SUSTAINABLE DATA CENTERS ROADMAP

CHAPTER 3.3

Embodied Greenhouse Gas Emissions (Scope 3)

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3.3 Embodied Greenhouse Gas Emissions (Scope 3)

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The embodied emissions of data centers can be significant, chiefly due to upstream emissions from manufacturing steel, cement, concrete and computer hardware. (These are often referred to as Scope 3 emissions.[1]) In cases where a data center consumes only very low-carbon power (e.g., from renewables or nuclear), embodied emissions can exceed 40% of a data center's total greenhouse gas emissions and may dominate the lifetime greenhouse gas emissions footprint.[2,3] For example, despite significant investments in renewable power and carbon dioxide (CO_2) removal since 2021,[4] Microsoft's corporate net greenhouse gas footprint increased in 2023 and 2024. This increase was due chiefly to Scope 3 (embodied) emissions from data center production and building, not Scope 2 emissions from power supplies.[5]

The growing size and complexity of data centers adds to the total carbon footprint of new sites. Individual sites can be many hectares and even more than 1 square mile (2.6 km^2) in some recent examples. In addition, chip production can contribute significant greenhouse gases to a facility's footprint due to fossil electricity and use of fluorinated gases (F-gases), such as sulfur hexafluoride (SF_6) and carbon tetrafluoride (CF_4), which are very potent greenhouse gases.

Unfortunately, there are few options to purchase low-carbon goods today. Supplies of low-carbon cement, concrete, steel and chips cost significantly more than conventional supplies. More importantly, total volumes of these goods are very small, making purchasing difficult. Production sites are often geographically distant from data center construction, adding cost and carbon to direct use.

Decision makers must better understand the scale of the embodied emissions from data centers and the challenges to abatement. *They should have as much familiarity with embodied and Scope 3 contributions as with power usage effectiveness (PUE)*. Practices such as extending server life cycles can reduce total embodied carbon and should be considered by operators. Opportunities for innovation in technology, policy and commercial models exist but will require sustained investment and commitment to achieve important climate and economic outcomes.

A. Primary Sources of Embodied Emissions (Scope 3)

The main infrastructure of a data center includes the core and shell,[6] pipes, wiring, cooling systems, IT hardware and ancillary systems, such as back-up power, batteries and low-voltage switchgear. (See Chapter 1 of this Roadmap.) All these contribute to Scope 3 emissions.

- The core is the space that houses pipes, wiring, cooling systems and related equipment. The core comprises load bearing walls, elevator shafts, pilings and interior foundations, including columns, beams, slabs and walls.
- The shell includes the exterior elements of the facility, including structural foundation, roofing, exterior walls, waterproofing and parking.
- Information technology (IT) hardware includes servers, power supplies, networking equipment and data storage/memory equipment.

Cement and concrete, steel, chips and other IT equipment release the largest greenhouse gas emissions associated with data center construction. Concrete and steel constitute the largest Scope 3 component of the core and shell, with different amounts and kinds of concrete and steel selected to match the facility design needs.[7]

Figure 3.3-1. *Embodied emissions of a modern data center (year-1 build)*
Selected categories only (per MW basis)

