Intelligent Low-Carbon Semiconductor Manufacturing

White Paper

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About Pragmatic

Pragmatic Semiconductor is a British semiconductor manufacturing company based out of Cambridge and Durham that develops ultra-low-cost flexible electronics that can help address society's challenges. We provide a unique, flexible platform and rapid turnaround time, with significantly lower footprint and cost than conventional silicon foundries.

Our approach to semiconductor manufacturing is reflected in our name. By using alternative materials and reducing complexity and cycle time, we are able to design and manufacture chips that are built to purpose, removing the need for overengineered and wasteful chips. A vast number of applications from retail to healthcare do not need extremely powerful microprocessors or high performing technology nodes. By designing based on specific application needs, we can make technology that optimises device complexity with sustainability as a key criterion, thereby bringing down the environmental impact significantly.

This white paper explains our ongoing efforts in making Pragmatic's semiconductor manufacturing process more sustainable with the help of Industry 4.0 knowhow and demonstrates our commitment to be a world leader in sustainable semiconductor manufacturing.

"As businesses everywhere respond to the climate emergency, it has become critical for semiconductor manufacturers to focus on the decarbonisation, resource efficiency and productivity of their operations."

Scott White, CEO

Introduction

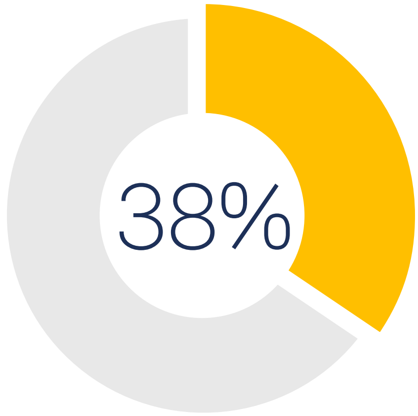
Electronics is globally one of the world's most polluting industries. Semiconductors have overtaken the automotive sector in overall carbon footprint, with the world's largest chip producer now producing more CO_2 than General Motors.

For a typical smartphone, manufacturing contributes to almost 74% of its total carbon footprint, with nearly half of this coming from the integrated circuits[1]. Between 2015 and 2020, the 16 Taiwanese electronic components manufacturers increased their greenhouse gas (GHG) emissions, electricity consumption, and water usage by 7.5, 8.9, and 6.1% per year, respectively[2]. The GHG emissions from the South Korean semiconductor sector was reported to be 22.7 million metric tons of CO_2e amounting to 3.2% of their national total emissions[3].

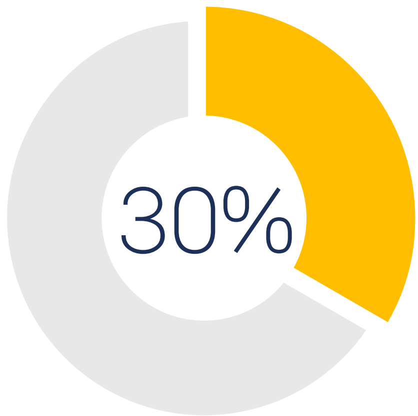
Semiconductor manufacturing has a significant contribution to the overall environmental footprint of everyday electronic devices such as smartphones and IoT sensors. Making a dent in this figure will mean redesigning entire manufacturing and supply chain production processes, as well as reducing transport emissions resulting from a complex global supply chain. So far, improvements to semiconductors have primarily focussed on maximising performance while overlooking the growth in carbon footprint[1].

With significant public and private investment going into the sector, semiconductor manufacturers have the opportunity to expand their capabilities and respond to the increasing demand to decarbonise their manufacturing operations.

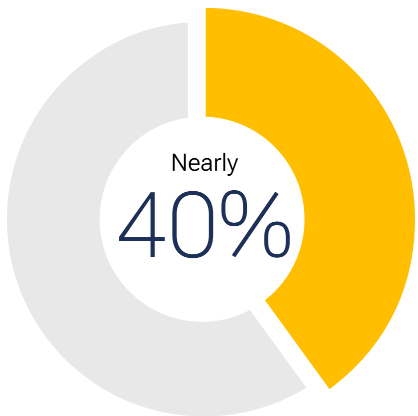
This complex challenge requires significant effort, investment, and creative thinking – however, now is the time for the industry to think smarter and position sustainability at the core of their operations.



