A Review of Sustainability Concerns and Possible Solutions in Semiconductor Manufacturing

Evan D’Souza

Introduction

The monumental growth and proliferation of the internet, computers, mobile phones, and other intelligent devices have defined the 21st century. With incredible breakthroughs in AI, such as GPT-4, it is clear that growth in technology is accelerating. As innovators worldwide continue to push the bounds of what is possible with current technology, they are shifting attention toward the hardware that makes all modern technology possible - microchips. As a result, investment in the semiconductor industry is skyrocketing. Arguably, the most significant indicator of this shift in the United States is the CHIPS and Science Act passed in August 2022. Provisions include $39 billion in manufacturing incentives, $13.2 billion in R&D incentives, and a 25% tax credit for purchasing equipment [1]. These incentives will ensure that semiconductor manufacturing will significantly increase in the coming years. In the wake of the announcement, companies like Qualcomm have pledged to dramatically increase chip production in the United States [1].

However, an increase in semiconductor manufacturing comes with environmental concerns. Emergent technology is poised to be an invaluable tool in fighting climate change, yet the current state of semiconductor manufacturing is harmful to the environment. Individual fabs use incredible amounts of energy and resources each year, often rivaling the needs of tens of thousands of families [2]. Therefore, reducing emissions and improving sustainability must be prioritized as new semiconductor fabrication plants (fabs) are built. This paper addresses the primary environmental issues present at fabs today, each issue's relative importance, and possible solutions to make the industry as sustainable as possible.

Primary Issues

Two main factors are important when reviewing an industry's environmental impact: greenhouse gas (GHG) emissions and scarce resource consumption. An industry’s GHG emissions include both direct and indirect sources of emissions. These emissions are categorized under three “scopes”: Scope 1 for direct GHG emissions from the industry, Scope 2 for indirect GHG emissions, and Scope 3 for GHG emissions related to other sectors in the supply chain. Because the industry has the most control over Scope 1 and 2 emissions, and because they make up 80 percent of the industry's total emissions, this article will focus on those two [3]. Since the only source of Scope 2 emissions are electricity-related GHG emissions, all discussions of Scope 2 emissions will concern electricity. Similarly, since Scope 1 emissions are direct GHG emissions, all Scope 1 emissions will be referred to as “direct GHG emissions”. The second factor is the industry's significant consumption of scarce resources. For semiconductor manufacturing, water is the most consumed resource of this nature. Therefore, this article will focus on the relative importance of water consumption, direct GHG emissions, and electricity use within the semiconductor industry. In the next section, the industry’s water usage will be discussed, which has a relatively low impact on overall commercial scarce resource consumption.

Water Consumption

Many articles discussing the semiconductor industry's environmental impacts detail how much water fabs consume. Indeed, a single large fab can use around 10 million gallons per day [4]. For example, TSMC's planned fab in Arizona will use 8.9 million gallons of water daily [2]. However, the industry's water usage pales in comparison to total U.S. water usage alone, much less global water usage, for several reasons. First, there are not many semiconductor fabs in general. While there are no specific records on how many semiconductor fabs exist in the United States or globally, unofficial lists estimate the number to be around 500 globally [5]. In the worst-case scenario, assuming all 500 fabs use 10 million gallons of water daily for the year, the *global* total water usage by the semiconductor industry would be 1.825 trillion gallons of water. However, the United States alone uses 322 billion gallons of water daily, or 117.530 trillion gallons per year [6]. In other words, the global semiconductor industry uses only 1.55% of the water used in the United States alone. Other estimates place the industry's water usage in the United States at 264 billion gallons per *year*, significantly less than the total water used in the United States in just one day [4] [6]. As a whole, the semiconductor industry does not use nearly as much water as many other industries [7].

Even more importantly, none of these calculations consider water recycling, an essential aspect of fabs' water usage. While water recycling rates vary drastically from fab to fab, almost all fabs employ some sort of water recycling method, with the industry average around 23% percent [4]. Some fabs have even devoted significant resources to water recycling and reached 98% efficiency, meaning only 2% of new water needs to be externally sourced daily [8]. Overall, as the adoption of water recycling technology continues to improve, the semiconductor industry's water usage will no longer be a significant sustainability issue to consider.

