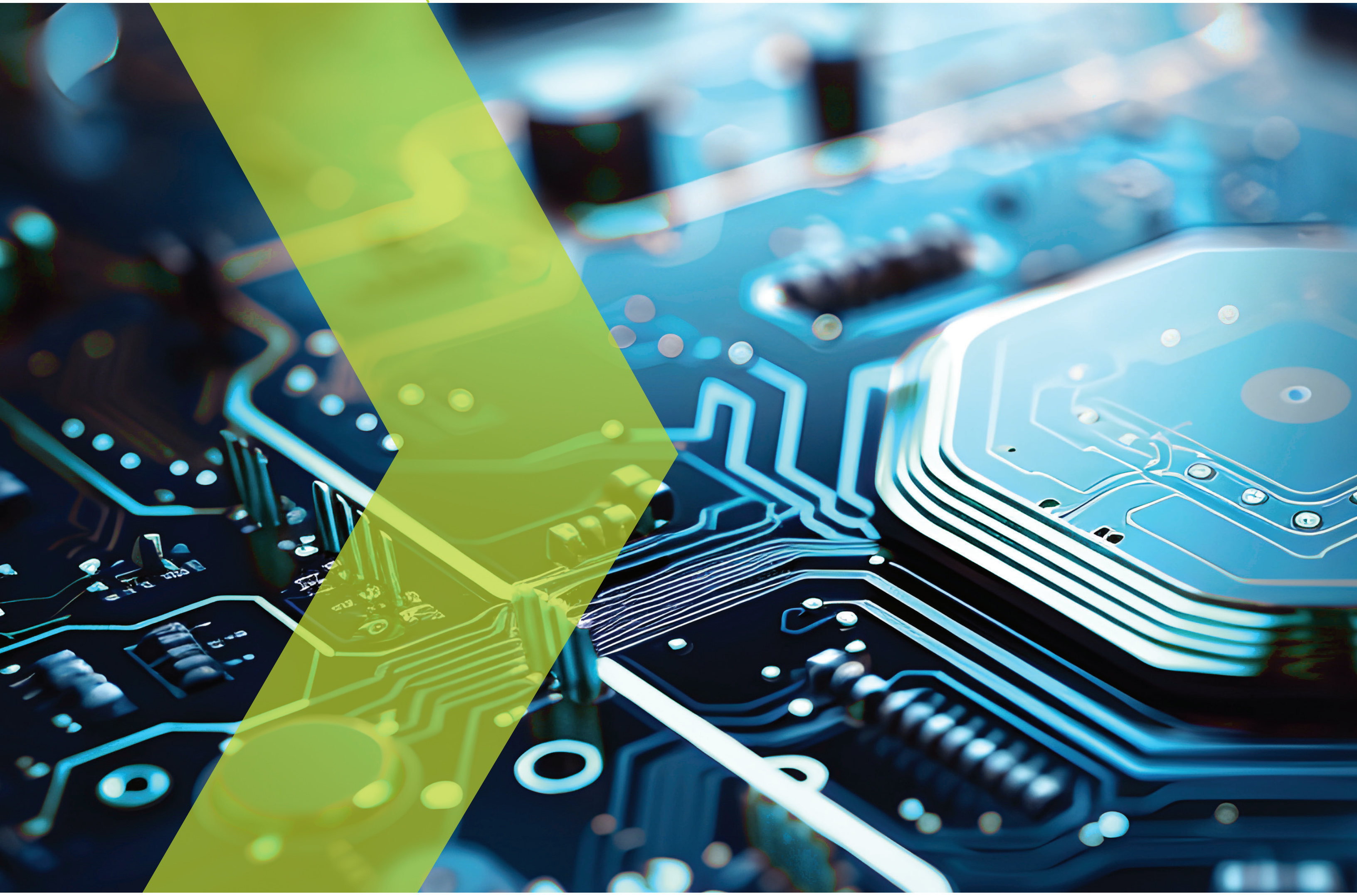
Transparency, Ambition, and Collaboration:

Advancing the Climate Agenda of the Semiconductor Value Chain



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Semiconductor Climate Consortium

BCG BOSTON CONSULTING GROUP

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Why this report is critical

Global organizations such as the United Nations are increasingly concerned that the world is not on a path toward net zero by 2050, resulting in increased urgency for virtually all industries to forge concrete commitments that result in tangible actions to reduce greenhouse gas emissions. Not surprisingly, then, as the semiconductor industry's value chain activities expand rapidly, the industry's carbon footprint is drawing more attention.

