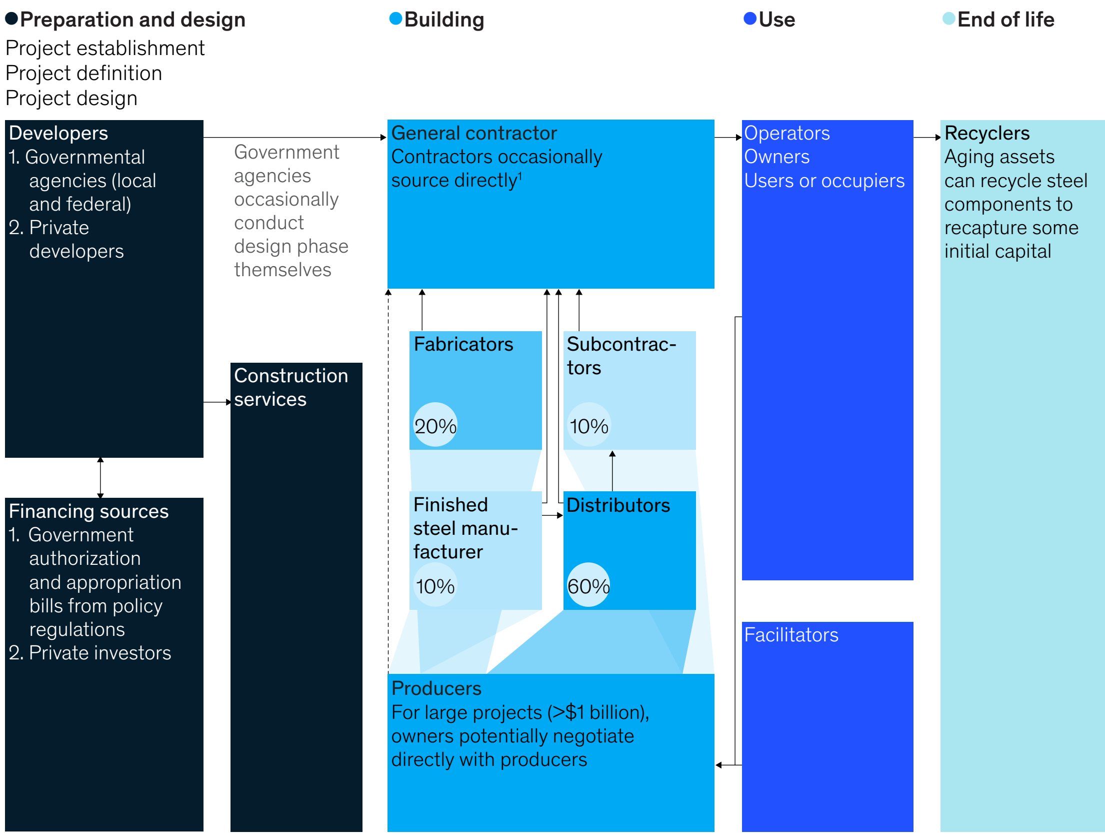
Another barrier to adoption is that individual developers do not routinely count emissions from the steel they consume because of a combination of factors, including a lack of industry standards, patchy regulation, and the absence of tools to measure embodied carbon (contained in construction materials from extraction to use).[12] Indeed, no certification or grading system has been widely adopted to date.[13]

The third significant barrier to adoption is that the steel industry services a highly fragmented construction landscape (Exhibit 1). In North America and Europe, the value chain is characterized by multiple intermediaries—

Exhibit 1

A fragmented value chain is a barrier to the construction industry's adoption of greener steel.

Construction value chain phases



Note: Percentages are the share of steel produced.
[1]Generally, finished steel, rebar, rods, rolls, and sheet metal.

[12] Denmark, France, and the Netherlands have rules regarding embodied carbon, and Finland and Sweden plan to follow suit in 2025 and 2027. US cities such as Santa Monica, California, have similar legislation in place. "Buy Clean Colorado" and "Buy Clean California" are state legislative acts focused on steel. A shift may be supported by legislation such as the US Bipartisan Infrastructure and Jobs Act, CLEAN Future Act, and SUPER Act of 2021.

[13] For example, the Partnership for Carbon Accounting Financials (PCAF) has not yet included embodied carbon emissions in required reporting of financed construction emissions due to feasibility constraints.

with thousands of companies competing for business—and supply chains that consist mainly of small manufacturers and merchants. Against this backdrop, effective change at scale is more difficult to achieve.

Breakthrough steelmaking technologies: Innovation and incentives

In some markets, steel decarbonization is already under way, driven by regulatory and commercial factors as well as a desire to test new production processes at scale (Exhibit 2). The potential impact

Exhibit 2

Innovation will support the transition to near-zero-emissions steel.