Global consumers believe businesses should prioritize responsible production and consumption of goods and services.



Global greenhouse gas emissions come from the manufacturing sector.



Emissions from a smartphone comes from the microprocessors inside the device

[1] Gupta et al., Chasing Carbon: The Elusive Environmental Footprint of Computing. https://arxiv.org/pdf/2011.02839.pdf'

[2] Roussilhe et al. From Silicon Shield to Carbon Lock-in? The Environmental Footprint of Electronic Components Manufacturing in Taiwan (2015-2020). https://arxiv.org/pdf/2209.12523.pdf

[3] Yang et al., 2022. High-Resolution Environmentally Extended Input–Output Model to Assess the Greenhouse Gas Impact of Electronics in South Korea. Environ. Sci. Technol. 2022, 56, 2107–2114.

Impact of semiconductor manufacturing

Semiconductor manufacturing is notoriously resource and energy intensive, from the management of cleanroom facilities to development of sub-fab tools and wafer processing. For instance, the total global IoT semiconductor primary energy demand is projected to increase from 555 billion kWh in 2016 to 9.7 trillion kWh in 2025[5]. As the performance and complexity of devices increases, so does the number of process steps and the consumption of water, chemicals, gases and energy. Alongside direct emissions from their facilities, manufacturers have to consider the impact from their supply-chain, energy generation, disposal of complex waste and technology life cycle.

The Greenhouse Gas (GHG) emissions can be broken down into three kinds:

Scope 1

Direct emissions from the manufacturing facility.

Scope 2

Emissions from the energy consumed, in the form of electricity and heat, at the facility.

Scope 3

Emissions in the supply chain and raw materials used in the production.

For a typical silicon chip foundry, 80% of emissions come from Scope 1 & 2.

FIGURE 2
CO2-equivalent emissions for typical fab profile (Source: McKinsey)

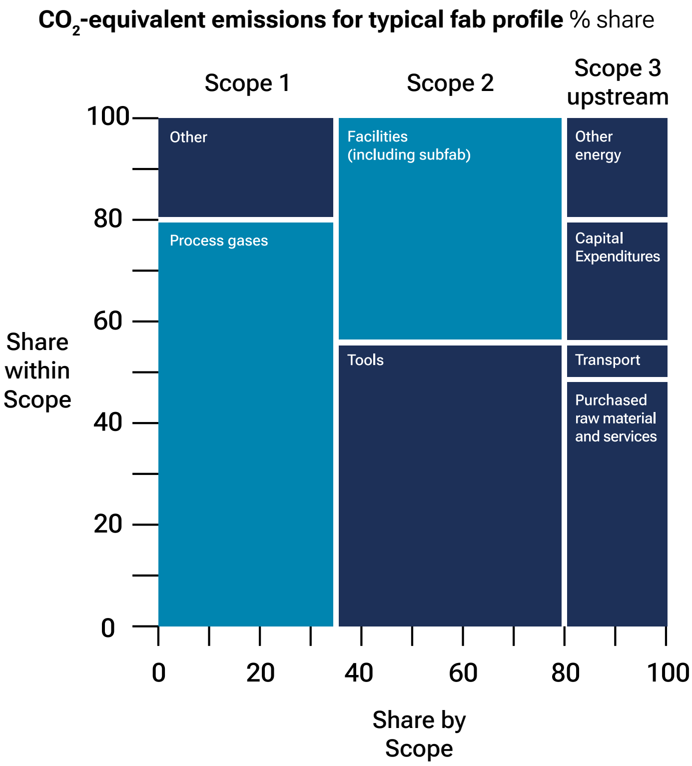
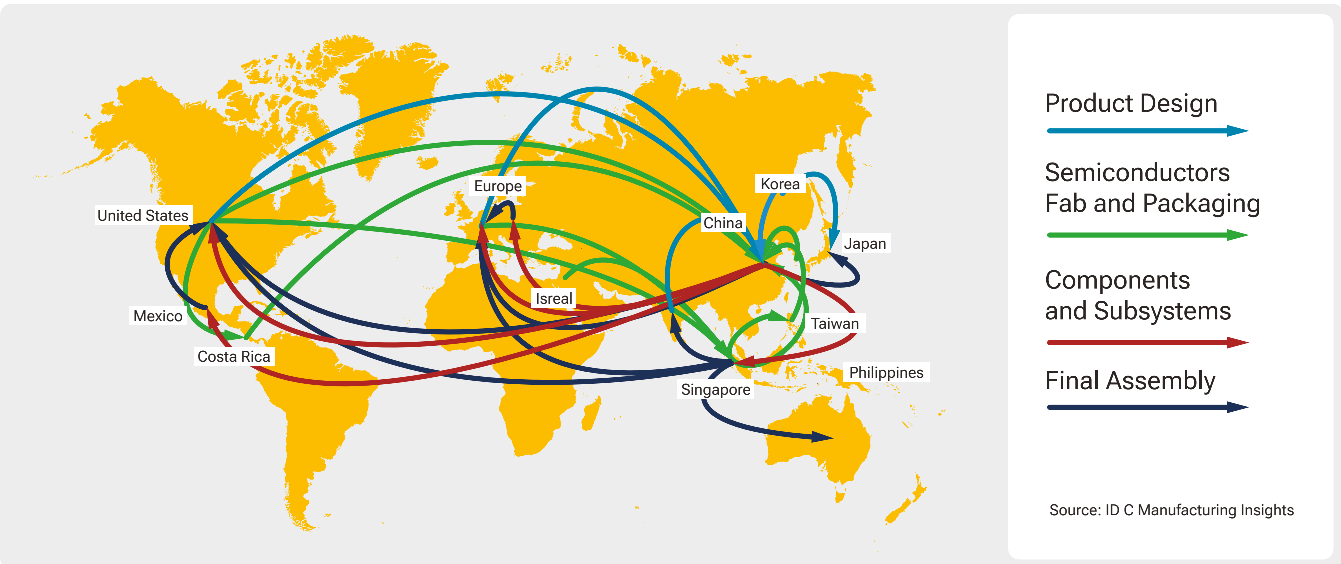


