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Cleaner Chips: Decarbonization in Semiconductor Manufacturing

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Abstract: The growth of the information and communication technology sector has vastly accelerated in recent decades because of advancements in digitalization and Artificial Intelligence (AI). Scope 1, 2, and 3 greenhouse gas emissions data of the top six semiconductor manufacturing companies (Samsung Electronics, Taiwan Semiconductor Manufacturing Corporation, Micron, SK Hynix, Kioxia, and Intel) were gathered from the publicly accessible Carbon Disclosure Project's (CDP) website for 2020. Scope 3 emissions had the largest share in total annual emissions with an average share of 52%, followed by Scope 2 (32%) and Scope 1 (16%). Because of the absence of a standardized methodology for Scope 3 emissions estimation, each company used different methodologies that resulted in differences in emissions values. An analysis of the CDP reporting data did not reveal information on strategies implemented by companies to reduce Scope 3 emissions. The use of renewable energy certificates had the largest effect on decarbonization centered on reducing Scope 2 emissions, followed by the deployment of perfluorocarbon reduction technologies to help reduce Scope 1 fugitive emissions. Technology-specific marginal abatement costs of CO_2 were also estimated and varied between −416 and 12,215 USD/t CO_2 eq., which primarily varied depending on the technology deployed.

Keywords: life cycle analysis; semiconductor manufacturing; marginal abatement cost curves; sustainability assessments; decarbonization levers of semiconductor manufacturing; information and communication technology

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Citation: Nagapurkar, P.; Nandy, P.; Nimbalkar, S. Cleaner Chips: Decarbonization in Semiconductor Manufacturing. *Sustainability* **2024**, *16*, 218. https://doi.org/10.3390/su16010218

Academic Editors: Jose Vicente Abellan-Nebot and Carlos Vila-Pastor

Received: 27 October 2023
Revised: 30 November 2023
Accepted: 13 December 2023
Published: 26 December 2023

1. Introduction

The Paris Agreement's goal of limiting average global temperature rise by 1.5 °C from the pre-industrial level is facing unprecedented challenges as the GHG emissions level in the atmosphere keeps rising, recording the highest monthly temperature ever recorded for July in 2023, as per the United in Science 2023 report released by the United Nations (UN) [1]. To reduce the emissions, contributions are needed from all industrial sectors to reduce their greenhouse gas (GHG) emissions, including the electronics manufacturing sector.

The electronics industry has a considerable CO_2 footprint; the sector's GHG emissions amounted to approximately 1.8–2.8% of the total global GHG emissions in 2020 [2]. The growth of the information and communication technology (ICT) sector has accelerated tremendously in recent decades because of advancements in digitalization and AI. This has raised concerns about the high energy use during the manufacturing phase and adverse environmental impact. The growth of the ICT sector has resulted in GHG emissions increasing by nearly 20% every decade since 2002 [2]. In 2030, the ICT sector is forecasted to consume nearly 7% of global energy [3].

Hardware manufacturing of ICT has increasingly dominated the carbon footprint relative to the use phase over the past decade. For an iPhone 13, the hardware manufacturing phase accounted for 81% of the total product's CO_2 footprint, whereas only 16% of emissions resulted from its use phase [4]. Within the hardware, the manufacturing of semiconductors such as NAND memory (Not And), DRAM (dynamic random-access memory), and microprocessor units (MPUs) can have considerable emissions during the entire life cycle of the ICT product. For instance, over the entire life cycle stages of Apple Products from manufacturing, transport, use, and recycling, the manufacturing stage of integrated circuits (ICs) (e.g., CPUs, DRAM, NAND) accounts for nearly one third of Apple's GHG emissions [3].

Only a few published studies have analyzed the environmental impact of semiconductor manufacturing, for several reasons. First, the semiconductor industry is extremely complex and constantly evolving due to a myriad of different semiconductor ICs that differ in their manufacturing process, end-use application, and technology node. Second, the number of transistors per unit area of ICs doubled every 1.4–2.7 years between 1960 and 2020 [5], resulting in ICs becoming smaller, faster, and more efficient during use-phase power consumption with every new generation of ICs. However, this rapid change in products significantly influences the materials and energy consumption of the IC manufacturing process, thereby affecting the life cycle analysis (LCA) and environmental impact. A previous study showed that the manufacturing energy demand of a DRAM has nearly doubled from 2004 to 2020 for node evolution from 110 to 14 nm [6].

The studies summarized in Table 1 focused on process-based granular LCAs. A macro-level analysis of the semiconductor manufacturing process is needed and can be particularly useful and may possess GHG emissions data as reported by respective semiconductor companies after the company's own in-depth internal sustainability audits and reviews. Furthermore, existing studies do not report the decarbonization efforts currently undertaken by these major companies, nor do they estimate the costs of the actual implementation of decarbonization strategies. Such cost information is extremely valuable because it is eventually the main factor that influences the decarbonization strategy's implementation at the commercial scale. The present study overcomes the shortcomings of the aforementioned studies through the following objectives:

- Gather and analyze GHG data of the top six semiconductor companies from the publicly available emissions data for Scope 1, 2, and 3 emissions;
- Analyze the measures implemented by each company in mitigating their CO_2 emissions via four decarbonization strategies—energy efficiency; industrial electrification; low-carbon fuels, feedstocks, and energy sources (LCFFES); and carbon capture, utilization, and storage (CCUS)—and examine each strategy's impact on decarbonization;
- Estimate CO_2 abatement costs in terms of US dollars per metric ton of abated CO_2 eq. for each decarbonization measure adopted by the six semiconductor manufacturing companies.

The remainder of this paper is organized as follows. Section 2 presents the modeling efforts. Section 3 discusses the results, along with limitations and future work recommendations. Section 4 presents the conclusions of this work.

Table 1. Studies focusing on LCAs in the semiconductor industry.