For the foreseeable future, natural gas direct reduced iron and electric-arc furnaces (NG DRI + EAF) and 100% scrap EAF are the most viable options

● Potentially considered as near-zero-emissions steel

Approach	Emerging example	Emissions, tCO_2/t steel[1] (Scope 1 / Scope 2 / total)	Logic or limitation	Maturity (Low–High)
BF/BOF[2] Replace iron ore sinter/pellets in the BF feed with carbon-free DRI/HBI	Cleveland-Cliffs (CLF), U.S. Steel	2.3 / 0.1 / 2.5	Not currently a viable investment, as emissions reductions are not large enough to decarbonize steelmaking for a 1.5° pathway	●
BF/BOF + CCUS[3] ● Add carbon capture and storage/utilization technology to existing BF/BOF plants	U.S. Steel (under consideration)	0.2 / 0.2 / 0.5	Technology is still in its infancy	● *No CCS cases, minor CCU*
NG DRI + EAF[4] Increase scrap utilization and convert NG to 100% renewable power	ArcelorMittal Contrecoeur and Lazaro Cardena; Ternium Guerrero; Algoma Steel (future)	0.3 / 0.2 / 0.5	Not currently a viable investment, as emissions reductions are not large enough to decarbonize steelmaking for a 1.5° pathway	●
NG DRI + EAF + CCUS[4] ● Combine natural-gas-based DRI with an EAF, and capture or use CO_2 emissions	DRI/HBI[5] widespread but no US examples + CCS	0.0 / 0.2 / 0.2	US steelmaking industry not currently invested in this production route	● *Only Emirates Steel*
H_2 DRI/HBI[5] + EAF ● Combine green-hydrogen-based DRI and EAF	H2 Green Steel; ArcelorMittal Dofasco (future "hydrogen ready")	0.2 / 0.0 / 0.2	Technology is still in its infancy	● *Industrial demo plants*
100% scrap EAF ● Melt high-quality scrap in EAF (long products only)	Gerdau, Nucor, SDI	0.1 / 0.2 / 0.3	Limited by scrap supply, and not all steel products can be produced by this route	●
40% AIU[6] scrap ● Upwards of 70% scrap possible (flat products only)	Nucor, SDI, SSAB	0.1 / 0.2 / 0.3	Not all steel products can be produced by this route	●

Note: Figures may not sum, because of rounding.
[1]Metric tons of CO_2 per metric ton of steel across Scopes 1 and 2. [2]Blast furnace and basic oxygen furnace. [3]Carbon capture, utilization, and storage; contingent on 90% CO_2 capture rate. [4]80/20 DRI scrap ratio and contingent on 90% CO_2 capture rate. [5]Hot briquetted iron; 80/20 DRI/scrap ratio. [6]Alternative iron unit.
Source: McKinsey US Decarbonization Pathways Analysis

of these efforts will be contingent on the pace at which externalities are priced into conventional pathways and how quickly cost reductions are achieved in new production routes.

One approach to reducing the CO_2 intensity of steel is to retrofit existing facilities, using maturing technologies to develop cleaner processes. An example is CCS and CCU. We estimate that 1.9 tCO_2 per metric ton of steel could be reduced in BF/BOF with CCS and CCU retrofit, if 90 percent CO_2 capture rate is achieved. CCS and CCU are maturing technologies and the precise balance of CO_2 management and CO_2 direct avoidance will depend on location-specific circumstances. However, there are significant limitations to this approach, including public and political skepticism (for example, historical opposition in Germany, a major steelmaking country), potential concerns relating to leakage from long-term geological storage,[14] and high capital costs (more than $250 per metric ton of steel).[15] Furthermore, while technologies such as CCS will go some way toward greening the steel industry, they are unlikely by themselves to be sufficient to get to net zero. One reason is that they leave residual emissions, due to partial capture rates that can only be abated at a cost. Steel producers need to weigh the costs of achieving higher capture rates and managing residual emissions early in the decision-making process.

Fully decarbonizing steel production requires a more fundamental switch. Among current technologies, the most promising are based on hydrogen. Most hydrogen production consists of “gray hydrogen,” made through a process called steam methane reforming (SMR). This creates a gas composed of about one-tenth hydrogen and nine-tenths CO_2. By contrast, cleaner “blue hydrogen” involves combining fossil fuels with steam to produce hydrogen and CO_2 and then storing the CO_2 underground. A still cleaner approach is to use electrolysis to separate hydrogen from water, producing “green hydrogen.”

Hydrogen is already used in ironmaking as a reduction agent, but has not yet been deployed at scale in steel production. One use case is as an alternative injection material to PCI (pulverized coal injection, a modern replacement for coke) in BF/BOF environments. This use can cut emissions by up to 30 percent but does not offer carbon-neutral potential, because significant coking coal is still required. Conversely, hydrogen-reduced DRI/HBI+EAF and renewable power would have a potential carbon intensity of less than 0.2 tCO_2 per metric ton of steel, compared with a current NG DRI+EAF (100 percent scrap EAF has limitations in sheet production).

Offsetting hydrogen’s benefits is its high cost. Despite being one of the most abundant elements on Earth, the gas barely exists in its pure form and must be extracted from compounds in an energy-intensive process. No steel producer has found an economically viable way to operate green hydrogen-reduced DRI/HBI+EAF (which currently costs approximately $5 per kilogram)[16] at scale. However, more than 25 projects are under development.[17] Other limitations include the availability and quality of scrap, especially outside the United States, and access to renewable power.[18] Still, as green-hydrogen technologies mature over the coming years, costs are expected to fall.

Apart from green-hydrogen development, several alternative technologies are starting to make a mark. These include ore electrolysis, which separates metallic iron from the oxygen to which it is bonded in iron ore, and ore smelting reduction (to produce pig iron at a lower energy intensity

[14] Christopher R. Jones, Lorraine Whitmarsh, and Dimitrios Xenias, “Framing effects on public support for carbon capture and storage,” Nature, February 2019, Volume 5, Number 17.
[15] For more on this approach, see “Metals & Mining Insights,” McKinsey, accessed September 2021.
[16] Dyna Mariel Bade, “US Department of Energy announces green hydrogen cost-cutting goal,” Institute for Energy Economics and Financial Analysis (IEEFA), June 8, 2021.
[17] “Metals,” September 2021; *Path to hydrogen competitiveness: A cost perspective*, Hydrogen Council, January 20, 2020.
[18] “Scrap use in the steel industry,” World Steel Association, May 2021.

