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VISION PAPER

# The green transition of the IC industry

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# Who should read this white paper?

This document is intended for anyone involved in IC manufacturing – **system and fabless companies, foundries, IDMs, tool suppliers, material suppliers** – and interested in achieving net-zero emission goals. More broadly, this paper also addresses those active in shaping up a greener IC industry: policy makers, members of governmental bodies or of the civil society as well as academics.

In this paper, we present a **holistic approach** to tackle the challenge of decarbonizing IC manufacturing. Based on a sound analysis of the complete industry supply chain, our proposal formulates targeted improvement scenarios and guides pathfinding for future technology nodes. To succeed, the **entire supply chain** needs to commit, and an ecosystem approach will be key.

One of the fundaments of imec is the extensive network of partners, doing joint R&D on future IC technologies. It's the perfect starting point for this next challenge in IC manufacturing.

# 1. Setting the scene

Climate change is the biggest challenge of our time leading to an age where extreme weather events and rising sea levels may durably damage our societies and economies and lead to irreversible deterioration of the ecosphere that supports humanity.

In the **2016 Paris Agreement**, 196 countries signed a legally binding international treaty on climate change, thereby committing to accelerated decarbonization. The hope is to limit the mean rise in temperature to 1.5 degrees Celsius above preindustrial levels.

Our societies are entering the digital age at a fast pace. Digitalization has been set as policy priority in many countries and, as a consequence, close to double-digit growth is forecasted for the entire IC industry in the coming 10 years. The climate impact of the full IC sector is estimated today to be above 900 megatons $CO_2$, which accounts for 1.8% of global anthropic emissions [1]. Within this, the IC chip manufacturing sector accounts for **around 50 megatons $CO_2$ (0.1% of total emissions)** and takes a dominant part within the full life-cycle of most consumer products. For example, research has shown that nearly 75% of a mobile device's carbon footprint is due to its fabrication. And of this, almost half is resulting from the underlying IC manufacturing [2].

Imec estimates that the IC manufacturing industry **can easily end up at 3%** of total emissions by 2040 (if all other sectors follow the Paris Agreement). This is a result of the substantial **growth of the IC industry** every year and the fact that every **new technology node** is associated with more energy usage and more complex processing. This means that if we do nothing to reduce IC manufacturing emissions, the total emissions of IC manufacturing in 2040 will increase to 400 megatons $CO_2$ equivalent, which is almost half of the emissions of the full ICT sector now. As a result, the IC industry, among many others, must commit to contribute to the Paris Agreement.

For the assessment of the climate impact of the IC industry, there are three sources of greenhouse gas emissions that need to be considered:

- **PROCESS GASSES** (scope 1) Very common semiconductor processes such as wafer etching and chamber cleaning rely on highly potent greenhouse gases. For example, $NF_3$ has a global warming potential that is 17.000 times more potent than $CO_2$ (Figure 1). A fraction of these potent gases are released to the atmosphere and directly contribute to global warming.

- **ELECTRICITY CONSUMPTION** (scope 2) There is a lot of energy required to run the extensive production facilities, packed with hundreds of manufacturing tools and requiring climate and humidity control. The generation of the electricity consumed by the industry can be a very important source of carbon emissions.

- **MATERIAL USAGE** (scope 3) The number and quantity of materials used for IC manufacturing is steadily growing with every technology node (e.g. Si wafers, bulk gases, gas precursors, minerals, chemicals, etc.). The upstream production of these materials also leads to greenhouse gas emissions that must be factored into the emission of the IC chip manufacturing.

It is estimated that today, 80 percent of semiconductor manufacturing emissions (averaged across 200mm and 300mm fabs) are falling under either scope 1 or scope 2 categories which can be directly leveraged by the industry through the implementation of modern abatement systems for potent greenhouse gas destruction and the switch to green electricity sources.

Besides climate change, the IC manufacturing industry has **other ecological impacts** that require monitoring. Of particular concern are its **very heavy water consumption** and its important usage of **abiotic resources** amongst which many are scarce and considered as critical.

There is a **strong awareness** within the IC community to act on climate change and a lot of **ambitious actions** have been taken in recent years. Several major system companies that play a dominant role in the world economy have committed to reaching net-zero emissions across their full value chain. Following their lead, major foundries and IDMs have presented ambitious plans in line with climate science to drastically reduce greenhouse-gas emissions in the coming 10 years and reach carbon neutrality or net-zero emissions at horizon ranging from 2030 to 2040 [3]. For sure, more semiconductor companies will follow this route towards climate-change action plans.