Reference	Process	Functional Unit	LCA Method Used	Conclusion
[7]	Wafer manufacturing, processing, assembly, and packaging to final products	Semiconductor products	Process-based	Intel's semiconductor product emissions are dominated by the use phase at 90% of total Scope 1, 2, and 3 emissions, followed by operations (6%), supply chain (2%), logistics (1%), and others (1%).
[8]	Wafer fabrication	8 in. wafer in the DDR SDRAM production	Process-based	Global warming potential arose due to large electricity use and perfluorocarbon emissions of thin film processes
[9]	Wafer fabrication	Digital logic chips	Process-based	Life cycle impacts are driven by electricity in the use phase and direct emissions from wafer fabrication processes.
[10]	Wafer assembly	Ball grid array package, chip-scale package	Process-based	Silicon dies dominated CO_2 eq. emissions for ball grid array packages. The introduction of wafer chip-scale packaging technology implies a significant environmental footprint reduction.
[11]	Raw material extraction, wafer fabrication	Wafers: 150, 200, or 300 mm	Process-based	Six regression models were developed to estimate the carbon footprint of wafers. Key parameters that affected emissions were mask layer, metal layer, and technology node.
[12]	Raw material acquisition, wafer fabrication, transport, assembly	Embedded nonvolatile memory (eNVM) for technology nodes 40, 30, and 20 nm	Process-based	Electricity use had the highest environmental impact on climate change and particulate matter. Wafer manufacturing had the highest impact on water resources, and tantalum for minerals and metals.

2. Methodology

2.1. Overview of Scope 1, 2, and 3 Emissions

As per the Greenhouse Gas Protocol [13], Scope 1 emissions are the direct emissions produced from the IC manufacturing or assembly facility including perfluorocarbons (PFCs) being emitted during the etching process as fugitive emissions. Scope 2 emissions are indirect emissions from the purchase of energy such as electricity, heating, or cooling. Scope 3 emissions of semiconductor manufacturing can be classified into two categories: upstream and downstream emissions from the semiconductor manufacturing facility. It is grouped into 15 different categories, including purchased goods (e.g., silicon wafer, nitrogen) and capital goods (e.g., equipment used for deep ultraviolet lithography, dry etching, and chemical vapor deposition). An overview of Scope 1, 2, and 3 emissions of the semiconductor industry are illustrated in Figure 1.

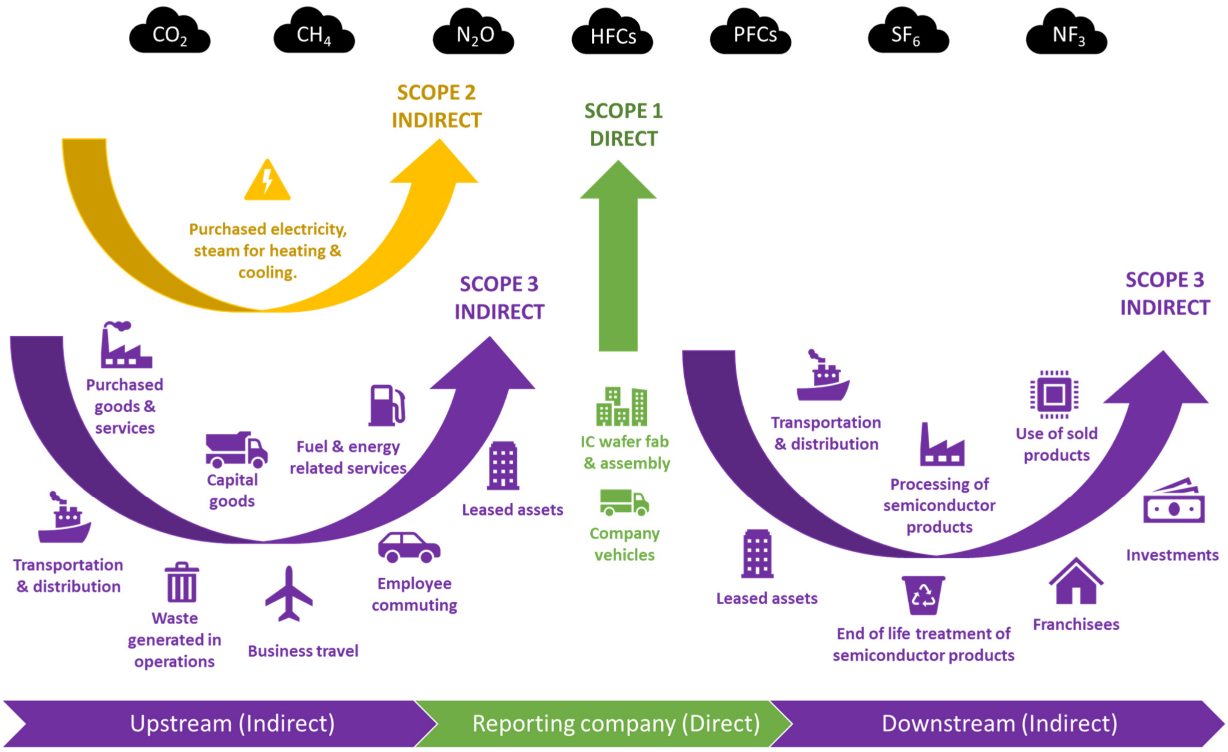

Figure 1. Overview of Scope 1, 2, and 3 emissions of the semiconductor industry [14].

2.2. Methodology for Analyzing GHG Emissions for the Top Six Semiconductor Manufacturing Companies

GHG emissions data of the top six semiconductor manufacturing companies—Samsung Electronics, Taiwan Semiconductor Manufacturing Corporation (TSMC), Micron, SK Hynix, Kioxia, and Intel—were gathered from the publicly accessible Carbon Disclosure Project's (CDP's) website [15]. The CDP is a private, not-for-profit, international organization that solicits environmental impact reporting data from companies around the world voluntarily. As of 2022, more than 18,000 companies annually report their environmental data on GHG emissions, lost forest cover, and water use data to CDP. Based on these data, CDP grades each reporting company on three environmental metrics: climate change, forests, and water security. Since most of the largest semiconductor companies (e.g., TSMC, Samsung Electronics) are located outside the United States, global CO_2 emissions data were gathered from the CDP reports and subsequently analyzed. The sustainability reports of the companies were also referred to gather additional insights.

Unlike the US Environmental Protection Agency, which has a mandatory reporting requirement only for facilities within the United States that emit more than 25,000 metric tonnes (MT) CO_2 eq. [16], the CDP does not have any such mandatory requirement concerning facility size or location. However, the CDP's data is extremely valuable as it allows companies to identify climate risks, compare emissions performance with peers, and meet stakeholder expectations.