The commercial development sector is characterized by a relatively low price elasticity of demand. In addition, ESG considerations are becoming an increasingly important differentiator.

than blast furnaces and without coke) combined with CCS.

Decarbonization levers in B&C projects: An illustrative case study

In the normal course of business, construction projects are broadly categorized as residential, infrastructure, or commercial. In the residential space, demand is mainly driven by factors such as price and location. Infrastructure projects such as bridges, highways, and railways are mostly publicly led investments, so they are subject to the vagaries of policy and funding. A first step toward wider use of greener steel in that space would be a change in procurement terms—requiring a marked shift away from the dominance of least-cost tendering.[19] Of the three categories, commercial projects offer the most immediate potential for deployment of decarbonized steel at scale.

A supportive factor for greening of the commercial development sector is that the sector is characterized by a relatively low price elasticity of demand. In addition, environmental, social, and governance (ESG) considerations are becoming an increasingly important differentiator.[20] LEED-certified[21] office buildings in US Class A urban markets have achieved a 21.4 percent higher average market sales price per square foot over the past three years.[22] Though embodied carbon is not a mandatory requirement for LEED certification, most LEED-certified office buildings are managed with low-carbon strategies.

To gauge the potential cost of abatement in a commercial setting, we measured the decarbonization potential of an illustrative eight-story commercial office building with a footprint of approximately 10,000 square feet (Exhibit 3).[23] In a business-as-usual scenario, total embodied carbon for the building would be about 1,900 metric tons, of which approximately 85 percent would be from building materials.[24] Of that total, some 37 percentage points would come from concrete and 25 percentage points from steel.[25]

The analysis shows that alternative technologies, materials, and steel production processes could reduce the embodied carbon in the same building to around 600 metric tons (approximately 70 percent reduction in emissions) by 2030. Given a 10 percent

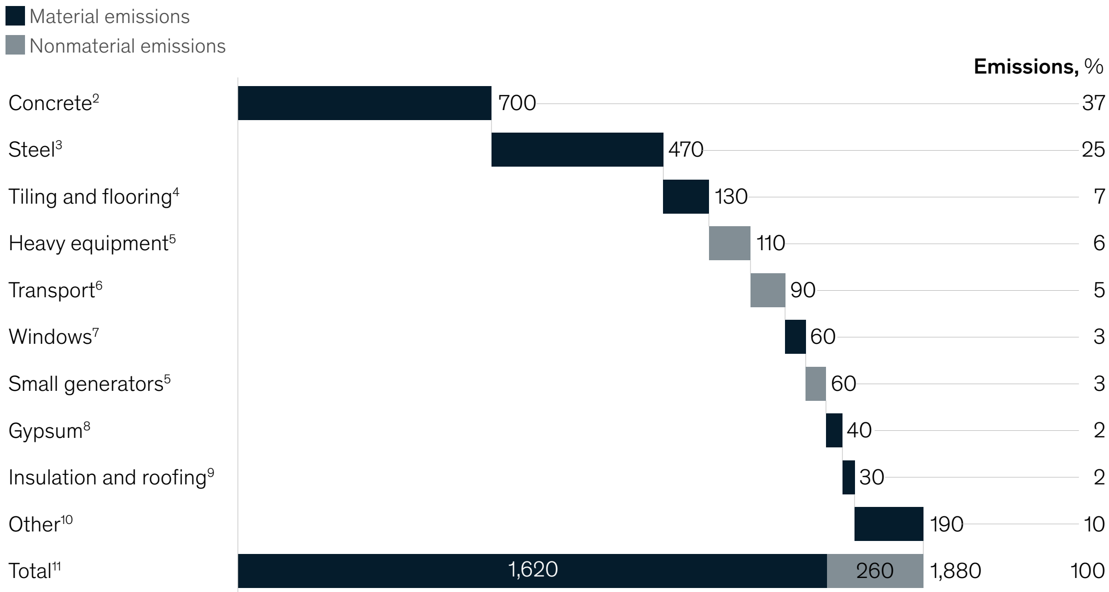
---

[19] Dirk Czarnitzki, Paul Huenermund, and Nima Moshgbar, "Public procurement as policy instrument for innovation," *Proceedings*, Academy of Management, July 2018, Volume 2018, Number 1.
[20] George Hammond and Sarah Provan, "Hybrid working and climate fears steer London office demand, say groups," *Financial Times*, August 10, 2021.
[21] LEED stands for Leadership in Energy and Environmental Design.
[22] *Green is good: Sustainable office outperforms in Class A urban markets*, Cushman & Wakefield, August 2021.
[23] For illustrative purposes only. Regional differences and differences in the construction type of the building (for example, cast-in-place versus hybrid versus structural steel) have a significant impact on both overall emissions and on the abatement potential of different levers.
[24] Nonmaterial emissions include heavy equipment, transport, and small generators.
[25] Mostly rebars used in reinforced concrete.

Exhibit 3

More than 60 percent of embodied emissions for an illustrative eight-story building come from concrete and steel.

