The Time is Now: Sustainable Semiconductor Manufacturing

MIKE CZERNIAK, Edwards Vacuum

Notwithstanding its relatively small contribution, the semiconductor industry has played a leadership role in coordinating worldwide action to reduce GHG emissions.

As this article is being written, scientists and political leaders from around the world are preparing to attend COP 26, shorthand for the 26th[st] Conference of Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) in Glasgow, Scotland. COP26 is the 5-year (plus a one-year delay for Covid) review meeting of the parties, in which they update their plans to limit human-caused global warming.

Paris Agreement

The last major meeting, COP21, was held in Paris in 2015 and yielded the Paris Agreement, in which the parties agreed to work together to limit warming to less than 2°C (preferably less than 1.5°C) above the pre-industrial global average temperature. Each of the 196 signers of the Paris Agreement submitted a nationally determined contribution (NDC) defining the steps they were committing to take to achieve the overall goal. It is these NDCs that they will review and update at COP26. Certainly among the most significant developments of the intervening years was the United States' departure from the agreement shortly after it was signed and, more recently, its return.

IPCC and AR6

The work of the UNFCCC is based on the analysis and support of the Intergovernmental Panel on Climate Change, an international group of climate scientists and climate change experts. The IPCC also issues regular assessment reports (AR), the most recent of which, AR6, was released in August 2021. The report was noteworthy for the nearly complete consensus it achieved on its firm conclusion that climate change is real, measurable, and human-caused. The report includes detailed predictions and paints a dire picture of changes that will almost certainly occur if humans do not curtail their climate-changing activities. Major conclusions enumerated in the report's summary for policymakers include

- It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred.
- The scale of recent changes across the climate system as a whole and the present state of many aspects of the climate system are unprecedented over many centuries to many thousands of years.
- Human-induced climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes, such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since AR5.
- Improved knowledge of climate processes, paleoclimate evidence and the response of the climate system to increasing radiative forcing gives a best estimate of equilibrium climate sensitivity of 3°C with a narrower range compared to AR5, the previous report issued in 2014.

The report goes on to describe 5 scenarios likely to result from various levels of global warming, demonstrating increasingly severe impacts for higher levels of warming.

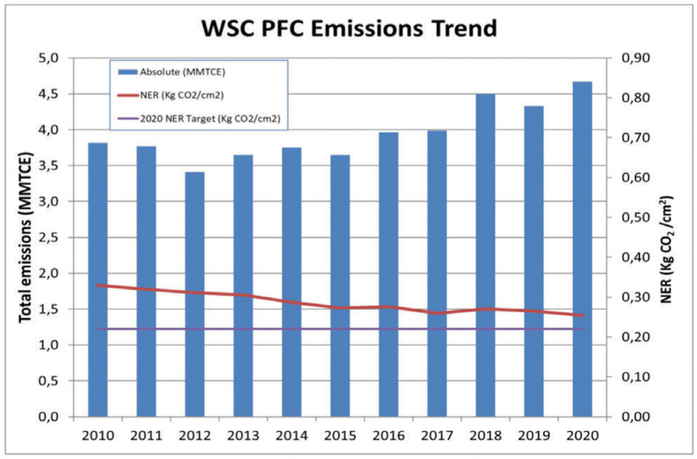

Figure 1. PFC emissions from semiconductor manufacturing have decreased steadily. [2]

Limiting greenhouse gases

Most discussion about ways to limit global warming focuses on reducing and eventually eliminating the emission of greenhouse gases (GHG) that is the underlying cause of global warming. There is evolving consensus that some form of carbon pricing is required, which would apply economic pressure to emitters by forcing them to pay the cost incurred by all for their degradation of a commonly shared environment. At this point, policy makers are struggling just to establish the basic concepts and definitions needed to make such a program work.

GHG are gases that absorb infra-red (IR) radiation, which is emitted from the earth's surface when it is warmed by the sun, thus trapping heat and raising the temperature of the atmosphere. Carbon dioxide is the principal greenhouse gas, though there are many others. Different gases may absorb IR radiation with different efficiencies and may persist in the atmosphere for different times. Scientists use global warming potential (GWP) to compare the warming caused by different gases over a specified period of time. By definition, CO_2 has a GWP of 1. GWPs for other gases commonly used in the semiconductor industry are much higher: CH_4 - 28, N_2O - 265, CF_4 - 6,630, NF_3 - 16,100, SF_6 - 23,500. Carbon dioxide equivalent (CO_2e) is another measure used to compare gases. Usually specified by weight, CO_2e is the amount of CO_2 that would cause the same amount of warming as the gas in question. To calculate CO_2e, multiply the weight of the gas in question by its GWP.