The voluntary reporting framework allows organizations to publicly disclose the sustainability and ethical performance of their operation. These frameworks provide a uniform, transparent approach to reporting and evaluating an organization's performance, practices, climate risks, and opportunities. Since sustainability reporting is still at its nascent stage, what information is reported relies on a standard-setting body and the discretion of the reporting organization. Third-party verification of sustainability data is at a very early stage, so in some cases the data reported might be misleading and incomplete. Advanced technology gives companies new tools for measuring and monitoring their environmental impact such as advanced sensors, data analytics platforms, and real-time measuring devices.

However, there is a lack of understanding of methods to quantity GHG emissions from their operations, particularly arising from Scope 3. There are multiple sustainability reporting standards, emissions reduction initiatives, frameworks, and guidelines around the world, which can make sustainability reporting a complex and repetitive process. Organizations can choose to report to one or multiple frameworks and are in line with the Global Reporting Initiative (GRI) with specific reference to the Sustainability Accounting Standards Board (SASB) and the United Nations Sustainable Development Goals.

GRI allows businesses, governments, and other organizations to understand and communicate their impacts on issues such as climate change. GRI is intended as a guide for developing company-specific sustainability reports. The Task Force on Climate-related Financial Disclosures (TCFD) is a voluntary reporting framework that allows organizations to report climate-related financial disclosure. TCFD provides transparency on the financial risk associated with climate change. Carbon Disclosure Project (CDP) is a global nonprofit focused on motivating and supporting companies to measure and disclose their environmental impacts. In this work, the CDP framework was chosen as it houses the largest environmental database in the world, with 18,000+ reporting companies in 2022 due to the framework's alignment with other global initiatives such as Science-based Targets Initiative (SBTi) and TCFD [15].

The methodology used in this work is outlined in Figure 2. In the initial steps, the Scope 1, 2, and 3 emissions data were gathered from CDP for the top six semiconductor companies. The top six semiconductor companies were selected based on the global wafer manufacturing capacities of these companies in 2020. The emissions data were then analyzed to estimate CO_2 abatement cost and marginal abatement cost curves (MACCs) were developed for each company.

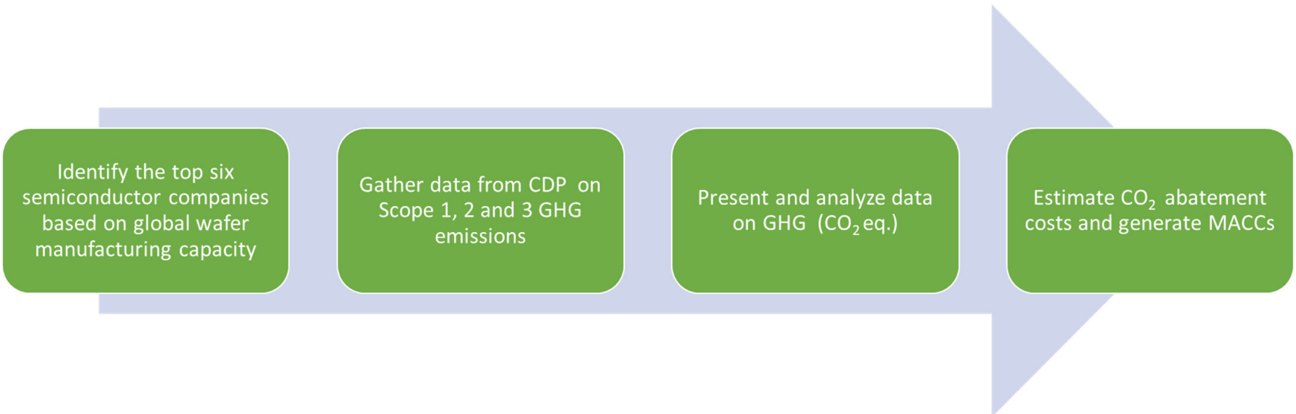

Figure 2. Methodology for analyzing GHG emissions for the top six semiconductor companies.

2.3. Global Annual Installed Wafer Manufacturing Capacity in 2020

There are thousands of semiconductor companies spanning four stages of semiconductor manufacturing—silicon wafer manufacture, IC manufacture comprising of production, assembly, and use phase—as depicted in Figure 3. These four phases of IC manufacturing have different carbon intensities with Steps 1, 2, and 3 accounting for the highest GHG emissions. To realize the high impact of IC manufacturing on energy and environmental footprint, this work targeted only the top six semiconductor manufacturing companies that together possessed nearly 58% of the global share of wafer manufacturing capacity in 2020 (i.e., 145 million wafers in 200 mm wafer-size equivalents) [17]. These six companies were Samsung Electronics, TSMC, Micron, SK Hynix, Kioxia, and Intel. Samsung Electronics, headquartered in South Korea, had the largest share of installed wafer capacity globally at 14.7% in 2020, followed by TSMC (13.1%), Micron (9.3%), SK Hynix (9.1%), Kioxia (7.7%), and Intel (4.3%).

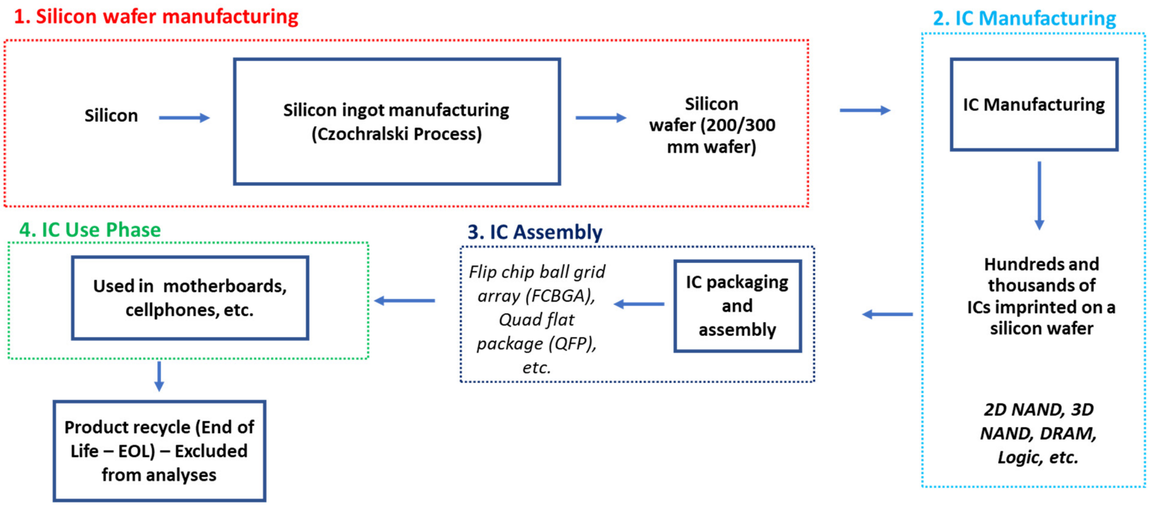

Figure 3. The four stages of IC manufacturing.