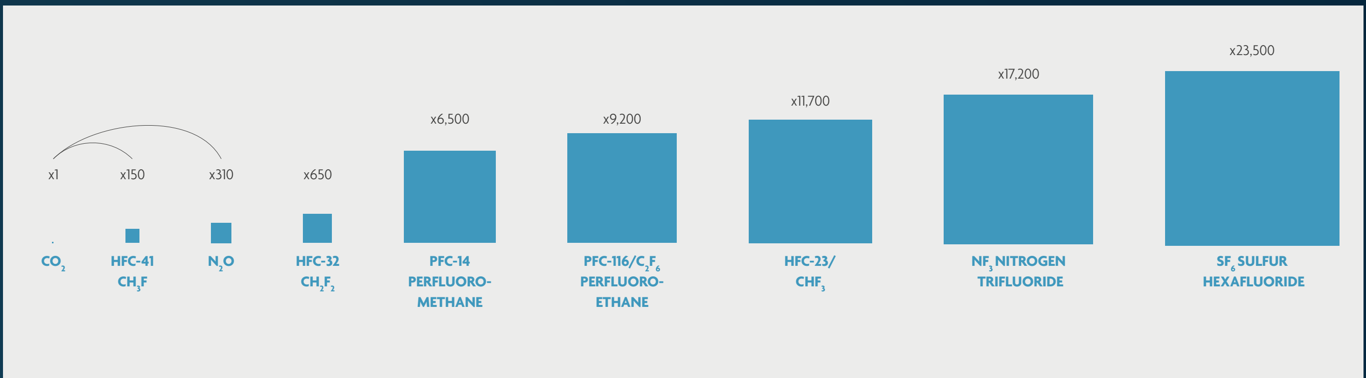
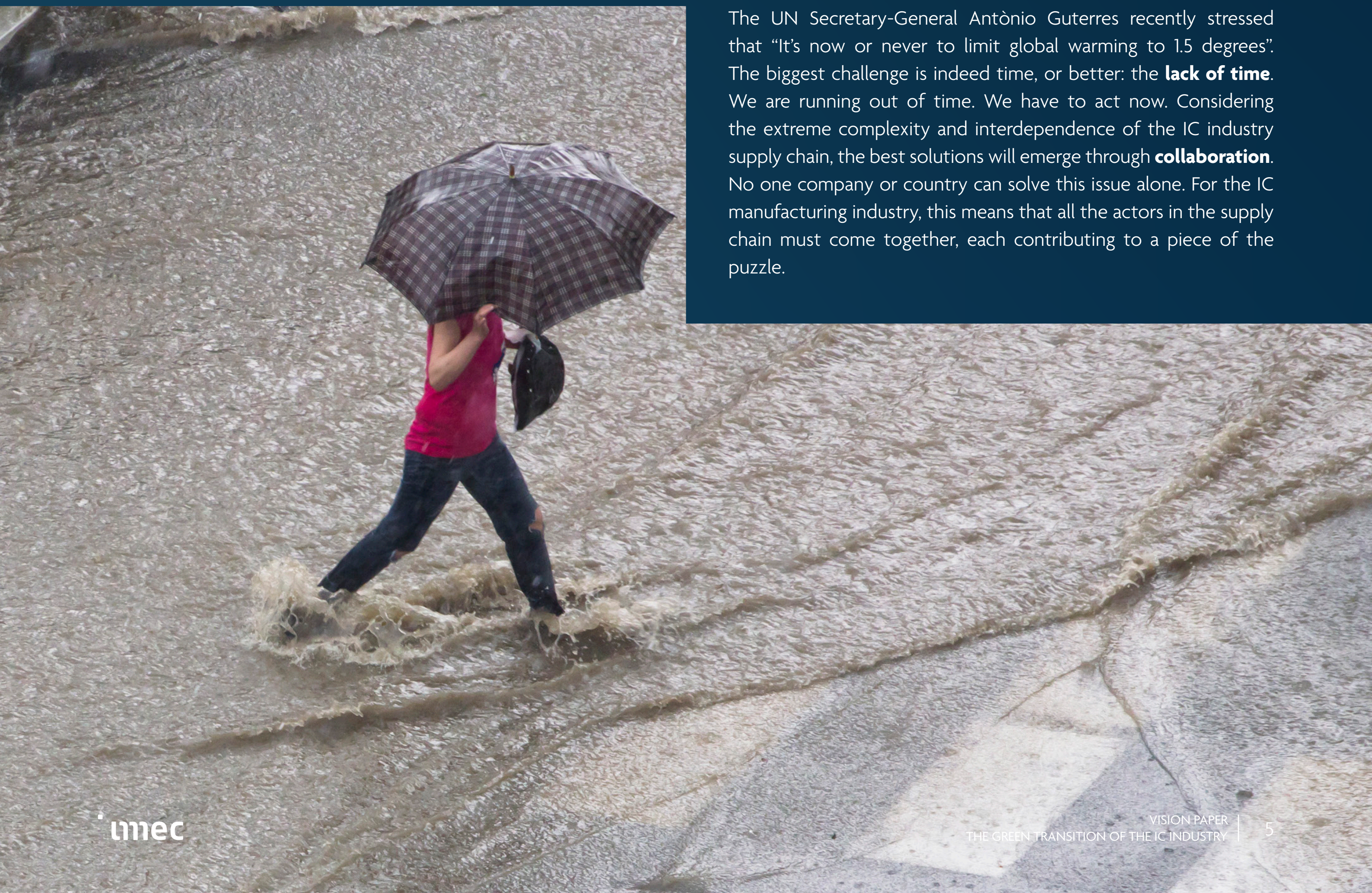