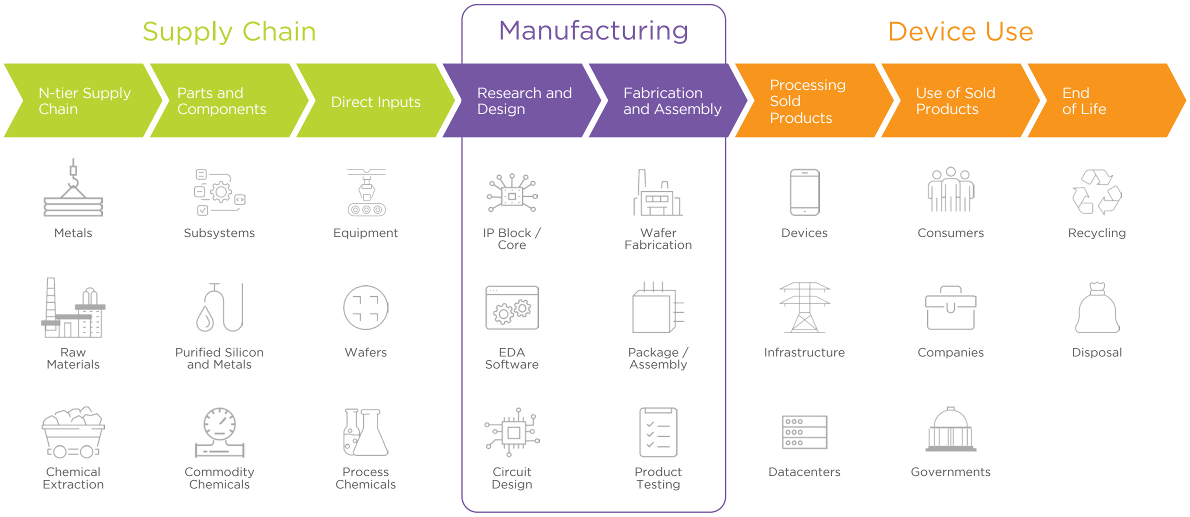
Semiconductor manufacturing, including electronic design automation and intellectual property (EDA & IP), wafer fabrication, chip design, and package, assembly, and test, is directly responsible for 0.3% of global carbon emissions today and induces another 1% in upstream and downstream suppliers and users. Companies in the industry recognize the need to come together to address the largest and most difficult sources of emissions and set the industry on a path toward net zero by 2050 within the 1.5°C pathway.

Past studies have attempted to provide visibility into the sources and quantities of emissions from semiconductor production. However, these studies have not been sufficiently comprehensive across the entire value chain, failed to examine each source of emissions in depth, and did not offer credible forecasts of how emissions may shift in the future. To address these shortcomings, BCG, SEMI, and the Semiconductor Climate Consortium (SCC) partnered to examine greenhouse gas (GHG) emissions from every source and from the supply chain, manufacturing processes, and device usage (see Exhibit 1).

Our goal is to distinguish this report by its comprehensiveness and the co-authorship of climate and sustainability leaders across the semiconductor value chain. Working with industry experts, we undertook the most expansive analysis to date of the semiconductor industry's current emissions profile and the possible future scenarios. This analysis is built upon 1 million data points across 200 companies in the semiconductor value chain that account for 80% of the emissions we studied; in all, we analyzed emissions involving fifteen types of greenhouse gases and nearly three dozen types of greenhouse gas sources. The authors deeply appreciate the support and partnership of CDP (www.cdp.net), the primary source of data for this effort.

Introduction:
Why this report is critical

Exhibit 1: Semiconductor value chain activities



Source: BCG analysis

Five takeaways from the research:

1. **Baseline of value chain emissions:** Semiconductor devices produced in 2021 have a lifetime CO_2e footprint of 500 megatonne (MT), 16% from supply chain, 21% from manufacturing, and 63% from device use.

2. **Electricity as the largest lever:** Low-carbon energy sources can address >80% of industry emissions primarily by reducing electricity used to manufacture and then use devices, which could be achieved with bold and decisive investments in low-carbon energy.

3. **Investment and innovation to solve remaining 16%:** Emissions from the supply chain and from manufacturing process gases will require considerable research and development to address, necessitating investments now.

4. **Future manufacturing emissions scenarios:** Current government and company commitments will substantially reduce manufacturing emissions, but they are still forecasted to overshoot the carbon budget for the 1.5°C pathway.

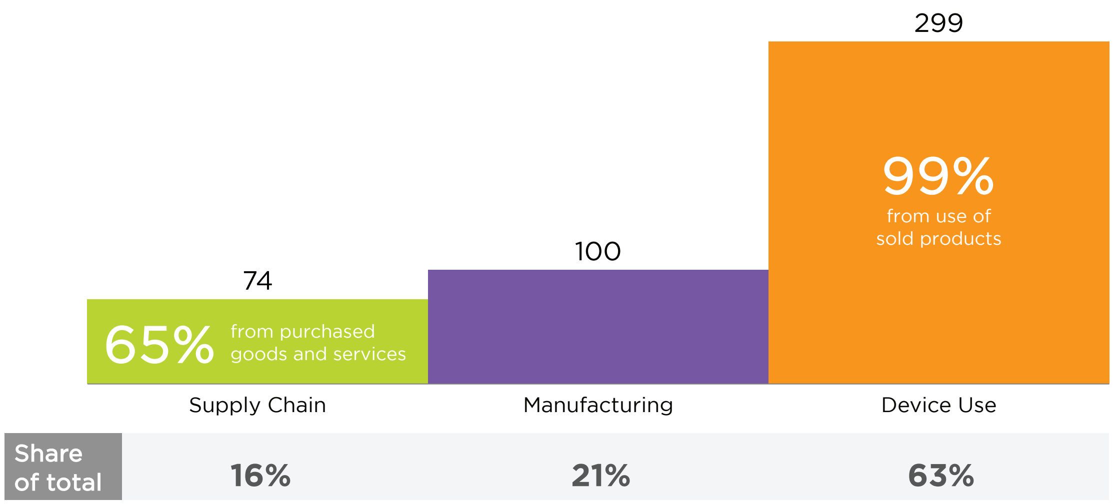
5. **Dilemma of value chain emissions:** Digital technologies which require semiconductors play a big and crucial role in reducing energy use and emissions across industries.