CO_2 emissions of an 8-story office building,[1] metric tons of CO_2



[1] ~10,000-square-foot footprint building (~900 m²) (rounded numbers). [2] Mostly RC40/50—CEM1, RC32/40—50% GGBS, and GEN1—CEM1. Includes emissions from 4% waste concrete. [3] Mostly rebars (reinforced concrete) but also hot-dip galvanized steel, global seamless tube, UO pipe, and engineering steel. Includes emissions from 10% waste steel. [4] Includes materials such as ceramic, clay, nylon, and carpet. [5] Part of "on-site emissions," heavy equipment is assumed to be 6% of total baseline, while small generators are assumed to be 3% of total baseline. [6] Transport is assumed to be 5% of total baseline. [7] Includes window frames. [8] Includes 22.5% emissions from gypsum waste. [9] Includes materials such as timber, aluminum, polystyrene, bituminous roof membrane, and cellulose. [10] Includes a combination of other smaller materials and accounts for simplifications in terms of items, allocating all item emissions to the main material. [11] Rounded totals. They do not include electrical cabling, heating system, electrical appliances, etc, which make up <10% of total material emissions of the building.
Source: Eight-story office building Bill of Quantities emissions model; *Building*; Commonwealth Scientific and Industrial Research Organisation (CSIRO); Embodied Carbon in Construction Calculator (EC3) database; European Union; Inventory of Carbon and Energy (ICE) database; Bernardino D'Amico, Jim Hart, and Francesco Pomponi, "Whole-life embodied carbon in multistory buildings: Steel, concrete and timber structures," Journal of Industrial Ecology, April 2021, Volume 25, Number 2; McKinsey analysis

premium on steel (assuming green-hydrogen based DRI EAF represents 40 percent of steel in building and construction), the overall increase in building costs would be 1 percent (Exhibit 4).

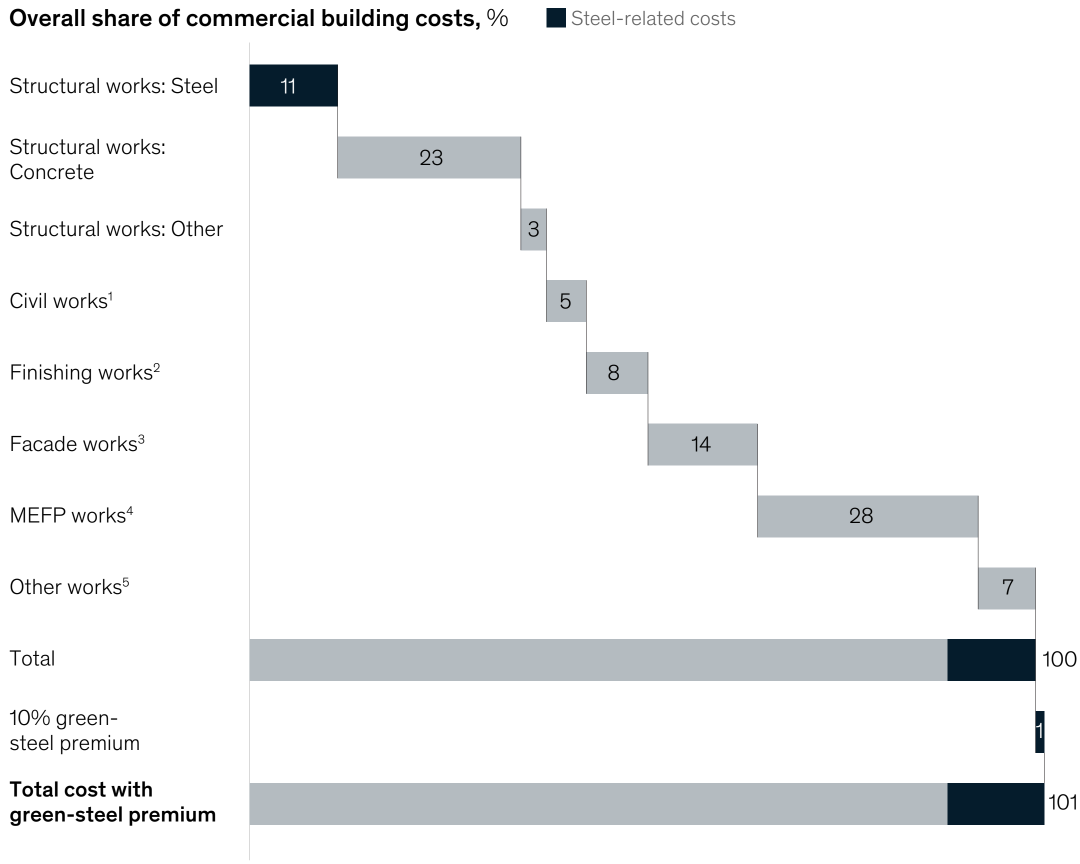
In modeling the decarbonization pathway for the office building, we assessed more than 25 individual levers.[26] These can be grouped under five decarbonization categories (Exhibit 5):

1. *Seek out efficiency in construction materials and design.* These are no-regret priorities that, by definition, will lower material and construction costs. Examples include hollow-core buildings, thinner load-bearing walls, and modern insulation. A change in materials mix could also contribute. Moving from "cast in place" buildings to hybrid buildings with concrete core and steel frames could significantly lower embodied CO_2 emissions by reducing concrete usage.[27]

[26] The CO_2 abatement curve is an illustrative example. Regional differences (for instance, in steel production, technology, or materials availability) can significantly change the levers. The mentioned costs are aggregated for the eventual lever.
[27] Seeking out efficiency in construction materials and design, assumes no incremental cost to reduce waste, and only cost saving from higher efficiency, including hollow-core design and reduction of bearing-walls. For concrete, typical waste of 4.0 percent can be reduced to 2.0 percent with best practices; for steel, typical waste of 10.0 percent can be reduced to 5.0 percent with best practices; for gypsum, typical waste of 22.5 percent can be reduced to 15.0 percent.