Direct GHG Emissions Breakdown

Direct GHG emissions account for 43.75 percent of Scope 1 and 2 emissions [3], a significant portion of the industry's emissions. Additionally, the overwhelming majority of Scope 1 GHG emissions arise from gasses necessary to process the chips [3]. Process gas is the largest source of direct GHG emissions because up to 80 percent of process gasses used in the chambers are released unreacted into the environment [9]. Chip processing includes the steps necessary to etch, or carve, the physical chip and clean the chemical vapor deposition (CVD) chambers where the chips are made. While many of the gasses used in etching the chip and cleaning the chambers are the same, for the sake of clarity, gasses used for CVD cleans will be referred to specifically, while the gasses used for etching the chip will still be referred to as process gasses.

Around 66 percent of GHG use in fabs arises from CVD cleans [10]. Consequently, fabs prioritize reducing GHG emissions in CVD cleans over general process gasses. Three additional factors also contribute to this prioritization. First, the fluorinated gasses used to etch the chip are incredibly hard to replace, and no viable substitutes exist. Therefore, almost no improvement is possible regarding general process gasses. Secondly, improving chamber cleans will not hurt productivity in chip production because the processes are independent [11]. Finally, and most importantly, significant opportunities exist to improve CVD chamber cleaning.

Currently, the semiconductor industry has four main strategies for reducing CVD clean-related GHG emissions. These strategies include alternative chemistries, gas abatement, capture and recovery of gasses, and process optimization [12]. Alternative chemistries and gas abatement are particularly noteworthy strategies to investigate for direct GHG emission reduction. Process optimization involves improving sensing technologies to use less gas and improving technology in the chambers, which fabs will naturally do to improve their bottom line. On the other hand, the capture and recovery of gas is costly, inefficient, and impossible to implement effectively in fabs for the foreseeable future [12]. Additionally, with improvements in the other strategies, primarily in alternative chemistries, there will be little remaining gas left to recycle.

Alternative Gasses

Fabs primarily use fluorinated gasses such as CF_4, C_2F_6, C_3F_8, c-C_4F_8, CHF_3, CH_3F, CH_2F_2, SF_6, and NF_3 [9]. The free fluorine atoms provided by the gasses are essential for both etching the silicon wafers and picking up extra material during cleaning [9]. Unfortunately, these gasses are highly potent greenhouse gasses. For example, C_2F_6, a gas primarily used in older CVD cleans, has a global warming potential 9200 times greater than CO_2 and lasts in the atmosphere for 10,000 years [3]. CF_4, a problematic byproduct of CVD cleans, has a global warming potential 6500 times greater than CO_2 and lasts in the atmosphere for 50,000 years [3]. This issue leaves manufacturers in a tough situation, as solutions not involving fluorinated gasses would be costly and ineffective. However, using more efficient process gasses can ameliorate the issue.

All GHGs are problematic when released into the environment, but not all are used as efficiently. Some gasses, such as C_2F_6, are only used with 30% efficiency, leaving 70% of gas unreacted [11]. Low-efficiency gas use is problematic because, while reacted gas doesn’t leave the facility, the unreacted gas gets released into the environment and contributes to climate change. On the other hand, modern-day remote plasma cleaners using NF_3, an alternative CVD cleaning gas, have reached 95–99% efficiency [12]. While NF_3 is a much more potent GHG than C_2F_6 [3], it is a much more efficient gas for CVD cleans because it is more reactive. Therefore, by switching all CVD cleans to NF_3, fabs can significantly reduce their GHG emissions from their most prominent source. However, fabs should take care to implement NF_3 cleans effectively because inefficient NF_3 usage in the past has caused its presence in the atmosphere to skyrocket [13]. Switching to NF_3 also requires handling larger quantities of F_2 and replacing equipment used for all the other fluorinated gasses, which is why many older fabs have not already made the switch [11]. Still, the change may decrease costs over time due to higher efficiency and benefit sustainability immensely [11].