FIGURE 1
Map of semiconductor manufacturing supply chains around the globe



[5] Das and Mao, 2020. The global energy footprint of information and communication technology electronics in connected Internet-of-Things devices. Sustainable Energy, Grids and Networks 24, 100408.

Primary contributors to Scope 1 and 2 emissions

Water

Water serves a critical role to semiconductor manufacturing, with a typical fab using several million litres of tap water every day. Ultrapure water, which is thousands of times purer than drinking water, is used throughout wafer processing to cool equipment and rinse and clean wafers as they are manufactured. Effluent wastewater streams from the fab can be complex to manage with various levels of contamination which has to be appropriately treated before disposal.

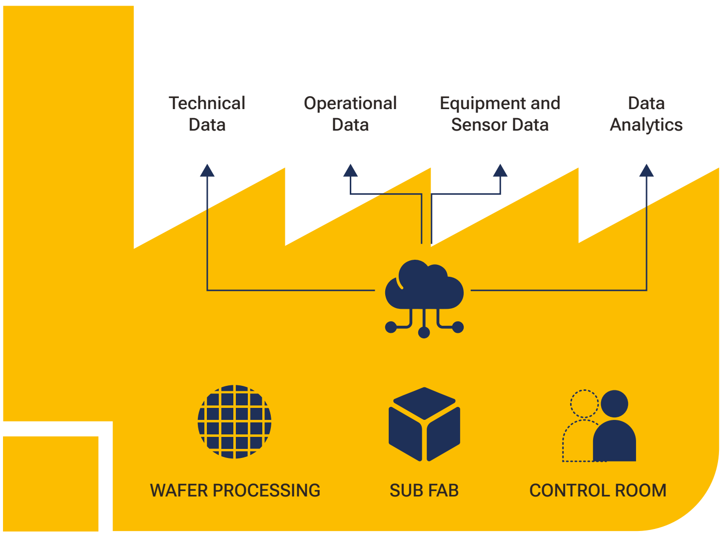
Energy

A typical advanced fab with a capacity of 50,000 wafers per month, consumes over 1TWh per year. With half of the consumption from wafer processing equipment, the other half from the sub-fab and facilities supporting the cleanroom. As the complexity of semiconductors continues to increase, so does the energy consumption for manufacturing. From 28nm to 2nm, the electrical energy required increases from 400kWh to 1400kWh per wafer (3.5 times).

