STUDY

Chip Production's Ecological Footprint: Mapping Climate and Environmental Impact

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Main Takeaways

Semiconductors are increasingly vital in our modern world and geopolitics, but their manufacturing process has a significant ecological footprint, consuming substantial energy and water while emitting toxic chemicals and greenhouse gases. This fact has been downplayed in recent years because policymakers and customers have prioritized supply security over ecological concerns.

Apart from the focus on supply security, Europe's lack of attention on the ecological footprint of semiconductor production can be explained by its small global production share of 8%-10%, outsourcing the most environmentally significant process of front-end manufacturing. But this position is increasingly untenable. If the EU Chips Act achieves its goal of 20% global production by 2030, emissions could increase up to eightfold, surpassing those of other emission-heavy industries. The climate issue will therefore become ever more pressing.

At the same time, the ecological footprint of chip production is evident in the operationalization of the Green Deal. Specifically, certain chemicals and gases used in semiconductor manufacturing are restricted under the updated F-gas regulation and the proposed ban on PFASs, to name just two examples. This creates conflicts between economic security and sustainability objectives.

Thus, it is imperative to ensure that the expansion of manufacturing capacity prioritizes climate and environmental considerations. This paper analyzes where the chip production process is particularly harmful to the environment or climate and where there is potential to make the process more sustainable, by addressing not only greenhouse gas emissions but also direct environmental impacts like water pollution and hazardous chemicals. Each individual chapter is dedicated to one aspect of semiconductor manufacturing that contributes to its ecological footprint, ultimately concluding with a projection of the EU semiconductor industry's CO2 emissions in 2030. The following section presents the key takeaways from this analysis.

Chemicals and Gases

Entirely new compounds are needed to reduce the ecological footprint.
Chip production relies on chemicals such as fluorinated gases and wet chemicals, contributing significantly to greenhouse gas (GHG) emissions and long-term environmental contamination. Finding alternatives is complicated because of process dependencies and regulatory uncertainties, emphasising the need for proactive sustainability planning and investment in research and development. While past efforts have reduced emissions by substituting longer-chain per-and

polyfluoroalkyl substances (PFASs) with short-chain alternatives, further reductions necessitate entirely new compounds, presenting a complex challenge.

The industry faces a dual challenge.
Switching to alternative chemicals involves balancing global warming potential (GWP) and atmospheric persistence, often leading to trade-offs. For instance, while CHF3 gas has a higher GWP than CF4 gas, CF4 stays longer in the atmosphere.

The transition will take time.
Despite the urgency, transitioning away from harmful compounds will require time, with challenges varying across processes. Solutions for cleaning processes may emerge within 5–10 years, while alternatives for dry etching could take more than 15 years. Generally, implementation of non-PFAS alternatives is expected to take 15 to more than 20 years. This transition incurs substantial research and transition costs, underscoring the need for a long-term commitment to sustainability.

Machinery

Assessing the ecological footprint of semiconductor machinery is complex.
Machinery is categorised as ‘capital goods’ in scope 3 upstream emissions, contributing 20%–30% of overall scope 3 emissions today. A more detailed assessment is difficult because of the diversity of more than 50 equipment types, their varying levels of complexity and the respective intricate supply chains.

Materials

The high environmental footprint from raw materials mainly stems from mining and energy-intensive processing.
The specific environmental and climate impacts of each raw material used in chip production vary depending on factors such as extraction methods, transportation and waste management. However, raw materials that are critical for manufacturing processes, such as palladium, copper, cobalt and rare earth elements (REEs), are typically mined, resulting in a significant environmental impact due to habitat destruction, water and soil pollution and high energy consumption during processing.

Measured by the global demand for raw materials, the semiconductor industry plays only a minor role.
Despite being critical for certain manufacturing processes, most raw materials are used in small quantities in front-end chip manufacturing. This suggests that, while they are essential inputs, their direct impact on the environment is relatively limited compared to other industries.

Silicon, the most common material used for wafers, has a much lower ecological footprint than wafers based on, for example, gallium or germanium for compound semiconductors.

Compound semiconductors, such as gallium arsenide, have higher melting temperatures compared to silicon, resulting in increased energy consumption and GHG emissions during raw wafer production. Consequently, the production of compound semiconductors tends to have a higher ecological footprint compared to that of silicon wafers.

Fuel and Energy

If the goal of a 20% production share stated in the EU Chips Act is met, it is expected that the electricity consumption of the European semiconductor industry will be around 47.4 tWh in 2030, half that of European data centres (98.5 tWh).
Electricity accounts for the major share of energy consumption in semiconductor manufacturing and constitutes the biggest single source of GHG emissions in chip production. The amount of electricity consumed varies considerably depending on factors such as chip type, manufacturing process complexity and lithography technology, with more advanced processes such as extreme ultraviolet lithography consuming substantially more energy.

Renewable energy certificates (RECs) do not necessarily result in additional renewable energy production.
RECs account for 84% of the renewable energy used in the semiconductor industry. However, by purchasing unbundled RECs, companies can certify compensation for sourcing non-renewable energy without actually using renewable energy. This can lead to double counting and may not contribute to real emission reductions or progress towards climate goals.

Power purchase agreements (PPAs) offer a more effective alternative to increase renewable energy use.
PPAs stand for a long-term commitment to purchasing electricity from specific renewable energy projects. They have been shown to stimulate the development of new renewable energy projects locally, resulting in tangible emission reductions and aligning with science-based targets for climate action.

Water

A large semiconductor fabrication plant (fab) uses up to 38 million litres per day, equivalent to the daily water consumption of around 300,000 people in Germany.
Water is primarily used for ultrapure water (UPW) production, a complex process that involves multi-stage treatments, such as reverse osmosis and ultrafiltration, with water reuse and recycling being common on-site practices.

Strategies for water procurement, withdrawal and recycling are influenced by factors such as water scarcity, local infrastructure and fab location.
Water management strategies vary based on fab location, with differences in water sources and recycling rates. Fabs in regions with high water scarcity, such as Taiwan, emphasise water reuse and recycling, achieving rates of around 80%, while

those in Europe typically have lower recycling rates (10%–14%).

End-of-Life Treatment

Assessing the contribution of chips to electronic waste is currently nearly impossible.
Resembling the assessment of emissions during usage, chip manufacturers do not have access to data and are not taking responsibility, as they are selling intermediate products. Efforts to improve recycling practices require collaboration and responsibility among chip designers and manufacturers.

The shrinking lifespan of electronics contributes to a significant increase in e-waste, which is estimated to reach 75 million tons by 2030.
However, only a small percentage (17.4%) is properly disposed of and recycled, leading to environmental and health risks from incineration and landfill dumping. Innovation is required to develop sustainable recycling solutions and extend the lifetime of electronics to mitigate these challenges.

Transport

As the global semiconductor value chain is based on a high transnational division of labour, the ecological footprint of up-and downstream activities is often underestimated: the components in a chip travel well over 50,000 km and cross international borders 70 times before reaching the end-customer.
The ecological footprint of semiconductor production extends beyond manufacturing, encompassing a complex supply chain involving upstream and downstream transport. The globalised process involves the journey of chips spanning continents, from mining critical raw materials in, for example, South Africa, the Democratic Republic of Congo or China to front-end manufacturing in Taiwan and back-end processes in Malaysia or China.

Usage of Chips

Semiconductor manufacturers typically do not report on the climate footprint of their products, as they are classified as ‘intermediate products’.
This lack of reporting, combined with gaps in research on the ecological footprint during the operation of end-products, makes it difficult to obtain reliable and detailed data on the ecological impact. There is a lack of studies examining the use of chips in various applications.

The ecological impact during the operation of end-products varies significantly depending on the final application.
Battery-powered devices, such as tablets and smartphones, have higher emissions during manufacturing. Data centres, characterised by their high energy consumption, contribute significant emissions during operation.

Waste

Over the past eight years, waste generation in the semiconductor industry has nearly doubled.
This waste includes chemical waste, solid waste, wastewater, slurries, abrasives and packaging waste. Hazardous waste, such as unused chemicals containing PFAS and waste slurries from processes such as chemical mechanical polishing, poses environmental and human health risks if not properly treated. While recycling rates for reuse in other industries are high (around 70%), only a small percentage can be reused for semiconductor manufacturing.

While solid waste is typically treated externally, wastewater is often treated and recycled on site.
Approximately 15%–20% of UPW and production wastewater can be reused, with wastewater treatment facilities recycling chemicals and materials such as calcium fluoride, ammonium sulphate and silicon aluminium oxide for reuse by other industries.

Outlook – Projected Emissions of EU Semiconductor Production

So far, EU semiconductor manufacturing has had a relatively small footprint.
In 2021, the CO2 emissions from semiconductor manufacturing in Europe were relatively low, ranging between 10.67 MMTCE (million metric tons / megatonnes of carbon equivalents) and 13.67 MMTCE, minor compared to high-emitting industries such as chemicals and iron and steel.

If the EU Chips Act's goal of 20% production share by 2030 is met, emissions are projected to at least quadruple by 2030, catching up and even surpassing high-emission industries today, even if renewable energy usage rises significantly.

Projections suggest that, by 2030, semiconductor manufacturing emissions will soar to a minimum of 38.91 MMTCE (ideal case, 4 times higher than 2021 levels) and could even exceed 100 MMTCE (business as usual, 8 times higher than 2021 levels), surpassing the emissions of other emission-heavy industries, such as chemicals and steel, in 2021. These projections highlight the significant ecological impact of Europe's plans to expand semiconductor production and suggest that relying solely on renewable energy will not be sufficient to mitigate these effects in the long term.

Short Overall Conclusion

The available data for assessing the ecological footprint of the semiconductor industry fall short in representing the complexity of its value chain.
The ecological footprint assessment of the semiconductor industry is hampered by insufficient data and a lack of standardisation, especially concerning scope 3 emissions and the differentiation between front-end and back-end processes.

These data gaps result in varying estimates of GHG emission distribution across scope 1, 2 and 3 categories, highlighting significant interpretational differences. Developing a comprehensive and standardised tool for evaluating the environmental impact of chip production, such as tailored lifecycle assessments, could improve accuracy and would need to involve collaborative efforts from various stakeholders.

Transitioning to more sustainable semiconductor production is a lengthy process.
The ecological footprint mapping of the semiconductor industry shows that short-term solutions are unlikely, especially in developing non-PFAS chemical alternatives and increasing renewable energy use, which may take decades. Increasing on-site renewable energy use is crucial for emission reduction, presenting an opportunity for Europe to lead in adopting and building climate-friendly manufacturing facilities.

Policy makers are yet to acknowledge the pivotal role of semiconductors in environmental regulations, overlooking their importance as both an enabling technology and a high-impact industry poised for significant growth over the next 5 to 10 years.
The twin transition—digital and green—requires recognising and addressing their interdependence to manage both synergies and conflicts. Increased chip manufacturing in Europe can support electric vehicles and renewable energy, but it can also lead to higher emissions and the use of harmful chemicals, highlighting the need for cohesive regulations. Future policies must involve multi-stakeholder collaboration, integrating sustainable manufacturing practices and aligning semiconductor, environmental and climate strategies for a holistic approach to the twin transition.

Introduction

Semiconductors are currently at the forefront of public discourse and increasingly vital in our modern world, not just for their strategic role in geopolitics but also as a fundamental technology in various industry sectors. Amidst a surge in demand and global expansion efforts, there is a crucial yet often overlooked aspect: their ecological footprint. The reality is that semiconductor manufacturing consumes significant energy and water and emits toxic chemicals and greenhouse gases (GHGs). This underscores the need to address the ecological impact of semiconductor production alongside technological advancements.

At the intersection of sustainability and chips, two key themes emerge frequently: their role in facilitating the green transition, such as in electric vehicles and smart grids, and the ecological impact during their operational phase, particularly in data centres. While graphics processing units (GPUs) in data centres draw attention for their high energy[1 2 3] and water consumption,[4 5] the overall ecological footprint extends beyond operation alone. Semiconductor manufacturing can significantly contribute to this footprint. In particular, battery-powered devices have high emissions during production (capex-related emissions) and only minimal carbon emissions during use (opex-related emissions),[6] whereas constantly connected devices tend to also have higher emissions during their usage phase.[7] Apple's annual carbon footprint exemplifies this. Manufacturing accounts for 74% of all emissions, with semiconductors alone responsible for half of their GHG emissions from electronic manufacturing.[8] Given that chip production generates significant capex-related emissions across various end-products, the projected rise in demand and global expansion of semiconductor manufacturing capacity will inevitably contribute to a continually increasing ecological footprint. Consequently, it is imperative to scrutinise both the front-and back-end manufacturing processes of semiconductors.

However, in reality, due to the growing recognition of chips' critical role across sectors, policymakers and customers have prioritised supply security over their significant ecological footprint. Over the past two years, global industrial policy initiatives have surged, such as the EU Chips Act[9] and the CHIPS and Science Act in the United States[10] offering subsidy packages to bolster domestic manufacturing capacity. The absence of consideration for subsequent ecological impacts underscores a clear emphasis on economic security, strategic autonomy and indispensability. Concurrently, companies falling short of sustainability targets or reporting higher emissions justify these discrepancies by citing the urgent need to meet escalating demand. On a broader scale, this means that the semiconductor industry is falling short of the Paris Agreement's objectives.[11]

1 Energy Innovation Policy & Technology LLC (2020). How much energy do data centers really use? Energy Innovation: Policy and Technology.https://energyinnovation.org/2020/03/17/how-much-energy-do-data-centers-really-use/.

2 Lauren Leffer (2023). The AI Boom Could Use a Shocking Amount of Electricity. https://www.scientificamerican.com/article/the-ai-boom-could-use-a-shocking-amount-of-electricity/.

3 James Vincent (2024). How much electricity does AI consume? https://www.theverge.com/24066646/ai-electricity-energy-watts-generative-consumption.

4 Shannon Osaka (2023). A new front in the water wars: Your internet use. https://www.washingtonpost.com/climate-environment/2023/04/25/data-centers-drought-water-use/.

5 David Mytton (2021). Data centre water consumption. Npj Clean Water, 4(1). https://doi.org/10.1038/s41545-021-00101-w.

6 To better understand the differentiation between capex- and opex-related emissions, it is helpful to reflect on the definition of capital expenditure and operational expenditure: Capital expenditure (CAPEX) involves investments in long-term assets like property, plant, and equipment, while operating expenditure (OPEX) encompasses day-to-day expenses necessary to sustain business operations, such as salaries, utilities, and maintenance costs.

7 Udit Gupta, Young Geun Kim, Sylvia Lee, Jordan Tse, Hsien-Hsin S. Lee, Gu-Yeon Wei, David Brooks, Carole-Jean Wu (2022). Chasing Carbon: The Elusive Environmental Footprint of Computing. Chasing Carbon: the elusive environmental footprint of computing. *IEEE MICRO/IEEE Micro*, *42*(4), 37–47. https://doi.org/10.1109/mm.2022.3163226.

8 Gary Cook (2024). Clean Clicks or Dirty Chips? Stand Earth. https://stand.earth/wp-content/uploads/2024/02/Clean-Clicks-or-Dirty-Chips-Feb-2024_230224.pdf.

9 European Commission (2024). European Chips Act. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/european-chips-act_en.

10 U.S. House of Representatives Committee on Science, Space, & Technology. CHIPS and Science. https://democrats-science.house.gov/chipsandscienceact.

11 Sebastian Göke, Mena Issler, Demi Liu, Mark Patel, and Peter Spiller (2022). Keeping the semiconductor industry on the path to net zero. McKinsey & Company. https://www.mckinsey.com/industries/semiconductors/our-insights/keeping-the-semiconductor-industry-on-the-path-to-net-zero.

Simultaneously, the intersections with current climate and environmental policy are becoming increasingly apparent in the operationalisation of the European Green Deal.[12] For instance, both the recently updated European F-gas regulation[13] and the proposed ban of PFASs[14] under the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)[15] directive, aimed at limiting the use of the so-called 'forever chemicals', encompass numerous substances utilised in semiconductor production. Moreover, various other initiatives on the EU legislative agenda—from due diligence requirements, eco-design for sustainable products regulation, the EU Emission Trading System, to directives addressing industrial emissions, packaging and waste—are also overlapping with the semiconductor industry. However, neither the critical role of chips for a successful green transition nor their ecological footprint are mentioned explicitly.

The relatively low attention paid to the ecological footprint of semiconductor production in Europe stems partly from the region's subordinate role in recent years, holding only 8%–10% of global production capacity and largely outsourcing environmentally significant front-and back-end manufacturing. For instance, emissions from EU chip production in 2021 amounted to between 10.67 MMTCE[16] and 13.67 MMTCE, significantly lower than those of other heavy industries, such as chemicals or iron and steel.[17] However, if the EU Chips Act's goal of achieving 20% of global production capacity by 2030 is realised, the scenario will change drastically. In this case, compared to the 2021 levels, emissions would at least quadruple (best case) and could even increase eightfold to more than 100 MMTCE, surpassing those of the EU chemicals industry, EU iron and steel industry and EU international aviation.[18]

Therefore, it is imperative to act now and ensure that both current and future capacity expansion strategies prioritise climate and environmental considerations. The initial step involves comprehensively examining the entire landscape. This paper aims to unravel the various factors that require analysis to determine how chip production can be made more climate and environmentally friendly. It helps navigate the intersection between chips and sustainability. This entails going beyond just GHG emissions to consider the direct environmental impact, such as water pollution or the persistence of hazardous chemicals in the environment.

12 European Commission (2024). The European Green Deal: Striving to be the first climate-neutral continent. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.

13 European Commission (2024). EU-Rules: Guidance on the EU's F-gas Regulation and its legal framework.

14 European Chemicals Agency (ECHA). Per- and polyfluoroalkyl substances (PFAS). https://echa.europa.eu/hot-topics/perfluoroalkyl-chemicals-pfas.

15 European Chemicals Agency (ECHA). Understanding REACH. https://echa.europa.eu/regulations/reach/understanding-reach.

16 Emissions are either measured in megatonnes or million metric tons, which are equal to one another. The abbreviation "MMTCE" means "million metric tons of carbon equivalents ". It would also be possible to use "MTCE" (megatonnes of carbon equivalents).

17 Own calculations, see figure 9 and annex A.

18 Own calculations, see figure 9 and annex A.

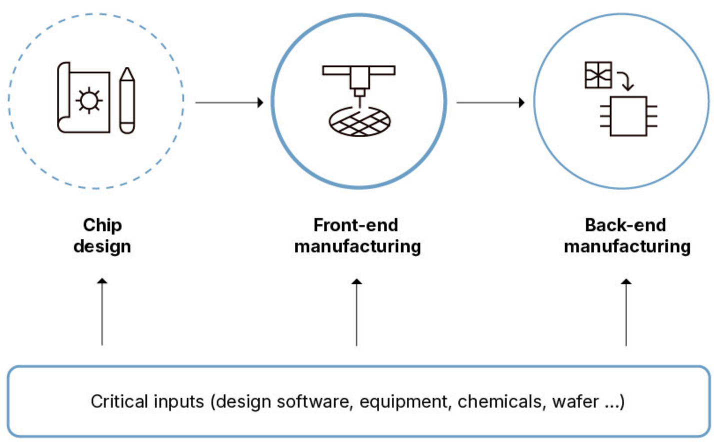
At the heart of this publication lies an overview chart, organising the various aspects crucial for assessing the climate and environmental footprints of chip production and serving as a comprehensive reference point. Following this overview, the paper dedicates individual sections to each aspect depicted in the chart. To make the ecological impact of chip manufacturing more tangible, the paper concludes with a projection of the CO2 emissions of the EU semiconductor industry in 2030. Directly above the introduction, the main takeaways from the mapping of the ecological footprint in semiconductor manufacturing are summarised. A glossary at the end helps define key terms referenced in the paper.