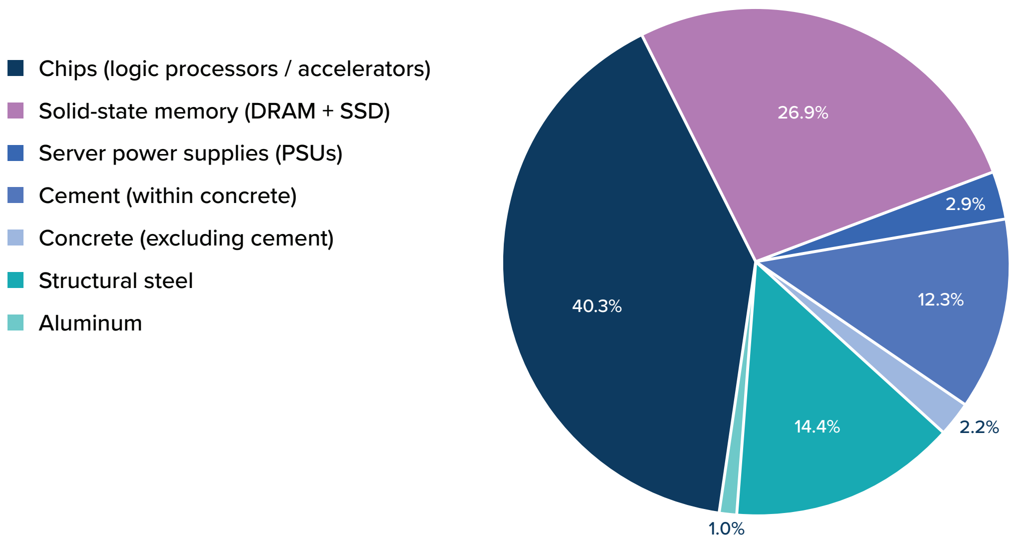


Table 3.3-1. *Embodied CO_2e by Category (Per MW and Scaled to Annual New Capacity)*

Category	tCO_2e per MW - year 1 build	$MtCO_2e$ per year at 20 GW (mid-case)	$MtCO_2e$ per year at 18 GW (low-case)	$MtCO_2e$ per year at 27 GW (high-case)
Chips (logic processors/ accelerators)	768.2	15.36	13.83	20.74
Solid-state memory (DRAM + SSD)	512.1	10.24	9.22	13.83
Server power supplies (PSUs)	54.9	1.1	0.99	1.48
Cement (within concrete)	235.0	4.7	4.23	6.34
Concrete (excluding cement)	41.5	0.83	0.75	1.12
Structural steel	274.9	5.5	4.95	7.42
Aluminum	19.2	0.38	0.35	0.52

Figure 3.3-1 and Table 3.3-1. Source: Schneider Electric (2023)[2], Schneider et al. (2025)[8]

Box 3.3-1

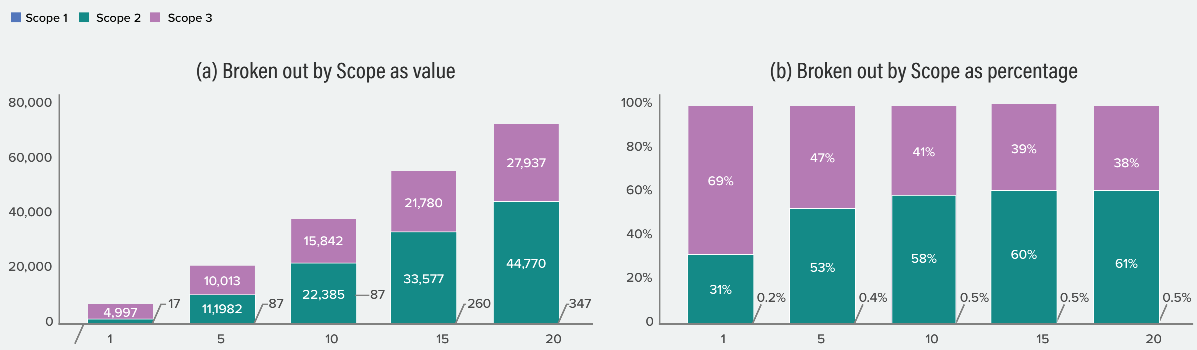
A 200 MW reference data center

To anchor the analysis of this chapter, we considered a 200 MW data center and the materials required to make it. The physical footprints of 200 MW data centers vary between roughly 60,000 m^2 (~650,000 ft^2) and 120,000 m^2 (~1.3 million ft^2), depending on energy density, geography, design, computational function and other factors.[9,10]

- We assume 93,000 m^2 (1 million ft^2) for a 200 MW data center.
- Some components of a data center are replaced or upgraded during its life, especially racks and computer hardware, while other components, such as core and shell, do not change. We use a 15 year life-cycle estimate, a typical number for a data center's life,[2] which will include some IT hardware replacement.
- A 200 MW data center can require a wide range of concrete volumes as a function of building code, seismic requirements and design. Estimates range between 55,000 and 500,000 m^3. We assume 300,000 m^3 of concrete for a facility of this size.
- Robust, validated estimates for use of structural steel and rebar in data centers are scarce. Assuming 50-75 kg/ft^2 of floor (535-802 kg/m^2), total steel would be 50-75 million kg for a 200 MW data center.
- The broad category of IT equipment comprises a wide variety of components, including servers, networking equipment, storage, and racks and enclosures. Some hyperscalers have developed detailed models for the embodied emissions of these systems, but the models are not comprehensively available. Rough estimates suggest that these systems collectively have embodied carbon[11] of 750-1500 tons of CO_2 equivalent (tCO_2e)/MW.