Exhibit 4

Given a 10 percent premium on steel, the overall increase in building cost would be 1 percent.



Note: Figures may not sum to 100%, because of rrounding. Results assume a 40 percent share of green hydrogen-based DRI EAF steel and a 60 percent share of EAF-based secondary steel. In Europe and the United States, many construction applications, such as rebar, are made entirely from secondary steel. However, there are limits to using secondary steel in construction due to supply constraints and metallurgical requirements of certain applications, such as steel sheets in composite slabs, roof purlins, and plate structures. A 20 to 25 percent premium on H2-DRI EAF steel would imply an overall increase in steel premium of 10 percent.

[1] Includes flooring, waterproofing, and masonry. [2] Includes flooring and cladding, doors and windows, and cafeteria. [3] Includes glass and brick facade works. [4] Mechanical, electrical, fire protection, and plumbing works. [5] Includes external development, car stackers, and furniture.

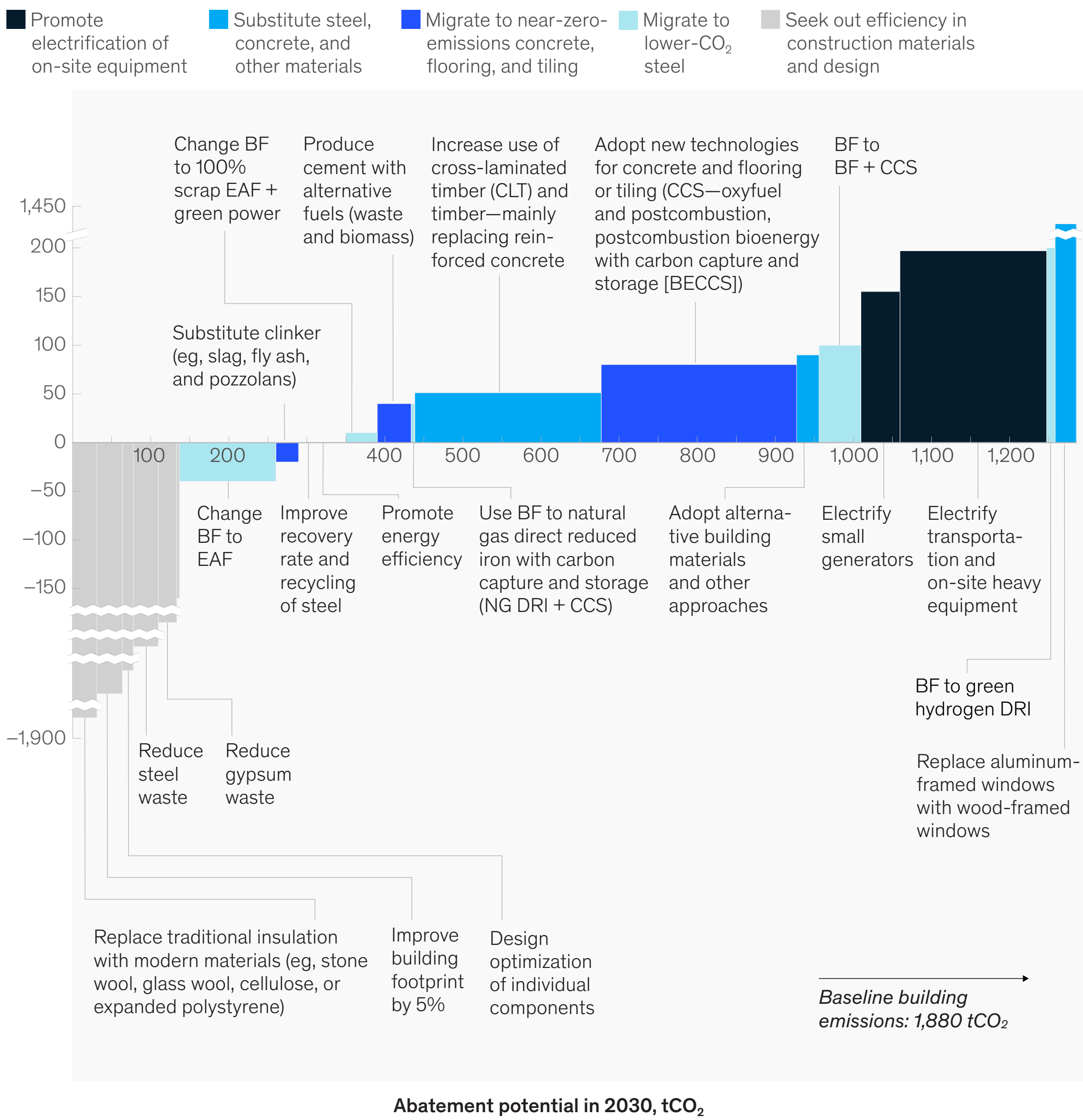
2. *Migrate to lower-CO_2 steel.* Moving from BF/BOF to EAF steel would have an immediate impact on embodied carbon (more than 100 metric tons of embodied CO_2 in our example, or more than 8 percent of total abatement potential). However, this measure would not change steel emissions on a macro level, due to leakage of demand to high-CO_2 production routes. Breakthrough steelmaking technologies include hydrogen-reduced DRI/HBI+EAF and are a potentially powerful decarbonization lever. However, this solution carries a larger premium due to lower technology readiness. The green-steel premium is expected to fall as the technology is scaled and adopted.