The Big Picture: Mapping the Ecological Impact of Semiconductor Front-End Manufacturing

Before diving into the ecological aspects, it is imperative to understand how chips are produced. As the semiconductor value chain is notoriously complex and involves numerous production steps, it is useful to break down the process into its distinctive phases and depict them schematically.

The context: structure of the semiconductor value chain

1 Process steps in the semiconductor value chain



Chip production involves three production steps: **chip design, front-end manufacturing** (fabricating the integrated circuits onto the wafer) and **back-end manufacturing** (connecting the single chip that is cut out from the wafer to the chip package). The first production step, chip design, is shown with a dotted circle because it is an immaterial design step whose footprint is negligible compared to front-end manufacturing. It is excluded from the following analysis. As described in the next paragraph, back-end manufacturing also has a significantly smaller footprint than front-end manufacturing, which is illustrated by the thinner frame of the circle. Consequently, **the focus of the paper is on the ecological footprint of front-end manufacturing**, framed with a thicker frame in the above chart. Measuring the ecological footprint also includes the critical inputs, which are listed as examples in the rectangle in the graphic.

Chip production is rooted in transnationally interdependent value chains with a high division of labour and ever-increasing specialisation. It can be divided into three production steps: **chip design, front-end manufacturing** (also called wafer fabrication) and **back-end manufacturing** [also called assembly, test and packaging (ATP)]. Equally important are the supplier markets providing **critical inputs,** such as intellectual property (IP) and electronic design automation software (EDA) for chip design, as well as equipment, chemicals and wafers for front-end and back-end manufacturing.[19]

Front-end manufacturing – the process of manufacturing integrated circuits (also known as dies) onto the wafer – is the most complex production step in semiconductor manufacturing. It is highly automated and requires more than 50 types of equipment and around 300 types of chemicals in more than 1000 process steps. Thus, it is also the production step with the highest climate and environmental impact. Next, ATP operations in the so-called back-end connect the single die that is cut out from the wafer to the chip package, which involves more manual process steps.

This paper aims to assess the direct and indirect ecological footprints of front-end manufacturing, which includes both environmental and climate impact. The following chapter first provides a structured overview of the overall ecological footprint, introducing the scope of the paper and the application of the GHG Protocol as a basis for mapping the climate impact of front-end manufacturing. Second, each aspect is classified in terms of its environmental and climate impacts.

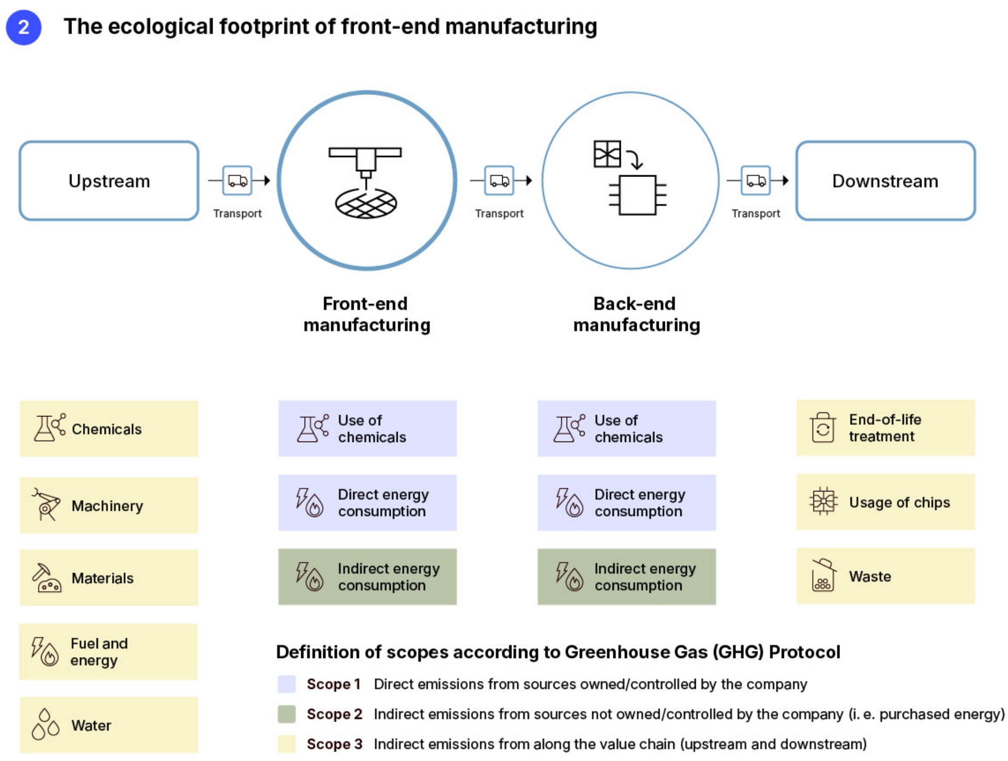
19 For more information on the structure of the semiconductor value chain, please refer to Jan-Peter Kleinhans and Julia Hess. 2021. ‘Understanding the global chip shortages: Why and how the semiconductor value chain was disrupted.’ and Julia Hess and Jan-Peter Kleinhans. 2022. ‘Governments’ role in the global semiconductor value chain #2’.

Ecological footprint of front-end manufacturing

When considering sustainability in semiconductor production, the focus often shifts between climate and environmental concerns. Climate issues primarily target GHG emissions, including those from high global warming potential (GWP) gases and energy usage in raw material refinement and chip production, monitored via the GHG Protocol – a largely standardised and globally used tool. This is discussed in detail below.

Meanwhile, environmental considerations encompass, for example, water consumption, raw material extraction’s ecological impact, chemical contamination risks to nature and humans and waste disposal challenges arising from chip production or electronic device end-of-life management. Despite efforts such as lifecycle analysis (LCA) and green supply chain frameworks to categorise and quantify the environmental footprint, there is still no universally applied international standard for such assessments across industries.

The structure of the paper and the following chart on the ecological footprint of front-end manufacturing attempt to do justice to both aspects (climate and environment) and show that the two are closely interwoven. In this context, the GHG Protocol, with its three scopes, is a helpful tool for assessing the climate footprint in a structured way and underpinning it with data, which unfortunately does not exist for environmental concerns.



Zooming in more closely into the ecological footprint of front-end manufacturing, it can be further broken down into four phases that differ in their environmental and climate impacts. The overview chart above differentiates among the ecological footprint created **upstream** (column on the left), during **front-end manufacturing** (2nd column), **back-end manufacturing** (3rd column) and **downstream** (column on the right).

- The **upstream ecological footprint** includes everything that arises from the production and provision of inputs by suppliers that is needed for chip manufacturing: from mining and processing raw materials and producing chemicals, as well as withdrawing water, to manufacturing equipment and supplying fuel and energy.
- The **ecological footprint during front-end manufacturing** mainly stems from the repetitive use of hazardous, fluorinated chemicals and direct and indirect energy consumption during the manufacturing cycle of three months or longer. After front-end manufacturing, the chips are separated, tested and assembled, also called back-end manufacturing. Unfortunately, a clear differentiation between these two production steps in terms of their ecological footprint is often not possible.

However, there are strong indications that front-end manufacturing has a significantly higher ecological footprint. Some studies have shown that front-end manufacturing is 4 to 13 times more energy intensive than back-end manufacturing.[20] This seems plausible since back-end manufacturing takes less time (one month or less) and needs far fewer equipment: front-end manufacturing equipment accounts for 87% of the share, leaving only a small fraction for back-end manufacturing.[21] In addition, in back-end manufacturing, the usage of fluorinated gases and wet chemicals[22] with a high GWP or long lifetime in the atmosphere is primarily limited to materials such as coatings, encapsulants and underfills to integrate individual semiconductors into chip packages.[23] **Against this backdrop, this paper predominantly emphasises front-end processes, recognising their primary impact.** This focus is particularly evident in the chapter addressing chemicals and gases.

Finally, it is difficult to come up with data and information that exclusively focus on the ecological footprint of either front-or back-end manufacturing. This can be explained by the variety of business models and manufacturing locations that exist in parallel in the semiconductor industry. Depending on the business model and type of chip production, companies either perform both manufacturing steps themselves in one geographic location – the wafer is simply taken to the next building to be finished there – or off-shore their front- or back-end manufacturing. However, this level of diversity and complexity of manufacturing practices and business models is not mirrored in corporate social responsibility (CSR) reports. In most cases, companies do not differentiate between the ecological footprints of front- and back-end. They report only aggregated data for their total chip production. For this reason, in some areas, such as measuring the energy and water consumption of semiconductor production, it is not possible to make a clear distinction between front-end and back-end based on publicly available data.

- Of course, the ecological impact of chips does not stop after back-end manufacturing. The impact during usage in a specific end-product, such as a car, smartphone or data centre, is also important to reflect in the **downstream ecological footprint.** Waste (as a direct result of chip manufacturing) and end-of-life treatment are other aspects of downstream ecological impacts.

Applying GHG Protocol to front-end manufacturing

As previously mentioned, the three scopes of the GHG Protocol are a helpful tool for better understanding the climate impact of chip production. Thus, these scopes are also visualised in the overview chart that was introduced in the previous section.

20 Antonio Varas, Raj Varadarajan, Jimmy Goodrich & Falan Yinug (2021). Strengthening the Global Semiconductor Supply Chain in an Uncertain Era. Boston Consulting Group and Semiconductor Industry Association. https://www.semiconductors.org/wp-content/uploads/2021/05/BCG-x-SIA-Strengthening-the-Global-Semiconductor-Value-Chain-April-2021_1.pdf.

21 SEMI (2023). Global total Semiconductor Equipment Sales Forecast to Reach Record $124 Billion in 2025, SEMI Reports. https://www.semi.org/en/news-media-press-releases/semi-press-releases/global-total-semiconductor-equipment-sales-forecast-to-reach-record-%24124-billion-in-2025-semi-reports.

22 The role of fluorinated gases and wet chemicals will be examined in detail in the chemicals chapter.

23 Emily Tyrwhitt (2023). The Impact of a Potential PFAS Restriction on the Semiconductor Sector. SIA PFAS Consortium, prepared by RINA Tech UK Limited. https://www.semiconductors.org/wp-content/uploads/2023/04/Impact-of-a-Potential-PFAS-Restriction-on-the-Semiconductor-Sector-04_14_2023.pdf.

They are displayed in differently coloured boxes (blue = scope 1, green = scope 2, yellow = scope 3).

The GHG Protocol is a standardised framework for global carbon disclosure and serves as a guidance for companies and other organisations to measure and manage GHG emissions.[24] It covers the accounting and reporting of seven GHGs according to the Kyoto Protocol:[25] carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF6) and nitrogen trifluoride (NF3).[26] The initiative roots in a multi-stakeholder partnership of businesses, non-governmental organisations and others. It was founded by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBSCD) in 1998.[27] Even though the GHG Protocol itself is not a binding regulatory framework, it was widely adopted across several industries as part of their sustainability and emissions management efforts voluntarily. Furthermore, emission-heavy industries, such as aluminium and cement, partnered with the initiative to develop industry-specific calculation tools.[28] Additionally, some regulatory bodies, such as the European Union Emissions Trading System[29] or the United Kingdom’s Greenhouse Gas Reporting Program, have already referenced and incorporated elements of the GHG Protocol into their regulations or standards.[30] Data reported in accordance with the GHG Protocol can usually be found in a company’s annual CSR report.

Scope 1

(highlighted in blue) includes direct emissions from sources owned or controlled by the company. These mainly come from the use of chemicals (fluorinated gases, wet chemicals) and from a fabrication plant’s (fab’s) own energy generation (such as gas, diesel, fuel, oil, petrol and firewood).

24 Greenhouse Gas Protocol (2024). What is GHG Protocol? https://ghgprotocol.org/about-us.

25 UN Climate Change. What is the Kyoto Protocol? United Nations Framework Convention on Climate Change (UNFCCC). https://unfccc.int/kyoto_protocol.

26 Janet Ranganathan, Laurent Corbier, Pankaj Bhatia, Simon Schmitz, Peter Gage &

27 World Business Council for Sustainable Development (WBCSD) (2004). The GHG Protocol: A corporate reporting and accounting standard (revised edition). https://www.wbcsd.org/Programs/Climate-and-Energy/Climate/Resources/A-corporate-reporting-and-accounting-standard-revised-edition.

28 World Business Council for Sustainable Development (WBCSD) (2004). The GHG Protocol: A corporate reporting and accounting standard (revised edition). https://www.wbcsd.org/Programs/Climate-and-Energy/Climate/Resources/A-corporate-reporting-and-accounting-standard-revised-edition.

29 European Commission. EU Emissions Trading System (EU ETS). Climate Action. https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en.

30 Department for Energy Security and Net Zero and Department for Business (2024). Government conversion factors for company reporting of greenhouse gas emissions. GOV.UK. https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting.

Scope 2

(highlighted in green) encompasses all indirect emissions. Due to the high energy intensity in front-end manufacturing, emissions in scope 2 mainly stem from the use of energy sourced from external energy suppliers by the fab.

Scope 3

(highlighted in yellow) also focuses on indirect emissions, but along the value chain, including all emissions that are a consequence of the company's activities but occur from sources not owned or controlled by the company. This describes everything that happens up-and downstream – including the emissions originating from the high energy consumption of refining certain raw materials (upstream) as well as those originating from the operation phase of a chip in a specific end-product, such as GPUs consuming high energy during operation in a data centre (downstream). Additionally, the transport of critical inputs and finished chips (small trucks depicted in the chart) also falls under this scope. [31]

Special case of scope 3 GHG emissions

For reporting scope 1 and scope 2 emissions, companies must follow a standardised framework as per the GHG Protocol. However, this requirement does not extend to scope 3 emissions, which comprise 15 categories that companies are not mandated to report on. Chart 3 below illustrates the actual reporting of these 15 categories listed in the left column, spanning from upstream to downstream activities, based on data from the CSR reports of the 20 largest (based on manufacturing capacity) semiconductor manufacturers.

31 Janet Ranganathan, Laurent Corbier, Pankaj Bhatia, Simon Schmitz, Peter Gage & Kjell Oren (2004). The Greenhouse Gas Protocol. A Corporate Accounting and Reporting Standard. Revised Edition. https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf.

3 Scope 3 emissions reporting across categories: largest 20 chip manufacturers

	2016	2017	2018	2019	2020	2021	2022
Purchased goods and services	6	6	8	8	9	10	12
Capital goods/assets	3	3	4	4	4	4	8
Fuel- and energy related activities	5	5	7	6	7	8	11
Upstream transportation and distribution	8	8	9	8	9	9	13
Waste generated in operations	6	8	9	8	9	10	13
Business travel	7	9	10	10	11	13	14
Employee commuting	5	6	8	7	8	9	12
Upstream leased assets	0	0	0	1	1	1	2
Downstream transportation	5	6	5	4	5	5	6
Processing of sold products	1	1	1	1	1	1	2
Use of sold products	2	2	2	2	3	4	4
End-of-life treatment of sold products	1	1	1	1	1	1	2
Downstream leased assets	2	2	2	2	2	2	2
Franchise	0	0	0	0	0	0	0
Investments	2	1	1	1	1	1	1

Reporting in scope 3 varies significantly between the individual categories. There is a clear trend that companies are increasingly reporting their upstream emissions (C1-C7).

Out of the 15 different categories (see chart above), a company can decide which of them to report on, or it can choose to report only accumulated data in scope 3. The above chart counts how many of the 20 companies with the largest global manufacturing capacity[32] have reported on a single category in a specific year. For example, in 2016, out of the 20 largest chip manufacturers, only 3 reported upstream emissions from the second category, 'capital goods/assets' (i.e. purchased manufacturing equipment). In 2022, 8 out of the 20 analysed companies reported emissions from the second category. The chart also illustrates the problems related to the reporting of scope 3 emissions due to the absence of standardised reporting categories and calculation methods:

1. Comparing reported scope 3 emissions is tricky because companies use either internal data (based on their own calculations) or external market data, making it difficult to determine accuracy with internal data typically closer to reality.
2. As the extent of reporting (number of reported categories) might change annually, it is also not possible to draw comparisons between two years or a longer time span for the same company.
3.

32 The companies analyzed were chosen based on market data of the largest wafer capacities (in 200mm equivalents). If a top 20 company was excluded due to lack of semiconductor division disclosure or insufficient sustainability reporting, the next company on the list was included. The final list comprises companies that provided the necessary information.

> Companies that report more transparently and extensively on scope 3 most likely have – at least on paper – much higher total GHG emissions, as scope 3 accounts for, on average, 75% of total GHG emissions across all industries.

For 2020, one recently published analysis of semiconductor companies' scope 3 emission reporting stated that the average share of scope 3 emissions in semiconductor manufacturing was 52% of the total annual emissions. This is well below the average of 75%, which is generally assessed across all industries for scope 3.[33] However, the above chart shows that, within the last six years, there has been a growing trend of chip companies reporting an increasing number of categories in scope 3. This is mostly the case for upstream emissions. For example, critical materials and chemicals are reported in the first category, 'purchased goods', and equipment is categorised as 'capital goods' in the second category.[34] Greater transparency in these areas can be explained by the increasing pressure from customer industries (B2B) due to the growing demand for sustainable products from end users (B2C)[35] and due diligence directives initiated by governments globally.

In contrast, the chart demonstrates that any emissions generated downstream – such as those originating from the operation phase of a specific product or its end-of-life treatment – are reported on by almost no company. Arguably, emissions from downstream activities are very hard to track but can have a significant ecological footprint when taking into account the specific products that a chip can be integrated into. An example would be a small microcontroller, which could be found either in an electric car, inside the power supply for a server in a data centre or inside an industrial robot. In each of these scenarios, the same microcontroller would have very different total energy consumption due to the varying frequency of use and lifetime. As manufacturers are selling their chip as an intermediate product, the responsibility to track emissions after the chip is produced mostly lies with the end-customer.

In conclusion, when mapping the climate footprint of front-end manufacturing, it is important to also consider the (indirect) emissions along the value chain – up- and downstream. However, note that how companies report these in scope 3 is not standardised, as is the case in scope 1 and scope 2. Therefore, data that fall under scope 3 must be treated with a certain degree of caution.

Despite its shortcomings, the GHG Protocol provides a sound framework for

33 Prashant Nagapurkar, Paulomi Nandy & Sachin Nimbalkar (2024). Cleaner Chips: Decarbonization in Semiconductor Manufacturing, in Sustainability 2024, 16(1), 218. https://www.mdpi.com/2071-1050/16/1/218.

34 Prashant Nagapurkar, Paulomi Nand y & Sachin Nimbalkar (2024). Cleaner Chips: Decarbonization in Semiconductor Manufacturing, in Sustainability 2024, 16(1), 218. https://www.mdpi.com/2071-1050/16/1/218.

35 One example is Apple's clean energy initiative with the commitment that 300 of its suppliers have committed to using 100% clean energy by 2030 when manufacturing for Apple. *Apple advances supplier clean energy commitments. Apple Newsroom. https://nr.apple.com/Dm9X5s8hv3.*

measuring the status quo of GHG emissions, i.e. the *climate* impact of chip production. However, there is no comparable framework to map and assess the impact of front-end manufacturing on the environment.To build a foundation for structuring the *environmental* impact, various reports on LCA and green supply chain theory have been studied and applied to the characteristics of front-end manufacturing.[36]

Ecological Footprint of Front-End Manufacturing

The following section aims to bring climate and environmental aspects together by explaining the ecological impact of the key inputs (in alphabetical order) during processing (upstream), production (in front-end manufacturing) and downstream activities.

Chemicals

The ecological impact of chemicals stems from three major sources. The first source is the ecological impact during chemical production due to energy-intensive processes and the leakage of toxic chemicals during transport and processing. The climate aspect in this regard is reported in scope 3 upstream emissions, with 16% attributable to process gas and 4% attributable to chemicals.[37]

Second, the high GWP of (mostly) fluorinated[38] gases used in etching and chamber cleaning in front-end manufacturing has a significant ecological impact, and its climate impact is measured in scope 1.