Gases

Semiconductor manufacturers use a variety of high GWP gases to create intricate circuitry patterns upon wafers and to rapidly clean chemical vapor deposition (CVD) tool chambers. Under normal operating conditions, anywhere between 10-80% of high GWP fluorinated gases that are passed through tool chambers are released into the air unreacted[6].

FIGURE 3
Schematic of data generation in a typical fab



Making sustainability a measure of fab performance

The high demand and complexities of semiconductor manufacturing have meant that the industry has led the way towards smarter factories, deploying advanced automation and data analytics technologies to improve productivity. Technologies such as artificial intelligence, machine learning, distributed sensors, and cloud-based data analysis have been adopted to make processes leaner, thereby increasing the productivity, throughput, and capacity of manufacturing operations.

Inside the fab today, you will see how this is achieved through an increasing level of automation, from automated materials handling systems to real-time dispatching and scheduling, all intricately connected to wafer processing equipment, sub-fab tools, and facilities through the manufacturing execution system. (Figure 3)

[6] Semiconductor Industry | US EPA

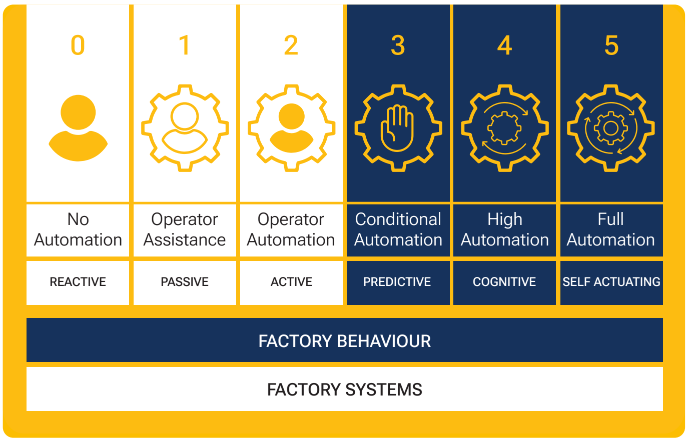
Advanced data generation and analytics

It is generally well understood how to analyse data to understand what is currently happening within the fab operations. By aggregating data sources with more sophisticated analytics, we can predict operational performance and even self-prescribe actions to optimise productivity and efficiency.

By measuring and monitoring the consumption, quality and disposal of resources and energy, and correlating this with operational performance data, there is a significant opportunity to use data to innovate within manufacturing processes and how sub-fab facilities are managed. Along with natively generated data from existing tools and machines, additional sensors can be deployed to fill in gaps in information.

Such an approach can provide manufacturers greater visibility into their production processes and energy usage. Armed with this data, organisations can optimise production and improve predictive maintenance to diminish energy loads as well as reduce material and water waste. (Figure 4)

FIGURE 4
Increasing levels of automation in semiconductor manufacturing (Source: www.appliedmaterials.com)



From productivity to sustainability

Historically, fab equipment and facilities have often been over engineered, driving towards the highest performance at any cost. While this approach supports innovation to reduce technology feature size, lower the power consumption and increase the performance of semiconductors, a large portion of electronic devices which are running on legacy technology do not call for top-level performance. As a result, inefficiencies can be found in various areas of manufacturing that can be optimised while ensuring operational and technical performance. There needs to be further measures in place to put sustainability higher on the agenda when designing equipment, systems, processes and facilities.

There is now more data being generated from fabs than ever before. By bringing together data from different sources, new methods of measuring sustainability performance can be determined to steer decision making and innovation.

[5] Das and Mao, 2020. The global energy footprint of information and communication technology electronics in connected Internet-of-Things devices. Sustainable Energy, Grids and Networks 24, 100408.

Sustainability at Pragmatic Semiconductor

At Pragmatic, our vision is to solve global problems by allowing innovators to develop and manufacture made-for-purpose ICs, balancing performance, cost, and sustainability to enable applications that would traditionally be out of bounds for silicon-based semiconductors.