Accurate data on physical materials going into modern data centers are scarce. Decision makers in industry and governments should prioritize making these data available to the public and ensuring their quality.

Figure 3.3-2. *Scope 1, 2 and 3 footprints for a representative data center at different years in its operation. Source: Schneider Electric (2023).*[2]



i. Cement and concrete

Cement production generates 1.6 Gt/year of CO_2 emissions, or roughly 6% of global annual greenhouse gas flux.[12] Approximately 50% is from fuel used to generate high-temperature heat and 50% is due to by-product emissions from production chemistry.[13] Concrete is a mixture of cement, aggregate (sand and gravel) and water. Although cement represents roughly 15% of concrete by weight, it contributes the overwhelming majority (roughly 88%) of concrete's greenhouse gas footprint.[14] Typical concrete emissions for 1 m^3 of concrete are 410 kg/m^3 but can range between 290 and 610 kg/m^3 depending on cement content (e.g., substitution of pozzolanic materials), energy input mix (coal, gas, biomass, used tires), water footprint, transportation and similar factors.[15]

A data center requires significant volumes of cement and concrete, which contributes significantly to its embodied emissions. Depending on setting and design, the embodied emissions from concrete for a 200 MW data center would equal 123,000 tCO_2e if built using 300,000 m^3 concrete (87,000-183,000 tons).

Estimates for total concrete used in data center construction globally in 2025 vary from 1.3 million to 4.5 million m^3. This equates to roughly 0.5-1.8 million tCO_2, with a median estimate of 1.15 million tCO_2 each year. For comparison, a single 200 MW natural gas plant would emit nearly 0.5 million tCO_2 each year, not including potential upstream emissions, which could significantly add to the total footprint. Said differently, the total annual emissions from concrete added by all new data centers globally could equal the annual emissions from 1-3 natural gas power plants.

ii. Steel

Steel production worldwide releases 3.6 Gt CO_2/year,[16] or roughly 8% of annual CO_2 emissions and 6.5% of greenhouse gas emissions. Each production pathway has different emissions profiles and different pathways to abatement.[17] On average, iron and steel production generates ~1.9 kg of CO_2 per kg of steel.[16] Given that, the embodied emissions of a 200 MW data center could range between 95,000 and 140,000 tonnes of CO_2.

- Roughly 75% of steel globally is produced through blast-furnace/basic oxygen furnace (BF/BOF) facilities. Like with cement, significant portions of these emissions are chemical production by-products from these operations.

- Electric arc furnaces (EAF) recycle scrap steel but cannot produce primary iron or steel. Roughly 20% of global supply comes from EACs. Their footprint is significantly lower than for BF/BOF systems, although the total embodied emissions will vary significantly based on the source of electricity (coal-fired, gas-fired, nuclear or renewable source).

- Roughly 5% comes from direct reduction of iron (DRI) facilities that use coal or natural gas for both heat and chemical reduction in tandem with an EAF to process the sponge iron made by the DRI. A very small volume (<1%) comes from DRI-EAF systems that run on low-carbon hydrogen.

Public data on total steel used in data center construction are not available, making estimation difficult. One estimate[18] asserts that data centers require 150-200 kg/m^2 (30-40 lbs/ft^2) but without additional documentation. Even if correct, the estimated square meterage of data centers built or projected is poorly known, preventing easy estimation. Using a value of 275 tons of steel/MW (from Schneider Electric[2]; see Table 3.3-1), a 2.4 carbon intensity for average steel (tonnes CO_2/tonne steel), and estimates of recent and projected builds, Table 3.3-2 estimates steel use in data center builds and associated Scope 3 emissions. This may be an under-estimate since it does not include emerging markets.

Given the anticipated growth of data centers discussed in Chapter 1 of this Roadmap, annual Scope 3 emissions from steel alone should grow to more than 10 Mt/year soon, most likely before 2030.

Ultimately, this estimate underscores the need for better data and greater attention on embodied emissions. It also suggests that gathering and sharing these data may prove complicated for governments, requiring greater transparency by builders and owners of data centers.

Table 3.3-2. Estimated data center construction and associated Scope 3 emissions in 2024.