3. *Migrate to near-zero-emissions concrete, flooring, and tiling:* Incorporating CCS technologies in concrete, flooring, and tiling production could enable roughly 25 percent of the abatement potential in our example

Exhibit 5

Embodied-carbon reduction demands new technology.

Abatement cost (2020),[1] $ per metric ton of CO_2 (tCO_2)



Compared with "cast-in-place" buildings, hybrid buildings with a concrete core and steel frame can significantly lower embodied CO_2 emissions by reducing concrete usage. Using structural steel instead of reinforced concrete can significantly reduce emissions.

Note: The horizontal axis shows the abatement potential of the technology switches. The vertical axis displays the average abatement cost as $ per metric ton of CO_2 (tCO_2) for each switch. "Concrete" includes concrete foundations, basement walls, basement slabs, ground-floor slabs, typical floor slabs, columns, load-bearing walls, and concrete blocks for the facade, stairs, and roof screed. This assumes no interactions in emissions abatement among different levers for the same material. This assumes 25% of concrete emissions and 15% of steel emissions are not abatable—eg, due to residual positive emissions from "green-steel" technologies—eg, electric-arc furnaces (EAF), blast furnaces and basic oxygen furnaces with carbon capture and storage (BF/BOF+CCS), etc—and a potential lack of green-steel supply. $10 is a tentative value for the BF to 100% scrap EAF + renewable-power lever.
Source: Eight-story office building Bill of Quantities emissions model; *Building*; Commonwealth Scientific and Industrial Research Organisation (CSIRO); Embodied Carbon in Construction Calculator (EC3) database; European Union website; Inventory of Carbon and Energy (ICE) database; Bernardino D'Amico, Jim Hart, and Francesco Pomponi, "Whole-life embodied carbon in multistory buildings: Steel, concrete and timber structures," *Journal of Industrial Ecology*, April 2021, Volume 25, Number 2; McKinsey analysis

building. While the decarbonization opportunity is large, the cost would be relatively high (between approximately $50 and $100 per tCO_2 abated).

4. *Substitute steel, concrete, and other materials.* Replacing structural steel with glulam beams and cross-laminated timber (CLT)—as well as replacing in-situ concrete slabs with CLT or using timber instead of concrete for load-bearing walls—could further reduce building embodied carbon emissions.[28] The levers in this methodology could theoretically abate more than 20 percent of embodied carbon emissions, but the cost would be relatively high (often around $50 to $100 per tCO_2—but sometimes significantly more).[29] This implies a need for market incentives to support uptake beyond lighthouse projects.

5. *Promote electrification of on-site equipment.* On-site emissions from small generators, transportation, and heavy equipment could be abated through electrification. The electrification of small generators seems likely in the short term, while the electrification of heavy equipment and transportation poses challenges associated with battery and charging infrastructure. While the cost to electrify small generators is slightly lower than that of heavy equipment or transportation, both are approximately $150 to $200 per tCO_2, representing a substantial cost.

To put the construction sector on a path to net zero, all of the identified levers need to play a role. However, given the price sensitivity of the construction industry, the cost of several new technologies must be reduced to make the proposed changes feasible at scale.

Next steps: Five key strategies for greener steel

To get to net-zero steel and decarbonize the construction sector, both public and private actors need to support the transition. Here, we gather five indispensable strategies that can move the agenda forward:

1. Create common definitions for near-zero-emissions steel and promote transparency

There is no industry alignment on the definition of "green steel," with industry bodies, steel producers, and consumers often applying their own definitions (see sidebar "Definitions of 'green steel' vary"). Priorities should include the following:

[28] This assumes no regulatory constraints on the use of cross-laminated timber (CLT) or timber (for example, limited to five-story buildings) and no recent price increase—for example, CLT or timber could be applied in in-situ concrete slabs, load bearing walls, or facades.
[29] For more, see "Call for action," July 14, 2021.

Definitions of 'green steel' vary

Companies have taken varying approaches to defining the terms of their transitions. Volvo Group announced in 2021 that it had signed an agreement to develop the world's first vehicles made of "fossil-free" steel, made using fossil-free electricity and hydrogen.[1] BMW Group said in 2021 that it plans to source steel produced with up to 95 percent less CO_2 emissions without requiring fossil resources.[2] Steel producer ArcelorMittal said that "recycled and renewably produced" means that physical steel is made with recycled material (scrap) using renewable electricity, leading to a CO_2 footprint of as low as approximately 300 kilograms of CO_2 per metric ton of finished steel when the metallics are 100 percent scrap.[3]

[1] "Volvo launches world's first vehicle using fossil-free steel," Volvo, October 13, 2021.
[2] "Harnessing wind and hydroelectric power from the Arctic Circle: BMW Group plans to source steel produced with green power and hydrogen from northern Sweden," BMW Group, October 20, 2021.
[3] "XCarb™ recycled and renewably produced," ArcelorMittal, accessed January 26, 2022.