The greenhouse gas protocol (GHGP) sets up standardized frameworks to measure and manage GHG emissions, a necessary antecedent to any carbon pricing or other control mechanism. The GHGP defines three scopes of emission, depending on who owns those emissions and the level of control they have at each stage.

- Scope 1 — Direct GHG emissions from operations that are owned or controlled by the reporting company (boilers, vehicles, process gases).
- Scope 2 — Indirect GHG emissions by others from the generation of purchased or acquired electricity, steam, heating, or cooling consumed by the reporting company
- Scope 3 — All indirect emissions (not included in scope 2) that occur in the value chain of the reporting company, including both upstream (from suppliers) and downstream emissions (transport, distribution, storage).

Figure 2. An inward fired combustor maintains uniform temperature and separates fuel gas from process gases to avoid creating PFCs in the abatement process.

A special IPCC report issued in 2018 concluded that countries must bring carbon dioxide emissions to "net-zero" by 2050 to keep global warming within 1.5 °C of pre-industrial levels. There is incomplete agreement as to which gases should be included in the net-zero definition. This has created ambiguity and allowed countries and organizations to define net-zero according to their own criteria. In Sept 2020, the CDP (carbon disclosure project) developed methods on behalf of the Science Based Targets Initiative (SBTi) for setting and assessing net-zero targets based on robust climate science.

Other terms, such as "carbon neutral", are also used to describe GHG emissions. Differences among definitions are problematic. For instance, China's definition of "carbon neutral" only includes CO_2 itself, whereas the EU has adopted "climate neutral", which includes all GHGs. Other methods for zero and neutral assessments exist, and the ambiguity problem has yet to be fully resolved. The CDP clearly defines net-zero targets that include GHGP scope 1, 2 and 3 emissions and align with 1.5°C science-based targets.

Semiconductor manufacturing

Semiconductor manufacturing is a minor contributor to GHG emissions. For example, in the US in 2015, it accounted for 0.18 % of total greenhouse gas (GHG) emissions from industrial sources and only 0.063% of all GHG emission sources [1]. Notwithstanding its relatively small contribution, the semiconductor industry has played a leadership role in coordinating worldwide action to reduce GHG emissions.

Scope 1: Direct Emissions — PFCs, a success story

Historically, volatile perfluorocarbon (PFC) compounds have played an important role in semiconductor fabrication as a source of reactive fluorine atoms used to remove material in etching and chamber cleaning processes. They are stable and tend to have long lifetimes in the atmosphere, making them potent greenhouse gases with high warming potential. In 1999, quite early in the history of global warming awareness, semiconductor manufacturers committed to reduce PFC emissions by at least 10% below baselines for each region over the next 10 years. By 2010 they had achieved a reduction of 32%, far surpassing the original goal. At that time, they recommitted to further reductions, targeting a normalized emission rate

(NER – kilograms of CO_2e per cm^2 of silicon) 30% lower than the 2010 baseline. By 2020 they had achieved a 22.9% decrease, this despite increasingly complex products with more layers, and advanced etch processes that use new gases. The WSC is now working to establish a new PFC reduction 10-year goal that will estimate emissions using the latest 2019 methodologies from the IPCC. (FIGURE 1).

The PFC story provides an excellent example of the challenges encountered in the search for solutions to complex environmental problems. The success in reducing PFC emissions had two major components: the switch to non-PFC NF_3 for many chamber cleaning applications and the adoption of abatement technologies that could destroy unconsumed PFC gases that exited the process chamber. PFCs can be destroyed by a plasma or fuel-based burner. Plasma has the advantage of not adding carbon emissions from the burning fuel. However, in practice the choice of technology is often driven by the relative cost and availability of electrical power versus fuel gas. Even when electrical power is available and cost-effective, the source of that power, i.e., coal or renewable, must also be considered in the net-zero carbon Scope 2 calculation. The solution is further complicated by the design of the burner. Although NF_3 itself contains no carbon, burning it in an open flame of hydrocarbon fuel can create PFCs. The problem originates in the wide variations of temperature across an open flame, and the solution lies in a specially designed burner, known as an inward fired combustor (FIGURE 2), which maintains a more uniform temperature in the critical regions and largely separates the carbon-containing fuel from the process gases.