Nevertheless, innovations could lead to an alternative chemistry that’s even better than NF_3. Fabs have been using fluorinated gasses for their fluorine, so why not use F_2 instead? F_2 is a perfect substitute for fluorinated GHGs because it has zero global warming potential. The issue is that F_2 is highly reactive and toxic, making it extremely dangerous. However, with emerging technologies for producing and storing F_2, companies like Linde have been able to introduce F_2 in CVD cleans [10]. F_2 is an outstanding substitute because it can replace NF_3 on the same equipment, operate three to five times faster, use less gas, and use less energy than NF_3 [10]. While F_2 may still be far from being widely adopted in the industry because the technology is so new and dangerous, it is the next step in reducing process gas consumption.

Gas Abatement

Universal adoption of F_2 technology will take fabs a long time. Thus, in the interim, fabs should also focus on gas abatement technology to improve the usage of NF_3 and other gasses. Gas abatement involves destroying remaining unreacted gasses before leaving the fab, implemented for each chamber or centralized for the entire plant. Regardless, plasma gas abaters can be the final piece in the puzzle to eliminate any final unreacted GHGs leaving the facility. Many commonly-implemented abaters use heat, fuel burns, or catalysis to destroy remaining fluorinated gasses [11]. However, most are ineffective at eliminating CF_4; some even produce additional greenhouse gasses [11]. On the other hand, newer systems implementing point-of-use plasma scrubbers have achieved over 99.9% destruction efficiency, including for CF_4 [14]. Plasma abaters such as the ones offered by Applied Materials [15] and Proteus [16] are also highly energy efficient, which helps cut costs and further reduce the fab's carbon footprint.

Overall, semiconductor fabs have a reasonably straightforward path to solving direct GHG emissions. The first step should be switching all CVD cleans to efficient plasma NF_3 cleans at the minimum. As the technology develops, fabs should transition all CVD cleans from NF_3 to F_2, or fabs should change directly to F_2 from other fluorinated gasses. Finally, fabs should immediately implement point-of-use plasma gas abaters for all of their chambers to destroy any gasses remaining from etching or CVD cleans. These strategies are not universally adopted already because they require additional investment and cutting-edge technology. However, by implementing these three strategies, fabs can negate nearly all of their Scope 1 greenhouse gas emissions.

Electricity Consumption Breakdown

While reducing direct GHG emissions is important, the largest source of emissions by the semiconductor industry is by far Scope 2 emissions arising from electricity usage. Electricity is a big concern for manufacturers — TSMC reports electricity usage accounting for 62% of emissions [17]. From a larger perspective, the semiconductor industry also significantly impacts total energy usage. Only a few fabs currently operate in the United States, yet, they already account for 2% of the energy used in the manufacturing sector [18]. While many other sectors, like the cement and paper sectors, currently use far more energy, this distribution will change dramatically as companies construct new plants under the incentives from the CHIPS Act [19]. For example, two new fabs under construction in New York by Micron and Global Foundries will use 9,346,000 megawatt-hours a year [20]. For context, New York State uses 141,423,778 megawatt hours of electricity per year, and the United States as a whole uses 3,805,874,253 megawatt hours per year [21]. That means *just two fabs* could equate to 6.6% of New York and 0.25% of the United States' *total* energy usage. As more and larger fabs are built, electricity usage could skyrocket.

Not all existing or new semiconductor fabs are identical, but trends in their energy usage can expose areas prime for improvement. Historically, energy consumption has been relatively consistent regarding allocation within a fab. For example, data breakdowns from 8 different fabs in 1999 [22] and an individual fab from 2008 [23] are very similar, with two areas standing out as the most power-hungry. The first area is silicon wafer processing, which accounts for around 40 percent of a fab's energy use [22] [23]. The second area is air heating, ventilating, and conditioning the air (HVAC) within the fabs. Combining all the elements that make up a fab’s HVAC system, their energy usage is around 45% [22], [23]. Combined, the HVAC and process systems comprise about 85-90 percent of a fab's energy consumption, thus offering the most extensive opportunities to save energy.