Third, the so-called 'forever chemicals' are used in lithography and contain PFASs. They do not break down in the environment or in human bodies, and thus, can severely impact the environment.[39]

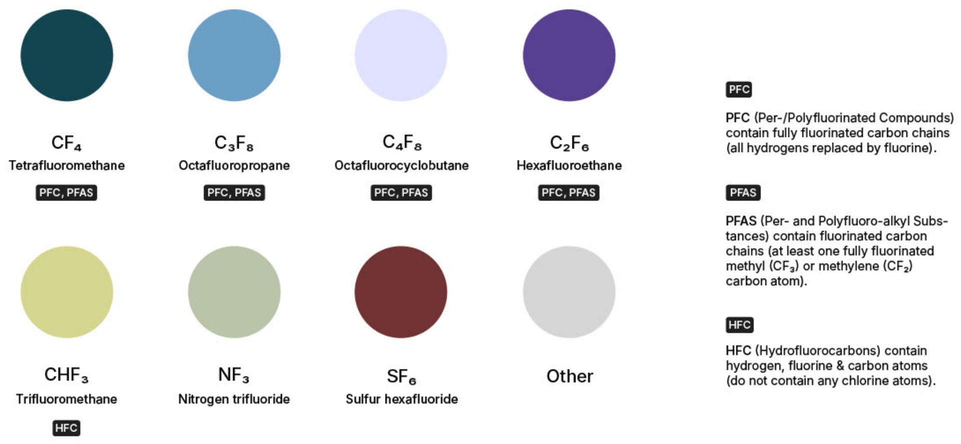
The following section differentiates among specialty gases, bulk and rare gases and liquid chemicals.

36 For more information, please refer to the glossary.
37 Jan-Hinnerk Mohr, Gaurav Tembey, Karl Breidenbach, Nadim Sah, Jörg Jeschke, and Tristan Harder (2023). For Chip Makers, the Decarbonization Challenge Lies Upstream. Boston Consulting Group. https://www.bcg.com/publications/2023/why-chip-makers-need-to-focus-on-the-upcoming-decarbonization-challenges.
38 Flourine (F) is a halogen and a gas at room temperature with the atomic number 9. It is described as the most reactive, does not occur free in nature and is extremely difficult to isolate. Its first recorded use is very similar to one of its functions in wafer fabrication today – as a material that was capable of etching glass. *National Library of Medicine. Florine. https://pubchem.ncbi.nlm.nih.gov/element/Fluorine#section=History*.
39 European Chemicals Agency (ECHA) (2024). Per- and polyfluoroalkyl substances (PFAS). https://echa.europa.eu/hot-topics/perfluoroalkyl-chemicals-pfas.

Specialty gases

Front-end manufacturing relies on various **specialty gases** that are provided in small quantities but are mostly highly toxic. Colourless, flammable gases, such as arsine (AsH3) or phosphine (PH3), are hazardous materials that are used as dopants and pose serious health hazards upon inhalation. Thus, these gases can pose a risk to living beings and the environment if not treated appropriately.[40] Consequently, their impact lies within their production and their health risks. There is no additional impact during front-end manufacturing.

4 7 fluorinated gases account for 96% of demand in chip production



96 % of the demand for fluorinated gases is attributable to these seven process gases. The addition of new gases, e. g., CH_2F_2, C_4F_6, C_5F_8 and C_4F_8O represent the remaining 4 % of total consumption in the “other” category.

In addition, several specialty gases used in etching and chamber cleaning are **fluorinated gases** (also known as F-gases). Seven process gases (see chart 4 above) make up for 96% of emissions from fluorinated gases in a fab: tetrafluoromethane (CF4), octofluropropane (C3F8), octafluorobutane (C4F8), hexafluoroethane (C2F6), trifluoromethane (CHF3), nitrogen trifluoride (NF3) and hexafluoride (SF6). Fluorinated gases have a much higher GWP than CO2, and thus a high climate footprint, and account for 80%–90% of direct emissions in a fab.[41] They are reported under scope 1 of the GHG Protocol and are regulated in the European F-gas regulation that was updated in January 2024 and adopted on 7 February 2024.[42]

40 Mark FitzGerald (1991). Liquid replacements for arsine/phosphine. https://shorturl.at/dJUUI.
41 Sébastien Raoux (2021). Fluorinated greenhouse gas and net-zero emissions from the electronics industry: the proof is in the pudding. Carbon Management, *14*(1). https://doi.org/10.1080/17583004.2023.2179941.

Even though the potential for leakage during transport and production is well below 1%, this can still have a significant environmental and climate impact.[43] Based on their different properties, fluorinated gases can be divided into subcategories that are prominent in the public discourse.

Per- and polyfluoroalkyl substances (PFASs): PFASs – also known as forever chemicals – are an umbrella term for a large class of synthetic organofluoride chemical compounds that are characterised by the presence of fluorinated carbon chains with at least one fully fluorinated methyl (CF3) or methylene (CF2) carbon atom.[44] [45] They are very popular in many industries and are commonly used in a wide range of products because of properties[46] such as temperature resistance or oil-, water- and stain-repellence.[47] These substances do not break down but accumulate over time, leading to irreversible environmental exposure if they are not countered with effective destruction technologies. This is why they are subject to regulation globally. Last year, the national authorities of Denmark, Germany, the Netherlands, Norway and Sweden submitted a proposal to the European Chemicals Agency (ECHA) to restrict the use of more than 10,000 different PFASs under the REACH framework.[48] In the context of front-end manufacturing, PFASs are primarily associated with wet chemicals used in lithography, which will be explained in the chapter 'Liquid chemicals'. However, some fluorinated gases also fall under the PFAS category, namely **CF4, C2F6**, **C4F8** and **C3F8**.

Per-and polyfluorinated compounds (PFCs): PFCs[49] are characterised by fully fluorinated carbon chains, where all hydrogens are replaced by fluorine. In semiconductor manufacturing, the fluorinated GHGs **CF4**, **C2F6, C4F8** and **C3F8** are PFCs; as mentioned, they are also PFASs.[50]

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42 European Commission (2024). EU-Rules: Guidance on the EU's F-gas Regulation and its legal framework.

43 Jan-Hinnerk Mohr, Gaurav Tembey, Karl Breidenbach, Nadim Sah, Jörg Jeschke, and Tristan Harder (2023). For Chip Makers, the Decarbonization Challenge Lies Upstream. Boston Consulting Group. https://www.bcg.com/publications/2023/why-chip-makers-need-to-focus-on-the-upcoming-decarbonization-challenges.

44 Swedish Chemicals Agency (KEMI) (2024). Chemical substances and materials: PFAS. https://www.kemi.se/en/chemical-substances-and-materials/pfas.

45 There is no clear, agree-upon definition of PFAS, especially when it comes different forms of regulation. Thus, there is room for interpretation that led to various discussions on whether PFCs and HFCs are all PFAS. *Semiconductor Industry Association (SIA) (2023). PFAS Release Mapping from Semiconductor Manufacturing Photolithography Processes. Semiconductor PFAS Consortium Photolithography Working Group. https://www.semiconductors.org/wp-content/uploads/2023/09/PFAS-Release-Mapping-from-Semiconductor-Photolithography-Processes-Rev.0.pdf.*

46 PFAS have one of the strongest bonds in organic chemistry that don't break down in the environment or in our bodies and have properties such as chemical inertness, radiation resistance, temperature resistance, weathering resistance, oil-, water-, and stain repellence, electrical inertness.

47 Juliane Glüge, Martin Scheringer, Ian T. Cousins, Jamie C. DeWitt, Gretta Goldenman, Dorte Herzke, Rainer Lohmann, Carla A. Ng, Xenia Trieri & Zhanyun Wangj (2020). An overview of the uses of per- and polyfluoroalkyl substances (PFAS). Environmental Science. Processes & Impacts, 22(12), 2345–2373. https://pubs.rsc.org/en/content/articlelanding/2020/em/d0em00291g.

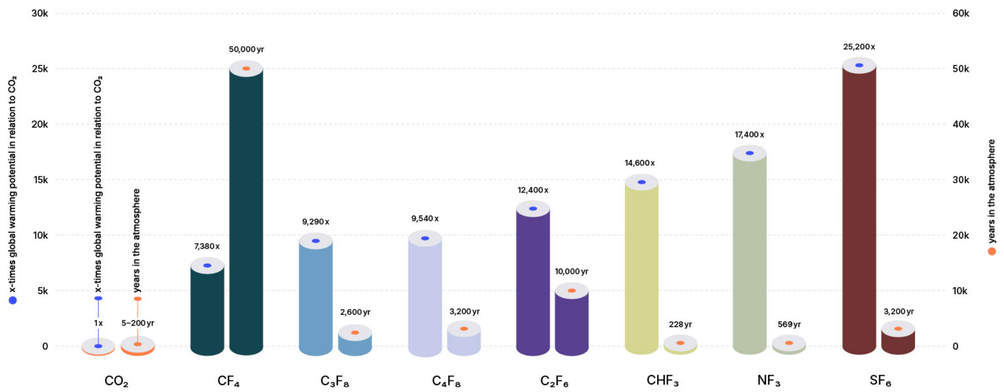
48 A six-month consultation period ended in September last year (2023). In 2024, opinions of the Committees for Risk Assessment (RAC) and Socio-economic Analysis (SEAC) will be published. The restriction, outlining which uses will be prohibited (full ban), enter 5 or 12 years for derogations or receive time-unlimited derogations for specific uses, is planned to become effective in 2026/2027. *European Chemicals Agency (ECHA) (2023). ECHA publishes PFAS restriction proposal. ECHA/NR/23/04. https://echa.europa.eu/de/-/echa-publishes-pfas-restriction-proposal.*

49 PFCs have remarkable water and oil repellency properties and a high chemical stability, leading to serious health risks.

50 Scott C. Bartos, C. Sheperd Burton (2000). PFC, HFC, NF3 AND SF6 EMISSIONS FROM SEMICONDUCTOR MANUFACTURING. https://www.ipcc-nggip.iges.or.jp/public/gp/bgp/3_6_PFC_HFC_NF3_SF6_Semiconductor_Manufacturing.pdf.

Hydrofluorocarbons (HFCs): HFCs are synthetic gases that contain fluorine and hydrogen atoms (no chlorine atoms) that are primarily used for cooling and refrigeration.[51] The most important HFC in front-end manufacturing is **CHF3.**[52]

5 **Global warming potential (GWP) and lifetime in atmosphere of key fluorinated gases**



Fluorinated GHGs in semiconductor manufacturing vary widely in terms of their global warming potential (GWP) and their atmospheric fate. CF_4, for example, remains in the atmosphere for 50,000 years, while while NF_3, on the other hand, only has a lifetime of 569 years in the atmosphere. However, the latter is 17,400x worse than CO_2.

The respective properties of the aforementioned fluorinated gases impact their GWP and lifetime in the atmosphere. The GWP compares the amount of heat trapped by a particular GHG in the atmosphere with that trapped by CO2 over a specific time horizon. Thus, the metric **‘CO2e’** displays the amount of CO2 that would cause the same amount of global warming as the GHG in question.[53] Chemicals not only have different GWPs but also persist in the atmosphere for different time periods. Their lifetime is influenced by various factors and only represents an estimation.[54] It is measured in the years until a gas breaks down in the environment.[55]

The above chart 5 puts the two aspects in relation to one another. The fundamental data are based on a timespan of 100 years, which is the time period generally used to compare emissions reduction opportunities across sectors and gases. The results

51 Climate Clean Air Coalition (2024). Short-lived climate pollutants: Hydrofluorocarbons. https://www.ccacoalition.org/short-lived-climate-pollutants/hydrofluorocarbons-hfcs.

52 In small quantities, CH2F2 and CH3F are used as well. ///// ICF (2021). Market characterization of the U.S. semiconductor industry. Prepared for: Stratospheric Protection Division, Office of Air and Radiation, U.S. Environmental Protection Agency. https://www.epa.gov/sites/default/files/2021-03/documents/epa-hq-oar-2021-0044-0002_attachment_3-semiconductors.pdf.

53 Edwards Vacuum Innovation Hub. The Time is Now: Sustainable Semiconductor Manufacturing. https://www.edwardsvacuum.com/en-uk/knowledge/innovation-hub/the-time-is-now-sustainable-semiconductor-manufacturing0.

54 Edwards Vacuum Innovation Hub. The Time is Now: Sustainable Semiconductor Manufacturing. https://www.edwardsvacuum.com/en-uk/knowledge/innovation-hub/the-time-is-now-sustainable-semiconductor-manufacturing0.

55 United States Environmental Protection Agency (EPA). Greenhouse Gas Emissions: Understanding Global Warming Potentials. https://www.epa.gov/ghgemissions/understanding-global-warming-potentials.

would be different if the comparison were based on 20 or 200 years. Note that both units of measure (GWP and lifetime in atmosphere) are under constant revision factoring in recent scientific advances.[56] The chart is based on the latest revision (AR6 published in 2021).[57] A comparison of the left-hand bars (which shows the GWP, marked with a blue dot) of CF4 and CHF3 indicates that CHF3 has a significantly higher GWP of 12,400x. For the lifetime in the atmosphere, in contrast, the right-hand bar (marked with an orange dot) for CF4 is significantly higher at 50,000 years.

NF3 and SF6 are good examples of how balancing processes between GWP and lifetime in atmosphere play out in reality. Both are used for similar purposes, but as NF3 has a lower GWP and is less persistent in the atmosphere, the industry switches from SF6 to NF3 wherever possible. NF3 has also proved to be a suitable alternative to C2F6.[58] In this case, NF3 is the better choice because of its shorter lifetime in the atmosphere and the fact that it does not contain PFASs. Thus, it is a good alternative to decrease the environmental footprint. However, because of its higher GWP than that of C2F6, it may (depending on the abatement processes in place) contribute to a higher climate footprint during usage.[59] [60]

56 United States Environmental Protection Agency (EPA). Greenhouse Gas Emissions: Understanding Global Warming Potentials. https://www.epa.gov/ghgemissions/understanding-global-warming-potentials.

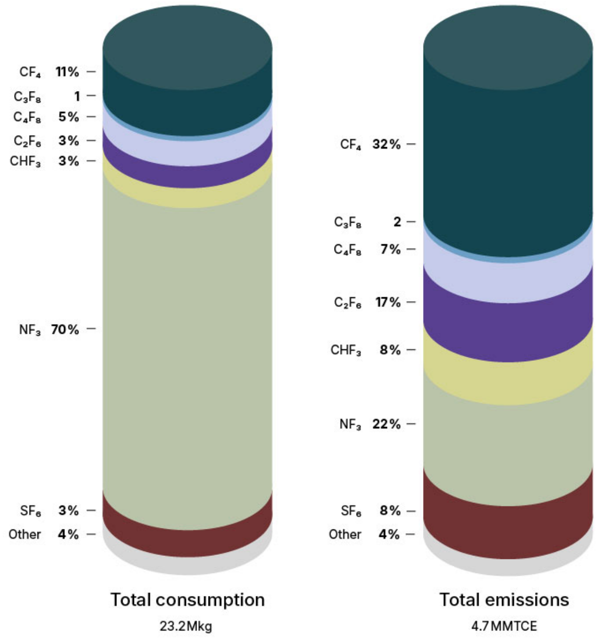
57 Chris Smith, Zebedee R. J. Nicholls, Kyle Armour, William Collins, Piers Forster, Malte Meinshausen, Matthew D. Palmer, Masahiro Watanabe (2021). The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity Supplementary Material. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://ipcc.ch/static/ar6/wg1. ||| Only data for C4F8 is based on the AR5 revision, as there was no update found in AR6. *Gunnar Myhre, Drew Shindell, François-Marie Bréon, William Collins, Jan Fuglestvedt, Jianping Huang, Dorothy Koch, Jean-François Lamarque, David Lee, Blanca Mendoza, Teruyuki Nakajima, Alan Robock, Graeme Stephens, Toshihiko Takemura, Hua Zhang (2023). Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf.*

58 The substitution took place in etching, CVD chamber cleaning processes and in some gas cluster ion beam processes.

59 Javier Martín-Torres (2020). What is Nitrogen trifluoride (NF3)? https://www.ercs.scot/wp/wp-content/uploads/2020/11/Nitrogen-Triflouride-Scientific-Brief-Prof-FJ-Martin-Torres.pdf.

60 Emily Tyrwhitt (2023). The Impact of a Potential PFAS Restriction on the Semiconductor Sector. SIA PFAS Consortium, prepared by RINA Tech UK Limited. https://www.semiconductors.org/wp-content/uploads/2023/04/Impact-of-a-Potential-PFAS-Restriction-on-the-Semiconductor-Sector-04_14_2023.pdf.

6 **Key fluorinated gases used in semiconductor manufacturing in 2020**



Due to their varying global warming potential (GWP), the most used fluorinated gases are not automatically responsible for the highest emissions.

NF_3, for example, accounts for 70 % of the total consumption, but only emits 22 % of the total emissions from fluorinated gases.

This also becomes apparent when comparing the share in total consumption (left bar) per fluorinated gas with that in total emissions (right bar) for the respective gas in chart 6.[61] To calculate emissions based on total demand for a particular chemical, the quantity must be multiplied by the GWP (see chart 5) of the chemical in question. However, the calculation path from consumption to emissions is much more complicated than that. In contrast, there are different abatement strategies for different gases, which vary considerably depending on the nature of the gas in question and the respective destruction and removal efficiencies.[62] This can be explained by different bond energies.[63] For example, 70% of all consumption in fluorinated gases is attributable to NF3, but NF3 is relatively low in emissions, with only 22% of all emissions being allocated to it. Moreover, NF3 has the lowest bond

61 The data is based on information published by the world semiconductor council in 2020. They haven't published an update since then. *World Semiconductor Council (WSC) (2020). Joint Statement of the 24th Meeting of the World Semiconductor Council on 26th August 2020.* [http://www.semiconductorcouncil.org/wp-content/uploads/2020/09/24th-WSC-Joint-Statement-Final.pdf.](http://www.semiconductorcouncil.org/wp-content/uploads/2020/09/24th-WSC-Joint-Statement-Final.pdf)

62 How Ming Lee, Shiaw-Huei Chen (2017). Thermal Abatement of Perfluorocompounds with plasma torches. Energy Procedia, 142, 3637–3643. [https://doi.org/10.1016/j.egypro.2017.12.256.](https://doi.org/10.1016/j.egypro.2017.12.256)

63 Bond energy quantifies the amount of energy needed to break a chemical bond between two atoms in a molecule. The higher the bond energy, the more energy is required to break the bond. NF3 has a bond energy of N-F, 2.76 eV and CF4 has a bond energy of C-F, 5.17 eV., which means that it is not only harder to abate, but also requires more energy for the abatement process. "eV" stands for the electron volt and 1 eV equals to 1.6´10-19 J. *How Ming Lee, Shiaw-Huei Chen (2017). Thermal Abatement of Perfluorocompounds with plasma torches. Energy Procedia, 142, 3637–3643.* [https://doi.org/10.1016/j.egypro.2017.12.256.](https://doi.org/10.1016/j.egypro.2017.12.256)

energy among fluorinated gases used in front-end manufacturing. In contrast, CF_4 is low in usage (11%) but emits 32% of all emissions.[64] This is because it has the strongest bond energy and is the most difficult to remove. On the other hand, both usage during manufacturing and abatement can generate other gases as byproducts. For example, during the abatement of C_2F_6, CF_4 is generated, adding to CF_4 emissions in front-end manufacturing.[65] **In conclusion, chart 6 underlines that it is not only important to put the GWP into relation with the lifetime in atmosphere but also to reflect on the effectiveness of abatement systems for a specific gas – dependent on their respective bond energies (destruction and removal efficiencies) and the potential generation of by-products.**

Special case: Heat-transfer fluids

While 85%–90% of all emissions from chemical usage originate from fluorinated GHGs used in etching and cleaning processes, 10%–15% originate from the use of fluorinated heat-transfer fluids (HTFs) that are also PFASs and have a high GWP (e.g. CH_2FCF_3 or C_2HF_5). Because of their liquid state, they do not appear in the overview of key fluorinated GHGs. HTFs are used in various process steps, where precise temperature control and heat dissipation are critical.[66] All applications have in common that there are currently no non-PFAS alternatives available, and that according to the industry, it will most likely take from 8 to more than 14 years to find them.[67] This is more or less in accordance with the evaluation of PFAS use in HTFs for REACH, proposing a 12-year derogation period.[68]

64 How Ming Lee, Shiaw-Huei Chen (2017). Thermal Abatement of Perfluorocompounds with plasma torches. Energy Procedia, 142, 3637–3643. https://doi.org/10.1016/j.egypro.2017.12.256.