	Estimated MW of construction in 2024	Estimated Scope 3 emissions from steel (tonnes CO_2) in 2024
United States	6900 MW[19]	4,500,000
Asia Pacific	1600 MW[20]	1,100,000
Europe-ME	750 MW[21,22]	500,000
Total	9250 MW	6,100,000

iii. Semiconductors, chips and other information technology (IT) hardware

Production of servers, power supplies, networking equipment and data storage/ memory equipment generates greenhouse gas emissions in two ways. First, the electricity generated to power manufacturing equipment leads to CO_2 emissions, depending on the emissions intensity of the generation source. The electricity (Scope 2) emissions of the global semiconductor industry were approximately 44 million tCO_2e in 2021.[23] (Other industries, such as electronics-component manufacturing, also consume electricity to produce IT equipment for data centers.) Second, semiconductor fabrication involves use of F-gases, such as SF_6 and CF_4, which can be vented to the atmosphere under some circumstances. While F-gas emissions intensity from the semiconductor industry has fallen, total emissions have continued to rise, exceeding 15 million tCO_2e in 2020.[24] Only a portion of these electricity-related and F-gas-related emissions are directly attributable to semiconductors produced for data centers because semiconductors are also used in a wide variety of other sectors. Comprehensive, recent data on these emissions are not readily available.

Additional equipment at data centers, such as gas-insulated electrical switchgear, can contain F-gases (specifically SF_6), which can potentially escape to the atmosphere during maintenance, fault events and end-of-life disposal. Estimates of current emissions rates from this type of equipment at data centers are not available, although the use of gas-insulated switchgear at data centers is growing.[25]

B. Technology Options for Low-Carbon Data Center Supply Chains and Construction

Builders and operators of data centers could significantly reduce their emissions with existing technologies. Although it is not possible to achieve zero Scope 3 emissions today, advanced technologies could potentially reduce these emissions dramatically. Innovative approaches, both in design and within supply chains, have the potential to reduce embodied emissions if developed, applied and purchased.

i. Material substitution

If approximately 30% of Scope 3 greenhouse gas emissions come from steel, cement and concrete, reducing the total amount of these materials could reduce embodied emissions in data centers. This strategy chiefly involves substituting materials that use less of the emitting constituents.

When making concrete, it is possible to substitute a portion of clinker with other materials that perform the same function (called pozzolinic materials or supplementary cementitious materials (SCMs)). Fly ash, steel slag and silica fume are examples of man-made SCMs, and volcanic ash, metakaolin and diatomaceous earth are natural examples.[26] In particular, fly ash, a byproduct of coal combustion, is used to some degree in 60% of US Portland Cement and can replace 15-40% of the clinker based on type of fly ash and concrete performance requirements.[27] In addition, new concrete formulations can use advanced cements, such as pozzolins, binding additional CO_2 into the concrete matrix.

Another strategy is to completely substitute one material for another. For example, some structural reinforced concrete can be replaced with novel wood products, including cross-laminated timber (CLT) or timber-concrete composites (TCC). This can represent an effective greenhouse gas reduction of 75% for the portions replaced.[28] This approach can be done at scale: Microsoft is building a new data center using CLT as a structural building material, representing an overall greenhouse gas reduction of 35% for the core and shell.[29]

Although this strategy can and should be adopted more widely, material substitution reductions are real but limited. Obtaining and using these materials can add cost and complexity to commercial projects. Moreover, concrete foundations and structural steel elements are very difficult and/or very expensive to replace. Additional steps and strategies are required to achieve deep Scope 3 reductions.

ii. Low-C manufacturing of building materials

Because many of the materials used in constructing data centers have high embodied carbon intensities, producers must change feedstocks or add technologies and practices to achieve significantly lower carbon production. Consequently, supply of low-carbon products is globally limited. To achieve economic viability, production facilities will require buyers willing to pay a green premium or additional market-aligning policies that support low-carbon production. However, producers could significantly reduce Scope 3 emissions of products by applying existing or novel technology, changing feedstocks, and innovating supply chains and business models as options develop and enter the market.

Box 3.3-2

Environmental attribute certificates (EACs)

It is often impractical, costly or carbon intensive to transport low-carbon goods from their point of manufacturing to the point of use. Increasingly, environmental attribute certificates (EACs) allow companies, in effect, to sever environmental attributes from low-carbon goods, pay for them, and claim them without direct physical transport or use. This technique has served buyers and producers of sustainable aviation fuel,[30] clean electricity[31] and low-carbon cement.[32]

EACs can help speed investment and development of clean goods, materials and services.[33] They also present risks, where carbon accounting practices are not strictly followed, potentially leading to false claims and misrepresentation of greenhouse gas enterprise emissions.