We do this by putting sustainability at the centre of our operations, allowing us to use alternative materials and significantly reduce the complexity of wafer manufacturing. We have developed a core semiconductor manufacturing process that removes resource and energy intensive process steps and significantly reduces wafer cycle time by 25x from months to a matter of weeks.

Our ethos within our FlexLogic™ manufacturing line is to only use ‘good enough’ quality resource, while minimising usage and maximising the recovery, rather than specifying performance at any cost. The characteristics of our technology and approach to manufacturing allows us to iterate and rapidly innovate to reduce the carbon footprint per wafer.

Intelligent manufacturing at Pragmatic Park

Pragmatic Park is the first large-scale semiconductor manufacturing facility to be announced in the UK in several decades and will house the very first state-of-the-art 300mm fab in the country. For Pragmatic, it represents an opportunity to innovate and define what best-in-class smart sustainable semiconductor manufacturing should look like moving forwards.

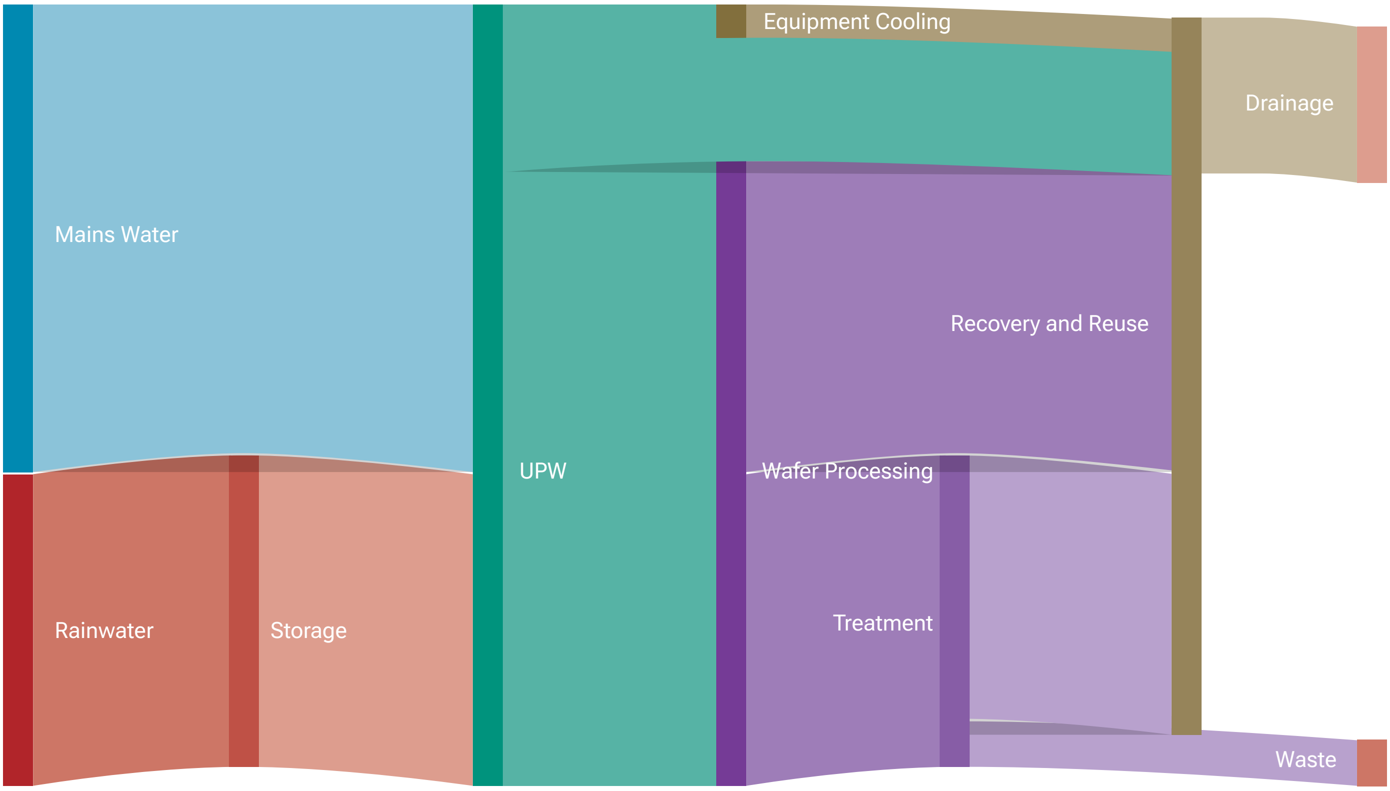
In addition to the inherent environmental advantages of our FlexLogic manufacturing approach when compared with a silicon fab, Pragmatic Park will see us improve the ecological footprint of our devices in a number of ways including the potential to use combined heat and power to bring down energy consumption and incorporating on-site ultra-pure water processing and wastewater reclamation.