Figure 1 | 100-year time horizon global warming potential of key process gases expressed as multiple of equivalent $CO_2$ emission. Based on the UN Intergovernmental Panel on Climate Change's second assessment report [3].



The UN Secretary-General Antònio Guterres recently stressed that "It's now or never to limit global warming to 1.5 degrees". The biggest challenge is indeed time, or better: the **lack of time**. We are running out of time. We have to act now. Considering the extreme complexity and interdependence of the IC industry supply chain, the best solutions will emerge through **collaboration**. No one company or country can solve this issue alone. For the IC manufacturing industry, this means that all the actors in the supply chain must come together, each contributing to a piece of the puzzle.

# 2. Imec's Sustainable Semiconductor Technologies & Systems Program

Imec's SSTS program is contributing to these net-zero goals by pursuing its three-pronged strategy to decarbonize emission from IC manufacturing:

- **Building a virtual fab** to simulate high-volume IC manufacturing, also for future nodes, and to identify the processes with highest carbon contributions. [The virtual fab is representative of a high-volume manufacturing (HVM) fab, which will be validated and enriched with actual manufacturing & equipment data.]

- Developing **real solutions for the fab floor**, involving equipment and materials suppliers, as well as manufacturing fabs, and working with them in imec's **actual fab** to minimize these contributions.

- Creating an **ecosystem-wide decision-making framework** and communicating results and insights to governmental bodies and policy makers who can set up incentives for selecting future technologies that will enable further decarbonization.

## 2.1 Identifying processes with the highest carbon contributions

Life-cycle assessment (LCA) is a methodology for assessing environmental impacts associated with the components and the stages of the life cycle of a product. Today, when applying LCA analysis of electronic products (see Figure 2), there is a **knowledge gap** concerning the environmental footprint of the fabrication of semiconductor ICs for more advanced technologies. In addition, a **holistic approach** across the semiconductor supply chain is lacking, making it extremely challenging to bring environmental considerations into the early stages of technology definition.