Improvements in Electricity Consumption

Of these two major contributors to a fab's energy usage, HVAC systems are much easier to optimize significantly than process tools. The energy used by process tools is nearly impossible to optimize further. When the product is so small, energy is primarily consumed based on the chemistry of the process, not the power efficiency of the tools [24]. Because the fluorinated process gasses are so hard to replace, it is almost impossible for fabs to improve energy consumption caused by the chemistry of the process. For now, that means that the minuscule improvements in process energy efficiency will only come from manufacturers buying and implementing newer and slightly more power-efficient tools as a natural course of business. As with any industry, devices become more precise, faster, and power efficient with time, and semiconductor manufacturing will be no different. Still, these changes are insufficient to solve fabs' energy concerns.

On the other hand, the HVAC systems implemented in most fabs can be improved in many ways to become far more power-efficient. Similar~~ly~~ to improving GHG emissions from CVD cleans, improving HVAC efficiency is relatively straightforward, especially for new fabs [24]. This is because improvements do not directly affect production yield and are often implemented in other industries [11]. Improving and upgrading chiller systems is a significant first step. Chillers alone use 25% of a fab's electricity, accounting for the greatest individual portion of HVAC energy requirements [22]. Replacing old and outdated chiller systems is an effective way to save energy and money since chiller upgrades can save significant money over time when energy costs decrease [23]. While replacing chillers may be more expensive initially than many other upgrades suggested, they help future-proof fabs as cooling requirements increase. Chillers are the most vital cog in energy-efficient fabs.

Next, fabs should focus on implementing the most energy-efficient HVAC design. A typical HVAC system for a semiconductor cleanroom incorporates one or more of the following apparatus: a make-up air unit (MAU), a recycled air unit (RCU), a fan coil unit (FCU), a fan filter unit (FFU), a direct cooling coil (DCC), and an axial fan system. While many configurations of those units are possible, a study by Hu and Tsao [25] found through operational data that an MAU and FFU were the most power-efficient combination. While the study did not mention a DCC, it is also included in the HVAC system. On the other hand, components like the RCU are inefficient and easily replaced. Changing entire HVAC layouts at existing fabs is no small task, but implementing this layout in new fabs will promote efficiency in the long run.

Fabs can further improve this basic layout. In this design, a humidifier is part of the MAU system. However, creating the steam necessary for humidification requires a large amount of energy. Instead, Jo et al. [26] proposed using an adiabatic pressurized water atomizer to humidify the air. A pressurized water atomizer uses a high-pressure pump to spray water and produce incredibly fine droplets. Adiabatic humidifiers inject these atomized water droplets directly into the air, which requires far less energy than turning the water into steam. By implementing this method, fabs can expect to consume 23% less energy compared to a traditional humidifier system [26].

Fabs can also improve energy efficiency in HVAC systems in broader ways. Fabs are prone to being over-engineered and inefficient, which presents itself across the entire facility, especially in air circulation [27]. Processes that run to heat or cool air will frequently overlap, run too long, or run far more powerfully than needed [23]. By installing smart sensors that accurately measure the situation in the cleanrooms, fabs can use only the energy necessary to keep the system in equilibrium [3] [27]. Installing smart sensors can also improve the consumption of resources and energy in the process tools, although certainly not to the same extent as the HVAC system. While the amount of power smart sensors will save varies widely between fabs, installing smart sensors will be a relatively small capital investment of around $200,000 [27]. By using this technology, fabs can decrease energy costs by 30% without making significant changes to the design of cleanrooms [27].

Finally, simple changes like switching all the lights to LEDs and ensuring that parts are correctly maintained are cheap and reliable ways to decrease energy consumption throughout the fab [3].