Pragmatic recently won UK government funding to lead a £1.2 million project to use digital technologies to accelerate the decarbonisation and resource efficiency of semiconductor manufacturing. The project, code named INSPIRE, will involve the deployment of additional sensors, advanced data analytics and active resource management to optimise the quality, consumption, reuse, and recycling of resources within wafer processing, sub-fab and facilities. The first large-scale production line FlexLogic-002 at Pragmatic Park will become a blueprint of our manufacturing technology that will be deployed globally.

INSPIRE will focus on the high impact areas where digital technologies can make most significant impact such as water management, energy monitoring and removal of gases and chemicals.

Active water management

FIGURE 5
Proposed water management at Pragmatic Park



FlexLogic uses 100 times less water than a typical fab, however there is further opportunity to deploy an active water management system to better control the capture, consumption, recovery, quality, and end of life of water used within our manufacturing.

- Monitoring and correlation of product demand and local weather forecasts to balance influent tap water and rainwater capture
- Storage of low quality, recovered and ultra-pure water in local storage tanks
- Optimising the ultra-pure water quality requirements as per the process control and operational performance needs
- Recovery, reuse, and treatment of wastewater streams onsite

The aspiration is to be able to reclaim >80% of spent ultra-pure water (UPW) for reuse and to treat wastewater on site, rather than shipping off site for disposal. The use of tap water will nearly be completely diminished and simultaneously the energy consumption for the UPW plant and facilities will also be significantly reduced.