Takeaway 1:
Baseline of value chain emissions

Baseline of value chain emissions

The most fundamental findings from the study – indeed, the necessary starting point for decarbonization roadmaps – involve the magnitude and sources of greenhouse gas emissions (see Exhibit 2). The deep interdependencies of this industry to produce such a complex product mean that most emissions reduction solutions will not come from within one company or activity but from collaboration across many.

Exhibit 2: Lifecycle emissions of a semiconductor or device (Megatonnes CO_2e, 2021)



Source: CDP, BCG analysis

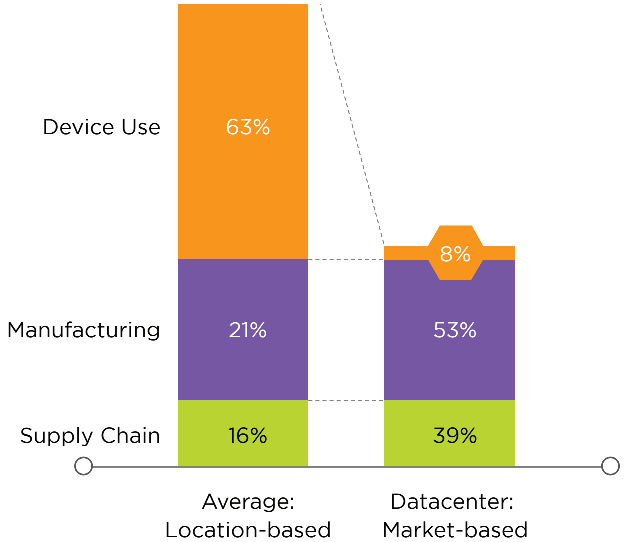
Supply chain emissions are calculated using wafer fabrication company's reported upstream scope 3 emissions as these companies have the best visibility into the equipment, materials, and services required during manufacturing. The supply chain accounts for 16% of a semiconductor's lifetime emissions, over half of which are from purchased goods and services used in manufacturing processes.

Semiconductor manufacturing is calculated directly from company reported emissions performing these activities. Over 20% of semiconductor emissions are produced during design, fabrication, and packaging and testing. Of manufacturing emissions, 65% is from electricity to power equipment and buildings. The remaining 30% is a result of direct company actions such as using process chemicals that enter the atmosphere during manufacturing.

Device use is calculated using chip designers' reported scope 3 downstream emissions, as they interface directly with end customers and have the most visibility. Device use accounts for 63% of a semiconductor's lifetime emissions due to collective energy consumption of billions of semiconductors in products worldwide. Chips consume electricity in phones, computers, cars, networks, datacenters, and just about any other electronic device you can think of.

It's important to note that all figures in this report use location-based energy emissions, which relies on average grid energy availability and does not consider any market-based tools to achieve lower carbon intensity from energy use. Typical market-based tools chosen by some companies are power purchase agreements to accelerate their and the entire grid's adoption of low-carbon energy sources. These tools have a significant impact on emissions across the entire semiconductor value chain. In fact, the largest purchasers of low-carbon energy are large hyperscalers, which operate datacenters powered by semiconductors. Therefore, a semiconductor deployed in a datacenter will likely have much smaller-than-average market-based emissions when compared to location-based emissions for device use (see Exhibit 3).

Exhibit 3:
Impact of market-based tools on use phase emissions



Source: CDP, BCG analysis

The SCC acknowledges that measuring, tracking, and influencing the trajectory of emissions from device use are exceptionally challenging because the emissions output is driven by global consumer behavior and low-carbon energy availability. Further, as is true for many industries, there is limited company reported data quantifying scope 3 semiconductor emissions. While 96% and 92% of the companies we studied reported scope 1 and 2 emissions to CDP respectively, only 70% reported any scope 3. And the reported data varies in granularity and completeness, sometimes utilizing different calculation methodologies. Overall, these factors tend to result in underreporting. As a result, the industry recognizes that scope 3 data has the greatest opportunity and need for improvement – and as that data is captured more complete emissions estimations will likely increase.