Improvements in Electricity Sourcing

The best way to reduce GHG emissions from electricity is to create and use electricity from renewable sources. For example, fabs can take inspiration from Tesla’s Gigafactory in Nevada, which is located in the desert and uses massive arrays of solar panels to power the plant [28]. Additionally, the factory has many water chilling needs that it meets by overproducing during cold desert nights [28]. Semiconductor manufacturers can use these innovations in almost an identical capacity in new fabs that are located in the desert. In addition to the solar energy being clean and renewable, it is also a great source of off-grid power. Sourcing off-grid power from cleaner sources is crucial because fossil fuels currently dominate off-grid power. This issue is particularly pervasive in the semiconductor industry, where many fabs own local fossil fuel plants [3]. Another way to improve off-grid power sustainability is to transition off-grid power reserves to green hydrogen. Green hydrogen is an excellent renewable energy storage option because the hydrogen is produced from clean energy processes like water electrolysis. The green hydrogen market is receiving massive support and investment, which will reduce costs and increase availability [29]. The cost of producing clean hydrogen is projected to drop 30% by 2030 due to cheaper renewables and scaled-up production [29]. While green hydrogen is currently not ready for commercial deployment, if this trajectory continues, green hydrogen will make it easier than ever for fabs to transition from fossil fuels to renewables for power reserves.

Regarding on-grid power, the best thing the industry can do is prioritize building fabs in areas with the most renewable energy. Although renewable energy is rapidly developing worldwide, it is not being adopted equally. Energy sourcing is a significant issue for the semiconductor industry primarily because of its over-reliance on Taiwan. Taiwan manufactures 60 percent of all semiconductors and 90 percent of advanced microchips [30], making itself the global semiconductor manufacturing hub. Such concentrated production in any country is dangerous to domestic interests, and Taiwan, in particular, poses significant political and clean energy challenges. On the political side, China poses an immense security risk to Taiwan, and an invasion could see an effective Chinese monopoly over semiconductor production [31]. As for energy, over 85% of Taiwan's energy comes from fossil fuels, compared to 65 percent in the United States [3]. Though Taiwan is making significant strides to increase renewable energy production, such as adding 5.7 GW of wind energy and 14.2 GW of solar energy to the power grid by 2025, this will still amount to only 20% of the country's energy supply being renewable [32]. With individual companies like TSMC taking up to 7.2% of the national power supply on their own, there will be little renewable energy left to go around [33]. This means the semiconductor industry must move away from Taiwan to be more climate-friendly. Recommending which countries the sector should move to is beyond the scope of this paper.

This will largely depend on policy decisions, or lack thereof, by individual countries and the companies' responses to these decisions. For fabs within the United States, manufacturers can focus on building them in states that predominantly get their energy from clean sources, such as Washington or Illinois [34]. Still, manufacturers must decide on the best locations for their needs. Ultimately, it is up to chip manufacturers to prioritize renewable energy and sustainability, even when it is not the most cost-effective option.

Policy Changes

The CHIPS Act is an excellent example of how legislation can help spur change in the semiconductor industry. Similar policy measures can be implemented to ensure the semiconductor industry follows through with the changes it needs to make to achieve sustainability. For example, legislation requiring fabs to recycle at least 50 percent of their water use by 2030 can be passed. States can also limit how much new water fabs can bring in daily, further incentivizing recycling. For direct GHGs, Congress can pass laws that effectively require all new fabs to implement NF_3 for CVD cleans.

An intriguing way to achieve this would be by implementing something similar to a carbon tax. While a general CO_2 equivalent carbon tax would work, historically, carbon taxes have been difficult to pass in the United States [35]. Instead, heavy taxes on the emissions of specific gasses like C_2F_6, C_3F_8, and CF_4 will compel manufacturers to use NF_3 in CVD cleans. Though specific taxes on gasses have not been implemented in the past, outright bans on gasses do have a precedent in the United States. For example, in 1994, through the Clean Air Act, the United States banned the use of hydrochlorofluorocarbons [36]. Because taxes on these gasses will have a much smaller scope than a carbon tax, legislation should not be nearly as controversial or challenging to pass as carbon taxes. To incentivize the development and adoption of F_2 technology, tax incentives and money for R&D can be provided similarly to the CHIPS Act. With respect to energy, minimum standards for energy efficiency and smart sensor usage can be enacted. While forcing fabs to upgrade their chillers or use specific HVAC designs is not feasible, creating general standards to promote energy efficiency across the fab is a step in the right direction.