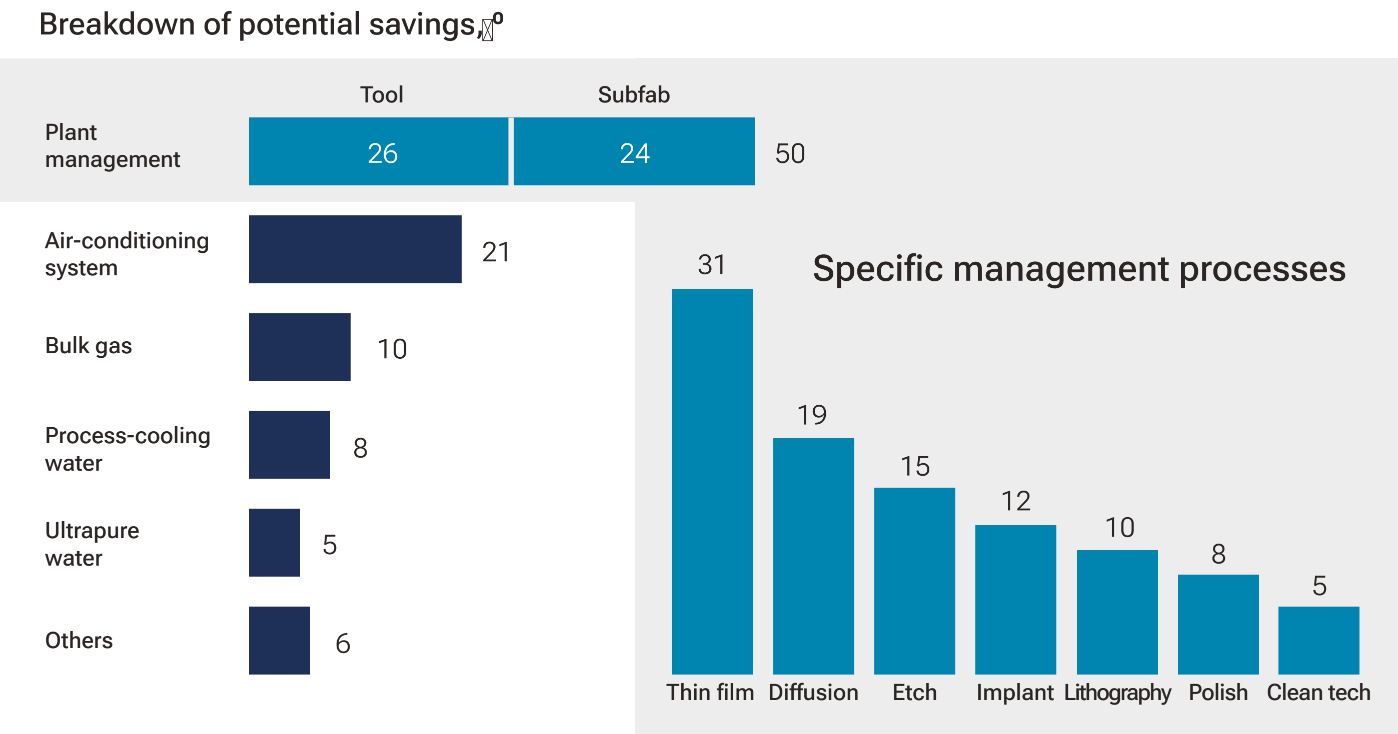
Smart energy monitoring

With half of energy consumption within a typical fab coming from wafer processing and the other from sub-fab tools, there is significant opportunity to deploy additional sensors to monitor consumption at a tool and module level to determine optimisation strategies. This allows for detailed review of equipment operating parameters and control according to production demand and performance.

According to a recent McKinsey report, a typical 300mm fab could achieve 20-30% energy savings by investing and deploying smarter approaches across the facility, most of which are within plant management.

Over the next couple of years, we forecast being able to save over 80,000 kWh per year using the aforesaid methods.

FIGURE 6
Potential energy savings at a 300-millimeter fab. Source: McKinsey & Company



Removal of bulk chemicals and gases

The removal of fluorinated chemicals and gases is particularly challenging due to their unique properties that are specific to the needs of semiconductor processing and the supporting equipment and infrastructure. Although with FlexLogic we use significantly fewer chemicals when compared to other manufacturers, it still accounts for more than 60% of the CO2eq emissions per wafer, including the manufacture, use and treatment of effluent waste streams offsite.

By using technical, operational and equipment data generated throughout the manufacturing stage, we are exploring alternative chemistries that carry leaner environmental footprint in its upstream manufacturing stage, are less harmful to the environment upon release, and are easier to treat at end of life, while still meeting the needs for our technology performance. In some cases, there are opportunities to also recover uncontaminated or unreacted gases to be diverted/reused in other parts of the manufacturing process or facility.

Using less potent gases and chemicals

- Conventional wafer fabrication uses highly potent gases such as NF3 that has a global warming potential (GWP) 17,000 times more than CO_2
- Our technology uses less potent gases which are easier to dispose through standard recycling processes

Future vision

Pragmatic is committed to work with industry leaders to create innovative techniques to decrease carbon emissions and improve resource efficiency and productivity and achieve net zero semiconductor manufacturing. Advancement of our manufacturing process, including considerations for our Scope 3 emission contributors, and customised micromanagement of the application of chemicals, materials, gases, water, and energy to avert the associated environmental implication demonstrates our commitment to achieve sustainable semiconductor manufacturing. With our new high-volume manufacturing facility in Durham, UK, Pragmatic envisions becoming a world leader in sustainable manufacturing.

The subsequent whitepaper will report our initial Life Cycle Analysis (LCA) study on the environmental footprint of a typical FlexIC, including a detailed characterisation of the manufacturing process and highlighting the hotspots for consideration.

Find out more

Visit our website www.pragmaticsemi.com

Contact info@pragmaticsemi.com to learn more about how we are enabling sustainability in semiconductor manufacturing.