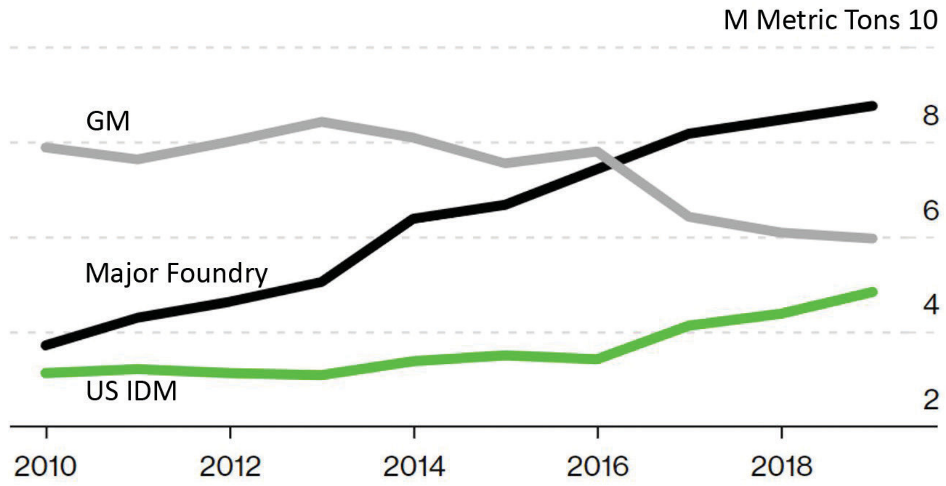

Figure 3. GHG emissions from semiconductor manufacturing are increasing while emissions from more traditional manufacturers are decreasing. [5]

Scope 2: Indirect Emissions — Power purchased from off-site generators

The ubiquity of electronic technologies and the exponential growth they have demonstrated over the last several decades could easily lead one to conclude that electronics will soon consume more power than the world can produce. The truth is somewhat less alarming but still important enough that it should not be ignored. In 2015 information and communication technology (ICT) accounted for about 5% of global energy demand. By 2030, ICT may represent as much as 20% of global demand, and even the most optimistic forecasts project it growing to 7% [3]. Energy consumed by electronic technologies can be split into two buckets: energy used to manufacture the devices, almost all of which is currently purchased from third party suppliers, and energy used to operate the devices. The first of these is included in Scope 2 of the GHGP, the second in Scope 3. Interestingly, and somewhat counter to the doomsday projection that computers will soon use all the power the world can produce, the conclusion drawn in a recent analysis that shows Scope 2 power used to manufacture devices far exceeds the Scope 3 power used to operate them.

Semiconductor manufacturers have long been sensitive to the large power demands of their manufacturing processes, if not from an environmental perspective, then from the point of view of cost. Most estimates put the share of energy used by process equipment at just under half of the total used by a fab. Of that, about half is used by the pumps used to maintain the vacuum conditions required for many processes to operate. Pump manufacturers have continuously improved the energy efficiency of their products since the early days of the industry. New mechanisms, higher shaft speeds, power inverter technology and new materials have all contributed. Much of the low hanging fruit was picked long ago, but some areas do remain where further improvements are possible. One of the most promising is the implementation of idle mode operation, sometimes called green mode, in which the pump is put into a low power state when the process it serves is idle. The greatest challenge is the close coordination required between process equipment in the fab and pumps in the sub-fab. Technologies already exist to support that coordination and some of the resistance to its implementation must be attributed to the reluctance of operators to change any aspect of a high-yield high-volume manufacturing operation. Green mode operations could provide near-term reductions in GHG emissions without requiring fundamental changes to ongoing production.

Unfortunately, other processes coming online now at advanced nodes have the potential to greatly increase power consumption, among them is EUV lithography which uses approximately 10X as much power as conventional 193nm immersion lithography. There are offsetting factors, such as a reduction in the number of processing steps. Still, an IMEC analysis [4] estimated a 3.46 increase in power consumption and a 2.5X increase in GHG emissions per wafer in going from the 28nm node to the 2nm node. The first manufacturer to implement EUV lithography in high-volume production, a major foundry, saw its normalized energy consumption (KWH per 8-inch equivalent wafer mask layer) increase more than 25%, to 12.5KWH in 2019 after hovering several years just below 10KWH.