65 How Ming Lee, Shiaw-Huei Chen (2017). Thermal Abatement of Perfluorocompounds with plasma torches. Energy Procedia, 142, 3637–3643. https://doi.org/10.1016/j.egypro.2017.12.256.

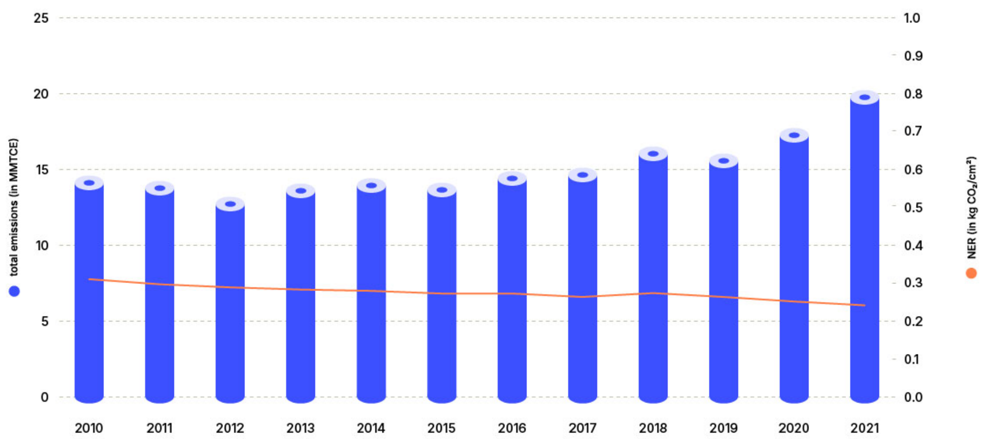
66 Their properties are a unique combination of being electrically non-conductive, compatible with all materials of construction, within suitable toxicity and flammability limits and resistant to catastrophic contamination. Among other applications, liquid heat transfer fluids (F-HTFs) are used in process equipment chillers and high energy dry etch manufacturing equipment in front-end manufacturing and fluorinated refrigerants are used within process equipment chillers.

67 Emily Tyrwhitt (2023). The Impact of a Potential PFAS Restriction on the Semiconductor Sector. SIA PFAS Consortium, prepared by RINA Tech UK Limited. https://www.semiconductors.org/wp-content/uploads/2023/04/Impact-of-a-Potential-PFAS-Restriction-on-the-Semiconductor-Sector-04_14_2023.pdf.

68 European Chemicals Agency (ECHA) (2023). Annex to the ANNEX XV Restriction Report: Proposal for a Restriction: Per- and polyfluoroalkyl substances (PFAS), Version Number 2. https://echa.europa.eu/documents/10162/57812f19-8c98-ee67-b70f-6e8a51fe77e5.

Development of fluorinated GHG emissions

7 **Development of emissions from fluorinated gases**



Emissions from fluorinated gases (85 - 90 % of scope 1) have risen slightly in recent years. But in light of the significant global expansion of semiconductor production, this can be equated with a slight downward trend (see normalized emission rate (NER)).

The development of fluorinated GHG emissions[69] over the last 10 years (chart 7) shows that despite ambitious industry goals to voluntarily reduce emissions from fluorinated gases, **the trend for absolute emissions from fluorinated GHGs does not reflect a clear decline but remains stagnated and even increased in 2021**. There are two possible explanations for this:

First, the demand for chips is growing steadily – even if companies manage to decrease their emissions per wafer, this could be hidden behind growing manufacturing capacities. Global production capacity increased by 69% in the period shown in the chart.[70] The slightly decreasing trend of the normalised emission rate (NER) (in kg CO2/cm²) supports this hypothesis.[71]

69 Note: The data is based on reports from the world semiconductor council (WSC). WSC currently defines PFC as „process HFCs, PFCs, SF6 and NF3", even though HFCs, SF6 and NF3 are per definition no PFCs. But the definition of fluorinated GHG emissions in this paper includes the same fluorinated GHGs: HFCs, PFCs, SF6 and NF3. Thus, the data can be used to look at aggregated fluorinated GHG emissions. No data was publicly available for 2022 and 2023.

70 IC Insights (2020). Taiwan Edges South Korea as Largest Base for IC Wafer Capacity. https://www.icinsights.com/news/bulletins/taiwan-edges-south-korea-as-largest-base-for-ic-wafer-capacity/.

71 The NER allows for a more direct comparison of the annual emissions in kilograms of carbon equivalents (CO2e) per area of silicon wafers processed and is the basis of reduction goals set by the world semiconductor council (WSC). Until 2020, the WSC also included their baseline 2020 NER target. *World Semiconductor Council (WSC) (2023). Joint Statement of the 27th Meeting of the World Semiconductor Council on 25th May 2023. Seoul.* http://www.semiconductorcouncil.org/wp-content/uploads/2023/06/WSC-2023-Joint-Statement-FINAL-with-Annex-1.pdf.; *World Semiconductor Council (WSC) (2020). Joint Statement of the 24th Meeting of the World Semiconductor Council on 26th August 2020.* http://www.semiconductorcouncil.org/wp-content/uploads/2020/09/24th-WSC-Joint-Statement-Final.pdf.

Second, the more advanced and cutting-edge the semiconductor, the more complex and repetitive the manufacturing process. For example, more etching steps and repetitions directly increase the use of fluorinated gases. Thus, the increasing demand for more powerful chips requires companies to double down on their efforts to reduce their emissions in scope 1, which mainly comes from fluorinated gases, and they must set specific targets and goals for fluorinated gases in order to operationalise the overall strategy to become carbon neutral.

According to the industry, the reason for the stagnation is that the search for alternatives goes hand-in-hand with significant changes in the manufacturing process. Thus, in most cases, the challenge goes beyond the long duration between development and implementation. It is also not always possible to change the manufacturing processes in existing fabs.

For fluorinated gases, it seems to be easier to find solutions for cleaning processes (pre-clean, seasoning, chamber cleans) (around 5–10 years) than for dry etching (more than 15 years). The latter is a process technology that needs various fluorinated gases in different quantities, depending on the type. At the time of writing, there are no viable substitutes that have a lower GWP and shorter persistence in the atmosphere and still have high destruction or removal efficiencies.[72] **Thus, the current solution to decrease GHG emissions from fluorinated gas usage is the implementation of abatement systems to contain and destroy the problematic compounds. However, the success of abatement systems significantly depends on the fluorinated gas.** Moreover, abatement systems consume considerable energy, which adds to indirect emissions that are reported in scope 2.[73]

Other gases

Bulk gases, such as nitrogen (e.g. used in deposition to clean up reactive gases), oxygen (used in etching and annealing) and hydrogen (used in lithography and annealing) are supplied in large quantities to fabs. Their environmental impact is usually the highest during production and negligible in front-end manufacturing. This impact significantly differs depending on the specific gas.

As the air in the earth’s atmosphere is made up of approximately 78% nitrogen (N2) and 21% oxygen (O2), producing and supplying these gases is easy and affordable and has no significant environmental impact.[74] N2 and O2 are commonly produced

72 Emily Tyrwhitt (2023). The Impact of a Potential PFAS Restriction on the Semiconductor Sector. SIA PFAS Consortium, prepared by RINA Tech UK Limited. https://www.semiconductors.org/wp-content/uploads/2023/04/Impact-of-a-Potential-PFAS-Restriction-on-the-Semiconductor-Sector-04_14_2023.pdf.

73 Merck Group (2023). Investing in a Sustainable Semiconductor Future: Materials Matter. https://www.merckgroup.com/en/expertise/semiconductors/technical-assets/tech-presentations/white-paper-sustainability.html.

on site in air separation units. Argon, another bulk (noble) gas, is a similar case.[75] For others, such as hydrogen (H), the picture looks different. The production of H is based on cryogenic processing, which means that the temperature of the gas stream needs to drop to approximately −85°C.[76] This consumes considerable energy and thus emits high indirect GHG emissions in production.[77] Hydrogen also needs to be scrubbed from poisonous and environmentally harmful substances before it can be released into the atmosphere and poses a high risk of leaking from piping and fitting systems.[78] The same holds true for other **noble gases**, such as neon, krypton and xenon, which are used for processes such as annealing, plasma etching and chemical vapor deposition.[79] The extraction of hydrogen from natural gas is not only energy intensive, emitting indirect GHGs, but also releases GHG by-products during the process. In addition, natural gas is occasionally vented or flared during the extraction, which again leads to direct GHG emissions.[80]

Liquid chemicals

Apart from gaseous chemicals (~42%), the other major share of a large variety of chemicals (~50%) is supplied to the fab in liquid state.[81] [82] **Wet chemicals**, such as acids (HCI, HNO3 and H2SO4), alkaline solutions (NH4OH and NaOH) or solvents (IPA, NMP and H2O2), are required to clean substrates, remove photoresist materials, etch patterns and deposit thin films.[83]

Hydrogen peroxide is the most demanded wet chemical in front-end manufacturing.[84] **Wet chemicals have a high carbon footprint due to high energy**

74 NASA (2016). 10 interesting things about air. Climate Change: Vital Signs of the Planet. https://climate.nasa.gov/news/2491/10-interesting-things-about-air.

75 Linde Gas Hungary. Electronics: An industry leader in gases for the electronics market—semiconductor, display, solar, and LED. https://www.lindegas.hu/en/industries/electronics-industry/electronics.html.

76 Nayef Ghasem (2020). CO2 removal from natural gas, in Advances in Carbon Capture (pp. 479–501). https://www.sciencedirect.com/topics/earth-and-planetary-sciences/cryogenics.

77 Aurélie Villard, Alan Lelah, Daniel Brissaud (2015). Drawing a chip environmental profile: environmental indicators for the semiconductor industry. Journal of Cleaner Production, 86, 98–109. https://doi.org/10.1016/j.jclepro.2014.08.061.

78 Lukas Rochlitz, Maximilian Steinberger, Ralf Oechsner, Alexander Weber, Stephan Schmitz, Karsten Schillinger, Michael Wolff, Alexander Bayler (2019). Second use or recycling of hydrogen waste gas from the semiconductor industry - Economic analysis and technical demonstration of possible pathways. International Journal of Hydrogen Energy, 44(31), 17168–17184. https://doi.org/10.1016/j.ijhydene.2019.05.009.

79 Reach Researcher (2023). Rare Gases for Semiconductor Market Share & Market New Trends Analysis Report By Type, By Application, By End-use, By Region, And Segment Forecast. https://www.linkedin.com/pulse/rare-gases-semiconductor-market-share-amp-new-trends/.

80 Juan Sebastian Serra Leal, Jimena Incer-Valverde & Tatiana Morosuk (2023). Helium: sources, applications, supply, and demand. Gases, 3(4), 181–183. https://doi.org/10.3390/gases3040013.

81 Sunju Kim, Chungsik Yoon, Seunghon Ham, Jihoon Park, Ohun Kwon, Donguk Park, Sangjun Choi, Seungwon Kim, Kwonchul Ha,and Won Kimg (2018). Chemical use in the semiconductor manufacturing industry. International Journal of Occupational and Environmental Health, 24(3–4), 109–118. https://doi.org/10.1080/10773525.2018.1519957.

82 Depending on a specific manufacturing process, either gases or wet chemicals are used to fulfill a specific function. One example is dry versus wet etching. In dry etching, gases are used to define the exposed pattern on the wafer. Wet etching, on the other hand, relies on chemical baths to wash the wafer.

83 Fortune Business Insights (2020). Wet Chemicals for Electronics & Semiconductor Application Market Size, Industry Share, Forecast 2032. https://www.fortunebusinessinsights.com/wet-chemicals-for-electronics-semiconductor-application-market-103470.

use in production, particularly due to purification, and in their disposal, mainly in the form of toxic wastewater—posing significant risks to the environment.[85] Around 25% of all liquid chemicals are used in lithography as surfactants, photoresists, coatings or substrates. Often, these chemicals contain the above-mentioned PFASs; 163 different PFASs[86] are in use at any point in time in the electronics and semiconductor industry.[87] The composition of PFAS chemicals is unique to their specific application.

According to industry stakeholders, stringent risk management measures and safety practices are put in place to prevent the release of PFASs during all stages of the manufacturing process. As semiconductor manufacturing is a highly automated process that takes place in a clean-room environment, 5% of PFASs used are estimated to enter the environment during semiconductor production.[88] There also appears to be a very small amount of PFAS that sometimes remains in the final chip.[89] Nonetheless, most of what remains of PFAS usage can be found in hazardous wastewater, which will be further explained in the chapter 'Waste'. In addition, emissions from gaseous PFASs are reported to be almost completely eliminated by incineration.[90]

PFASs in liquid state used in lithography have high environmental and climate impacts in front-end manufacturing. The different uses of PFASs in lithography depend on the respective lithography generation measured at the specific wavelength of light in nanometres (nm). What makes it even more complex is the fact that manufacturing a chip on, for example, a 28 nm node needs the entire range of different lithography technologies, from 365 nm wavelength to every more advanced lithography process. Thus, advancing non-PFAS alternatives only at 193 nm or lower wavelength solves just one part of the problem, because it does not

84 Fortune Business Insights (2020). Wet Chemicals for Electronics & Semiconductor Application Market Size, Industry Share, Forecast 2032. https://www.fortunebusinessinsights.com/wet-chemicals-for-electronics-semiconductor-application-market-103470.

85 Aurélie Villard, Alan Lelah, Daniel Brissaud (2015). Drawing a chip environmental profile: environmental indicators for the semiconductor industry. Journal of Cleaner Production, 86, 98–109. https://doi.org/10.1016/j.jclepro.2014.08.061.

86 The most common PFAS (65%) are fluoropolymers such as polytetrafluoroethylene (PTFE), paraformaldehyde (PFA), polyvinylidene difluoride (PVDF), ethylene tetrafluoroethylene (ETFE) and fluorinated ethylene propylene (FEP). In solvent cleaners and heat transfer fluids, non-polymeric ionic PFAS such as perfluorobutanesulfonate (PFBS) are commonly used. *Semiconductor Industry Association (SIA) (2023). PFAS Release Mapping from Semiconductor Manufacturing Photolithography Processes. Semiconductor PFAS Consortium Photolithography Working Group. https://www.semiconductors.org/wp-content/uploads/2023/09/PFAS-Release-Mapping-from-Semiconductor-Photolithography-Processes-Rev.0.pdf.*

87 European Chemicals Agency (ECHA) (2023). Annex to the ANNEX XV Restriction Report: Proposal for a Restriction: Per- and polyfluoroalkyl substances (PFAS), Version Number 2. https://echa.europa.eu/documents/10162/57812f19-8c98-ee67-b70f-6e8a51fe77e5.

88 European Chemicals Agency (ECHA) (2023). Annex to the ANNEX XV Restriction Report: Proposal for a Restriction: Per- and polyfluoroalkyl substances (PFAS), Version Number 2. https://echa.europa.eu/documents/10162/57812f19-8c98-ee67-b70f-6e8a51fe77e5.

89 European Chemicals Agency (ECHA) (2023). Annex to the ANNEX XV Restriction Report: Proposal for a Restriction: Per- and polyfluoroalkyl substances (PFAS), Version Number 2. https://echa.europa.eu/documents/10162/57812f19-8c98-ee67-b70f-6e8a51fe77e5.

90 Semiconductor Industry Association (SIA) (2023). PFAS Release Mapping from Semiconductor Manufacturing Photolithography Processes. Semiconductor PFAS Consortium Photolithography Working Group. https://www.semiconductors.org/wp-content/uploads/2023/09/PFAS-Release-Mapping-from-Semiconductor-Photolithography-Processes-Rev.0.pdf.

address older lithography generations.

In many of these applications, non-PFAS alternatives have not yet been demonstrated, and implementation is expected to take 15 to more than 20 years. Factoring in the industry’s current timeline to develop alternatives leads to the sobering realisation that PFASs will remain a part of front-end manufacturing for a very long time. The analysis of the costs and benefits under REACH and the potential PFAS restriction come to a similar conclusion, stating weak evidence that PFAS alternatives will be available within the derogation period of 12 years.[91]

In recent decades, the semiconductor industry has achieved significant reductions in the usage of hazardous ‘forever chemicals’.[92] However, the initial situation was fundamentally different. The goal was not to find non-PFAS alternatives but to substitute longer-chain PFASs with short-chain PFASs that still exhibit the necessary technical performance. Even though the transition required minor to significant changes in manufacturing processes, it was still manageable because the chemical suppliers could still use similar materials and compositions. As a result, the use of the ‘most environmentally friendly PFAS solution’ became standard in many areas and has positively impacted the ecological footprint of semiconductor manufacturing. However, now, the industry is facing a much greater challenge: **How can the use of PFASs be completely dispensed in the long term?**

Machinery

The ecological footprint of machinery, such as equipment and fab technology, is complex to assess. First, we are dealing with many different types of equipment. Second, these machines have various levels of complexities. They are categorised as ‘capital goods’ in scope 3 upstream emissions, where they contribute 20%–30% of the total emissions in scope 3.[93] [94]

A fab needs more than 50 different types of **front-end equipment** that make technological innovation and new manufacturing processes possible in the first

91 European Chemicals Agency (ECHA) (2023). Annex to the ANNEX XV Restriction Report: Proposal for a Restriction: Per- and polyfluoroalkyl substances (PFAS), Version Number 2. https://echa.europa.eu/documents/10162/57812f19-8c98-ee67-b70f-6e8a51fe77e5.

92 In the early 2000s, the industry collectively decided to transition away from perfluorooctane sulfonic acids (PFOS) and perfluorooctanoic acid (PFOA) which are two specific types of PFAS that were subject to regulation in many countries, such as the EU PFOS ban in 2006, not only because of their long persistence in the atmosphere, but also their potential to bioaccumulate in animals and humans. *European Chemicals Agency (ECHA) (2023). Annex to the ANNEX XV Restriction Report: Proposal for a Restriction: Per- and polyfluoroalkyl substances (PFAS), Version Number 2. https://echa.europa.eu/documents/10162/57812f19-8c98-ee67-b70f-6e8a51fe77e5.*

93 Jan-Hinnerk Mohr, Gaurav Tembey, Karl Breidenbach, Nadim Sah, Jörg Jeschke, and Tristan Harder (2023). For Chip Makers, the Decarbonization Challenge Lies Upstream. Boston Consulting Group. https://www.bcg.com/publications/2023/why-chip-makers-need-to-focus-on-the-upcoming-decarbonization-challenges.