Companies and regulators should acquaint themselves with the use of EACs to speed technology entry into markets. They should also use quality criteria to ensure that use of EACs avoids double-counting estimated carbon benefits or misrepresenting them in corporate claims. Quality criteria are beginning to emerge based on both procurement practices and science-based technical assessment (e.g., Carbon Direct and Microsoft (2025)[33]).

a: CCUS

Carbon capture, use and storage (CCUS) is a set of established technologies to directly control carbon emissions. CCUS includes the following:

- Carbon capture, which separates and concentrates CO_2 from air or industrial facilities, such as power or steel production. This process most commonly involves chemical or physical separation with solvents.[34-36]

- CO_2 transportation, which brings CO_2 from the capture facility to the site of use or storage.[37,38] This process most commonly involves dedicated CO_2 pipelines, but it can also involve transport by ship, barge, truck or rail.[39]

- Use of CO_2, either through direct use or conversion into other products like fuel, chemicals or building materials.[40,41]

- Geological storage of CO_2 in dedicated storage facilities. This process most commonly involves storage in deep saline formations or depleted oil and gas fields, but it can also involve storage in basaltic formations or direct mineralization.[42-44]

More than 50 CCUS facilities operate today, capturing and storing over 60 million tons of CO_2 per year.[45] However, while many workers have identified CCUS as a promising technology to reduce the greenhouse gas footprint of heavy industrial production,[46,47] very few plants operate on these facilities.

Because of cement's intrinsic chemistry, CCUS remains one of the few ways to deeply decarbonize cement production.[13,48] Similarly, CCUS remains an important opportunity for decarbonizing steel production that uses blast furnaces,[17] both due to blast-furnace chemistry and high temperature heat requirements. CCUS can also provide low-carbon “blue” hydrogen for DRI production, as it does today in Abu Dhabi.[42] However, the timeline for decarbonized steel appears to be much longer than that for cement.

Box 3.3-3

Brevik low-carbon cement facility (Norway)

Recently, Heidelberg Materials commissioned the carbon capture, use and storage (CCUS) facility at their Brevik plant in Norway, which will capture 400,000 tonnes of CO_2 each year, ship it to the North Sea and store it over 1 km below the sea floor.[49] This will reduce the carbon intensity of the cement they produce by 50%.[50]

The Brevik facility, with integrated cement production and CCUS. Source: Heidelberg Materials[51]

Although CCUS technologies are well established, deployment today is limited. Commercial deployment is capital and energy intensive, adding significant cost. CCUS for heavy industrial applications would enter markets with small margins and lack of global standards for product carbon intensity. The EU carbon border adjustment mechanism (CBAM) covers both steel and cement but does not yet impact production.

Ultimately, CCUS is promising for emissions reductions. Additional policy measures are required to cover the green premium or additional costs.

b: Biomass

In producing low-carbon building materials, biomass is both prominent and promising. Industrial-grade biomass comprises forestry residues, agricultural wastes, municipal wastes and biomethane, which could provide a low-carbon, high energy-density fuel for many industrial applications, including steel and concrete production.[13,52,53] In the case of primary iron production, biocoke can also provide the chemical energy and physical properties necessary for blast-furnace operation,[54,55] as demonstrated in commercial operations in both Brazil[56] and Japan.[57] When combined with CCUS, use of biomass creates the potential for both profound emissions reductions and CO_2 removal in production—carbon-negative manufacturing.[17,58]

Several factors and conditions must be met for biomass use to significantly reduce the carbon intensity of manufactured goods:

- **Sustainability**: First and foremost, biomass must be sustainably sourced.[33,59] If biomass is not harvested and sourced sustainably, it could lead to increased deforestation, loss of soil carbon, and other direct and indirect greenhouse gas emissions.[60] Multiple international standards exist, but nations and operators have not yet agreed to adopt one standard or set.

- **Energy density**: Different forms of biomass have different energy content and energy density. Industrial operations commonly require high energy density fuels for heat, and biocoke in particular requires both high energy density and specific physical properties (e.g., high yield strength).

- **Continuous supply**: Commercial manufacturing operations require biomass delivery that is consistent in volume, energy content, moisture and schedule. Many biomass conversion facilities face challenges in maintaining consistent and regular biomass supply.