The global wafer manufacturing capacity of these companies has been illustrated in Figure 4. According to the gathered data, South Korea-headquartered companies (i.e., Samsung Electronics, TSMC, and SK Hynix) possessed the largest share (~36.9%) in global installed wafer manufacturing capacity in 2020, followed by US-headquartered companies (i.e., Intel and Micron) at 13.6%, and Japan-headquartered companies (i.e., Kioxia) at nearly 7.7% [17]. Not all the wafer manufacturing facilities operate at 100% capacity; a typical value for actual production in 2021 would be nearly 80% of installed wafer capacity, and some facilities operate at as high as 90–100%, depending on market demand [18].

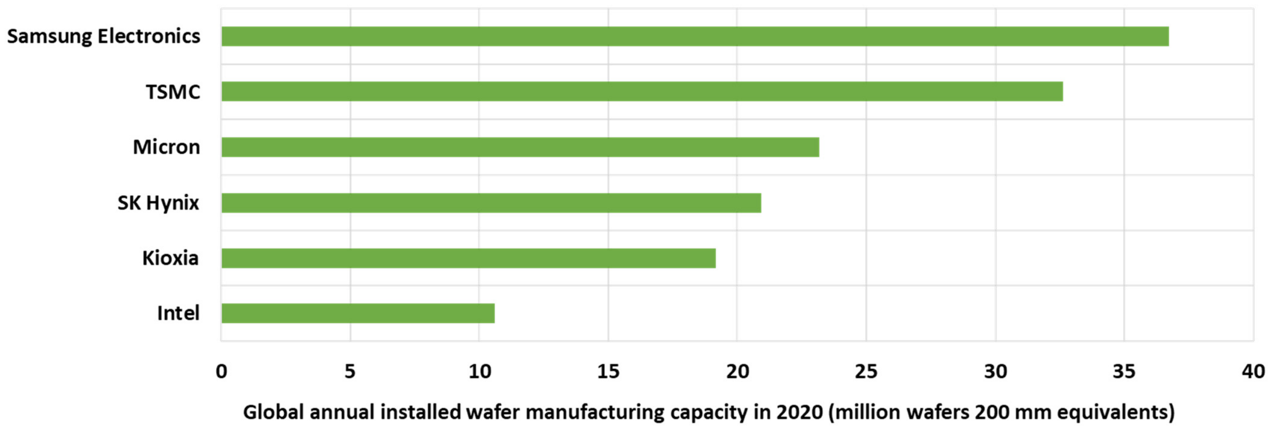

Figure 4. Global installed wafer capacity by the top six semiconductor manufacturing companies in 2020 [17].

2.4. Information on the Six Companies Analyzed in this Study

Information on the six companies was gathered from company websites and is provided in Table 2. Information regarding each company's headquartered location, semiconductor products, and global revenue for 2021 is provided in Table 2. The headquartered location can be different from the product manufacturing location, and the electricity grid mix of the country where products are manufactured can affect the company's GHG emissions. For instance, Intel, headquartered in the United States, has three IC manufacturing facilities within the United States, but four of its manufacturing facilities are outside the United States (in Ireland, Israel, and China). Furthermore, Intel has only one IC assembly facility located in the United States and six outside the United States (in China, Costa Rica, Malaysia, and Vietnam) [19].

Table 2. Information on the six companies analyzed in this work.

Company	Headquartered City, Country	Product Scope in CDP Emissions Data	Global Revenue in 2021
Samsung Electronics	Suwon, South Korea	Electronics sector for digital media, semiconductors, mobile phones, refrigerators, washers, dryers, etc.	USD 81 billion [20]
TSMC	Hsinchu, Taiwan	Central processing units, graphics processing units, chip sets, embedded processors, network interface controllers, etc.	USD 49 billion [21]
Micron Technology	Boise, ID, USA	Memory semiconductors such as DRAM, SSD, NAND flash, and DDR4 SDRAM	USD 27.7 billion [22]
SK Hynix	Icheon, South Korea	DRAM, NAND flash, etc.	USD 37 billion [20]
Kioxia	Tokyo, Japan	3D NAND, SSD, etc.	USD 13.4 billion [20]
Intel	Santa Clara, CA, USA	Central processing units, motherboard chip sets, systems on a chip, SSDs, etc.	USD 79 billion [23]

The manufacturing facility location can considerably affect GHG emissions, particularly Scope 2 emissions (because of electricity and steam), as the electricity grid mix can differ considerably from country to country. For instance, in the case of Ireland where Intel's wafer fabrication facility is located, the country has an average grid emission factor of 0.33 kg CO_2/kWh, which is 60% lower than the average grid emission factor of China [24]. Therefore, Scope 2 emissions estimated for a facility in Ireland would be considerably different from those estimated for a facility in China for an identical manufacturing facility. However, such disaggregated emissions data by location of a specific IC manufacturing or assembly facility were not reported by companies through their sustainability reports, nor via CDP, and are therefore beyond the scope of this study.

Despite the absence of country-specific disaggregated data in the CDP database by individual fabrication and assembly facilities, two layers of data disaggregation do exist, as illustrated in Figure 5. In the first layer, the global CO_2 emissions data were divided into three categories: Scope 1, 2, and 3 emissions. In the second layer, the emissions data were further divided by region (Scope 1 and 2), pollutant category (Scope 1), fabrication vs. assembly emissions (Scope 2), or emission category (Scope 3), as shown in Figure 5.