94 Prashant Nagapurkar, Paulomi Nandy & Sachin Nimbalkar (2024). Cleaner Chips: Decarbonization in Semiconductor Manufacturing, in Sustainability 2024, 16(1), 218. https://www.mdpi.com/2071-1050/16/1/218.

place. The different types of equipment – such as deposition, lithography and etching equipment – are time consuming to produce. The time period ranges from weeks for older generation equipment to months for the most advanced ones, such as extreme ultraviolet (EUV) lithography equipment, going hand-in-hand with a high demand for electricity.[95] In addition, equipment manufacturers rely on a highly complex and diversified supplier network themselves. ASML, the leading lithography equipment manufacturer, has a supply chain of more than 5000 suppliers.[96] Assessing this in more detail is beyond the scope of this paper. Nonetheless, three things must be stressed here. Interestingly, most of the equipment suppliers are part of many different initiatives to become greener – from setting science-based targets to pledges to using 100% renewable energy by 2030.[97] In addition, equipment manufacturers are investing into research and development to improve the energy efficiency of their machines during operation. Combining both actions, initiatives such as Tokyo-Electron's E-Compass aim to reduce the impact of their equipment during their whole lifecycle.[98] In addition, it is also important to note that many fabs are in operation for decades and have service contracts with their equipment suppliers.

Automation and cleanroom technology also have a high demand for electricity when manufactured and rely on a complex supplier network, but it has a much longer lifetime of up to 50 years. This significantly reduces it ecological footprint.[99] Apart from cleanroom technology, the installation of **abatement systems** is also a growing market as a tool to cut down GHG emissions in the short term. However, this goes hand-in-hand with high energy consumption during use.

Materials

Materials can be categorised between **raw materials** that are critical for the manufacturing process and **materials for wafers**. The main impact on the climate and the environment is rooted in the production process of these materials, particularly the mining and refining aspects: according to one estimate, 24% of all upstream emissions in scope 3 originate from metals and 9% from raw wafers.[100]

95 Think Wireless IoT Group. EUV LITHOGRAPHY IN SEMICONDUCTOR MANUFACTURING: ASML. https://www.rfid-wiot-search.com/asml-euv-lithography-in-semiconductor-manufacturing.

96 Advanced Semiconductor Materials Lithography (ASML). Responsible supply chain: Setting the bar higher for the high-tech industry. https://www.asml.com/en/company/sustainability/responsible-supply-chain.

97 Result of the analysis of CSR reports published in 2023.

98 Tokyo Electron Limited (TEL). Our Approach to the Environment. https://www.tel.com/sustainability/management-foundation/environment.

99 Jan-Hinnerk Mohr, Gaurav Tembey, Karl Breidenbach, Nadim Sah, Jörg Jeschke, and Tristan Harder (2023). For Chip Makers, the Decarbonization Challenge Lies Upstream. Boston Consulting Group. https://www.bcg.com/publications/2023/why-chip-makers-need-to-focus-on-the-upcoming-decarbonization-challenges.

100 Jan-Hinnerk Mohr, Gaurav Tembey, Karl Breidenbach, Nadim Sah, Jörg Jeschke, and Tristan Harder (2023). For Chip Makers, the Decarbonization Challenge Lies Upstream. Boston Consulting Group. https://www.bcg.com/publications/2023/why-chip-makers-need-to-focus-on-the-upcoming-decarbonization-challenges.

Raw materials

Raw materials, such as palladium, copper, cobalt and rare earth elements (REEs), are critical inputs that are required in countless steps in the manufacturing process, such as substrates, barrier layers and interconnects. However, they are only needed in small quantities. Before these materials can be used in a fab, they are produced in three distinct steps: 1) mining, 2) refining and 3) conversion and processing.[101] **The environmental and climate impacts of raw materials vary depending on the specific type, but all mined materials significantly affect the environment. They are naturally limited, and their processing typically requires considerable energy, further increasing their climate impact.**

Most raw materials are only used in small quantities in front-end manufacturing. When comparing the **palladium** demand by industry in 2022, the largest share (79%) is attributable to the automotive industry and only 16% is used in industrial applications, including front-end manufacturing.[102] The same goes for copper and cobalt, the latter also being a by-product of copper ore and nickel ore mining.[103] **Copper** is mainly used in transport, appliances and infrastructure (74% in total), while **cobalt**[104] is mostly used for electric vehicles (40%) and portable batteries (30%).[105] The demand for semiconductors is less than 10%.[106]

The so-called **REEs** encompass a group of 17 different types of metals[107] originating from the same geological formations and sharing similar chemical properties, such as being magnetic, electrochemical and luminescent.[108] In fact, they are not 'rare'

101 Joris Teer, Mattia Bertolini (2022). Reaching breaking point: The semiconductor and critical raw material ecosystem at a time of great power rivalry. https://hcss.nl/wp-content/uploads/2022/10/Reaching-breaking-point-full-HCSS-2022-revised.pdf.

102 Statista Research Department (2024). Palladium demand share worldwide by industry [chart].https://www.statista.com/statistics/1421333/palladium-demand-share-worldwide-by-industry/.

103 Joris Teer, Mattia Bertolini (2022). Reaching breaking point: The semiconductor and critical raw material ecosystem at a time of great power rivalry. The Hague Centre for Strategic Studies. https://hcss.nl/wp-content/uploads/2022/10/Reaching-breaking-point-full-HCSS-2022-revised.pdf.

104 Cobalt is an interesting example of the complex climate and environmental footprint of raw materials. 70% of global cobalt mining takes place in the Democratic Republic of Congo (RC), the only place in the world where cobalt can be extracted on its own. Studies examining the environmental impact of the mining of this valuable metal in the cobalt regions of Congo found that not only landscapes, water, animals and crops are contaminated with cobalt and toxic waste, but that there is also significant health damage to workers and the population through radioactive emissions. For more information, please refer to: *Joris Teer, Mattia Bertolini (2022). Reaching breaking point: The semiconductor and critical raw material ecosystem at a time of great power rivalry. https://hcss.nl/wp-content/uploads/2022/10/Reaching-breaking-point-full-HCSS-2022-revised.pdf.; Osama Alshantti (2022). Cobalt mining in the Democratic Republic of the Congo: The human and environmental costs of the transition to green technology. Spheres of Influence. https://spheresofinfluence.ca/coblat-mining-drc-green-technology/; NIFDAR Consulting (2024). From riches to Woes: Understanding the complex relationship between cobalt mining, climate change, and public health in the DRC. Global Public Health. https://nifdarconsulting.com/cobalt-mining-climate-health-drc.*

105 Stefanie Klose, Stefan Pauliuk (2023). Sector-level estimates for global future copper demand and the potential for resource efficiency. Resources, Conservation and Recycling, 193, 106941. https://shorturl.at/LLRAy.

106 Madhumitha Jaganmohan (2024). Distribution of cobalt demand worldwide in 2022, by application. https://www.statista.com/statistics/1143399/global-cobalt-consumption-distribution-by-application.

107 Out of 17 rare earth elements, 15 are lanthanides with the atomic numbers 57 to 71 and the other two are scandium (atomic number 21) and yttrium (39).

108 Tony Zuberbuehler (2023). The most important metals in electronics - rare earth metals. Versa Electronics - Electronic Manufacturing Services. https://versae.com/the-most-important-metals-in-electronics-manufacturing-rare-earth-metals.

but exist in abundance. The rarest REE, thulium, is 125 times more prevalent in the earth's crust than gold, and the most prolific REE (cerium) is 15000 times more abundant than gold.[109] However, REEs are not found in solid clumps or seams. They are unevenly distributed over the earth's crust and, consequently, much harder to mine and expensive to produce and process.[110] In conclusion, they have a high environmental footprint during production, even higher than that of raw materials. Even though the volume of REEs in semiconductor manufacturing may be small, they still play an indispensable role.[111] For example, **neodymium** is used as a magnet in lasers in lithography, sensors and plasma material processing, whereas **yttrium oxide** is used in plasma etching and **erbium** is being studied for enabling silicon to emit light.[112] In addition, **lanthanum** and **cerium** are used as catalysts to facilitate specific chemical reactions and purify semiconductor materials. Polishing compounds for glasses, semiconductors and ceramics are also one of the largest uses for lanthanum.[113]

Wafers

Even though minerals such as silicon, gallium or germanium can also be categorised as raw materials, this section exclusively focuses on their most common usage as materials for wafers. **Most wafers today (more than 95%) are made of silicon, which is expected to remain the key material for almost all volume applications in 2030.**[114] Silicon originates from the second most abundant element on earth: sand. The specific type of sand used is the so-called silica sand, originating from quartz (silicon dioxide). Thus, its environmental impact is negligible, and most of the climate footprint comes from the high level of purification, which is very energy intensive.[115] [116]

Particularly in power and radio frequency applications, out of a wide range of compound semiconductors, the use of gallium or germanium substrates has proven highly effective in improving specific functionalities. **In 2022, 15% of the total**

109 Neil Sharp (2019). Why are rare earth elements so crucial for electronics manufacturing? https://www.escatec.com/blog/rare-earth-elements-electronics-manufacturing.

110 Neil Sharp (2019). Why are rare earth elements so crucial for electronics manufacturing? https://www.escatec.com/blog/rare-earth-elements-electronics-manufacturing.

111 Emerging Information and Technology Conference (EITC) (2024). Rare Earth Metals and Semiconductor. http://eitc.org/research-opportunities/new-materials-technology-and-applications/emerging-semiconductor-and-electronics-technologies/the-future-of-semiconductor-technology/semicomductor-materials/rare-earth-metals-and-semiconductor.

112 Amr Elharony (2024). The Unseen Role of Rare Earth Elements in Semiconductor Manufacturing. https://www.linkedin.com/pulse/unseen-role-rare-earth-elements-semiconductor-amr-elharony-n7jmf/.

113 Mpila Makiesse Nkiawete, Randy Lee Vander Wal (2024). Rare earth elements: Sector allocations and supply chain considerations. https://doi.org/10.1016/j.jre.2024.01.020.

114 Rupert Krautbauer (2023). The Wafer Market Mechanics and Trends. Siltronic AG. https://www.siltronic.com/fileadmin/user_upload/Siltronic_Capital_Markets_Day_Dr_Rupert_Krautbauer.pdf.

115 Joris Teer, Mattia Bertolini (2022). Reaching breaking point: The semiconductor and critical raw material ecosystem at a time of great power rivalry. https://hcss.nl/wp-content/uploads/2022/10/Reaching-breaking-point-full-HCSS-2022-revised.pdf.

116 Sul Mulroy (2019). Mining the Elements Used in Semiconductors. https://www.azomining.com/Article.aspx?ArticleID=1532.

germanium consumption was attributed to the electronics and solar industry.[117] **For gallium, 36% of the global demand was attributed to integrated circuits and photovoltaics.**[118]

Both gallium [which is mainly used for the manufacturing of gallium arsenide (GaAs) in semiconductor manufacturing] and germanium are often produced as by-products of bauxite (aluminium ore) or zinc processing; 80% of the manufacturing capacity is located in China.[119] [120] As aluminium production is highly energy-intensive and emits a host of toxic by-products, it has a high ecological footprint.[121] In addition, compound semiconductors have higher melting temperatures than silicon, and thus, consume more energy and emit higher GHGs during raw wafer production.[122] **In conclusion, wafer production for compound semiconductors has a much higher ecological footprint than silicon.** [123]

Fuel and energy

The environmental and climate impacts of energy in fabs are categorised into direct and indirect energy. **Direct energy** includes every form of energy that is generated in the fab, whereas **indirect energy** is every form of energy that is generated outside the fab by an external energy supplier. Consumption of direct energy is accounted for in scope 1 of the GHG Protocol (controlled by the company). Indirect energy consumption, in contrast, is reported in scope 2 of the GHG Protocol. **Regardless of the form of energy, the main solution to reduce the environmental and climate impacts is a switch to renewable energy. This not only reduces emissions during fabrication but also prevents permanent damage to the environment during generation.**

117 Statista Research Department (2024). Distribution of germanium consumption worldwide in 2022, by end-use [chart]. https://www.statista.com/statistics/1446296/distribution-of-germanium-consumption-worldwide-by-end-use/.

118 Statista Research Department (2024). Distribution of gallium consumption worldwide in 2022, by end-use [chart]. https://www.statista.com/statistics/605987/distribution-of-world-gallium-consumption-by-end-use/.

119 Critical Raw Materials (CRM) Alliance (2024). Critical Raw Materials: Gallium. https://www.crmalliance.eu/gallium.

120 Jan-Hinnerk Mohr, Gaurav Tembey, Karl Breidenbach, Nadim Sah, Jörg Jeschke, and Tristan Harder (2023). For Chip Makers, the Decarbonization Challenge Lies Upstream. Boston Consulting Group. https://www.bcg.com/publications/2023/why-chip-makers-need-to-focus-on-the-upcoming-decarbonization-challenges.

121 Aluminium production generates so-called "red must wastes" and toxic pollutants (NOx, Sox, toxic fluorides, volatile hydrocarbons, etc) and uses high amounts of water.

122 Jan-Hinnerk Mohr, Gaurav Tembey, Karl Breidenbach, Nadim Sah, Jörg Jeschke, and Tristan Harder (2023). For Chip Makers, the Decarbonization Challenge Lies Upstream. Boston Consulting Group. https://www.bcg.com/publications/2023/why-chip-makers-need-to-focus-on-the-upcoming-decarbonization-challenges.

123 Jan-Hinnerk Mohr, Gaurav Tembey, Karl Breidenbach, Nadim Sah, Jörg Jeschke, and Tristan Harder (2023). For Chip Makers, the Decarbonization Challenge Lies Upstream. Boston Consulting Group. https://www.bcg.com/publications/2023/why-chip-makers-need-to-focus-on-the-upcoming-decarbonization-challenges.

Direct energy

Own energy generation includes gas, diesel, fuel, oil, petrol and firewood produced in the fab. Firewood, a very minor share of total direct energy consumption, is labelled as renewable energy.[124] Approximately 5%–15% of scope 1 direct emissions come from direct energy consumption through on-site fossil fuel combustion and heating.[125] [126] The main lever for direct energy consumption reduction from own energy generation is to install on-site renewable energy (e.g. wind parks or solar plants).

Indirect energy

Aside from steam and district heating, electricity accounts for the largest share of energy consumption in semiconductor manufacturing. Indirect energy consumption that is sourced from external power suppliers mostly comes from the high amounts of electricity required in front-end manufacturing; **56% comes from electricity used in manufacturing itself, and 44% is attributable to the operation of facilities and utilities.**[127] Quantifying the average amount of electricity consumed by a fab or aggregated annually for the whole industry is not simple, mainly because the amount of electricity consumed strongly depends on the type of chip and the matching manufacturing process. **With smaller node sizes, manufacturing processes become more complex, and specific process steps are repeated more often.** EUV lithography, the most advanced form of lithography required to manufacture the most advanced chips to date, uses approximately 10 times as much electricity as conventional 193 nm immersion lithography.[128] As a result, in 2019, normalised energy consumption increased by 25% with the introduction of EUV for 7 nm process nodes.[129]

Similar to a lack of clarity on the manufacturing process technology, it is often not

124 See for example *Sustainability at Infineon. Supplementing the annual report 2023 (2023).* *https://www.infineon.com/dgdl/Sustainability_at+Infineon_2023.pdf?fileId=8ac78c8b8b657de2018c009d03120100.*

125 August Rick, Katrin Wu & Tianyi Luo (2023). Invisible Emissions: A forecast of tech supply chain emissions and electricity consumption by 2030. Greenpeace East Asia. https://www.greenpeace.org/static/planet4-eastasia-stateless/2023/04/620390b7-greenpeace_energy_consumption_report.pdf.

126 Sébastien Raoux (2021). Fluorinated greenhouse gas and net-zero emissions from the electronics industry: the proof is in the pudding. Carbon Management, *14*(1). https://doi.org/10.1080/17583004.2023.2179941.

127 August Rick, Katrin Wu & Tianyi Luo (2023). Invisible Emissions: A forecast of tech supply chain emissions and electricity consumption by 2030. Greenpeace East Asia. https://www.greenpeace.org/static/planet4-eastasia-stateless/2023/04/620390b7-greenpeace_energy_consumption_report.pdf.

128 Interuniversity Microelectronics Centre (imec). Sustainable semiconductor technologies and systems (SSTS): The green transition of the IC industry. https://www.imec-int.com/en/expertise/cmos-advanced/sustainable-semiconductor-technologies-and-systems-ssts/stss-white-paper.

129 Edwards Vacuum Innovation Hub. The Time is Now: Sustainable Semiconductor Manufacturing. https://www.edwardsvacuum.com/en-uk/knowledge/innovation-hub/the-time-is-now-sustainable-semiconductor-manufacturing0.

clear whether the semiconductor supplier’s GHG data include back-end manufacturing and if the data are location- or market-based. Location-based emissions are based on the average emissions at the location where the electricity is used, factoring in the energy mix that is accessible. Market-based emissions are based on electricity purchases, supplier offerings, renewable energy certificates (RECs), etc., which offer companies to source a specific energy mix even if this is not aligned with or cannot be matched by the local grid resources.[130]

Recently, numerous reports[131] have emphasised the significant electricity consumption in front-end manufacturing by drawing comparisons with homes,[132] cities[133] [134] and even national energy usage levels.[135] According to our calculations, the electricity consumption of the European semiconductor industry in 2030 will be around 47.4 tWh (a steep increase from 10tWh in 2021), which is around half that of European data centres (98.5 tWh).[136] **Electricity is the biggest single source of GHG emissions.**[137]

Accordingly, a switch to more renewable energy is the biggest motivation to reduce the ecological footprint of front-end manufacturing, which reduces not only scope 2 emissions but also the depletion of natural resources caused by energy consumption from fossil sources.[138]

But the share of renewable energy in the electricity consumption of the 20 largest

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130 August Rick, Katrin Wu & Tianyi Luo (2023). Invisible Emissions: A forecast of tech supply chain emissions and electricity consumption by 2030. Greenpeace East Asia. https://www.greenpeace.org/static/planet4-eastasia-stateless/2023/04/620390b7-greenpeace_energy_consumption_report.pdf.

131 Reports do not refer to the same metrics and often give examples that are hard to grasp. A report by McKinsey estimated that a fab’s hourly electricity consumption is around 100-megawatt-hours, which is then compared to an annual electricity consumption of 50 000 homes. Stand.earth recently analysed the energy consumption of the new semiconductor fabs from Intel, TSMC, Samsung and Micron that are being built in the US. They predict that these additional fabs could use more than twice as much electricity as the city of Seattle. According to a Greenpeace report, the semiconductor industry is on track to consume 237 terawatt hours of (TWh) of electricity globally in 2030 which can be compared to Australia’s 2021 electricity consumption.

132 Steve Chen, Apoorv Gautam & Florian Weig (2013). Bringing energy efficiency to the fab. McKinsey & Company. https://shorturl.at/VrYQd

133 Justine Calma (2024). How much energy will new semiconductor factories burn through in the US? Semiconductor factories are coming back to the US, and they’re going to use a lot of energy. The Verge. https://www.theverge.com/2024/3/6/24091367/semiconductor-manufacturing-us-electricity-consumption-renewable-energy-report.

134 Gary Cook (2024). Clean Clicks or Dirty Chips? Stand Earth. https://stand.earth/wp-content/uploads/2024/02/Clean-Clicks-or-Dirty-Chips-Feb-2024_230224.pdf.