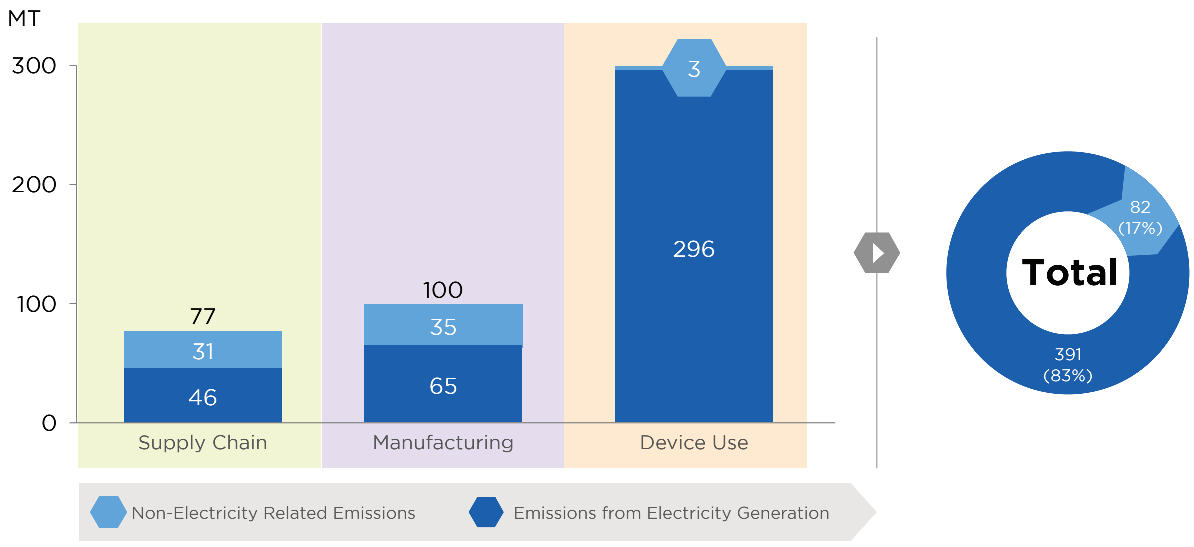
Takeaway 2:
Electricity as the largest lever

Electricity as the largest lever

Reaching net zero by 2050 and minimizing carbon expenditure should start by pulling the largest levers with the most available solutions. For this value chain, as for many others, the largest single lever is low-carbon electricity. Eighty-three percent of semiconductor device emissions are tied to generating electricity consumed by activities across its lifecycle, reported as scope 2 by individual companies (see Exhibit 4).

Exhibit 4:
Emissions by Relation to Electricity Generation (Megatonnes CO_2e, 2021)

There are three primary actions semiconductor companies have been taking and



Note: Figures use location-based data Source: CDP, BCG analysis

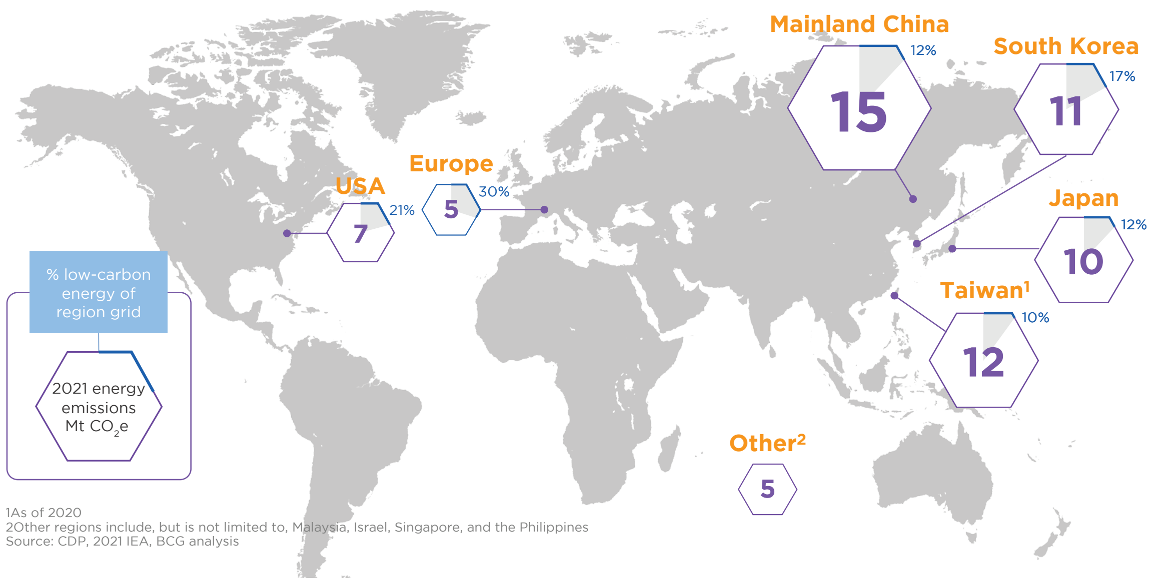
must accelerate to eliminate emissions from electricity generation. First, building and designing more efficient manufacturing facilities and offices which consume less electricity. Second, working with suppliers to use less electricity and to manufacture more energy-efficient equipment and materials. Finally, in partnership with device users, designing and manufacturing more energy-efficient devices.

These three actions are critical to addressing >80% of value chain emissions, but progress on energy efficiency has historically been outpaced by increased consumption and utilization of devices. That is, as semiconductors become more economical to purchase and operate, consumers demand more. If energy consumed by semiconductors continues to increase, reducing energy-related

Takeaway 2:
Electricity as the largest lever

emissions will require investments to accelerate transitioning the global electrical grid to low-carbon energy. This process has already started, but the transition rate varies greatly by market. For instance, it is especially difficult to source low-carbon energy in markets where semiconductor manufacturing emissions are greatest, such as Mainland China, Taiwan, South Korea, and Japan (see Exhibit 5). Further, reducing supply chain and device use emissions from electricity requires access to low-carbon energy for consumers and companies worldwide.