2.5. Decarbonization Pillars of Industrial Decarbonization

The US Department of Energy identified four pillars of industrial decarbonization—energy efficiency, industrial electrification, LCFFES, and CCUS—to reduce CO_2 emissions [25]. Energy efficiency pertains to reducing emissions via energy performance improvements to equipment, machines, processes, and building operations. Industrial electrification lever relates to substituting existing fossil fuel combustion technologies with technologies that utilize electricity thereby leveraging advancements in low carbon electricity from the grid and on-site generation sources. Examples of electrotechnologies include the deployment of heat pumps, microwaves, and infrared technologies for process heating.

In the LCFFES pillar, emissions could be reduced by substituting fossil fuel feedstocks with low carbon feedstocks or renewable energy sources such as solar, wind including renewable energy certificates (RECs), biofuels, concentrating solar power, nuclear, and alternative sources of hydrogen, such as using electrolyzers instead of conventional steam methane reforming. CCUS pillar comprises a variety of technologies that capture CO_2 before it enters the atmosphere such as post- or pre-combustion CO_2 capture from high-concentration gas streams emanating from industries or utilization of captured CO_2 into products. In this work, the measures implemented by each company in abating their CO_2 emissions are categorized into the four decarbonization pillars to analyze each pillar's impact on decarbonization. It should be noted that the decarbonization pillars presented through this work were focused only on abating Scope 1 and 2 emissions while excluding Scope 3 emissions as the CDP data did not report any abatement measures that focused on reducing Scope 3 emissions.

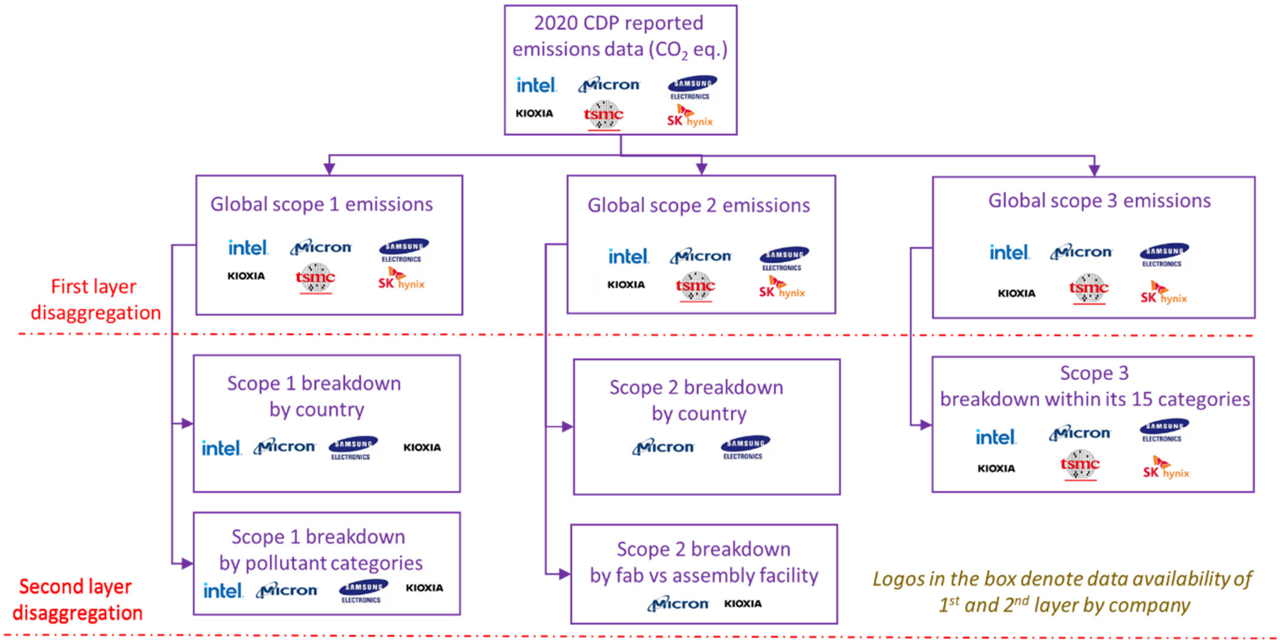

Figure 5. Breakdown and methodology of disaggregating CDP data.

The magnitude and therefore the significance of Scope 3 emissions depend on the industry under consideration. For instance, some industry sectors such as cement, steel, etc., may possess Scope 3 emissions share of emissions as low as 17% with the majority of emissions attributed to Scope 1 or 2. However, for other industry sectors such as construction, metals, mining, etc., the Scope 3 emissions share can be as high as 92%. Overall, a 2021 analysis performed by CDP for 15 different industry sectors such as agricultural commodities, capital goods, cement, chemicals, coal, construction, electric utilities, financial services, food–beverage–tobacco, oil–gas, paper–forestry, steel, etc., found that Scope 3 emissions account, on average, for nearly 75% of total Scope 1 + 2 + 3 emissions [26]. This indicates that Scope 3 emissions can be a significant contributor to total emissions far exceeding Scope 1 or 2.

For semiconductor manufacturing, the Scope 3 emissions share was found to be as much as 42% in 2022. Scope 3 emissions could be more than 1/3 of a semiconductor manufacturing facility's emissions. Purchased goods category including silicon wafers, process gases (nitrogen, hydrogen, silane, etc.), metals (gold, aluminum, copper, etc.), chemicals (photoresists, solvents, epoxies, acids, etc.), ultrapure water, etc., together accounted for nearly 61% of total Scope 3 emissions as shown in Figure 6 [27]. A separate analysis by Mckinsey Inc. also revealed a similar finding that the share of purchased goods category within Scope 3 could be as high as 60% of total Scope 3 emissions as shown in Figure 7 [28]. The remaining 40% of Scope 3 emissions could be attributed to equipment maintenance (16%), facilities (7%), capital equipment (6%), and others (5%).