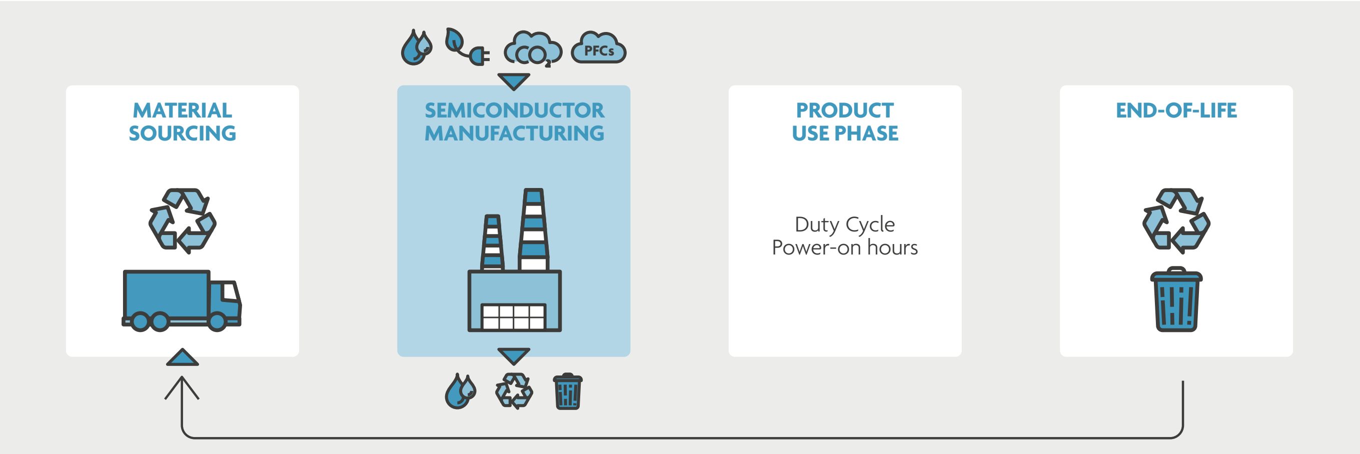



Figure 2 | Life-cycle analysis of electronics. When considering the environmental impact of electronic products, there is today a knowledge gap concerning the fabrication of ICs.

To meet these data needs, expertise in state-of-the-art devices and their fabrication is key. Because of imec's unique leadership position and research roadmap for future technologies, we have been able to develop **dedicated analytical techniques** to assess the environmental impact of semiconductor manufacturing for future CMOS logic and memory technologies.

More specifically, using data from its own 300mm fab complemented with data coming from its ecosystem of material & equipment suppliers, imec is working on the consolidation of databases for process equipment, recipes, infrastructure, and libraries of process flows.

These datasets are combined in a **software platform 'imec.netzero'** that is developed in-house. Imec.netzero functions as a **virtual fab** to deliver a quantified bottom-up view of IC manufacturing for a wide range of technologies, including future ones. This information is then analyzed to identify processes with high associated carbon emissions.

A schematic illustration of the imec.netzero platform is provided in Figure 3. Data-wise, it relies on iterative improvement and versioning through cycling. Technology assessments are run early, on entire flows, to obtain high-level results rapidly, then rerun regularly to refine them, propagating the reviews of the databases (updates based on inputs and calibration) and the new features in modelling (upgrades such as yield model, utilization model, extension to materials, chemicals, and infrastructure).

Furthermore, we intend to validate the source data and enrich the methods by benchmarking results from the imec.netzero platform against comparable manufacturing data provided by foundries and integrated device manufacturers.

## High-level learning and recommendations

**SCOPE 1 EMISSIONS** The manufacturing of technologies with extremely small dimensions requires very sophisticated processes, some of which rely on the usage of greenhouse gases (GHGs) such as $NF_3$, $CF_4$ or $SF_6$ that have very significant global warming potential. Modern abatement solutions exist to **significantly reduce greenhouse gas emissions**. Their implementation throughout the entire industry still requires an appropriate and systematic global effort.

**SCOPE 2 EMISSIONS** The semiconductor industry consumes a large amount of electricity to run its cleanroom facilities and advanced manufacturing equipment. Unfortunately, semiconductor fabs located in regions that rely on coal-based electricity will have a very large carbon footprint. Therefore, any solutions to **reduce electricity consumption** or switching to **clean and renewable sources** of electricity will help reduce the industry's environmental footprint.

Figure 4 shows the distribution of carbon emissions (scope 1, 2 and 3) for three scenarios for the same advanced technology. It illustrates the need to start with greenhouse gas abatement and clean renewable electricity, which together can deliver an overall 84% reduction in CO2eq. In addition, it is also clear that once the impacts of direct greenhouse emissions and electricity use are reduced, the embedded carbon footprint of the material production will increase in relative importance (from 10% to 66%) and must also be reduced.

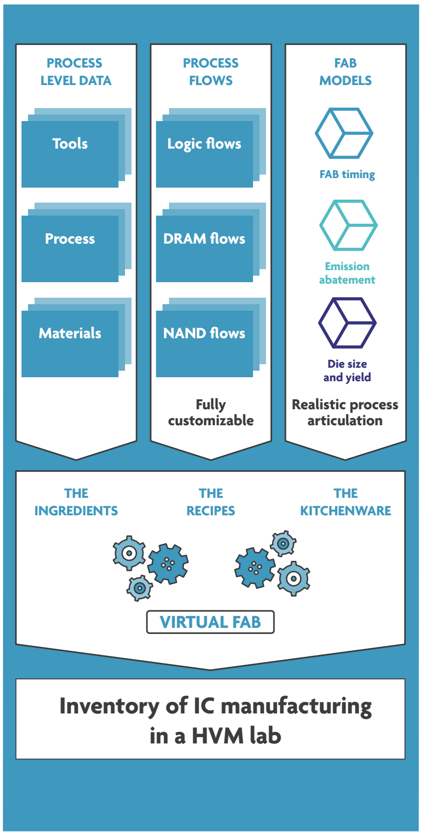



Figure 3 | Schematic illustrating the bottom-up model implementation of the imec.netzero platform. It enables gate to gate fab life cycle inventory.