To avoid poor or counterproductive purchases, data center buyers and builders must acquaint themselves with the potential risks of biomass-based reduction strategies, chiefly from compromised feedstock supplies.

c: Clean direct electrification

Electrification of heavy manufacturing is challenging. This is particularly true for processes that involve chemical reduction or dissociation or require F-gas use.[48] In some cases, key geographies (e.g., Taiwan, Korea, Japan) lack low-carbon electricity supplies, limiting what emissions reduction is possible simply due to the high carbon intensity of the grid. Finally, cases where high-quality heat is essential[13,61] often cannot be electrified at all, meaning significant greenhouse gas reductions through direct electrification (i.e., >10%) are extremely difficult.[17]

However, the situation is improving. Cost reductions, technology development and performance improvements have created decarbonization opportunities within specific assets and regions. Many companies have emerged since 2020 to produce low-carbon goods through direct or indirect electrification, with some technologies and companies reaching pilot or early demonstration stages.

EAFs are a mature technology to process scrap metal or sponge iron into usable steel or steel feedstock. Use of EAFs represents 30% of global steel production today.[62] While EAFs are incapable of new iron and steel production, they are essential for recycling steel and DRI production.[17,63] The industry has increased the fraction of steel produced with EAFs, with this trend expected to continue.[64] To reduce their Scope 1 and 2 emissions, some operators of scrap-EAFs have transitioned their electricity supply to renewable power,[65-67] which in turn reduces the Scope 3 emissions of their buyers, including data center builders.

For primary iron production, molten oxide electrolysis (MOE) and electrowinning are novel electrochemical technology approaches that convert iron ore into iron using electricity directly. MOE immerses iron ore in a molten oxide bath, electrically heated to ~1600 °C, at which point electric currents break down the ore into molten iron. In electrowinning, iron ore is suspended in a low-temperature alkaline solution (~110 °C), where a current reduces the iron ore to iron in a process similar to electroplating. Unlike the DRI process described below, MOE and electrowinning eliminate the need for an EAF to process sponge iron. Today, the technical readiness is low (TRL 5) with only small pilot plants in operation or design.[68]

Compared to the steel industry, direct electrification in the cement industry is not close to commercial deployment. There are no commercial-scale pilots in operation or construction. Conventional rotary kilns cannot be electrified, and few are near retirement today in China, India or the United States.[69] Advanced technologies—TRL 5 or lower today—are promising but still at the pilot scale. Promising technologies include electric calciners like LEILAC[70] and electrifying the kiln burning zone with resistive heating, mechanical heating, plasmas, or a combination of approaches.[71] Even then, these technologies would still require that by-product CO_2 be managed with CCUS for deep abatement—roughly 50% of the total footprint. Unlike with MOE or electrowinning with steel, there is no cement production pathway without byproduct CO_2.

LIMITS: While technical readiness is a principal challenge to direct electrification, supply of low-carbon electricity presents major challenges in most geographies:

- Overall, the lack of capacity in nuclear, wind or solar presents a challenge—indeed, data centers themselves are challenged finding such power to operate with minimal Scope 2 emissions. (See Chapter 3.2 of this Roadmap.)

- To make efficient use of the capital invested, high-capacity factors for facilities must be patched to high-capacity production of green electricity. This greatly limits geographies of operation.

- For plants seeking to develop renewable power, land access for wind and solar is increasingly challenging. This is particularly true in densely populated areas where industrial production is concentrated.

- All together, these three elements can add significant cost. Since these are commodity industries with small margins, small increases in manufacturing cost can end investment without advanced market commitments, pre-purchase or other kinds of guaranteed offtake.

- Finally, addition of large loads onto the grid to operate electrified industrial production could lead to addition of fossil generation, either new generation or increased capacity factors of existing plants. These could affect the system-wide footprint of electricity and prove counterproductive to climate goals.

Wide deployment of these technologies will have to overcome these challenges in many contexts, markets and geographies.

d: Clean indirect electrification - green hydrogen

Electrolytic hydrogen production using low-carbon electricity, also called green hydrogen production, provides both thermal energy and chemical reduction for manufacturing low-carbon materials in data centers.[17,72,73] The most prominent pathway involves DRI, using hydrogen instead of natural gas, in tandem with an EAF to convert the sponge iron to pig iron.[74] Interest in this pathway has grown significantly, with new projects announced and under development.[75] Several small commercial facilities are being built or are in operation today, including SSAB's (Svenskt Stål AB's) Hybrit facility.