There is limited visibility into Scope 3 emissions in the construction value chain, which can reduce the appetite for investment in near-zero-emissions steel.

— *Seek industry alignment on a common definition along the spectrum of greenness.* "Green steel" could be defined as having a Scope 1, 2, and 3 intensity of less than 0.2 tCO_2 per metric ton of steel. Near-zero-emissions steel could be defined as having a Scope 1, 2, and 3 intensity of less than 0.5 tCO_2 per metric ton of steel. High-CO_2 steel could be defined as having a Scope 1, 2, and 3 intensity of more than 0.5 tCO_2 per metric ton of steel.

— *Define a measurement system.* Develop a common CO_2 intensity methodology along the lines of European standard EN 19694-2, specifying how industry participants should estimate GHG emissions.

— *Label near-zero-emissions steel.* Create common labeling or grading of CO_2 intensity to support decision making—for example, the ResponsibleSteel label.

2. Foster public- and private-sector demand by creating visibility into embodied carbon

There is limited visibility into Scope 3 emissions in the construction value chain, which can reduce the appetite for investment in near-zero-emissions steel. To create visibility, stakeholders should consider the following actions:

— *Develop a uniform methodology to track emissions of embodied carbon.* This would require increased traceability of material GHG emissions through life cycle assessments (LCAs) and environmental product declarations (EPDs), and standardized reporting of embodied emissions. In effect, this would mean expanding and standardizing embodied calculators, such as EC3.[30]

— *Incorporate embodied carbon into standards and certifications.* Industry entities could create requirements for low thresholds of embodied carbon emissions in green-building rating systems, such as LEED and BREEAM,[31] leveraging EPDs and LCAs.

— *Set embodied-carbon targets.* Actors across the construction value chain could create Scope 3 carbon targets at the portfolio, project, and materials levels. They could prioritize absolute reductions over intensity reductions and align with goals based on Paris Agreement 1.5° pathways. They could adopt established calculation methods—for example, from the Science Based Targets initiative.[32]

— *Translate targets into decision-making processes.* Owners, financiers, developers,

[30] EC3 is the Embodied Carbon in Construction Calculator, Building Transparency's free database of construction EPDs and matching building impact calculator for use in design and material procurement.
[31] Building Research Establishment Environmental Assessment Method.
[32] The Science Based Targets initiative is a collaboration among CDP, the United Nations Global Compact, World Resources Institute, and the World Wide Fund for Nature to help companies set science-based climate targets.

Moving the dial on demand

Executives across the construction industry offer a range of perspectives on the challenges ahead:

"If a developer is keen to reduce CO_2, they will put on pressure and set requirements. However, developers have only been focused on price."
—*VP general contractor*

"Currently, within the construction industry, there has been dialogue about low-CO_2 steel, but there has not been any formal request for low-CO_2 steel."
—*Director of commercial, distributor*

"Construction will be the second mover. When the construction industry starts asking the steel industry for low-CO_2 products, the steel industry will have already reacted to the automotive industry."
—*VP general contractor*

Source: Expert interviews

or operators could create templates for procurement and reporting in both the public and private sectors. In particular, they could incorporate internal carbon-pricing mechanisms into decision-making processes or significant green-steel quotas into procurement targets.

3. Unlock demand for near-zero-emissions steel
Near-zero-emissions steel cannot compete with established technologies on the basis of price alone (see sidebar "Moving the dial on demand"). To unlock demand, developers, operators, owners, and large occupiers could prioritize the following:

— *Develop a buyers' club for near-zero-emissions steel.* Bring together developers, owners, operators, occupiers, and other construction value-chain actors willing to buy net-zero (or near-net-zero) steel at a premium. These could signal demand by aggregating future purchase commitments for net-zero steel.

— C*ommit to offtake agreements for select breakthrough near-zero-emissions steel mills.* Construction companies or developers that procure directly from steel producers could guarantee a proportion of the output of a "lighthouse" net-zero (or near-net-zero) steel mill project for a predetermined period of time.

— *Unlock funding for steel mill projects.* Large developers and owners that buy steel could further derisk net-zero (or near-net-zero) steel mill projects by assembling willing capital providers or becoming equity investors themselves.

— *Scale and replicate.* Scale pilots to potential near-zero-emissions buyers, steel producers focused on breakthrough technology mills, and capital providers willing to invest to reduce the green premium (see sidebar "Demand for near-zero-emissions steel: A hydrogen-reduced DRI/HBI+EAF mill").

4. Tilt capital formation toward near-zero-emissions steel
Most capital providers, including banks, infrastructure funds, and pension funds, still do not consider embodied carbon in their investment and underwriting decisions. To marshal capital toward low-emissions steel, they should undertake the following actions:

Demand for near-zero-emissions steel: A hydrogen-reduced DRI/HBI+EAF mill

We estimate the capital expenditure for a greenfield hydrogen-reduced DRI/HBI electric-arc furnace (DRI/HBI+EAF) mill to be approximately $1.2 billion. The illustrative mill would have a 1.2 million metric ton capacity, an 85 percent utilization rate, and input of 40 percent DRI and 60 percent scrap. The example assumes that North American prices for green hydrogen, including electrolysis, drop from $4.89 per kilogram to $1.62 per kilogram over 20 years.

For the investment to be as economical as BF/BOF production, the steel would require a green premium of 20 to 25 percent over a 20-year period (exhibit).