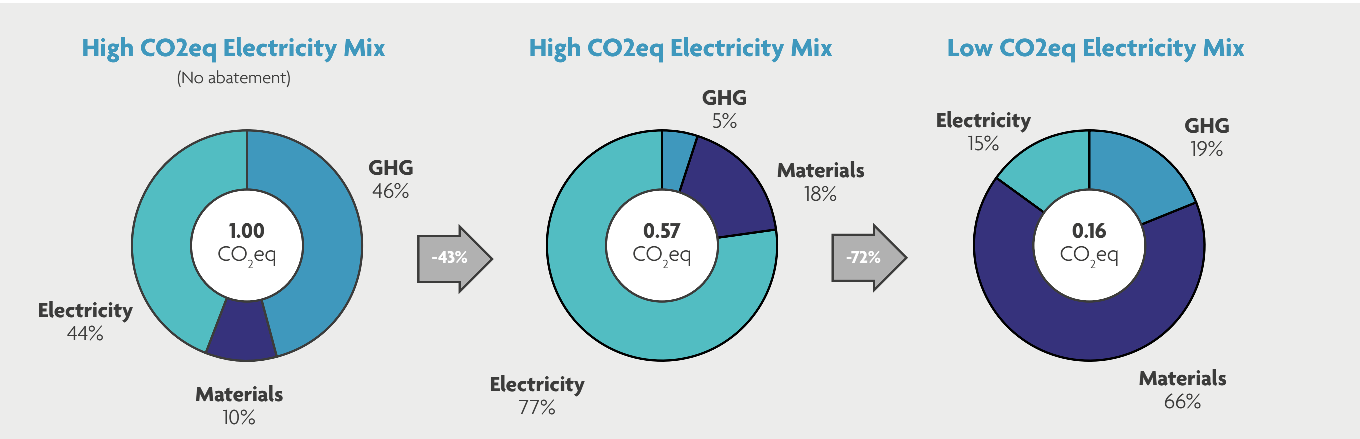



Figure 4 | Distribution of carbon emissions for three scenarios for the same advanced technology. CO2eq emissions are normalized to the first scenario (provided left). The normalized CO2eq values shown are composed of three groups or 'scopes' of emissions under the Greenhouse gas protocol: (1) direct greenhouse gas (GHG) emissions, (2) indirect emissions associated with power generation, and (3) indirect emissions associated with material production (incomplete accounting for materials dominated by the production of the Si wafer, and Si wafer production is assumed to use a high CO2eq electricity mix in all three scenarios).

To understand how emissions will evolve in the future, we further estimated the increase in emissions with the evolution of the IC technology. We find an approximate 2x increase in 10 years. Furthermore, the industry is growing tremendously and by taking this into account, we estimate that the emissions might increase by 4 times and reach 200 Mton/year by 2030 assuming that the current energy mix is used and that no action is taken. Deployment of renewable energy will naturally help (as shown in Fig. 4), but unfortunately, with the current estimated deployment of renewable energy [4], emissions from IC manufacturing will still be about 3 times too high compared to the target set by the Paris accord. Thus, further work is urgently needed by the IC manufacturing industry to bring down emissions and close the gap.