Exhibit 5: Sourcing electricity to reduce manufacturing emissions from energy generation requires investing to increase low-carbon energy availability



1As of 2020
2Other regions include, but is not limited to, Malaysia, Israel, Singapore, and the Philippines
Source: CDP, 2021 IEA, BCG analysis

To speed up the transition to low-carbon energy, semiconductor producers and their suppliers and customers must invest in low-carbon onsite energy production, purchase available low-carbon energy, and advocate for a faster grid transition, especially where semiconductors are manufactured and used. All while continuing to reduce energy consumption.

The full global transition to low-carbon energy will require robust and collaborative efforts among multiple parties to address the foremost challenges in attaining net zero status. This calls for the private sector, public advocates, government bodies, and low-carbon energy providers and energy investors to unite to forge cooperative partnerships, make courageous decisions, allocate assets, and take bold, decisive actions. This collective endeavor can alter the trajectory of carbon emissions, leading to the realization of ambitious net zero goals.

Takeaway 3:

Investment and innovation to address the remaining 16%

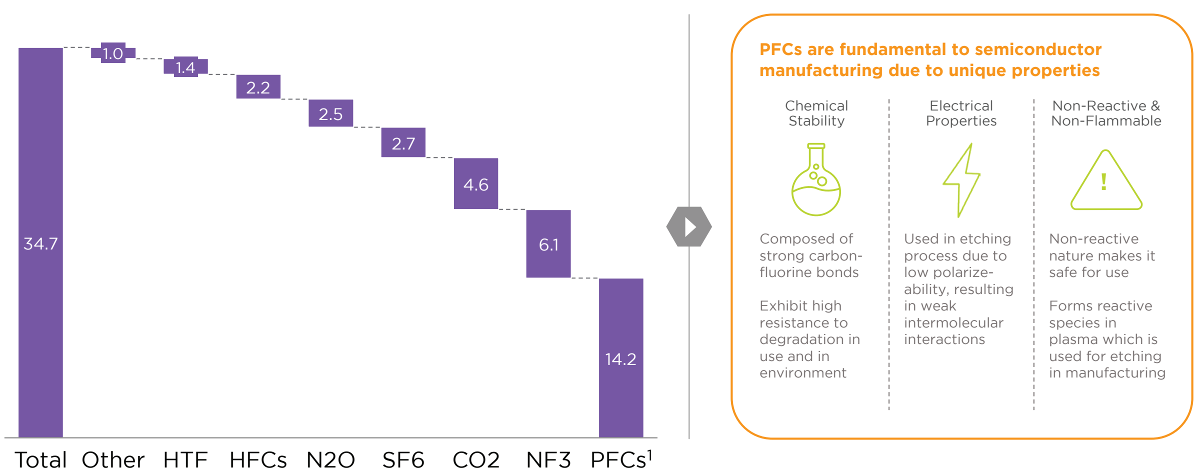
Investment and innovation to address the remaining 16%

While emissions from electricity generation can be addressed through known and viable solutions, this is not the case for emissions from many other sources. Emissions from extracting and refining materials used in semiconductor manufacturing are difficult to eliminate, especially for lower-margin activities and when materials refinement requires high heat or unique chemical processes.

Companies in the semiconductor supply chain are pursuing and achieving their own reduction targets to address their emissions. Still, as major customers, semiconductor manufacturers can collaborate with their existing suppliers in developing equipment and materials with smaller carbon footprints. Additionally, they can engage with new suppliers to explore ways of further reducing emissions.

Direct manufacturing emissions, which an individual company would report as scope 1, account for about 7% of value chain emissions and eliminating them is very challenging; this requires altering fine-tuned, highly complex production methodologies and recipes. Of the process gases used, perfluorinated compounds (PFCs) have the greatest global warming potential (GWP), 100 to 20,000 times greater than CO_2 due to their unique chemical properties which also make them so extraordinarily useful (see Exhibit 6). Alternatives for critical gases such as PFCs are now being evaluated by leading research institutions worldwide.

Exhibit 6: Direct semiconductor manufacturing emissions (Mt CO_2e, 2021)



Acronyms: Heat Transfer Fluids, Hydrofluorocarbons, Nitrous Oxide, Sulfur Hexafluoride, Carbon Dioxide, Nitrogen Trifluoride, Perfluorinated Compounds. 1 PFCs include carbon tetrafluoride (CF4), hexafluoroethane (C2F6),fluoroform (CHF3), octofuoropropane (C3F8), octafluorocyclobutane (C4F8). Source: CDP, ECHA, BCG analysis

Takeaway 3:
Investment and innovation to address the remaining 16%

Companies are also actively exploring various technologies to convert or capture high GWP gases to reduce emissions. Abatement technologies are a key part of this solution, and electrification is driving the development of more efficient solutions. However, we anticipate this to be a long journey for the industry, with many deeply technical challenges remaining to be solved.

Investment in research and development to decarbonize the supply chain and manufacturing processes is critical to accelerate now and will require coordination across many players of the value chain to realize return. International research institutions are working with companies to address these sources of emissions and help companies surpass their emission reduction targets.