135 The Greenpeace Report 2023 is not giving an estimation of the electricity globally used today. *August Rick, Katrin Wu & Tianyi Luo (2023). Invisible Emissions: A forecast of tech supply chain emissions and electricity consumption by 2030. Greenpeace East Asia. https://www.greenpeace.org/static/planet4-eastasia-stateless/2023/04/620390b7-greenpeace_energy_consumption_report.pdf.*

136 Calculations based on EU JRC report and Greenpeace projections. The Greenpeace Report 2023 is not giving an estimation of the electricity globally used today. *August Rick, Katrin Wu & Tianyi Luo (2023). Invisible Emissions: A forecast of tech supply chain emissions and electricity consumption by 2030. Greenpeace East Asia. https://www.greenpeace.org/static/planet4-eastasia-stateless/2023/04/620390b7-greenpeace_energy_consumption_report.pdf.; George Kamiya, Paolo Bertoldi (2024). Energy consumption in data centres and broadband communication networks in the EU (No. JRC135926). Publications Office of the European Union. https://doi.org/10.2760/706491. ; European Commission (2020). Energy-efficient cloud computing technologies and policies for an eco-friendly cloud market – Final study report, Publications Office, https://data.europa.eu/doi/10.2759/3320*

137 August Rick, Katrin Wu & Tianyi Luo (2023). Invisible Emissions: A forecast of tech supply chain emissions and electricity consumption by 2030. Greenpeace East Asia. https://www.greenpeace.org/static/planet4-eastasia-stateless/2023/04/620390b7-greenpeace_energy_consumption_report.pdf.

138 Marcello Ruberti (2023). The chip manufacturing industry: Environmental impacts and eco-efficiency analysis. Science of the Total Environment, 858, 159873. https://shorturl.at/MEwoi.

chip manufacturers[139] in 2022 varies significantly – from 0% to 100%. Of the 20 companies analysed, more than half (13) used less than 10% renewable energy and only 2 companies used more than 80% renewable energy. When looking at the bigger picture, i.e. the current national energy mix of major semiconductor manufacturing countries, it becomes apparent that the current access to renewable energy also varies greatly. In 2022, South Korea and Taiwan had only 4% of renewables in their energy mix, followed by the United States (11%) and Japan (13%).[140] China (16%) and Europe (19%) had the highest share of renewable energy.[141] [142]

Although renewable energy is currently less prevalent, numerous semiconductor companies have established ambitious goals to achieve carbon neutrality by 2030.[143] As it is not possible to source 100% renewable energy locally by 2030, many companies rely on the purchase of unbundled RECs. RECs are a form of carbon offsetting that is focused on compensation for fossil fuel consumption and were designed to increase renewable energy production. A REC certifies that one megawatt-hour of electricity was generated from a renewable source. The electricity provider can then sell the REC and the electricity itself – either bundled or unbundled. This allows a company to only buy the REC (from a different grid, different year, etc.) and obtain the electricity from a fuel-based source located close to the facility. **Thus, the REC does not stand for transferred renewable energy; instead, it only certifies the compensation for sourcing non-renewable energy.**[144] [145] **Nevertheless, a company that matches their total electricity usage with an equal amount of RECs can essentially pledge that it is working with 100% renewable energy.**[146] **As RECs account for 84% of renewable energy use in the semiconductor industry, this is highly problematic.** Essentially, emissions are counted twice, and no additional capacity for renewable energy production is added.[147] If emission

139 The companies analyzed were chosen based on market data of the largest wafer capacities (in 200mm equivalents). If a top 20 company was excluded due to lack of semiconductor division disclosure or insufficient sustainability reporting, the next company on the list was included. The final list comprises companies that provided the necessary information.

140 Hannah Ritchie, Max Roser & Pablo Rosado (2024). Renewable Energy. Our World in Data. https://ourworldindata.org/renewable-energy.

141 Hannah Ritchie, Max Roser & Pablo Rosado (2024). Renewable Energy. Our World in Data. https://ourworldindata.org/renewable-energy.

142 According to national data sources, numbers are slightly higher. See for example the European Environment Agency (23%) or the US Energy Information Administration (13%).

143 See for example Infineon, Intel and STMicroelectronics.

144 Gary Cook (2024). Clean Clicks or Dirty Chips? Stand Earth. https://stand.earth/wp-content/uploads/2024/02/Clean-Clicks-or-Dirty-Chips-Feb-2024_230224.pdf.

145 James Chen (2024). Renewable Energy Certificate (REC): Definition, Types, Example. Investopedia. https://www.investopedia.com/terms/r/rec.asp.

146 Justine Calma (2024). How much energy will new semiconductor factories burn through in the US? Semiconductor factories are coming back to the US, and they're going to use a lot of energy. The Verge. https://www.theverge.com/2024/3/6/24091367/semiconductor-manufacturing-us-electricity-consumption-renewable-energy-report.

147 August Rick, Katrin Wu & Tianyi Luo (2023). Invisible Emissions: A forecast of tech supply chain emissions and electricity consumption by 2030. Greenpeace East Asia. https://www.greenpeace.org/static/planet4-eastasia-stateless/2023/04/620390b7-greenpeace_energy_consumption_report.pdf.

reductions claimed through RECs are removed, companies will no longer be in line with their science-based targets, and consequently, not on track to meet the 1.5°C goal.[148] Power purchase agreements (PPAs) could be a better alternative to increase renewable energy use. PPAs represent a long-term commitment to pay for a certain amount of electricity that is sourced from a specific renewable energy project.[149] This has proven to be more successful in installing new renewable energy projects locally, leading to real emission reductions.[150] [151]

Water

In a fab, there are four main areas of water usage: 1) ultrapure water (UPW) (production and usage), 2) cooling, 3) heating, ventilation and air conditioning and 4) drinking water.[152] Water supply accounts for 4% of all upstream scope 3 emissions.[153] Even though the share of emissions in scope 3 that can be attributed to water is minor, the environmental impact can be severe. This is rooted in the fact that the amount of water consumed by a fab is immense. **A large semiconductor fab uses up to 38 million litres (L) (equal to 10 million gallons) per day, equivalent to the daily water consumption of 300,000 people in Germany**[154] **or 500 swimming pools (76,000 L per pool).**[155] An average hyperscale data centre consumes 11 to 19 million litres of water every day, only half the consumption of front-end manufacturing.[156]

Most of the water is used for UPW, which is either procured externally from specialised companies providing UPW services or generated on site in water treatment plants to produce UPW tailored to the fabs' specific manufacturing needs, such as different purity specifications and adoption of evolving manufacturing processes. The latter is more common, as millions of litres of UPW are needed in

148 Anders Bjørn, Shannon M. Lloyd, Mathew Brander & H. Damon Matthews (2022). Renewable energy certificates threaten the integrity of corporate science-based targets. *Nature Climate Change*, *12*(6), 539-546. https://doi.org/10.1038/s41558-022-01379-5.

149 Justine Calma (2024). How much energy will new semiconductor factories burn through in the US? Semiconductor factories are coming back to the US, and they're going to use a lot of energy. The Verge. https://www.theverge.com/2024/3/6/24091367/semiconductor-manufacturing-us-electricity-consumption-renewable-energy-report.

150 Justine Calma (2024). How much energy will new semiconductor factories burn through in the US? Semiconductor factories are coming back to the US, and they're going to use a lot of energy. The Verge. https://www.theverge.com/2024/3/6/24091367/semiconductor-manufacturing-us-electricity-consumption-renewable-energy-report.

151 Anders Bjørn, Shannon M. Lloyd, Mathew Brander & H. Damon Matthews (2022). Renewable energy certificates threaten the integrity of corporate science-based targets. *Nature Climate Change*, *12*(6), 539-546. https://doi.org/10.1038/s41558-022-01379-5.

152 ST Microelectronics (2023). ST 2023 Sustainability report. https://www.st.com/content/dam/about-us/sustainability/stmicroelectronics-sustainability-report-2023.pdf.

153 Jan-Hinnerk Mohr, Gaurav Tembey, Karl Breidenbach, Nadim Sah, Jörg Jeschke, and Tristan Harder (2023). For Chip Makers, the Decarbonization Challenge Lies Upstream. Boston Consulting Group. https://www.bcg.com/publications/2023/why-chip-makers-need-to-focus-on-the-upcoming-decarbonization-challenges.

154 Statistisches Bundesamt (2022). Zahl der Woche Nr. 12 vom 22. März 2022. https://www.destatis.de/DE/Presse/Pressemitteilungen/Zahl-der-Woche/2022/PD22_12_p002.htm.

155 Syed F. Alam, Timothy Chu & Metthew Haggerty (2023). The Pulse of the Semiconductor Industry: Balancing resilience with innovation. Accenture. https://www.accenture.com/de-de/insights/high-tech/semiconductor-research.

156 Olivia Solon (2021). Do water-intensive data centers need to be built in the desert? NBC News. https://www.nbcnews.com/tech/internet/drought-stricken-communities-push-back-against-data-centers-n1271344.

wafer fabrication. The more advanced the manufacturing process, the more water is needed.[157] The production of UPW is a highly complex process, including multi-stage reverse osmosis, ultrafiltration and UV treatment. Moreover, fabs reuse and recycle water on site.[158] [159]

Even though it is safe to say that every fab relies on an immense amount of water being supplied to it and that there is a trend of withdrawing more and more water, one must be careful about general assumptions regarding the environmental footprint of water consumption. **When looking at water consumption, it is important to consider whether the portion of withdrawn water is returned to the original source or if it is effectively lost from the immediate ecosystem.** In many cases, companies put into place actions to balance out the total amount of water taken from rivers, lakes, groundwater, etc. by discharging water somewhere else.[160] This is why some manufacturers state in their CSR reports that they are 'net-positive' in terms of their water consumption.[161]

Strategies on how to procure, withdraw and recycle water are closely linked to the availability of water and infrastructure surrounding the fab. While most of the fabs predominantly rely on surface water intake and municipal water supply, there are cases in which companies almost entirely rely on third-party supply (e.g. private wells).[162] The degree of water scarcity also plays a huge role regarding water sources and recycling rates. **Fabs located in Europe have significantly lower water recycling rates (10%–14%) than those located in Taiwan (~80%).**[163] As the latter country is often under severe water shortage stress, being able to reuse and recycle water can be key to guaranteeing the quantity and quality of UPW supply for fabrication.[164]

157 Marcello Ruberti (2023). The chip manufacturing industry: Environmental impacts and eco-efficiency analysis. Science of the Total Environment, 858, 159873. https://shorturl.at/MEwoi.

158 Marcello Ruberti (2023). The chip manufacturing industry: Environmental impacts and eco-efficiency analysis. Science of the Total Environment, 858, 159873. https://shorturl.at/MEwoi.

159 Qi Wang, Nan Huang, Zhuo Chen, Xiaowen Chen, Hanying Cai & Yunpeng Wu (2023). Environmental data and facts in the semiconductor manufacturing industry: An unexpected high water and energy consumption situation. Water Cycle, 4, 47–54. https://doi.org/10.1016/j.watcyc.2023.01.004.

160 Qi Wang, Nan Huang, Zhuo Chen, Xiaowen Chen, Hanying Cai & Yunpeng Wu (2023). Environmental data and facts in the semiconductor manufacturing industry: An unexpected high water and energy consumption situation. Water Cycle, 4, 47–54. https://doi.org/10.1016/j.watcyc.2023.01.004.

161 One example is Intel's CSR report: *Intel (2023). Corporate Responsibility Report 2022-23. https://csrreportbuilder.intel.com/pdfbuilder/pdfs/CSR-2022-23-Full-Report.pdf.*

162 Qi Wang, Nan Huang, Zhuo Chen, Xiaowen Chen, Hanying Cai & Yunpeng Wu (2023). Environmental data and facts in the semiconductor manufacturing industry: An unexpected high water and energy consumption situation. Water Cycle, 4, 47–54. https://doi.org/10.1016/j.watcyc.2023.01.004.

163 Result of the analysis of CSR reports published in 2023.

164 Qi Wang, Nan Huang, Zhuo Chen, Xiaowen Chen, Hanying Cai & Yunpeng Wu (2023). Environmental data and facts in the semiconductor manufacturing industry: An unexpected high water and energy consumption situation. Water Cycle, 4, 47–54. https://doi.org/10.1016/j.watcyc.2023.01.004.

End-of-life treatment

Resembling the lack of transparency and traceability in terms of the ecological footprint of chips during operation, as depicted in chart 3, semiconductor manufacturers also lack control over the recycling and disposal of chips in the end-product, as they only supply intermediate products. Thus, assessing the level of contribution to electronic waste (e-waste)[165] is difficult.[166] Currently, the concept of circular economy and recycling primarily focuses on waste generated in manufacturing and not on the end-of-life treatment of products containing chips. End-of-life treatment encompasses any activities to reuse or recycle parts and pieces of electronics.

As the average lifespan of electronics is increasingly shrinking – from laptops being replaced after only three years or smartphones with an average lifetime of four years – the amount of e-waste is growing significantly.[167] It is estimated that, worldwide, e-waste will grow to 75 million tons by 2030, a 1,5x increase from 50 million tons in 2019.[168] Of this gigantic amount of e-waste, only 17.4% is currently properly disposed of and recycled.[169] The great remainder is incinerated or dumped in landfills, releasing toxins into the environment, soil and groundwater, which ultimately poses serious environmental and health risks.[170] Additionally, the process of shredding and burning e-waste releases dust and toxic particles into the air.[171]

The reason behind the fact that there are no stringent recycling practices for reusing and recycling electronics and chips is that the process is not only complex but also not climate-friendly and sustainable. In an electronic device, chips are soldered to a printed circuit board (PCB). The recovery of any chip or its materials always starts with techniques to pry the PCB out of the device and separate it from batteries and other components. The latter components undergo a separate recycling process.[172] As some of these components contain toxic materials, this recycling needs to be

165 E-waste includes appliances, such as computers, cell refrigerators or smartphones, as well as components from manufacturing.

166 Steve Watkins, Duncan Stewart & Jeroen Kusters. *Semiconductor sustainability: Efforts across the value chain.* Deloitte United States. https://www2.deloitte.com/us/en/pages/consulting/articles/addressing-scope-3-emissions-in-the-semiconductor-industry.html.

167 Quantum Lifecyle (2021). What's the Average Lifespan of Your Electronics? https://quantumlifecycle.com/en_CA/blog/whats-the-average-lifespan-of-your-electronics/.

168 James Morra (2023). Erasing E-Waste: Is a Circular Economy Possible for Power Electronics? Electronic Design. https://www.electronicdesign.com/blogs/the-briefing/article/21273487/electronic-design-erasing-e-waste-is-a-circular-economy-possible-for-power-electronics.

169 Sydney Travers (2023). The journey of e-waste and how it affects the environment. Fluid Truck Blog. https://www.fluidtruck.com/blog/the-journey-of-e-waste.

170 Sydney Travers (2023). The journey of e-waste and how it affects the environment. Fluid Truck Blog.

171 Sydney Travers (2023). The journey of e-waste and how it affects the environment. Fluid Truck Blog.

172 James Morra (2023). Erasing E-Waste: Is a Circular Economy Possible for Power Electronics? Electronic Design. https://www.electronicdesign.com/blogs/the-briefing/article/21273487/electronic-design-erasing-e-waste-is-a-circular-economy-possible-for-power-electronics.

performed with caution, often by dismantling it manually.[173] Next, the semiconductor itself also has different recycling needs due to the variety of materials used (plastics, metal alloys and hazardous materials such as lead, cadmium, beryllium and mercury).[174] After removing valuable materials from the PCB, the circuit board is shredded into flakes and incinerated to recover precious metals, such as gold and silver, which are then again roasted, smelted and refined to be reused in other products.[175] [176] However, in most cases, the recycling of REEs, raw materials, etc. is not yet possible. **The whole recycling process requires large amounts of electricity and water that can be contaminated with toxic solvents. In addition, it is often linked to exploitative labour practices.**[177] [178]

In conclusion, this climate-unfriendly process is hardly worthwhile for the extremely small quantities of recovered materials, which are not economically viable in most cases. This situation could change in smaller markets, such as power electronics that are increasingly switching to wide-bandgap semiconductors – silicon carbide and gallium nitride – which are pricier than silicon.[179] For example, there is ongoing research on biodegradable substrates for PCB power devices that could lead to more sustainable recycling practices without shredding or incinerating.[180] [181] However, these have yet to prove their ability to withstand complex and harsh manufacturing practices.

This example shows that the primary responsibility for efficient and sustainable recycling lies with chip designers and manufacturers and heavily depends on the type of chip that is manufactured – the more unified or standardised it is, the easier it is to recycle.[182] It is also beneficial if manufacturers introduce buy-back or collection schemes of materials to incentivise recycling and reuse of materials.[183]

173 Synergy Electronics recycling (SER). End-of-Life Processing (EOL). http://www.synergyrecycling.com/end-of-life-processing.html.

174 CAS Science Team (2024). Science Fact Fiction: Can we really recycle semiconductors? A division of the American Chemical Society. https://www.cas.org/resources/cas-insights/sustainability/science-fact-fiction-can-we-really-recycle-semiconductors.

175 James Morra (2023). Erasing E-Waste: Is a Circular Economy Possible for Power Electronics? Electronic Design. https://www.electronicdesign.com/blogs/the-briefing/article/21273487/electronic-design-erasing-e-waste-is-a-circular-economy-possible-for-power-electronics.

176 Lucas Podmore (2022). How Do We Recycle Semiconductors? AZO Materials. https://shorturl.at/6abYI.

177 James Morra (2023). Erasing E-Waste: Is a Circular Economy Possible for Power Electronics? Electronic Design. https://www.electronicdesign.com/blogs/the-briefing/article/21273487/electronic-design-erasing-e-waste-is-a-circular-economy-possible-for-power-electronics.

178 CAS Science Team (2024). Science Fact Fiction: Can we really recycle semiconductors? A division of the American Chemical Society. https://www.cas.org/resources/cas-insights/sustainability/science-fact-fiction-can-we-really-recycle-semiconductors.

179 James Morra (2023). Erasing E-Waste: Is a Circular Economy Possible for Power Electronics? Electronic Design. https://www.electronicdesign.com/blogs/the-briefing/article/21273487/electronic-design-erasing-e-waste-is-a-circular-economy-possible-for-power-electronics.

180 James Morra (2023). Erasing E-Waste: Is a Circular Economy Possible for Power Electronics? Electronic Design. https://www.electronicdesign.com/blogs/the-briefing/article/21273487/electronic-design-erasing-e-waste-is-a-circular-economy-possible-for-power-electronics.

181 JIVA Materials. The World's First Fully Recyclable Printed Circuit Board Laminate. https://www.jivamaterials.com/.

182 CAS Science Team (2024). Science Fact Fiction: Can we really recycle semiconductors? A division of the American Chemical Society. https://www.cas.org/resources/cas-insights/sustainability/science-fact-fiction-can-we-really-recycle-semiconductors.

183 CAS Science Team (2024). Science Fact Fiction: Can we really recycle semiconductors? A division of the American Chemical Society. https://www.cas.org/resources/cas-insights/sustainability/science-fact-fiction-can-we-really-recycle-semiconductors.

Meanwhile, a longer lifetime of electronics can significantly impact the reduction of e-waste and the ecological footprint of chips and electronics in general.