The government also has a wide array of possible policies available to encourage semiconductor manufacturers to use more sustainable energy. The United States already implements the Investment Tax Credit and Production Tax Credit to incentivize solar and other renewable energy production [37]. The government can offer similar credits for new fabs provided they source a determined amount of their energy from on-site solar energy. In Australia, the government created the Renewable Energy Target to compel energy distributors to source a certain percentage of their energy from renewables [38]. The United States could implement a similar scheme for domestic energy providers, or if the legislation is specific to semiconductor manufacturers, the government could directly require fabs to source a certain percentage of their energy from renewable sources. Finally, the United States could take inspiration from Germany’s feed-in tariff system, which purchases renewable energy at above-market prices from suppliers. This system has dramatically increased renewable energy production [39]. By emulating this system, the United States could rapidly expand renewable energy use across the board, including in the semiconductor industry.

Regardless of the policies the government decides to implement, one thing is clear: passing legislation is essential. The world can not rely on semiconductor manufacturers to address sustainability issues purely out of goodwill. Policy changes will be the crucial link between supporting sustainability improvements and actually implementing them.

Conclusions

At first glance, the semiconductor industry is far from sustainable. Fabs certainly have much work to do if they want to implement all the most impactful changes in a reasonable timeframe. However, many of the changes fabs need to make are quite straightforward. Water consumption is already not a big issue, but it can be solved entirely by implementing more effective recycling technology. Direct GHG emissions can be solved by installing plasma gas abaters, transitioning to $NF_{3,}$ and transitioning to F_2 for CVD cleans when possible. Most importantly, fabs can solve energy concerns by using the most efficient devices and setup for the HVAC systems, implementing smart energy-saving sensors throughout the fab, and prioritizing clean energy.

The semiconductor industry is irreversibly intertwined in our efforts to combat climate change and pave the way for a more sustainable future. If the industry can make the necessary changes, the future of technology and our globe will look incredibly promising.

References

[1] “Fact sheet: Chips and science act will lower costs, create jobs, strengthen supply chains, and Counter China,” The White House, https://www.whitehouse.gov/briefing-room/statements-releases/2022/08/09/fact-sheet-chips-and-science-act-will-lower-costs-create-jobs-strengthen-supply-chains-and-counter-china/ (accessed Jul. 11, 2023).

[2] S. Brunswick, “A Tale of Two Shortages: Reconciling Demand for Water and Microchips in Arizona,” American Bar Association, https://www.americanbar.org/groups/environment_energy_resources/publications/wr/a-tale-of-two-shortages/#:~:text=The%20TSMC%20plant%20is%20a,the%20City%27s%20current%20water%20production (accessed Jul. 11, 2023).

[3] O. Burkacky et al., “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 (accessed Jul. 11, 2023).

[4] S. Davis, Ed., “Water Supply Challenges for the Semiconductor Industry,” Semiconductor Digest,https://www.semiconductor-digest.com/water-supply-challenges-for-the-semiconductor-industry/#:~:text=Our%20industry%20consumes%20copious%20amounts,scarce%20in%20a%20changing%20climate (accessed Jul. 11, 2023).

[5] “List of semiconductor fabrication plants,” Wikipedia, https://en.wikipedia.org/wiki/List_of_semiconductor_fabrication_plants (accessed Jul. 11, 2023).

[6] Water Resources Mission Area, “Total Water Use,” U.S. Geological Survey, https://www.usgs.gov/mission-areas/water-resources/science/total-water-use?qt-science_center_objects=0#qt-science_center_objects (accessed Jul. 11, 2023).