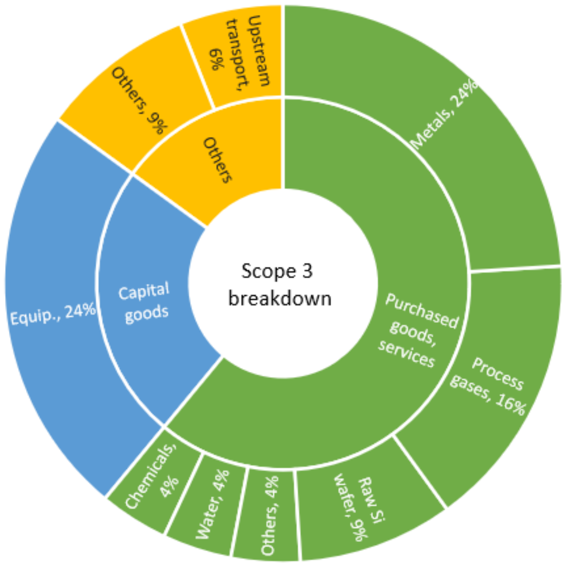

Figure 6. Breakdown of Scope 3 emissions for semiconductor companies [27].

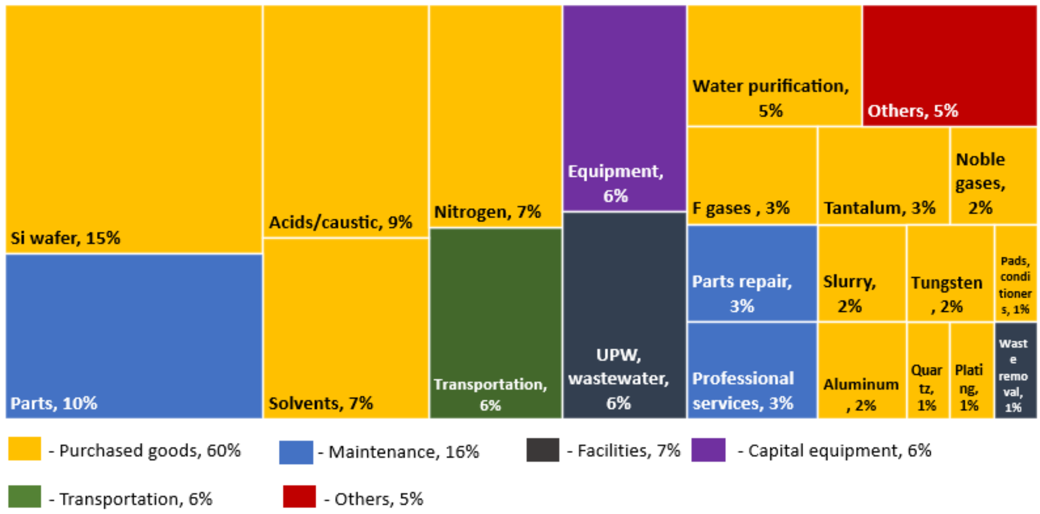

Figure 7. Breakdown of Scope 3 emissions for semiconductor companies [28].

2.6. Marginal Abatement Cost Curve (MACCs)

Marginal abatement cost curves (MACCs) are commonly used policy tools that aid in evaluating the economics of climate change mitigation options. MACC presents the CO_2 emissions abatement potential of each decarbonizing technological measure and its associated incurred expense or benefit. McKinsey & Co. presented MACCs for semiconductor manufacturing operations based on proprietary industry data [29]. Despite valuable insights, the report lacked transparency in assumptions, source data, and methodology used to develop the MACCs. The analysis presented average MACCs for a typical fabrication facility. However, each semiconductor company may implement different technological options for decarbonization depending on the manufacturing process, facility location, and end product type. This work overcomes those shortcomings and presents a unique MACC for each company based on actual implemented measures as self-reported by the publicly available CDP data. The following equation was used to calculate the marginal abatement cost for each semiconductor company [30]:

$$Marginal\ abatement\ cost\ of\ each\ technological\ option\left(\frac{\$}{MT\ abated\ CO_2\ eq.}\right) = \frac{-Net\ present\ value\ of\ each\ option(\$)}{Total\ GHG\ emissions\ abated\ over\ the\ lifetime\ of\ the\ option(MT\ CO_2\ eq.)}$$

Here,

$$Net\ present\ value = \frac{(Total\ project\ costs - Total\ project\ savings)}{(1 + discount\ rate)^{project\ lifetime}}$$

The financial data for project costs, savings, and lifetime, along with emissions values for each of the six companies analyzed in this study, were gathered from CDP data. A discount rate of 5% was assumed in this study to determine the net present value [31].

3. Results and Discussion

3.1. GHG Emissions of the Top Semiconductor Companies

The 2020 global emissions of CO_2 eq. for the six semiconductor companies are illustrated in Figure 8 according to the CDP data. The CDP data reported by these companies were not disaggregated by individual product type but were reported on a company level. Out of the six companies considered, Samsung Electronics had the highest CO_2 eq. emissions at 71.6 million metric tons (MMT) in 2020—approximately 4 to 12 times higher than the other companies. Kioxia had the lowest CO_2 eq. emissions at 3.4 MMT in 2020.

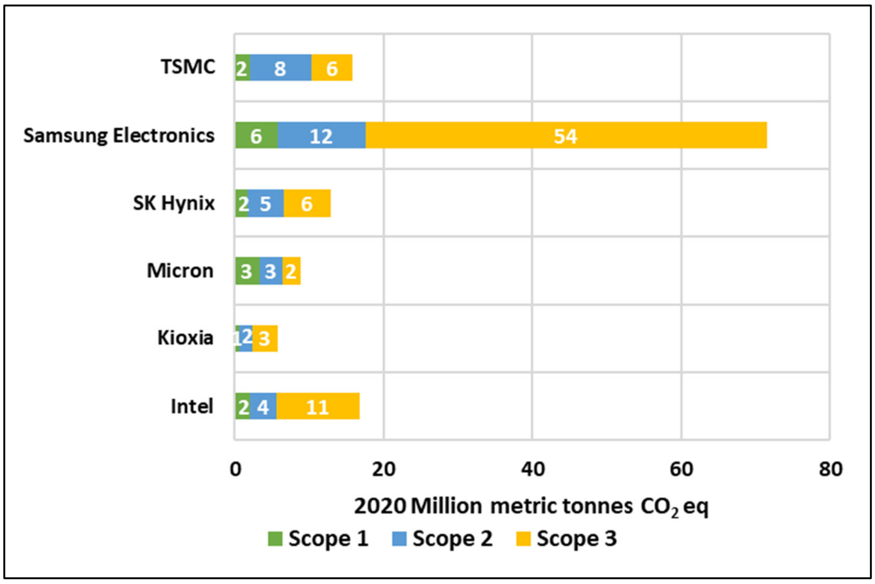

Figure 8. GHG emissions of the top six semiconductor manufacturing companies in 2020.