Transport

The transport category (depicted by the small trucks in the overview chart) plays a special role in this analysis, as it refers to the supply and movement of chip intermediates between production steps. Therefore, it cannot be assigned to just one phase but has a significant ecological footprint upstream and downstream due to the high complexity and number of suppliers (upstream) and the variety of possible applications for semiconductors (downstream). As previously emphasised, the data available on scope 3 remain limited, which makes assessing the climate impact of this category very difficult and almost impossible to measure. According to one study, upstream emissions from transport account for 6% of total scope 3 emissions; this includes internal transport (between different manufacturing locations operated by one company) or external transport (between different suppliers upstream).[184]

In the wake of the global chip shortage, prominent figures and examples emerged in the discourse to stress the involvement of a large number of countries and make the gigantic distance a semiconductor travels during its production process more tangible. It is estimated that the components of a chip travel more than 50,000 km[185] and cross international borders 70 times before reaching the end-customer.[186] **Against this background, it is highly likely that the ecological footprint in the upstream and downstream sections of the global value chain is significantly larger than the aforementioned value of 6%.**

To visualise the globalised nature, one can think of all inputs required in a front-end fab in Taiwan to produce a chip. The fab sources critical raw materials, such as palladium, cobalt and copper, from South Africa (palladium), Zimbabwe (palladium), Democratic Republic of Congo (cobalt) and China (cobalt). Meanwhile, silicon dioxide is mined and refined, for example, in the United States before being shipped to Japan, where it is melted down and processed into a silicon ingot, which is then sliced into single wafers.[187] These wafers form the basis for front-end manufacturing that might take place in a fab in Taiwan but is made possible by

184 Prashant Nagapurkar, Paulomi Nandy & Sachin Nimbalkar (2024). Cleaner Chips: Decarbonization in Semiconductor Manufacturing, in Sustainability 2024, 16(1), 218. https://www.mdpi.com/2071-1050/16/1/218.
185 Mark Harris (2022). These 5 Charts Help Demystify the Global Chip Shortage …and reveal why even infusions of cash from the U.S. and European Union won't solve it. https://spectrum.ieee.org/global-chip-shortage-charts.
186 Kate Magil (2024). CHIPS and Science Act not enough to strengthen the semiconductor industry: CSCMP report. https://www.supplychaindive.com/news/council-supply-chain-management-professionals-semiconductor-global-supply-chain-report-chips/703763/.
187 DHL. Globalization: Four strategies for future-proofing semiconductor supply chains. https://www.dhl.com/global-en/delivered/globalization/future-proofing-semiconductor-supply-chains.html.

sourcing complex lithography equipment from the Netherlands and several other equipment types from the United States and Japan, as well as chemicals from Germany and France. After the dies are finished on the wafer, the wafer might be shipped to Malaysia or China for back-end manufacturing. Once the single chips are assembled and tested, the chip starts its final journey to be built into the end-product – a graphics processing unit (GPU) could be supplied to a data centre in the United States or a microcontroller might end up in an electric vehicle manufactured in South Korea or Germany.[188] However, this example is greatly simplified and only depicts one of the many potential scenarios that strongly depend on the type of chip and the business model of the company manufacturing it and those involved in this process.

Usage of chips

When it comes to measuring the ecological impact of chips during their operation in the end-product, it is difficult to come up with reliable and detailed data. One key challenge is that, according to the GHG Protocol guidance for scope 3, semiconductor manufacturers (both in front- and back-end manufacturing) do not need to report on their climate footprint, particularly with regard to emissions, as their products are classified as 'intermediate products' and are not directly sold as end-products.[189] Moreover, manufacturers explain the missing reporting of the 'use phase' category in scope 3 because of a lack of data reliability and accuracy.[190]

There are also major gaps in the state of research on the ecological footprint during the operation of end-products. **However, research comparing manufacturing and operational emissions in consumer electronics and data centres has revealed a significant difference in the final application. For battery-powered devices (e.g. tablets, phones, wearables and laptops), emissions during (front-end) manufacturing dominate those during operation.** Importantly, amortising the high manufacturing footprint for battery-powered devices necessitates a lifetime of three years or longer, which often goes beyond their typical lifetime.[191] **In contrast, devices that are always connected (e.g. desktop PCs and game consoles) have higher emissions during operation and fewer during manufacturing.** The result is most evident for data centres – the extremely high energy consumption during operation

188 Semiconductor PFAS Consortium (2023). Background on semiconductor manufacturing and PFAS. https://www.semiconductors.org/wp-content/uploads/2023/05/FINAL-PFAS-Consortium-Background-Paper.pdf.
189 Prashant Nagapurkar, Paulomi Nandy & Sachin Nimbalkar (2024). Cleaner Chips: Decarbonization in Semiconductor Manufacturing, in Sustainability 2024, 16(1), 218. https://www.mdpi.com/2071-1050/16/1/218.
190 Prashant Nagapurkar, Paulomi Nandy & Sachin Nimbalkar (2024). Cleaner Chips: Decarbonization in Semiconductor Manufacturing, in Sustainability 2024, 16(1), 218. https://www.mdpi.com/2071-1050/16/1/218.
191 Udit Gupta, Young Geun Kim, Sylvia Lee, Jordan Tse, Hsien-Hsin S. Lee, Gu-Yeon Wei, David Brooks, Carole-Jean Wu (2022). Chasing Carbon: The Elusive Environmental Footprint of Computing. Chasing Carbon: the elusive environmental footprint of computing. *IEEE MICRO/IEEE Micro*, *42*(4), 37–47. https://doi.org/10.1109/mm.2022.3163226.

leads to significantly higher emissions during operation.[192] Analogous to energy-intensive manufacturing, a switch to renewable energies is the biggest motivation for reducing emissions in data centre operations. In addition to the high energy intensity in data centres, another severe environmental impact is the demand for large quantities of water for cooling operations.[193] Of course, this only covers part of the usage of chips in the respective product. Similar studies on usage in the automotive, healthcare or industrial sector are yet to be conducted.

Waste

Although the ecological footprint of water and wastewater overlaps in some cases, they differ greatly in terms of on-site or external treatment and potential recycling options. Their environmental impact is, therefore, considered separately.

Waste

Apart from GHG emissions and various volatile organic compounds that are released into the atmosphere, front-end manufacturing generates chemical waste, solid waste, wastewater, slurries and abrasives and packaging waste. In the last eight years, the amount of waste generated in the semiconductor industry has nearly doubled.[194]

Regarding the environmental impact, it is important to differentiate between general or non-hazardous waste and hazardous waste.[195] [196] For most semiconductor manufacturers, the ratio between hazardous and non-hazardous waste is 40%–60%.[197] Unused or spent chemicals, such as those that can be categorised as PFASs, often contain waste acids, waste solvents, waste copper sulphate, heavy metals, etc., which end up in either chemical waste or wastewater.[198] [199] If not treated properly, they pose a high risk to environmental and human health. The same applies to waste slurries, which consist of solid and potentially abrasive and hazardous particles suspended in water from chemical

192 Udit Gupta, Young Geun Kim, Sylvia Lee, Jordan Tse, Hsien-Hsin S. Lee, Gu-Yeon Wei, David Brooks, Carole-Jean Wu (2022). Chasing Carbon: The Elusive Environmental Footprint of Computing. Chasing Carbon: the elusive environmental footprint of computing. *IEEE MICRO/IEEE Micro*, *42*(4), 37–47. https://doi.org/10.1109/mm.2022.3163226.

193 Shannon Osaka (2023). A new front in the water wars: Your internet use. https://www.washingtonpost.com/climate-environment/2023/04/25/data-centers-drought-water-use/.

194 Ian King (2022): Chipmakers’ $52 Billion US Bonanza Imperils Environmental Gains. Bloomberg.

195 United Microelectronics Corporation (UMC) (2020). Corporate Social Responsibility Report 2020. https://shorturl.at/UiQAs.

196 NXP. Environment, Health & Safety: Waste. https://www.nxp.com/company/about-nxp/sustainability-and-esg/environment-health-and-safety/waste:ENVIRONMENT-WASTE.

197 Comparison of annual CSR reports.

198 United Microelectronics Corporation (UMC) (2020). Corporate Social Responsibility Report 2020. https://shorturl.at/UiQAs.

199 NXP. Environment, Health & Safety: Waste. https://www.nxp.com/company/about-nxp/sustainability-and-esg/environment-health-and-safety/waste:ENVIRONMENT-WASTE.

mechanical polishing (CMP) processes.[200] [201]

Front-end manufacturers have put in place waste classification and separation, as well as safe treatment practices to comply with regulations and increase the share of recyclable waste. Within the last decade, most manufacturers have achieved high external recycling rates and very low rates of disposal to landfill.[202] A low share of hazardous waste needs to be treated by specially authorised companies. On average, around 70% of all hazardous and non-hazardous wastes can be recycled for reuse in **other** industries.[203] For example, fluoride sludge can be transformed into pellets for the metallurgy industry, sulfuric acids are used in battery recycling and palladium is recovered for reuse in the automotive industry.[204] **It is much more difficult to recycle waste to be reused within the front-end manufacturing process itself. The share of preparation for reuse in a fab varies significantly and is mostly applied to chemical reuse from hazardous waste.** A recent example is the invention of neon gas recycling technology, which can reduce emissions in the production and usage of neon gas, as well as in waste treatment.[205] Additionally, waste is burnt with recovery for energy; only 1%–5% of waste is sent to landfill.[206]

Wastewater

While all waste is diverted off site, wastewater (mostly from CMP processes) is often treated and recycled on site.[207] It contains a range of harmful contaminants (solvents, arsenic, fine oxide particles, etc.) that could pose risks to the environment and human health. Thus, proper treatment is crucial to contain toxic components and recycle chemicals.[208] **Around 15%–20% of UPW and production wastewater can be reused. Several chemicals and materials are recycled by wastewater treatment facilities for reuse by other industries.**[209] [210] Ammonium sulphate, for example, is commonly used in fertilizer manufacturing.[211]

200 United Microelectronics Corporation (UMC) (2020). Corporate Social Responsibility Report 2020. https://shorturl.at/UiQAs.

201 NXP. Environment, Health & Safety: Waste. https://www.nxp.com/company/about-nxp/sustainability-and-esg/environment-health-and-safety/waste:ENVIRONMENT-WASTE.

202 Comparison of annual CSR reports.

203 Comparison of annual CSR reports.

204 ST Microelectronics (2023). ST 2023 Sustainability report. https://www.st.com/content/dam/about-us/sustainability/stmicroelectronics-sustainability-report-2023.pdf.

205 Antony Wright (2024). Industry's first neon gas recycling technology announced by SK Hynix, TEMC. Gas World. https://www.gasworld.com/story/industrys-first-neon-gas-recycling-technology-announced-by-sk-hynix-temc/2136766.article/.

206 Comparison of annual CSR reports.

207 Chien-wen Shen, Phung Phi Tran, Pham Thi Minh Ly (2018). Chemical waste management in the U.S. semiconductor industry. *Sustainability*, *10*(5), 1545. https://doi.org/10.3390/su10051545.

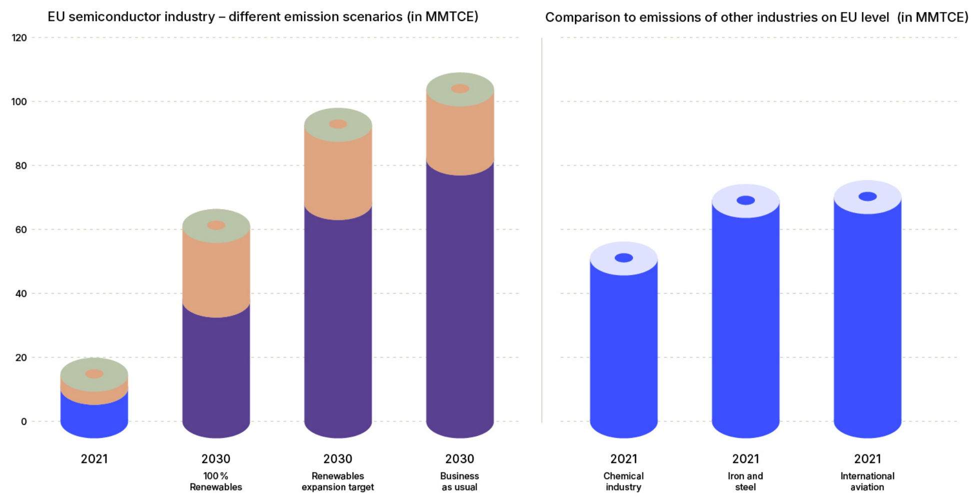
208 Chien-wen Shen, Phung Phi Tran, Pham Thi Minh Ly (2018). Chemical waste management in the U.S. semiconductor industry. *Sustainability*, *10*(5), 1545. https://doi.org/10.3390/su10051545.

209 Taiwan Semiconductor Manufacturing (TSMC) (2022): Sustainability Report. https://esg.tsmc.com/download/file/2022_sustainabilityReport/english/e-all.pdf.

210 Taiwan Semiconductor Manufacturing (TSMC) (2022): Sustainability Report. https://esg.tsmc.com/download/file/2022_sustainabilityReport/english/e-all.pdf.

Outlook: Projected GHG Emissions of the European Semiconductor Industry in 2030

8 EU semiconductor emissions if 20 % of global production is achieved



By 2030, chip production in Europe could emit more GHGs than Europe's chemical industry today. Emissions 2021 Increasing scope 3 Emissions 2030

The chart forecasts emissions in European semiconductor manufacturing for 2030, assuming 20% of the global production share. It shows emissions in 2021 (1st bar, based on 8% of global production share) and presents three scenarios: ideal (100% renewable energy, 2nd bar), EU renewables expansion target (42.5%, 3rd bar) and business as usual (current energy mix, 4th bar). Each scenario includes the impact of higher GHG scope 3 emissions, represented by stacked orange bars. Despite efforts, emissions could quadruple in the best case (4x higher) and increase eight-fold in the worst case (8x higher) compared to the 2021 levels. On the right, three industries with high carbon footprints in Europe in 2021 are used for comparison: chemicals, iron and steel and international aviation. This shows that emissions from chip production in 2030 could very well be on the same level or even higher than these industries. The underlying assumptions for the scenarios and the method of calculating emissions can be found in Annex A.

As mentioned in the introductory chapter, the GHG Protocol is a very helpful tool for quantifying GHG emissions in semiconductor manufacturing, despite its

211 Kathleen Fiehrer, Angie Esparza, Taimur Burki & Linda Quian (2019). Semiconductor manufacturing environmental sustainability. *Intel.* https://community.intel.com/legacyfs/online/files/Circularity-at-Intel-Waste-Recovery-and-Reuse-November-2019.pdf.

shortcomings in scope 3. Since there is no comparable measurement of environmental aspects, this section will conclude the main part of this paper with a forecast for the climate impact of chip manufacturing[212] in Europe by 2030 that relates only to GHG emissions. It presents a range of possible emission scenarios for EU chip production in 2030, as explained below.

Expanding on the point about the significant variation in reporting scope 3 emissions, as previously discussed in this paper, an analysis was conducted to determine the proportion of scope 3 emissions relative to total emissions. It was found that, for the analysed manufacturer, scope 3 emissions accounted for 51% of total emissions in 2022. In comparison, the average share of scope 3 emissions among the 20 largest chip manufacturers[213] was 65%. To address this discrepancy, projections for higher scope 3 emissions (illustrated by stacked orange bars) were incorporated into each scenario.

The starting point of chart 8 is the emissions from front-end manufacturing located in Europe in 2021. With 10.67 MMTCE and even when factoring in a higher scope 3, which adds an additional 3 MMTCE, this figure is far below that reported by high-emitting industries. In the same year, the EU chemical industry emitted 52 MMTCE,[214] EU iron and steel production accounted for MMTCE[215] and EU international aviation accounted for 70 MMTCE.[216]

Fast forward to 2030, the picture will change significantly if the goal of the EU Chips Act were to be achieved. Scenario 1 (second bar) presents the assumption that EU chip production is entirely based on renewable energy (ideal case, 100% renewables). As semiconductor manufacturers source renewable energy not only based on the location (from the local grid) but also RECs, it is plausible to assume that they may source a larger amount of renewable energy than 42.5% of the total energy usage (scenario 2). However, it is necessary to revisit the problems explained in the chapter 'Fuel and energy' regarding the use of RECs. Even if these are considered equivalent to using renewable energy from the local grid, it does not only reflect the fact that fossil energy is still used but also that it is often unclear where and when the purchased renewable energy was generated to offset the fossil energy

212 Due to the lack of separate reporting of emissions in front- and back-end manufacturing, the projections include both front- and back-end manufacturing.

213 The companies analyzed were chosen based on market data of the largest wafer capacities (in 200mm equivalents). If a top 20 company was excluded due to lack of semiconductor division disclosure or insufficient sustainability reporting, the next company on the list was included. The final list comprises companies that provided the necessary information.

214 European Environment Agency (EEA) (2023). Greenhouse gas emissions from industrial processes and product use - selected source sectors, EU, 1990 and 2021 (million tonnes of CO2 equivalent), EUROSTAT, https://shorturl.at/14je6.

215 European Environment Agency (EEA) (2023). Greenhouse gas emissions from industrial processes and product use - selected source sectors, EU, 1990 and 2021 (million tonnes of CO2 equivalent), EUROSTAT, https://shorturl.at/14je6.

216 Statista Research Department (2024). Greenhouse gas emissions in the European Union 1990-2022, by sector. https://www.statista.com/statistics/1171183/ghg-emissions-sector-european-union-eu.

used. The reason for re-emphasising the central role of RECs and their dangers is to highlight that it would likely not be possible for the EU semiconductor industry to achieve 100% renewable energy without RECs. This aspect needs to be considered when examining scenario 1. Assuming that European semiconductor manufacturing in the EU is powered 100% by renewables in 2030, emissions will total 38.91 MMTCE, with potentially an additional 23.78 MMTCE from increased scope 3 emissions. This means that, even in this very unrealistic ideal case, emissions would roughly quadruple and catch-up with those of the EU chemical industry[217] in 2021 when factoring in higher scope 3 emissions.

Considering most semiconductor manufacturers' ambitious targets to increase renewable energy use by 2030, the second scenario (third bar) appears more likely. Assuming that 42.5% of chip production will be powered by renewables (in accordance with the EU's renewable energy expansion target), emissions would still reach 70 MMTCE. Including an increase in scope 3 emissions, a further 23.3 MMTCE would be added. Consequently, emissions in scenario 2 would surpass those of the EU chemicals[218] and EU iron and steel industries[219] in 2021 and align with EU international aviation in 2021.[220]

Assuming the current energy mix in chip production in the **third scenario (fourth bar)**, emissions in semiconductor manufacturing are projected to increase to 83.7 MMTCE and thereby overtake the 2021 emissions of the other industries shown in the chart. In this case, if we also assume that scope 3 emissions continue to rise over time, emissions in the semiconductor industry would even exceed 100 MMTCE (83.7 MMTCE plus an additional 23.6 MMTCE).

These projections show that Europe's goals, as stated in the EU Chips Act, of massively expanding semiconductor production will not remain without far-reaching consequences for the climate (and environment). Moreover, a sole focus on renewable energy will not be enough in the long term but can still be a main motivation for reducing the climate footprint of chip production. As the expansion of renewable energy is already strongly pursued, it can be assumed that emissions by the EU chip industry in 2030 will most likely range between the second and third scenarios. This suggests that the emissions will be on par with or even surpass those of the EU chemical industry, EU iron and steel industry and EU international

217 European Environment Agency (EEA) (2023). Greenhouse gas emissions from industrial processes and product use - selected source sectors, EU, 1990 and 2021 (million tonnes of CO2 equivalent), EUROSTAT, https://shorturl.at/14je6.

218 European Environment Agency (EEA) (2023). Greenhouse gas emissions from industrial processes and product use - selected source sectors, EU, 1990 and 2021 (million tonnes of CO2 equivalent), EUROSTAT, https://shorturl.at/14je6.

219 European Environment Agency (EEA) (2023). Greenhouse gas emissions from industrial processes and product use - selected source sectors, EU, 1990 and 2021 (million tonnes of CO2 equivalent), EUROSTAT, https://shorturl.at/14je6.

220 Statista Research Department (2024). Greenhouse gas emissions in the European Union 1990-2022, by sector. https://www.statista.com/statistics/1171183/ghg-emissions-sector-european-union-eu.

aviation in 2021.

Conclusion

This paper offers a guide for assessing the ecological impact of semiconductor manufacturing by considering inputs, process steps and post-production usage. By merging sustainability and semiconductor ecosystem knowledge, it enables focused examination of each area's importance without making specific judgements. Instead, it establishes a foundation to identify and assess current challenges and provides the first indications of where short-and long-term solutions to the various environmental and climate concerns could lie.