[7] M. Ellis, S. Dillich, and N. Margolis, “Industrial Water Use and its Energy Implications,” ACEEE 2001 Archives, https://www.aceee.org/files/proceedings/2001/data/index.htm (accessed Jul. 23, 2023).

[8] D. Johnson, “Scarcity Drives Fabs to Wastewater Recycling,” IEEE Spectrum, https://spectrum.ieee.org/fabs-cut-back-water-use (accessed Jul. 11, 2023).

[9] “Semiconductor Industry,” EPA, https://www.epa.gov/f-gas-partnership-programs/semiconductor-industry (accessed Jul. 11, 2023).

[10] P. Stockman, “Fluorine Use in the Electronics Industry,” Linde Gas, https://www.linde-gas.com/en/images/Fluorine%20Use%20in%20the%20Electronics%20Industry%20by%20Paul%20Stockman%20for%20Specialty%20Gas%20Report%20Q32016_tcm17-402242.pdf (accessed Jul. 11, 2023).

[11] Laurie S. Beu Consulting, Reduction of Perfluorocompound (PFC) Emissions: 2005 State-of-the-Technology Report, https://www.epa.gov/sites/default/files/2016-02/documents/final_tt_report.pdf (accessed Jul. 11, 2023).

[12] F. Illuzzi and H. Thewissen, “Perfluorocompounds emission reduction by the semiconductor industry,” *Journal of Integrative Environmental Sciences*, vol. 7, no. sup1, pp. 201–210, Aug. 2010. doi:10.1080/19438151003621417

[13] R. Conniff, “The greenhouse gas that nobody knew,” Yale Environment 360, https://e360.yale.edu/features/the_greenhouse_gasthat_nobody_knew (accessed Aug. 13, 2023).
[14] B. Glocker, B. Aburass, C. C. Cheng, and N. H. Guo, “A plasma scrubber as exhaust gas pou abatement system,” ISPC 19, https://www.ispc-conference.org/ispcproc/papers/173.pdf (accessed Jul. 11, 2023).
[15] “Aeris-G Plasma Abatement System,” Applied Materials, https://www.appliedmaterials.com/eu/en/product-library/aeris-g-plasma-abatement-system.html (accessed Jul. 10, 2023).
[16] Edwards, “Proteus Edwards,” Edwards, https://www.edwardsvacuum.com/en-us/our-markets/semiconductor-and-electronics/abatement/proteus (accessed Jul. 10, 2023).
[17] P. Belton, “The Computer Chip Industry Has a Dirty Climate Secret,” Earth Island Journal, https://www.earthisland.org/journal/index.php/articles/entry/computer-chip-industry-dirty-climate-secret/#:~:text=Energy%20consumption%20accounts%20for%2062,building%20in%20the%20Taiwan%20Strait (accessed Jul. 10, 2023).
[18] B. Gopalakrishnan, Y. Mardikar, and D. Korakakis, “Energy Analysis in semiconductor manufacturing,” *Energy Engineering*, vol. 107, no. 2, pp. 6–40, Feb. 2010. doi:10.1080/01998591009709867
[19] “Industrial Sector Energy Consumption - U.S. Energy Information ...,” EIA, https://www.eia.gov/outlooks/ieo/pdf/industrial.pdf (accessed Jul. 17, 2023).
[20] R. F. Ward, “A surge in chip fabs could make renewable energy targets harder to reach,” Times Union, https://www.timesunion.com/news/article/microchip-fabs-climate-goals-renewable-electricity-17681352.php (accessed Jul. 10, 2023).
[21] “US Electricity Profile 2021,” EIA, https://www.eia.gov/electricity/state/ (accessed Jul. 10, 2023).
[22] R. Patton and S. Wiese, “Worldwide Fab Energy Survey Report,” EPRICSG, https://www.epri.com/research/products/TR-113499 (accessed Jul. 10, 2023).
[23] M. S. Branham, “Semiconductors and sustainability : energy and materials use in integrated circuit manufacturing,” DSpace@MIT, http://hdl.handle.net/1721.1/46056 (accessed Jul. 10, 2023).
[24] K. Derbyshire, “Saving energy in the fab,” Semiconductor Engineering, https://semiengineering.com/saving-energy-in-the-fab/ (accessed Jul. 10, 2023).
[25] S.-C. Hu and J.-M. Tsao, “A comparative study on energy consumption for HVAC systems of high-tech fabs,” *Applied Thermal Engineering*, vol. 27, no. 17–18, pp. 2758–2766, Dec. 2007. doi:10.1016/j.applthermaleng.2007.03.016
[26] M.-S. Jo, J.-H. Shin, W.-J. Kim, and J.-W. Jeong, “Energy-saving benefits of adiabatic humidification in the air conditioning systems of semiconductor cleanrooms,” *Energies*, vol. 10, no. 11, p. 1774, 2017. doi:10.3390/en10111774
[27] S. Chen, F. Weig, and A. Gautam, “Bringing energy efficiency to the FAB,” McKinsey & Company, https://www.mckinsey.com/~/media/mckinsey/dotcom/client_service/operations/pdfs/bringing_fabenergyefficiency.ashx (accessed Jul. 12, 2023).
[28] A. Peters, “Inside Tesla’s 100% renewable design for the Gigafactory - fast company,” Fast Company,