Sources

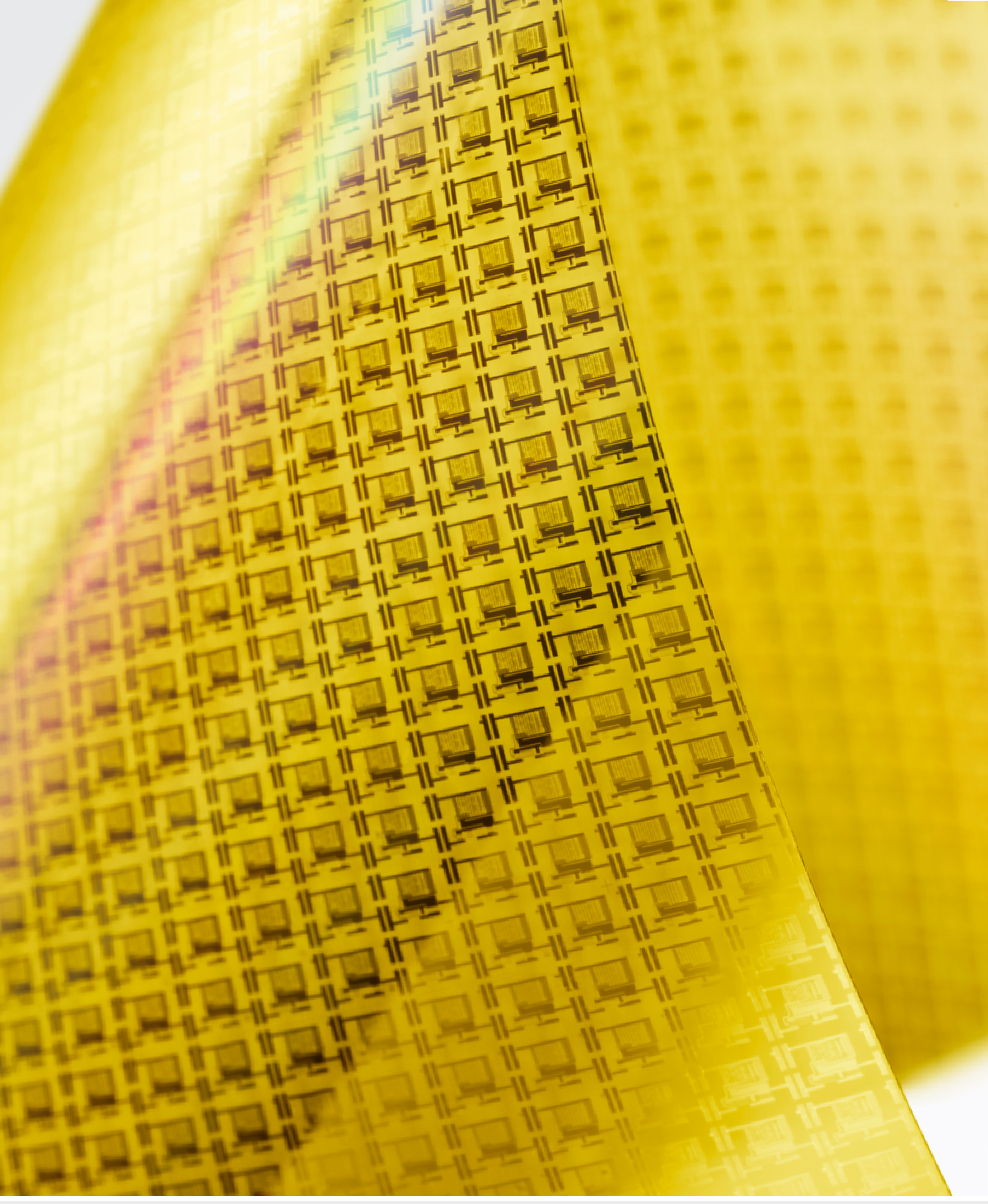
Sustainable Manufacturing: Fixing the Factory Floor (forbes.com)

How can manufacturing be sustainable and sustainability be manufacturable? (ey.com)

McKinsey Executive Summary

IMEC Sustainable semiconductor technologies and systems White Paper

tesco-reuse-report.pdf (tescoplc.com)



Learn more about Pragmatic

www.pragmaticsemi.com

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