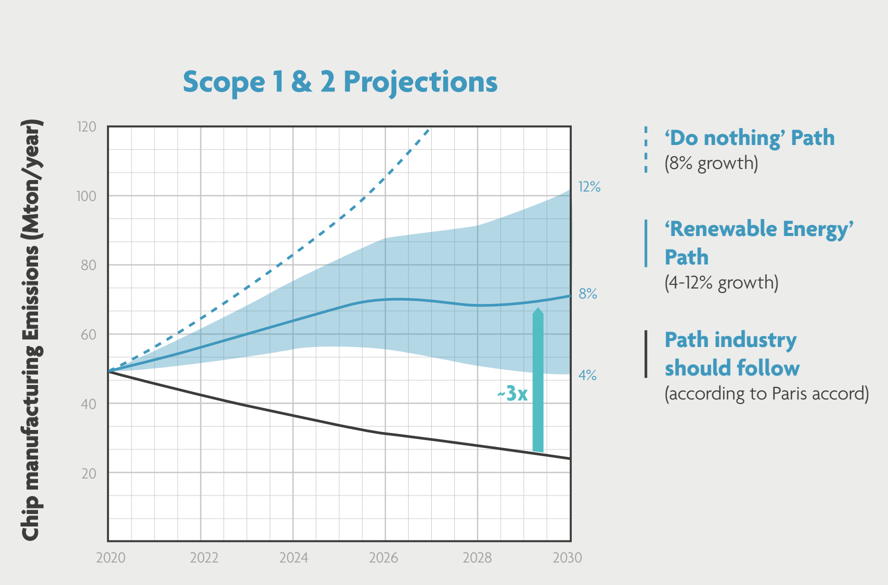



Figure 5 | Projection of the scope 1 and 2 emissions from IC manufacturing. The projections are based on an assumed 8% wafer volume growth [5], and the increase in emissions per technology node projected by imec and normalized by market shares [6]. Without action and no renewable energy deployment beyond 2020, the gap to the trend where the industry should be according to the Paris accord is rapidly increasing, but even with the current projected deployment of renewable energy according to IEA [4] there is a projected 3x gap at 2030.

**OTHER ENVIRONMENTAL IMPACTS** To get the full 'environmental picture', water use and the impact of raw material extraction and refinement will also be included in the SSTS analysis. In pathfinding, this will help assess the impact of introducing new materials in process flows, especially if they are deemed critical. For these materials, options to use recycled materials or improve process tools for minimal material use should be considered.

## 2.2 Real solutions for the fab floor

Imec.netzero is a great tool to identify, document and classify most of the high-impact problems existing in industry. The voice from the industry is however highly needed to uncover other environmental problems that escape the analysis due to their complexity, to identify practical solutions to all identified problems, and to judge their relevance/feasibility for the industry.

To foster such practical solutions, imec is working with material and equipment suppliers as well as with IDMs and foundries to **ideate industry-relevant solutions** that reduce the environmental impact while keeping performance intact. From these ideations, **small-scale practical projects** are set up in imec's fab that involve multiple stakeholders from the supply chain of the process in question, whereby tool and process experts conduct **real-world hardware and/or process development in the fab**. Input/output flows measurement campaigns are also programmed in order to gather data around certain processes and tools.

Project results require an evaluation that weighs in environmental parameters. In the past, technology development was typically guided by its power-performance-area-cost (PPAC) score with little regard for the environment (E) score. Imec is adopting a **PPAC-E scoring system** for process evaluation, by using the developed E-metrics [6]. Furthermore, the data collected during these small-scale practical projects also enriches the data sources at the foundation of imec.netzero.

## 2.3 Ecosystem-wide decision-making framework & incentives

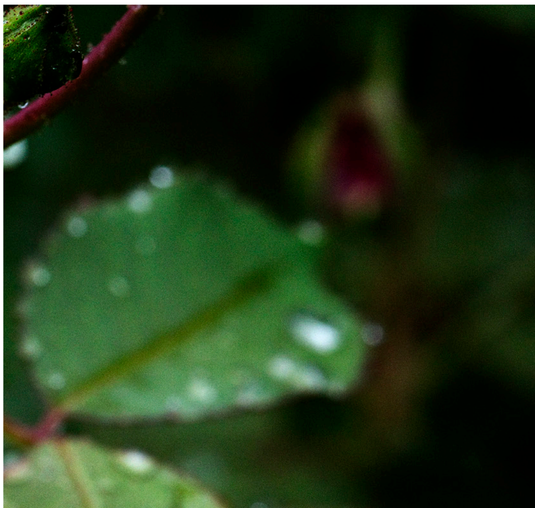
For the last 25 years, imec has helped the manufacturing ecosystem **conceptualize and develop future IC technologies**. Considering today's global ecological threats, this pathfinding mission must include quantified and balanced environmental considerations to guide decision- and policy-making along the best possible paths.