While the trend in semiconductor manufacturing is clearly one of increasing power consumption (FIGURE 3), the solution is equally clear. Energy consumption must switch to renewable sources. It is a solution not lost on major manufacturers. In 2020, the same foundry signed the world's largest renewable energy purchase agreement, a 20-year deal buying all the energy from a 920-megawatt offshore wind farm being built nearby, and committed to using 100% renewable energy by 2050. [6]. The largest US IDM has committed to 100% renewable energy by 2030. Other major players have made similar commitments, though, as always, the devil is in the details.

Scope 3: Upstream/Downstream — Scope assignment becomes a little more challenging for Scope 3 – it depends on who is counting. For a manufacturer, the GHG emitted to generate the power consumed by a user in a data center is downstream, Scope 3. For the data center, that GHG is indirect emissions from purchased power, Scope 2, and the manufacturing emissions are upstream, Scope 3. Regardless of scope, the ultimate solution for usage emissions lies in the switch to renewable energy sources. Some of the largest users of computing technology are well ahead of their manufacturing counterparts in that switch. Google and Facebook began purchasing renewable power in 2013. Although overall data-center energy consumption has risen since then, carbon emissions from operational energy consumption has fallen. Another factor in the reduction of emissions has been the dramatic increase in computational energy efficiency over the history of the industry. As transistors became smaller, faster and more energy-efficient, the number of instructions executed per Watt increased. This trend has accelerated in recent years as demand for more capability and extended battery life in mobile devices applied additional pressure to improve both performance and energy efficiency.

By far the biggest impact of semiconductor devices in driving sustainability is the contribution they make to energy efficiency throughout the economy. Semiconductors – the fundamental enabling technology of modern electronics – provide the technological foundation for solutions that advance sustainability and energy efficiency gains in virtually all sectors of the economy. Semiconductors increase energy efficiency and reduce GHG emissions in transportation, manufacturing, health care, heating and cooling, and other major areas of the economy. From almost any perspective, environmental, economic, or societal, the downstream benefits of advanced electronic technologies far outweigh the costs.

COP26

The IPCC's evidence-based conclusions are unequivocal: humans are causing the environment to warm. Its predictions are dire, and the costs of inaction, human and economic, far exceed the costs of mitigation. Although the semiconductor industry is not today among the largest emitters of greenhouse gases, our emissions are significant and growing rapidly. Measures exist that can provide short-term reductions in GHG emissions from the semiconductor manufacturing process, including well designed PFC abatement and green-mode vacuum pump operation. By far the most critical change is a shift to renewable energy sources across the industry and throughout the supply chain. With the return of the United States to the Paris Agreement, the conference of parties once again includes all the major economic powers. We must demand coordinated leadership and financial commitments from our national leaders and continue to work at all levels, local to global, to reduce GHG emissions. SD

DR. CZERNIAK is Environmental Solutions Business Development Manager at Edwards Vacuum, where over a long career, he has previously served in a number of leadership positions. He is also a visiting industrial professor of chemistry at Bristol University and a semiconductor industry representative to the IPCC, in which capacity he participated as a reviewer of the recent assessment report (AR6).

REFERENCES

1. Semiconductor Industry to Continue Action on Climate Change, David Isaacs, VP Governmental Affairs, SIA Blog, Wednesday, Jun 07, 2017, 3:17pm https://www.semiconductors.org/semiconductor-industry-to-continue-action-on-climate-change/
2. Joint Statement of the 25th Meeting of the World Semiconductor Council http://www.semiconductorcouncil.org/wp-content/uploads/2021/08/FINAL-25th-WSC-Joint-Statement_0602.pdf
3. Chasing Carbon: The Elusive Environmental Footprint of Computing, Udit Gupta, et al, IEEE International Symposium on High-Performance Computer Architecture (HPCA 2021) https://ugupta.com/files/ChasingCarbon_HPCA2021.pdf
4. The environmental footprint of logic CMOS technologies - A DTCO-based analysis, IMEC https://www.imec-int.com/en/articles/environmental-footprint-logic-cmos-technologies
5. The Chip Industry Has a Problem With Its Giant Carbon Footprint, Bloomberg Green, Alan Crawford, Ian King, and Debby Wu, April 8, 2021, 5:01 PM EDT https://www.bloomberg.com/news/articles/2021-04-08/the-chip-industry-has-a-problem-with-its-giant-carbon-footprint
6. The computer chip industry has a dirty climate secret, The Gaurdian, Pádraig Belton, Sat 18 Sep 2021 08.00 EDT https://www.theguardian.com/environment/2021/sep/18/semiconductor-silicon-chips-carbon-footprint-climate