https://www.fastcompany.com/90334858/inside-teslas-100-renewable-design-for-the-gigafactory (accessed Jul. 11, 2023).
[29] IEA, “The Future of Hydrogen,” IEA, https://www.iea.org/reports/the-future-of-hydrogen (accessed Jul. 10, 2023).
[30] The Economist, Taiwan’s dominance of the chip industry makes it more important, https://www.economist.com/special-report/2023/03/06/taiwans-dominance-of-the-chip-industry-makes-it-more-important (accessed Jul. 13, 2023).
[31] Y. Lee, N. Shirouzu, and D. Lague, “Taiwan chip industry emerges as a battlefront in u.s.-china showdown,” Reuters, https://www.reuters.com/investigates/special-report/taiwan-china-chips/ (accessed Jul. 10, 2023).
[32] K. Chen, “Taiwan Renewable Energy Market,” International Trade Administration | Trade.gov, https://www.trade.gov/market-intelligence/taiwan-renewable-energy-market#:~:text=Taiwan%27s%20booming%20renewables%20market%20creates,%E2%80%9Cnuclear%2Dfree%20homeland%E2%80%9D (accessed Jul. 11, 2023).
[33] A. Tsai, “TSMC’s push toward green energy,” Taipei Times, https://www.taipeitimes.com/News/editorials/archives/2020/07/17/2003740051 (accessed Jul. 11, 2023).
[34] Nuclear Energy Institute, State Electricity Generation Fuel Shares, https://www.nei.org/resources/statistics/state-electricity-generation-fuel-shares (accessed Jul. 13, 2023).
[35] R. Meyer, “Carbon Tax, Beloved Policy to Fix Climate Change, Is Dead at 47,” The Atlantic, https://www.theatlantic.com/science/archive/2021/07/obituary-carbon-tax-beloved-climate-policy-dies-47/619507/ (accessed Jul. 25, 2023).
[36] D. D. Campt, “Pesticide Regulation (PR) NOTICE 93-4,” EPA, https://www.epa.gov/pesticide-registration/prn-93-4-ban-aerosol-products-containing-cfcs-and-hcfcs-under-clean-air-act (accessed Jul. 29, 2023).
[37] “Office of Energy Efficiency & Renewable Energy,” Energy.gov, https://www.energy.gov/eere/office-energy-efficiency-renewable-energy (accessed Jul. 17, 2023).
[38] “About the Renewable Energy Target,” The Clean Energy Regulator, https://www.cleanenergyregulator.gov.au/RET/About-the-Renewable-Energy-Target (accessed Jul. 17, 2023).
[39] “Lessons from Germany,” Clean Coalition.org, https://clean-coalition.org/feed-in-tariffs/lessons-from-germany/ (accessed Jul. 17, 2023).