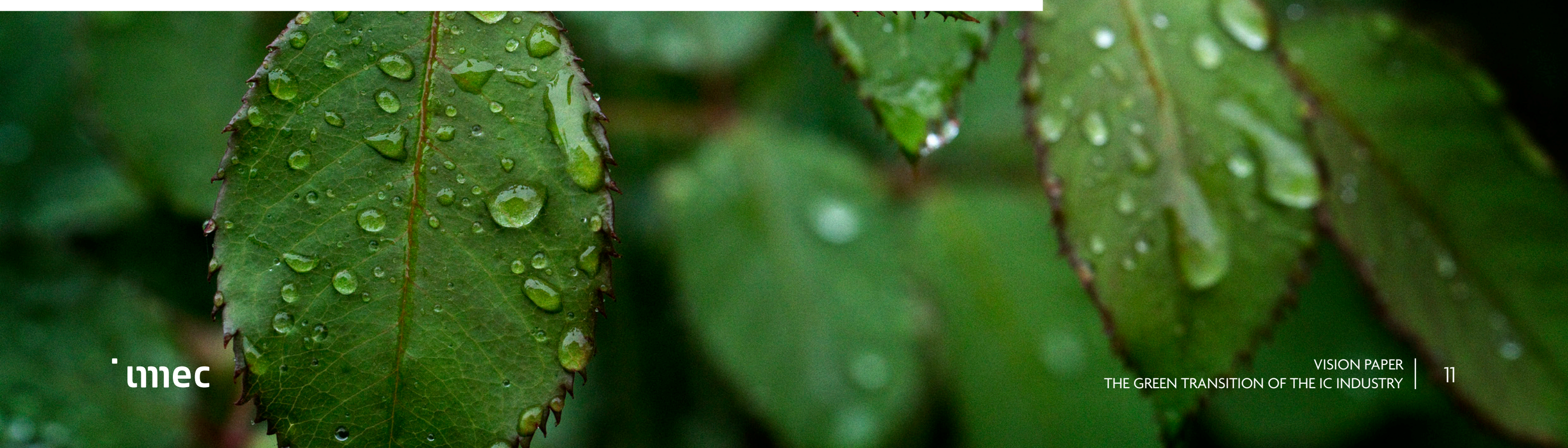
In addition to future logic and memory technologies, imec's framework will gradually be extended to **include system-level technologies** – by incorporating metrics related to packaging, 3D ICs, printed circuit boards, and overall systems. This will further empower system-level companies to make environmentally responsible decisions regarding their IC technology choices. The assessment of these future technologies using imec's approach will emphasize their driving forces and bottlenecks:

- Provide insights and identify actions that enable carbon emission reduction, in the form of quantitative and directional guidelines
- Locate bottlenecks (largest contributors to carbon footprint)
- Identify knobs with the largest sensitivity
- Forecast impact for the introduction of new products & process solutions on the total footprint

Achieving a net-zero carbon future is a **collaborative effort** across the semiconductor value chain. Several actions have been identified to get all stakeholders on board:

- Publish dedicated life cycle analysis and sensitivity **data** for the manufacturing phase of semiconductor ICs, enabling policy makers and actors across the entire value chain to account for IC manufacturing-related emissions
- Leverage E-scores for **procurement** purposes and promote them to relevant stakeholders
- Identify achievable carbon reduction **targets** and solutions for each actor in the value chain to help them reach their net-zero emission objectives
- Enable a platform providing holistic IC sustainability **white papers**, comprising for example a library of 'how to guides", for equipment and material suppliers, manufacturing fabs, and system and fabless players
- Establish a **net-zero roadmap** for the industry and define new standards for environmental assessment in the semiconductor industry in collaboration with SEMI





# 3. Conclusion

For decades, striking the ideal balance between low power, high performance, small area and minimal cost was the main concern for manufacturers of ICs. But the worldwide fight against ecological degradation and climate change compels this industry to include their environmental impact into the equation – making PPAC-E the new formula for sustainable growth.

With its SSTS program, imec aims to bring together all actors in the IC manufacturing supply chain to jointly identify actions that can be taken to reduce the carbon footprint of the IC industry, for today's and for future technology nodes.