Samsung Electronics was expected to have high CO_2 eq. emissions likely due to their emissions were attributed not only to their semiconductor products (e.g., processors, DRAMs) but also to other electronic products, such as washers, dryers, and refrigerators, that may possess higher emissions than semiconductor products. For example, the manufacturing emissions of a typical refrigerator could be 326 kg CO_2 eq. [32], whereas those of a typical complementary metal-oxide semiconductor (CMOS) logic die could be only 1 kg CO_2 eq. [9]. By including these additional products within the company's product scope, the CO_2 eq. emissions of Samsung Electronics could be higher than other companies.

The exact causes of GHG emissions are difficult to ascertain because a company's emissions may depend on a variety of factors, such as the number of manufactured products, manufacturing technology, pollutant abatement technology, and manufacturing location (especially considering the local electricity grid mix). However, owing to the absence of such granular data within the CDP database and publicly available databases, the exact reasons cannot be ascertained. Despite this lack of data availability, the total emissions data of the companies are enormously valuable because they enable a macro-level comparison of GHG emissions across companies.

Another merit of the macro-level CDP data is that they provide insight into the breakdown of total emissions among Scope 1, 2, and 3 categories. As shown in Figure 8, Scope 3 had the largest share in total annual emissions, with an average share of 52%, followed by Scope 2 (32%) and Scope 1 (16%). In this work, the supply chain emissions, i.e., Scope 3 far exceeded the direct and indirect emissions (Scope 1 and 2) of the companies. In 2022, McKinsey & Co. also concluded on a similar note that Scope 2 and 3 could comprise nearly 65% of the total semiconductor manufacturing facility's emissions, while the remaining 35% could be attributed to direct Scope 1 emissions [29]. NXP also determined that the majority of their total emissions in 2022 (54%) were attributed to indirect emissions of purchased electricity (Scope 2), followed by PFC emissions (34%), heat transfer fluids (5%), and other emissions (7%) [33]. This finding reveals a valuable insight that indirect emissions (Scope 2, 3) may possess a relatively larger environmental impact than direct (Scope 1) emissions for these semiconductor companies thereby constituting an environmental hotspot.

3.2. Scope 1 Emission Analysis

The Scope 1 emission of semiconductor manufacturing depends on various factors, such as manufacturing process, chemicals, and materials used in the process; abatement technologies deployed; generation of fluorinated chemicals; the number of fluorinated gas steps; and waste management practices for solvents and chemicals. The data for Scope 1 emissions by different companies revealed that Samsung Electronics possessed the largest share of total Scope 1 emissions at 37%, followed by Micron (21%), TSMC (13%), Intel (13%), SK Hynix (11%), and Kioxia (4%). This trend was similar to the trend observed for total CO_2 eq. emissions of all companies, as shown in Figure 9. Additionally, the CDP data also presented a breakdown between Scope 1 emissions by eight pollutant types: CO_2, CH_4, N_2O, hydrofluorocarbons (HFCs), PFCs, SF_6, NF_3, and other heat transfer fluids (HTFs). TSMC and SK Hynix did not provide a breakdown of Scope 1 emissions data, so they were excluded from Figure 9.

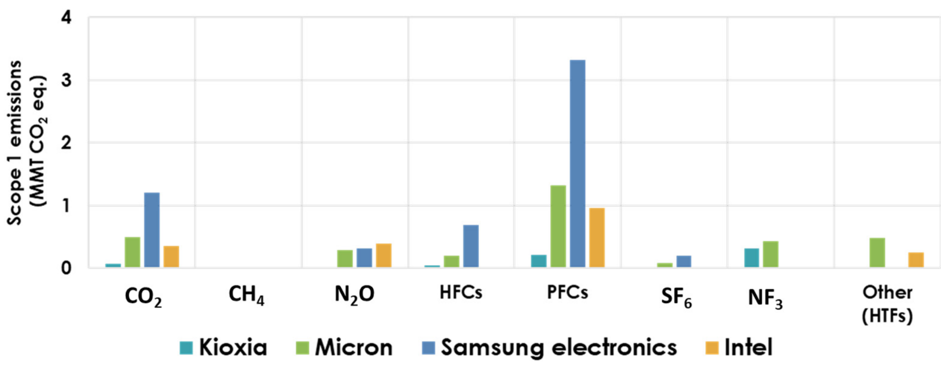

Figure 9. Breakdown of Scope 1 emissions for Kioxia, Micron, Samsung Electronics, and Intel in 2020.

The Scope 1 emissions profile was dominated by PFCs at an average share of 45% within total Scope 1 emissions, followed by CO_2 (16%), NF_3 (15%), N_2O (9%), other HTFs (7%), HFCs (6%), and SF_6 (2%). One of the reasons why PFCs dominated CO_2 eq. emissions could be their extremely high global warming potentials—approximately 6290–11,100 times that of CO_2, and with long lifetimes in the atmosphere (2000–50,000 years) [34]. PFCs are synthetic chemicals such as CF_4, C_2F_6, C_3F_8, C_4F_8, C_5F_8, NF_3, and SF_6; they have unique properties of hydrophobicity and oleophobicity, so they are used as etching gases to etch submicron circuit patterns on metal and dielectric layers of ICs [35]. They are also used to clean internal chambers of chemical vapor deposition equipment. Analysis of CDP data of Kioxia, Micron, Samsung Electronics, and Intel revealed that Samsung Electronics had the largest share of PFC emissions at 57%, and Kioxia had the lowest share at 4%, as shown in Figure 9. Micron and Intel also possessed considerable total PFC emission shares at 23% and 16%, respectively.

3.3. Regional Breakdown of Scope 1 Emissions

A regional breakdown of Scope 1 emissions was also provided within the CDP data for Kioxia, Micron, Samsung Electronics, and Intel, as shown in Figure 10. For Kioxia, all the Scope 1 emissions were in Japan because all the company's facilities are situated there. However, Intel has 15 fabrication facilities located in more than 10 countries, so its Scope 1 emissions were distributed around the world. Therefore, even though Intel is headquartered in the United States, the largest share of its Scope 1 emissions was in China at 41%, followed by the United States (38%), Ireland (9%), Israel (7%), Malaysia (2%), Vietnam (2%), and others (1%). Similarly, even though Micron is headquartered in the United States, the US share in total Scope 1 emission was only 15%, and the largest shares were attributed to Singapore (41%) and Japan (32%), likely because of the high wafer fabrication production capacity in those countries.