Exhibit

The required green premium for a new-build hydrogen DRI/HBI+EAF mill would be 20 to 25 percent over 20 years.

Preliminary, illustrative North America example

	Capital expenditure (capex) included[1]								
Route	EAF[2]	DRI[3]	CSP[4]	Hot mill	Cold mill	Galvanized line	CCS[5]	**Included capex,** $ billions	**Needed green premium[6] for breakeven vs ongoing BF/BOF[7]**
Ongoing BF/BOF route[8]									
Hydrogen DRI/HBI+EAF route with EAF capex[9]	●	*Assumes DRI will be purchased in the market*						0.8	5–10%
Hydrogen DRI/HBI+EAF route with EAF and DRI capex	●	●						1.2	20–25%
Hydrogen DRI/HBI+EAF route with integrated facility capex	●	●	●	●	●	●		2.2	40–45%
Ongoing BF/BOF route with CCS capex							●	0.6	40–45%

Note: Cash flows are aggregated from 20 years and terminal value with a discount factor of 8%. Cash flow includes revenues from steel, operating expenditure, and capital expenditure (when applicable). Price of steel assumed to be 2019 average price of hot-rolled coil ($598.74) and adjusted for a constant inflation over time (2% a year). Mills with included capital expenditure have a building time of 2 years (ie, operating expenditure is not included for first two years). All mills have an average 1.2 metric megatons of capacity and 85% utilization rate. Mills including EAF have a distribution of 40% direct reduced iron and 60% scrap.
[1]Mills with included capital expenditure divide capex over first two years. [2]Electric-arc furnace. [3]Direct reduced iron. [4]Continuous strip production. [5]Carbon capture and storage. [6]Green premium is assumed to last for 20 years; does not account for selling, general, and administrative expenses (SG&A). [7]Blast furnaces or basic oxygen furnaces. [8]Capital expenditure not included for BF/BOF mills due to existing operations and small likelihood of new mills being constructed. BF/BOF operating expenditure is the average of both sinter and pellet mills. [9]DRI/HBI+EAF is direct reduced iron and hot briquetted iron plus electric-arc furnaces. Assumes green-hydrogen price steadily decreases from $4.89 per kg in 2021 to $1.62 per kg in 2041. Lower end of price range used due to North American power pricing.

— *Track and report financed embodied carbon emissions.* Estimate and publish investment and underwriting activities associated with emissions, including embodied carbon, while using LCAs and EPDs to track embodied carbon footprints.

— *Track and report the transition risks associated with embodied carbon.* Assess exposure to embodied carbon emissions from investing or underwriting activities—for example, in relation to embodied-carbon taxes.

— *Include embodied criteria in financing decisions.* Take into account embodied carbon in underwriting and financing activities, using references such as an internal carbon price or shadow carbon price.

— *Tilt funding to near-zero-emissions steel.* Create green-debt and green-equity products focused on near-zero-emissions steel. These might include green bonds, transition or emission bonds, green loans, or green revolving-credit facilities, with interest rates linked to output intensity and interest payments pegged to green-steel prices.

5. Disseminate knowledge and awareness
Not all actors in the construction value chain are aware of construction embodied carbon footprints, the GHG emissions associated with specific materials, or the near-term options for addressing embodied carbon. Market participants should spread the word about carbon footprints, steel carbon footprints, and potential decarbonization solutions. Platforms such as conferences, training sessions, and roundtables would all serve the purpose. Discussions should be backed by science-based assessments of quality and performance, case studies, and technical data.

Assuming progress on the five strategies, decision makers considering capturing the decarbonization opportunity should ask themselves six key questions:

1. How can I capture the true economic cost and value of near-zero-emissions steel in construction projects?
2. How is near-zero-emissions steel positioned versus other abatement options?
3. When and how can I secure a supply of near-zero-emissions steel? Where do competitors stand?
4. Which engineering processes and systems need to be modified, if any?
5. How can information about the embodied emissions of steel products be best shared across the supply chain?
6. What are the implications for procurement and contracting practices?

The construction industry is at a crossroads. Rising demand for new approaches and the emergence of viable solutions (albeit at a cost) put the onus on companies and stakeholders to accelerate the process of greening the industry. Green technologies could enable significant reductions by 2030 and almost complete abatement by 2050. However, progress is contingent on collaboration through the value chain, from steel production to choices regarding building design, architecture, and construction. In our example, a concerted effort across a range of levers could reduce embodied carbon in a commercial office building by more than two-thirds. The imperative, therefore, is for the industry to seize the moment, adopt a radical mindset, and prepare for the transition to a greener future.

Pedro Assunção is a consultant in McKinsey's New York office, where **Trevor Burns** and **Ingrid Koester** are consultants and **Alex Ulanov** is a partner; **Brodie Boland** is a partner in the Washington, DC, office; **Emanuele D'Avolio** is a consultant in the Chicago office; **Focko Imhorst** is a partner in the London office; and **Rory Sullivan** is a consultant in the Dubai office. **Alasdair Graham** is the head of industry decarbonization for the Energy Transitions Commission in London. **Carl Kühl** is an analyst for the Energy Transitions Commission in Munich.

The authors would like to thank David Wigan for his editorial support.

MISSION POSSIBLE PARTNERSHIP

This report was co-developed by McKinsey's Metals & Mining and Sustainability Practices and the Energy Transition Commission for the Mission Possible Partnership

Designed by McKinsey Global Publishing