Takeaway 4:

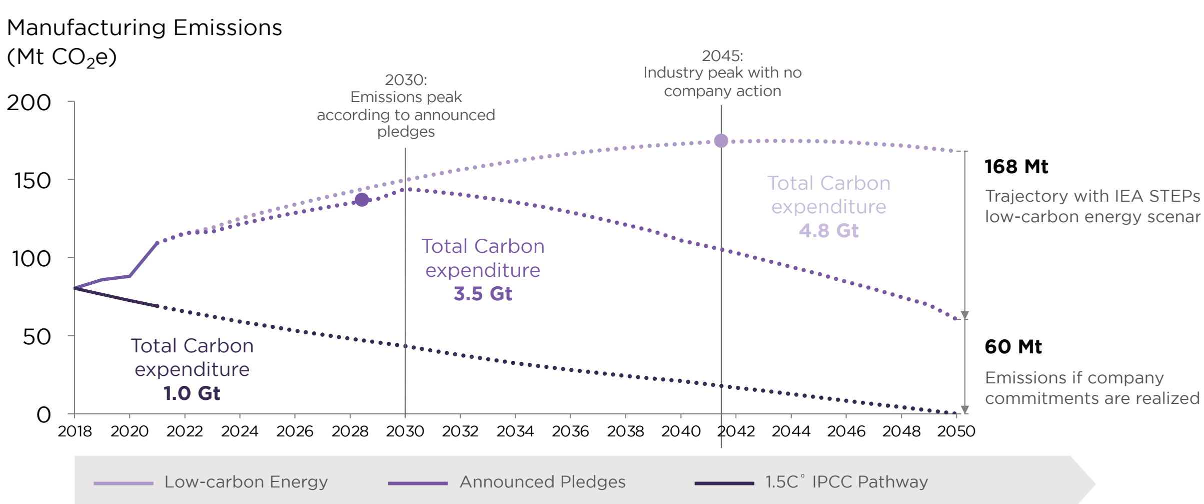
Future manufacturing emissions scenarios

Future manufacturing emissions scenarios

There is a viable pathway to dramatically reduce emissions from semiconductors over the following years and decades. To map out this pathway and possible obstacles to limiting global warming to 1.5°C by 2050, we forecasted how emissions from semiconductor manufacturing activities could shift under different conditions. Given the current difficulties in quantifying supply chain and device usage emissions, we did not include them in our forecasts.

First, viewing global greenhouse gas emissions benchmarks broadly, the 1.5°C pathway scenario requires a 43% reduction in GHG emissions from 2019 to 2030, an additional 50% reduction to 2040, and then net zero emissions by 2050, according to the 2022 Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report. This analysis allocates 1.0 gigaton (Gt) of emissions to the whole semiconductor industry during this period. However, from 2019 to 2050, even if company CO_2 reduction commitments are met, the industry is unlikely to meet this goal, instead emitting 3.5 Gt. (see Exhibit 7).

Exhibit 7:
Announced sustainability pledges reduce total 2019–2050 emissions by 30% and are within 60 Mt CO_2e of 2050 net zero



1 Emissions growth based on projected capacity growth (3.25%) and average intensity growth (1.01%), all else constant
Note: Low-carbon energy scenarios use IEA STEPS for North America, Europe, and Asia-Pacific. Source: BCG analyses on data from: CDP, imec, SEMI, IEA

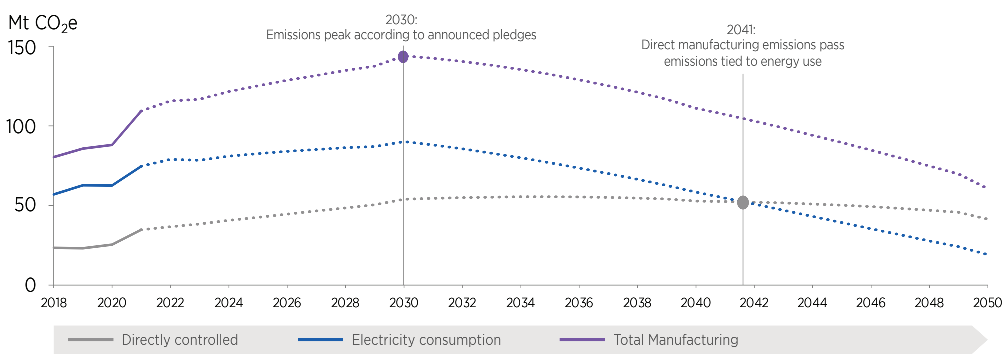
Takeaway 4:
Future manufacturing emissions scenarios

Looking more closely at the scenarios, in the low-carbon energy analysis, semiconductor industry emissions will flatten and stabilize in the next 20-25 years if the IEA Stated Policies Scenario (STEPS) – based on policymaker low-carbon energy goals in North America, Asia Pacific, and Europe – is met. In this scenario, the only action taken by the semiconductor industry would be to help accelerate the adoption of low-carbon energy. But this outcome leaves chip manufacturing emissions at 168 MT, well above net zero and carbon expenditure targets.

In the announced pledges scenario, company commitments by the forty highest emitters in semiconductor manufacturing further reduce emissions in 2050 by 70%. However, this still falls short of reaching net zero emissions in 2050 by about 60 Mt and results in 3.5x the carbon budget.

Drilling down into company commitments to further identify contributors to the carbon expenditure, we anticipate that directly controlled emissions, or the emissions produced from the manufacturing process itself, will experience an average annual increase of 5% through 2035 (see Exhibit 8) before starting to decline as significant net zero milestone years of 2040 and 2050 are approached. Low-carbon energy adoption will cause electricity-related emissions to begin declining at 9% on average annually from 2030 to 2050, becoming less than direct emissions by 2041.