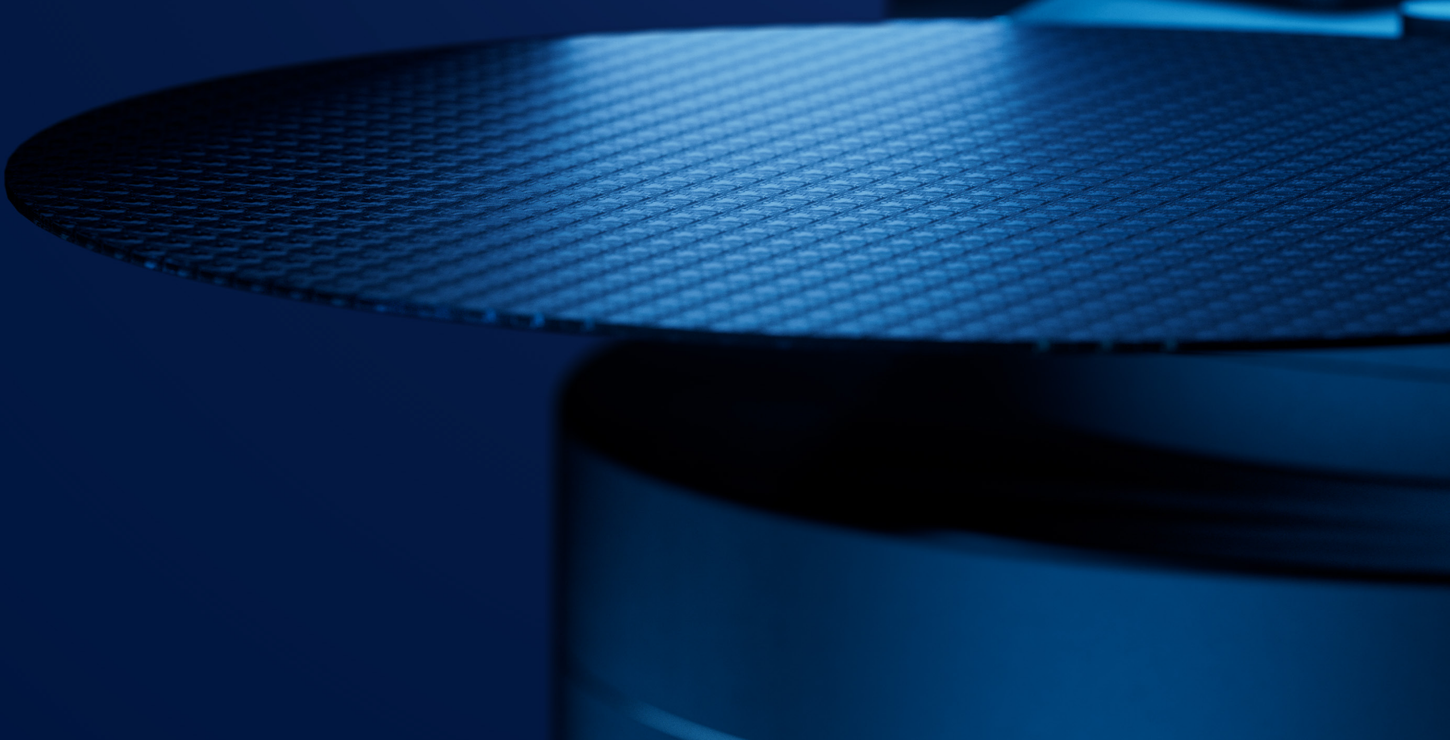
# 4. How to join this initiative

Imec is reaching out to the entire semiconductor value chain to join us in contributing to a net-zero carbon future and decarbonizing the IC manufacturing phase. If interested, please **contact us** at ssts@imec-int.com

**Visit our website for more information:** www.imec-int.com

**Read our SSTS-related press releases:**

- Apple joins as first public partner in new imec research program that helps entire semiconductor value chain reduce its ecological footprint
- Imec unites partners from the semiconductor value chain to jointly target net-zero emissions for chip manufacturing



# 5. About imec

Imec is a world-leading research and innovation center in nanoelectronics and digital technologies. Imec leverages its state-of-the-art R&D infrastructure and its team of more than **5,000 employees** and top researchers, for R&D in advanced semiconductor and system scaling, silicon photonics, artificial intelligence, beyond 5G communications and sensing technologies, and in application domains such as health and life sciences, mobility, industry 4.0, agri-food, smart cities, sustainable energy, education, ...

Imec unites world-industry leaders across the semiconductor value chain, international tech, pharma, medical and ICT companies, start-ups, and academia and knowledge centers.

Imec is headquartered in Leuven (Belgium), and has research sites across Belgium, in the Netherlands and the USA, and offices in China, India, Taiwan and Japan. In 2021, imec's revenue (P&L) totaled 732 million euro.

Further information on imec can be found at www.imec-int.com.

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