Sweden has pioneered production of "green steel" using green hydrogen and direct reduction of iron (DRI). In particular, two Swedish companies have built and are building green steel facilities.

SSAB built and operates the Hybrit facility,[76] which it describes as "fossil free steel." Begun in 2016 in partnership with Vattenfall, Hybrit received research and development (R&D) support from the Swedish government from 2018 to 2024.[77] The plant began construction in 2018 and produced the first sponge iron in 2020. In 2025 the pilot plant became fully operational. As of 2024, the facility has produced 5000 tons of steel, with expectations to expand to 1.2 million tonnes per year before 2030.

Volvo, Mercedes-Benz, Ruukii Construction and several other companies have purchased offtake from Hybrit, but to date, no data center builders or operators have purchased this steel.

The Hybrit demonstration plant. Source: High North News.[78]

Stegra is deploying the same technology as SSAB at their Bowen Plant.[79] This facility will be Europe's first greenfield steel plant in 50 years and is set to commission in 2030. It uses 700 MW of renewable power (mostly hydropower) to make enough hydrogen for 5 million tonnes of steel per year.

LIMITS: The limits of direct electrification (above) with electricity supply also apply to indirect electrification and green hydrogen production—cost, duty cycle, grid impacts, etc. Moreover, electrolytic hydrogen faces challenges in the capital costs of electrolyzers and balance of plan. In addition, DRI-EAF production requires a special iron ore (magnetite) that is higher cost and has limited supply.

iii. Low-C manufacturing of IT equipment

The production of IT and related equipment for data centers involves many distinct manufacturing steps for hundreds to thousands of individual components and associated assembly, testing, packaging and shipment. Unlike structural materials, such as concrete and steel, IT equipment and the related systems that support them are highly heterogeneous. Thus, the methods to reduce emissions from their production vary widely. However, some general guidelines for emissions reductions include the following:

- Maximize the use of low-carbon electricity at all stages of production, including initial materials extraction and processing, electronic and electrical component production, semiconductor fabrication, final assembly and testing.

- Maximize the use of recycled materials (e.g., copper, steel, printed circuit board resins).[80]

- Extend the lifespan of IT equipment, including servers and networking equipment.[81,82] Notably, while refresh intervals for most IT equipment are generally lengthening, graphics processing unit (GPU) lifetime may be an exception to this, driven by factors such as rapid technology development.[83]

- Follow low-embodied-emissions procurement standards for electronics developed by industry consortia, such as the Global Electronics Council.[84]

- For semiconductor fabrication, ensure that F-gas emissions are minimized through exhaust gas destruction and related methods.[85]

- For gas-insulated switchgear, explore use of alternatives to SF_6 for electrical insulation.[86]

While some IT equipment providers have released estimates of the embodied emissions of specific hardware components,[8,87] comprehensive studies on optimizing overall embodied emissions reductions across data center IT and related equipment are lacking. Thus, there is a clear need for these assessments in a transparent and accessible form.[88,89]

Box 3-3.4

CO_2 removal and superpollutant reductions.

Even with significant action and investment, all pathways find that a significant fraction of emissions cannot be reduced by existing technology. This is particularly true for the embodied emissions of data centers, which lack cost-effective solutions and clean manufacturing capacity today and in the near term (before 2035).

Acknowledging these facts, many technology firms and data center builders have made significant commitments to purchasing valid, durable CO_2 removals to complement their commitments to rapid and profound greenhouse gas reductions, including their Scope 3 burden. Microsoft,[90,91] Google,[92] Meta,[93] Apple[94] and Amazon[95,96] have made significant corporate commitments and have large programs in CO_2 removal. These include the LEAF (Lowering Emissions by Accelerating Forest finance) program[97] and significant CO_2 removal purchases, such as nature-based,[98] engineered,[99] hybrid[100] and novel approaches.[101] All these companies acknowledge that emissions reductions—including Scope 3 emissions—are their priority but that they must be complemented by high quality CO_2 removal to manage irreducible emissions.[102]

Reducing short-lived, very strong greenhouse gases (sometimes called "superpollutants") is another complementary approach to direct reductions. This approach includes investments in the destruction of potent non-CO_2 greenhouse gases like methane, nitrous oxides and F-gases outside of their direct value chain.[103] Recently, Google announced new commitments in superpollutant destruction,[103,104] again to complement their existing reduction targets and to strengthen their overall corporate commitments to achieving net-zero.