Exhibit 8:
With current announced pledges by governments and companies, direct emissions from manufacturing will surpass those from electricity use by 2041



Note: Forecast uses IEA STEPS for North America, Europe, and Asia-Pacific
Source: BCG analyses on data from: CDP, imec, SEMI, IEA

Takeaway 4:
Future manufacturing emissions scenarios

These projections clearly show that more companies must take more aggressive steps to reduce emissions over the next 25 years to reach net zero and stay within the carbon budget. Further, the global transition to renewable energy will not solve the problem itself. Proactive company action to increase and accelerate clean energy adoption must be paired with aggressive efforts to reduce direct manufacturing emissions.

It is important to note that the industry is cyclical and emissions will fluctuate with shifts in economic conditions that impact utilization rates year-to-year. The forecasted scenarios represent an average view over 30 years rather than precise emissions estimates in any particular year. Further, since nearly no public commitments provide annual-level targets, the slope of the emissions forecast is an estimation that will be highly impacted by the timing of substantial actions, affecting the estimate of the total carbon expenditure over time.

Takeaway 5:
Dilemma of value chain emissions

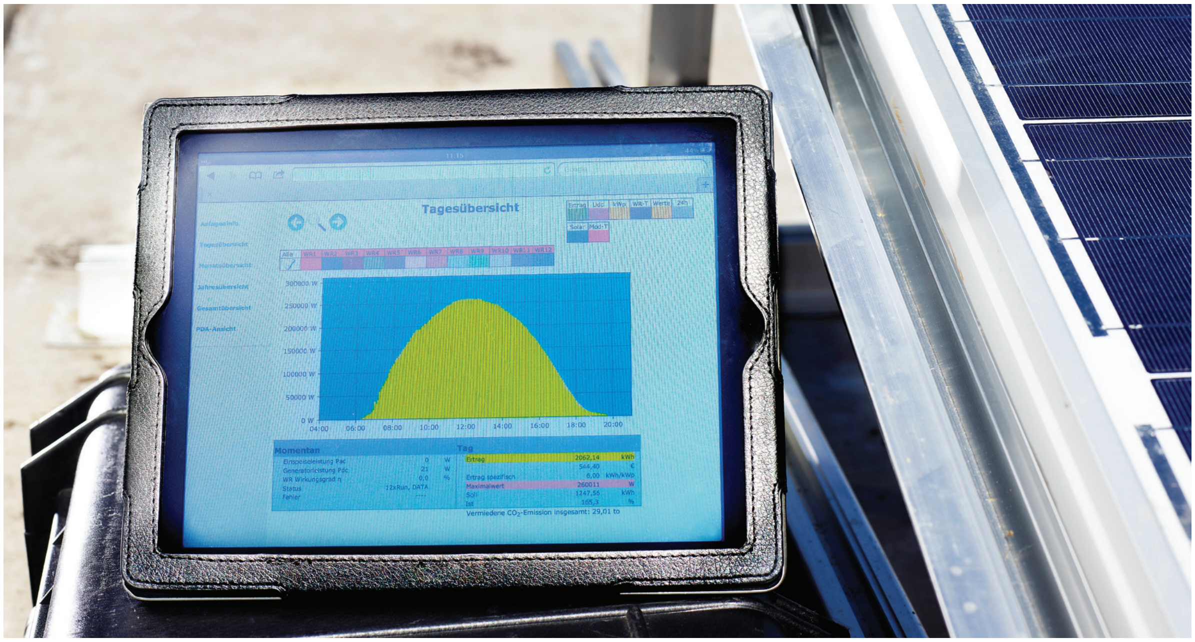
Dilemma of value chain emissions

While the industry contends with its emissions, manufacturing expansion and advancement are required to, among other things, support the global economy and limit the impacts of climate change on all industries, adding an intriguing level of nuance to the semiconductor emissions story.

Semiconductors are required for climate change solutions such as electrification, low-carbon energy, electric vehicles, and digitalization, which have led to a reduction in global emissions of 1 to 2 gigatons in 2020 with potential to enable annual emissions avoidance of 2 to 5 Gt by 2025[2].

In addition to more chips, the world demands greater computational power for applications, such as artificial intelligence, which could aid in climate change solutions. Advanced semiconductors require more steps to manufacture, and these steps utilize more electricity and chemicals. Growing emissions intensity per unit of production compounds the emissions impact of increasing manufacturing output.

However, companies in the semiconductor value chain are not accepting the status quo. Many are already taking steps to reduce emissions in alignment with the 1.5°C pathway and are working toward roadmaps to reach net zero by switching to low-carbon energy, collaborating with suppliers and customers, and changing manufacturing processes.



[2]Goldman Sachs. (2023). GS SUSTAIN: Avoided Emissions: How quantifying Avoided Emissions can broaden the decarbonization investment universe.

Conclusion:

Semiconductor Climate Consortium aspirations

There is still a lot of work to be done, but companies in our industry are committed to doing it together, and we see tangible signs of progress and actions. With the understanding that the quality of this report and ongoing tracking of emissions are a function of reported data, the SCC continues to encourage full transparency from all industry companies. Over the past few years, companies across the value chain have increased their efforts to report GHG emissions more accurately. Since the inception of SCC, working groups have been established within scopes 1, 2, and 3 to measure and track the industry's performance in each area, share best practices with peers, and drive concrete actions.