Three key conclusions emerge from this analysis and point to possible avenues for further research:

1. The available data for assessing the ecological footprint of the semiconductor industry fall short in representing the complexity of its value chain. Key issues include

- the lack of standardisation in measuring scope 3 emissions, hindering the inclusion of transnational value chain realities.
- the lack of differentiating between front-end and back-end processes, creating intransparency.
- reporting market-based emissions in scope 2 that may not accurately reflect renewable energy usage.
- the lack of specific emission measurements for downstream activities and scrutiny of their contribution to e-waste.

Overall, these data gaps leave significant room for interpretation in many aspects of assessment. In conclusion, different analyses yield contrasting results regarding the distribution of GHG emissions across scope 1, scope 2 and scope 3 categories of the GHG Protocol. Estimates vary widely, from 80% allocated to scope 1 and scope 2, with only 20% for scope 3,[221] to 79% attributed to scope 3 (16% from supply chain upstream and 63% from device use downstream), with the remaining 21% in scope 1 and scope 2.[222]

221 Ondrej Burkacky, Sebastian Göke, Mark Nikolka, Mark Patel, Peter Spiller (2022). Sustainability in semiconductor operations: Toward net-zero production. McKinsey & Company. https://www.mckinsey.com/Industries/Semiconductors/Our-Insights/Sustainability-in-semiconductor-operations-Toward-net-zero-production.

222 Gaurav Tembey, Trey Sexton, Chris Richard, Ramiro Palma, Jan-Hinnerk Mohr (2023). Transparency, Ambition and Collaboration: Advancing the Climate Agenda of the Semiconductor Value Chain. SEMI, Semiconductor Climate Consortium & Boston Consulting Group. https://discover.semi.org/rs/320-QBB-055/images/Transparency-Ambition-and-Collaboration-BCG-SEMI-SCC-20230919.pdf.

Additionally, a comprehensive and standardised tool for evaluating the environmental impact of chip production does not exist. LCA methodologies tailored specifically for the semiconductor industry could be one potential solution if these are based on collaborative efforts involving various stakeholders from across the whole semiconductor value chain.

2. Transitioning to more sustainable semiconductor production is a lengthy process.

The result of the ecological footprint mapping shows that the industry will not find short-term solutions in many areas, particularly in gases, chemicals and renewable energy.

- Developing and implementing non-PFAS chemical alternatives and gases with lower GWP will probably take another 10 to 20 years. It is crucial for chip manufacturers to establish science-based targets aligned with the Paris Agreement, prioritising sustainability as a primary design consideration and enhancing transparency regarding progress.
- Increasing the use of renewable energy represents the most effective short-term approach to reducing emissions. It is crucial that instead of the previously popular RECs, more emphasis is being placed on the expansion of renewable energies on site, for example, through PPAs. However, the limited availability of renewable energy, particularly in countries such as Taiwan and South Korea with significant manufacturing capacities, poses a challenge. This presents an opportunity for Europe to take a leadership role in renewable energy adoption and to build fabs that are more climate and environmentally friendly from the beginning.

3. Policy makers are yet to acknowledge the pivotal role of semiconductors in environmental regulations, overlooking their importance as both an enabling technology and a high-impact industry poised for significant growth over the next 5 to 10 years.

- The twin transition—digital and green—cannot progress in isolation, as advancements in one area affect those in the others. Recognising and addressing interdependence among these transitions is crucial, as it leads to both synergies and conflicts.
- For instance, increased chip manufacturing in Europe can support the expansion of electric vehicles, smart grids and renewable energy, creating synergies. However, scaling chip production also results in higher emissions and conflicts with the use of forever chemicals in front-end manufacturing, a factor often overlooked. This oversight is exemplified by proposals, such as the Blank Ban on PFASs and the EU Chips Act, introduced simultaneously without acknowledging their conflicting implications.
- Future regulations must acknowledge and address synergies and conflicts in advance. This requires increased collaboration among various stakeholders, including policymakers from different fields, the semiconductor industry, academia and civil society. Multi-stakeholder consultations are crucial for connecting diverse policy areas and mitigating potential conflicts, particularly in complex intersections such as environmental, climate and semiconductor policy.
- Encouraging more research into sustainable manufacturing and implementing minimum requirements, such as using a certain percentage of renewable energy or investing in eco-friendly chemicals, could be initial steps. This approach mirrors the

efforts observed in the implementation of the US CHIPS Act in the United States.

This paper lays the groundwork for facilitating exchange among stakeholders involved in the intersection of semiconductor, environmental and climate policies. Future research endeavours to offer specific policy recommendations for integrating sustainability recommendations into a comprehensive long-term EU semiconductor strategy. Simultaneously, it aims to broaden environmental and climate regulations to encompass the crucial linkages with chip production, fostering a more holistic approach to regulation and strategy development for a successful twin transition.

Glossary of Important Terms and Definitions

The glossary of terms and definitions functions as the basis for the assessment of the climate and environmental impacts of front-end manufacturing.

Back-end manufacturing: This is the last step in chip production, which connects the single chip cut out from the wafer to the chip package. It is also called assembly, test, packaging (ATP).

Carbon Disclosure Project (CDP) and Science Based Targets (Initiative): CDP is a non-profit organisation providing a global disclosure system for organisations (e.g. investors, companies and states) to manage and report their environmental impact in a standardised manner.[223] The **Science Based Targets Initiative (SBTi)**[224] introduced methods for setting and assessing net-zero targets based on robust climate science. Their common definition of net-zero targets includes reporting on scopes 1, 2 and 3 of the GHG Protocol, which are in line with the 1.5°C science-based targets.[225] While CDP provides a comprehensive database collecting GHG reporting, SBTi is a forum for organisations to show that they have set net-zero targets. With the goal of defining and promoting best practices in emissions reductions and net-zero targets in line with climate science, SBTi also tracks the individual progress of every participant on their website categorised by industry. Consequently, **science-based targets (SBTs)** bridge the gap between voluntary company-level emissions reduction targets and the alignment of those with the Paris Agreement.[226] [227] [228]

223 Carbon Disclosure Project (CDP). Disclosure Insight Action. https://www.cdp.net/en.

224 Science Based Targets Initiative (SBTi). Ambitious Corporate Climate Action. https://sciencebasedtargets.org.

225 Edwards Vacuum Innovation Hub. The Time is Now: Sustainable Semiconductor Manufacturing. https://www.edwardsvacuum.com/en-uk/knowledge/innovation-hub/the-time-is-now-sustainable-semiconductor-manufacturing0.

Carbon Offsetting: If a nation or company has a high carbon footprint and characterises certain direct GHG emissions as unavoidable, carbon offsetting is used as a popular accounting method that allows for investing in an increase in carbon storage (through land restoration or the planting of trees).[229] By purchasing **carbon credits**, they convey ‘a net climate benefit from one entity to another’.[230] This method is highly controversial. The main counter-argument is that carbon offsets distract from direct emissions reduction and are often used as a way for high-emitting companies or industries to continue using fossil fuels.[231] Furthermore, in addition to various counter-arguments, civil society actors such as Greenpeace emphasise that, while the use of fuel emissions has an immediate impact, the impact of the offset mechanism – removing CO2 from the atmosphere – by, for example, planting trees, takes much longer.[232]

Chip Design: Chip design represents the initial stage of production and is not factored in the analysis due to its intangible nature. It involves a highly intricate process in which chip designers, whether working at integrated device manufacturers or fabless companies, depend on design software and IP blocks.

F-Gas Regulation: Ten years ago, in 2014, the European Commission (EC) adopted the first F-gas regulation with the goal of reducing F-gas emissions in the EU to two-thirds of 2014 levels by 2030. The relevant f-gas groups[233] that are restricted in the regulation are PFCs, NF3, SF6, HFCs and PFPEs. On 16 January 2024, the EC adopted a new update on the F-gas regulation, which had a minor impact on the semiconductor industry because the focus was mostly on HFCs, as they account for the highest consumption and emissions across all sectors in Europe. However, HFCs play a minor role in front-end manufacturing. Furthermore, there are some additional restrictions on labelling. Containers with fluorinated gases for etching and chemical vapor deposition need to be labelled for specific use. Suppliers and manufacturers are now required to specifically state quantities of gases used/provided.[234]

226 Science Based Targets Initiative (SBTi). About Us. https://sciencebasedtargets.org/about-us.

227 Science Based Targets Initiative (SBTi). Companies Taking Action. https://sciencebasedtargets.org/companies-taking-action#anchor-link-test.

228 Anders Bjørn, Shannon M. Lloyd, Mathew Brander & H. Damon Matthews (2022). Renewable energy certificates threaten the integrity of corporate science-based targets. *Nature Climate Change*, *12*(6), 539–546. https://doi.org/10.1038/s41558-022-01379-5.

229 Carbon Offset Guide. What is a Carbon Offset? GHG Institute & Stockholm Environment Institute. https://www.offsetguide.org/understanding-carbon-offsets/what-is-a-carbon-offset/.

230 Carbon Offset Guide. What is a Carbon Offset? GHG Institute & Stockholm Environment Institute. https://www.offsetguide.org/understanding-carbon-offsets/what-is-a-carbon-offset/.

231 Jia Wei, Xueying Wu (2021). Race to Green: Scoring Tech Companies from China, Japan and South Korea on their Climate Action and Renewable Energy Use. Greenpeace East Asia. https://www.greenpeace.org/static/planet4-eastasia-stateless/2021/12/a29b3a1d-race-to-green-report.pdf.

232 Jia Wei, Xueying Wu (2021). Race to Green: Scoring Tech Companies from China, Japan and South Korea on their Climate Action and Renewable Energy Use. Greenpeace East Asia. https://www.greenpeace.org/static/planet4-eastasia-stateless/2021/12/a29b3a1d-race-to-green-report.pdf.

233 For further information, please refer to the section “specialty gases” in the “chemicals” chapter.

Front-end manufacturing: This is the process of manufacturing integrated circuits (dies) onto the wafer – the most complex production step in semiconductor manufacturing. It is highly automated and requires more than 50 different types of equipment and around 300 types of chemicals in more than 1000 process steps. This is also called wafer fabrication.

Green Supply Chain: A green supply chain involves activities that aim at minimising the environmental impact of a product throughout its lifecycle, such as green design, resource saving, harmful material reduction and product recycling.[235]

Greenhouse Gases (GHGs): In the earth's atmosphere, GHGs absorb and emit infra-red radiation when the surface is warmed by the sun. Thus, these gases effectively trap heat, which leads to rising temperatures in the atmosphere, the so-called greenhouse effect. Common GHGs are carbon dioxide, (CO2), methane (CH4), nitrous oxide (N2O), ozone (O3) and water vapor (H2O). GHGs may absorb infra-red radiation with different efficiencies.[236]

Global-Warming Potential (GWP): To quantify how much heat a particular GHG traps in the atmosphere over a specific time horizon, it is compared to how much heat CO2 traps over the same time. The metric **'CO2e'** displays the amount of CO2 that would cause the same amount of global warming as the GHG in question. The GWP differs with time; thus, it is always important to compare between the same time span. For example, CF4 has a much higher GWP than CO2 for a period of 100 years; its GWP is measured in 6500 CO2e.[237]

Lifetime in Atmosphere: Chemicals not only have different GWPs but persist in the atmosphere for different times. Their lifetimes are influenced by various factors, including the rates of emission, removal and chemical reactions. Thus, the atmospheric lifetime can only be estimated. Sticking to the example of CF4, this GHG persists in the atmosphere for 50,000 years. CO2, in contrast, has a lifetime between 5 and 200 years in the atmosphere.[238]

Greenhouse Gas Protocol (GHG Protocol): The GHG Protocol forms the basis of global carbon disclosure. It establishes a standardised framework – such as the

234 EU REGULATION 2024/573 of 07.02.2024. **https://shorturl.at/G7×5e**.
235 Bang-Ning Hwang, Chi-Yo Huang, Chih-Hsiung Wu (2016). A TOE Approach to Establish a Green Supply Chain Adoption Decision Model in the Semiconductor Industry. *Sustainability*, *8*(2), 168. https://doi.org/10.3390/su8020168.
236 Edwards Vacuum Innovation Hub. The Time is Now: Sustainable Semiconductor Manufacturing. https://www.edwardsvacuum.com/en-uk/knowledge/innovation-hub/the-time-is-now-sustainable-semiconductor-manufacturing0.
237 Edwards Vacuum Innovation Hub. The Time is Now: Sustainable Semiconductor Manufacturing. https://www.edwardsvacuum.com/en-uk/knowledge/innovation-hub/the-time-is-now-sustainable-semiconductor-manufacturing0.
238 Edwards Vacuum Innovation Hub. The Time is Now: Sustainable Semiconductor Manufacturing. https://www.edwardsvacuum.com/en-uk/knowledge/innovation-hub/the-time-is-now-sustainable-semiconductor-manufacturing0.

'Corporate Accounting and Reporting Standard', the 'GHG Protocol for Cities' or the 'Policy and Action Standard' to measure and manage GHG emissions.[239] The definition of GHG emissions is taken from the Kyoto Protocol. The reporting is based on three categories: **Scope 1,** including direct emissions from sources owned or controlled by the company (e.g. their own facilities); **Scope 2,** describing indirect emissions from the generation of purchased energy consumed by the company and **Scope 3,** encompassing all emissions that are a consequence of the activities of the company but occur from sources not owned or controlled by the reporting company, including both up-and downstream emissions.[240]

Life-Cycle-Assessment (LCA) Approach: This method can be applied to every industry to measure the climate and environmental impacts of a specific product. Since the early 2000s, several scientists have adapted this method to the specific characteristics of the semiconductor industry to obtain a schematic model of a bottom-up LCA approach. This is under constant development and revision. Currently, there is no standardised framework that can easily be applied to specific types of semiconductors; the closest is a methodology published by Body (2012).[241]

Net-zero: Net-zero describes the achievement of companies, industries, countries or the world in bringing their emissions to 'net-zero'. According to the Paris Agreement, the target year is 2050. There is no clear definition or agreement on whether this includes all GHGs. Consequently, countries and organisations use this ambiguity to define net-zero according to their own criteria. China, for example, uses the term **'carbon neutral'** and only includes CO2 in its definition. Europe, in contrast, has adopted the term **'climate neutral'**, encompassing all GHGs.[242]

Paris Agreement: In 2015, as a result of the COP21, 196 countries signed the Paris Agreement as a commitment to work together to limit global warming to less than 2°C (preferably less than 1.5°C) above the pre-industrial global average temperature. Along with the agreement, each of the signers submitted a nationally determined contribution (NDC), proposing steps to achieve this goal. In 2026, these NDCs will be reviewed and updated. In 2018, an IPCC report concluded that, by 2050, countries must bring CO2 emissions to 'net-zero' to be in line with keeping global warming within 1.5°C of pre-industrial levels.[243]

239 Greenhouse Gas Protocol (2024). What is GHG Protocol? https://ghgprotocol.org/about-us.

240 Janet Ranganathan, Laurent Corbier, Pankaj Bhatia, Simon Schmitz, Peter Gage & Kjell Oren (2004). The Greenhouse Gas Protocol. A Corporate Accounting and Reporting Standard. Revised Edition. https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf.

241 Marcello Ruberti (2023). The chip manufacturing industry: Environmental impacts and eco-efficiency analysis. Science of the Total Environment, 858, 159873. https://shorturl.at/MEwoi.

242 Edwards Vacuum Innovation Hub. The Time is Now: Sustainable Semiconductor Manufacturing. https://www.edwardsvacuum.com/en-uk/knowledge/innovation-hub/the-time-is-now-sustainable-semiconductor-manufacturing0.

243 dwards Vacuum Innovation Hub. The Time is Now: Sustainable Semiconductor Manufacturing. https://www.edwardsvacuum.com/en-uk/knowledge/innovation-hub/the-time-is-now-sustainable-semiconductor-manufacturing0.

PFAS Restriction: In January 2023, a proposal to restrict 10 000 per- and polyfluoroalkyl substances under the "Registration, Evaluation, Authorisation and Restriction of Chemicals" (REACH) was submitted by the national authorities of Germany, the Netherlands, Norway, Denmark and Sweden.[244] In March 2023, interested parties were invited to share their opinion in a six-month open consultation and the two committees under the ECHA – the Risk Assessment Committee (RAC) and the Socio-economic Analysis Committee (SEAC) – were given nine months to hand in their opinion about the socio-economic impacts of the suggested restrictions.[245] The proposal suggested two restriction options: a full ban and a ban with use-specific derogations.[246] In a press release on 13 March 2024, the ECHA stated that they are now in the process of evaluating the proposed restriction together with the comments from the consultation in batches. They are planning to hold a series of meetings in March, June and September 2024, focusing on the different sectors that may be affected. The final opinions will be voted on by the EC.[247]

Renewable Energy Certificate (REC): RECs were designed to increase renewable energy production. A REC certifies that one megawatt-hour of electricity was generated from a renewable source. The electricity provider can then sell the REC and the electricity itself – either bundled or unbundled. This allows a company to only buy the REC (from a different grid, different year, etc.) and source the electricity from a fuel-based source located close to the facility. Thus, the REC does not stand for transferred renewable energy; instead, it only certifies the compensation for sourcing non-renewable energy.[248] [249] As a result, the effectiveness of RECs is highly questioned as emissions are counted twice and no additional capacity is added for renewable energy production.[250] The possibility of including RECs in GHG reporting lies in the differentiation between **market-** and **location-based metrics.** While location-based reporting of scope 2 emissions refers to the emissions factors of the local grid from which the electricity has been sourced, market-based reporting includes contractual agreements, such as RECs,

244 European Chemicals Agency (ECHA). Per- and polyfluoroalkyl substances (PFAS). https://echa.europa.eu/hot-topics/perfluoroalkyl-chemicals-pfas.

245 European Chemicals Agency (ECHA). Per- and polyfluoroalkyl substances (PFAS). https://echa.europa.eu/hot-topics/perfluoroalkyl-chemicals-pfas.

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that are independent of the average grid mix.[251] Thus, as long as this 'loophole' is part of the GHG Protocol, companies can always reduce their emissions by reporting market-based emissions, which are, on average, 17% lower than location-based emissions.

Annex A

Calculation method of GHG emissions in EU chip production in 2021 and scenarios for 2030

The data were sourced from the CSR reports of a major semiconductor manufacturer covering 2013 to 2022. It encompasses various production facets as a contract manufacturer (foundry). Analysis of scopes 1 to 3 emissions, following GHG Protocol guidelines,[252] was conducted, focusing on emissions per wafer and renewable energy utilisation. The CSR reports of the 20 largest manufacturers were used for comparison. Calculations were based on the following assumptions:

a) In 2021, Europe held an 8% share of global semiconductor production,[253] with a market volume of 100 million wafers,[254] resulting in 8 million wafers manufactured.

b) Global semiconductor demand is projected to double by 2030, with the EU Commission aiming to increase the European production share to 20% by that time, implying 40 million wafers manufactured in Europe if achieved (20% of 200 million wafers globally).[255]

c) Emissions per wafer are expected to increase due to more complex manufacturing processes.[256] The analysis results indicate an average annual increase of 5.79% in emissions per wafer since 2013 (start of GHG Protocol reporting).

d) Semiconductor companies exhibit diverse energy mixes. To assess the impact of

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increased renewable energy usage, three scenarios were evaluated: 1. Ideal case (100% renewable energy, scope = 0), 2. Scenario aligning with the EU renewable energy expansion target[257] for 2030 (42.5%) and 3. Business as usual (maintaining the energy mix from 2021).

e) Chapter 'Special case of scope 3 emissions' in this analysis highlights a lack of reporting on scope 3 emissions due to missing standardisation. The analysis results of the share of scope 3 emissions for the analysed manufacturer revealed that they accounted for 51% of total emissions in 2022. Comparatively, the average share of scope 3 emissions among the 20 largest chip manufacturers was 65%. To address this disparity, projections for higher scope 3 emissions (represented by stacked orange bars) were added to each scenario.

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