C. Innovation Agenda

The high cost and difficulty of reducing Scope 3 emissions demands investing in innovation that leads to solutions in global markets. Many governments, including Japan, the United States, the United Kingdom and European Union nations, have substantial research, development and demonstration (RD&D) programs focused on reducing embodied emissions through novel manufacturing processes, carbon management, electrification and dematerialization. In addition, many technology company buyers and manufacturers have ambitious sustainability targets and have made significant and sustained investment in RD&D to reduce Scope 3 greenhouse gas emissions in their value chains.[104]

Ultimately, rapid and profound reductions in embodied emissions requires more effort and investment. Specifically, the range of pathways to lowering embodied emissions and the focus on data center-related products and practices must increase. In some cases, promising pathways must receive additional support and scale to manifest solutions that can scale commercially. Examples include the following:

- **Targeted research**
    - Minimizing F-gas leakage and use in IT hardware manufacturing.
    - Developing novel pozzolinic materials that can reduce total clinker use in concrete.
    - Improving capital costs for green hydrogen, MOE and electrowinning pathways, with a focus on reducing balance of system cost.
    - Integrating carbon capture systems into cement and BF-BOF iron production.
    - Increasing energy density and mechanical strength in biocoke.
- **Cross-cutting research**
    - Identifying and removing adoption barriers for dematerialization strategies.
    - Identifying new options to generate low-carbon electricity in critical markets for producing IT hardware (e.g., Taiwan).
    - Generating novel design options for data centers that are inherently low embodied emissions.
    - Ranking opportunities based on speed of implementation, levelized cost and readiness (technical, infrastructure, workforce).

Given the rapid changes in data center markets, both technology evolution and emergence of needs, governments should not develop programs in isolation. Rather, they should tune existing programs in partnership with industry to maximize impact and avoid waste. Doing so will require a new level of trust and transparency, well beyond existing circumstances. The proprietary nature of many industrial innovations makes this difficult. Industrial, academic and governmental actors should come together to prioritize pre-commercial and shared RD&D agendas that can demonstrate progress against the rate and scale of embodied emissions growth.

D. Recommendations

1. *Governments should* ***assemble and share data related to direct, indirect and embodied greenhouse gas emissions from data center construction and operation****. Data center owners and operators should* ***volunteer to share site-specific estimated Scope 3 emissions data proactively and invite third-party review****. If necessary, governments should* ***require disclosure of this information****.*

2. *All stakeholders should* ***gain familiarity with the embodied emissions of data centers. They should recognize that abatement options today are real but limited and potentially expensive.***

3. *Before designing and siting data centers, data center owners and operators should* ***identify and assess potential options to reduce Scope 3 emissions through material reduction and substitution****. Companies should use existing scientific criteria for high-quality, low-carbon goods and should consider developing their own criteria.*

4. *During procurement and construction phases, data center owners and operators should* ***assess the availability of low-carbon strategies and materials, including IT materials and building materials*** *and use those low-carbon strategies and materials wherever possible. They should consider EACs to speed emissions reduction and support low-carbon manufacturing facilities, such as biocoke in blast furnaces, carbon-free steel production and cement with CCUS. They should also consider adhering to low embodied-carbon procurement standards for electronics developed by industry consortia.*

5. *Governments should support* ***comprehensive, transparent studies on optimizing overall embodied emissions reductions*** *across the full spectrum of data center IT equipment. These studies should be conducted by independent, third-party researchers, with relevant data shared voluntarily by data center operators.*

6. *During the operational phase, data center operators should **minimize IT equipment refresh rates** and seek to procure low embodied-emissions servers, networking equipment, memory and related equipment.*

7. *Governments should **assess the current supplies of low-carbon building materials** and **consider adding production capacity through policy measures**, including direct grants, government-backed procurement, contracts for differences, etc. They should also consider regulating production of IT hardware to reduce emissions, in particular focusing on F-gas use, leakage and destruction.*

8. *Governments should **support development of advanced technologies that limit the greenhouse gas footprint** associated with data center construction. They should explore and support applied research into alternative production approaches to chip-making that use less F-gases and manage their leakage better. They should explore alternative pathways to manufacturing cement, concrete and steel.*

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