The climate consortium has three key focus areas – (i) Evolving toward full transparency within the value chain; (ii) Enabling a swift transition to low-carbon energy, impacting their own operations, decarbonizing upstream suppliers, and addressing product use energy; (iii) Collaborating with research institutions to find solutions for high GWP process gases.

The scope 1 working group is focused on sharing mitigation strategies for high GWP greenhouse gases. In parallel, the scope 2 working group is focused on three areas: first, accelerating the adoption of low-carbon energy; second, improving access to low-carbon energy in Asian operations; and third, discovering novel methods for low-carbon energy. In the scope 3 working group, members are studying how to increase transparency into upstream emissions and identify actions to decarbonize them.

These actions aim to steer the industry's commitments and actions toward a 1.5°C pathway. The Baseline, Ambition Setting, and Roadmapping working group, which was responsible for this report with BCG, is now developing short and long-term targets that the value chain can use to hold itself accountable in the journey to net zero. Although substantial work lies ahead, the industry is highly motivated to pursue the appropriate and practical measures required to reach the collective ambition.

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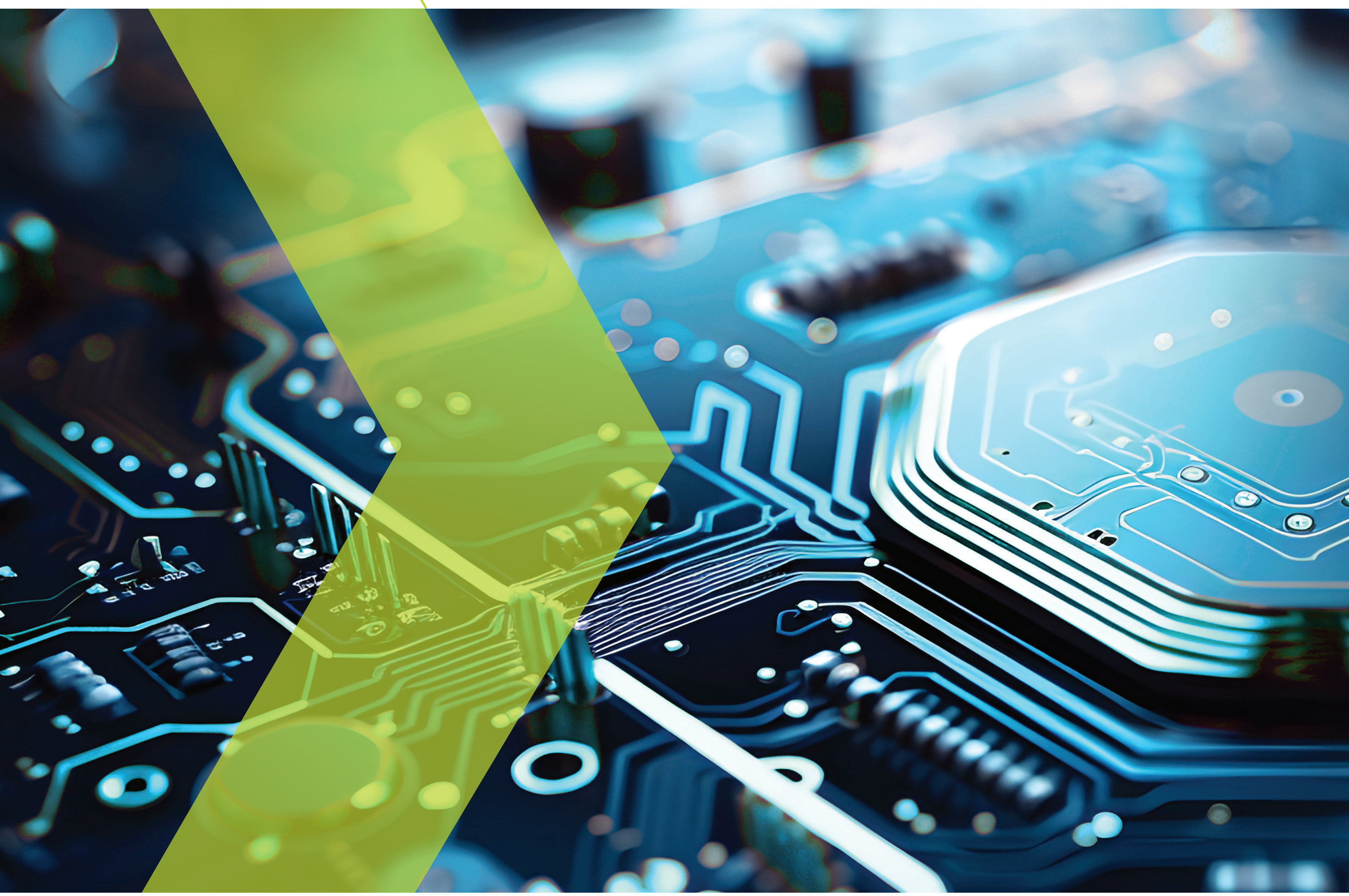

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