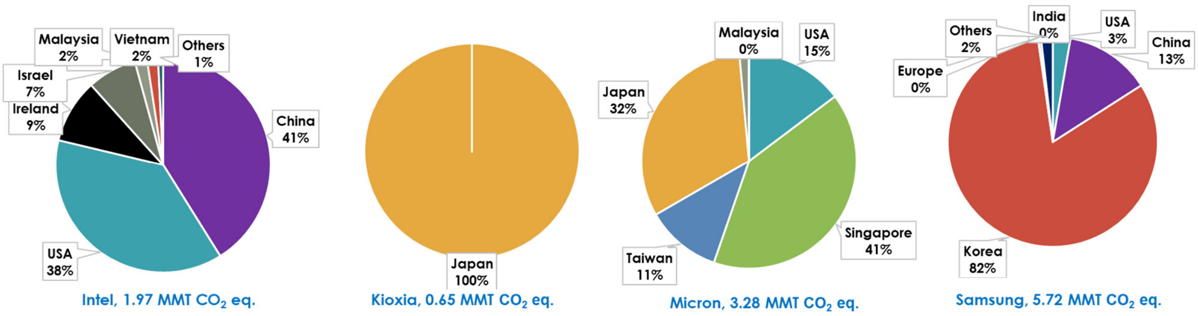

Figure 10. Regional breakdown of Scope 1 emissions for Intel, Kioxia, Micron, and Samsung Electronics in 2020.

Global distribution of Scope 1 emission was expected for US-headquartered companies. This is because in 2020 only 12% of the global semiconductor manufacturing capacity is located in the US while the remaining capacity is located in Taiwan (22%), South Korea (21%), Japan (15%), China (15%), Europe (9%), and others (7%), in descending order [36]. For Samsung Electronics (a South Korea-headquartered company), the analysis of CDP data revealed that 82% of the company's Scope 1 emission originated from South Korea, likely because of the larger presence of wafer fabrication and assembly facilities in the same country.

3.4. Scope 2 Emissions Analysis

Scope 2 emissions of semiconductor manufacturing are indirect emissions related to purchases of electricity, steam, heating, and cooling. The Scope 2 emissions reported by the six companies could be reported via market-based and location-based metrics. Market-based emissions are estimated from emission factors derived from contractual agreements such as RECs, guarantees of origin, and other tradable certificates. Location-based emissions are estimated from emission factors of the local electricity grid from which electricity has been sourced [14].

Out of the six companies considered, Samsung Electronics had the highest location-based Scope 2 GHG emissions at 11.8 MMT CO_2 eq. in 2020, and the lowest emissions were attributed to Kioxia at 1.7 MMT CO_2 eq., as depicted earlier in Figure 8. The market-based Scope 2 emissions of semiconductor companies were observed to be 17% lower, on average, than their corresponding location-based emissions. This could be because of the incorporation of contractual agreements, such as RECs, which help them reduce Scope 2 emissions. REC is a market-based instrument that represents the environmental, social, and other non-power attributes of 1 MWh of renewable energy generated and delivered to the grid. RECs can be purchased through contractual agreements such as physical or virtual power purchase agreements. RECs are also generated when you have onsite generation. Market-based emissions accounting gives credit to companies that proactively purchase energy sources with lower emissions. On the other hand, location-based emission reflects the average grid mix based on location.

As stated earlier, the manufacturing facility location can considerably affect GHG emissions, particularly Scope 2 emissions (because of electricity and steam), as the electricity grid mix can differ considerably from country to country. Out of the six companies considered, only Micron and Samsung Electronics provided a breakdown of Scope 2 emissions (market based) within the CDP data, as depicted in Figure 11. For Samsung Electronics, most of the market-based Scope 2 emissions (87%) were attributed to South Korea, likely because the location of the company's facilities in that region led to the purchase of electricity and other utilities in the same region. This trend was similar to that observed for Scope 1 emissions as shown earlier in Figure 8. However, most of Micron's Scope 2 emissions (market based) were attributed to countries aside from the United States, such as Taiwan (49%), Singapore (22%), Japan (10%), and China (4%). Only a minor share was attributed to the United States (14%), which was similar to the share of Micron's scope 1 emissions (15%), as shown earlier in Figure 10. One of the reasons for lower Scope 2 emissions in the U.S. could be due to more advanced energy markets and the high availability of renewable energy products compared to other countries.

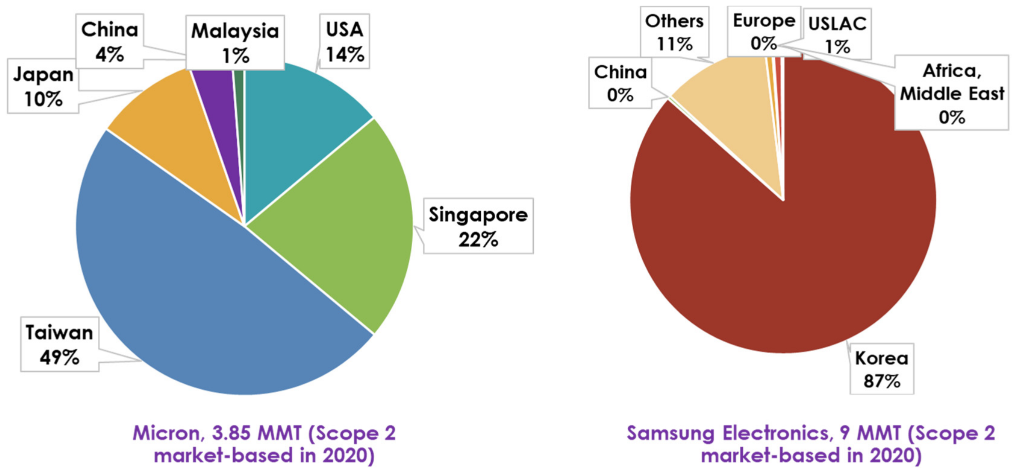

Figure 11. Breakdown of market-based Scope 2 emissions of Micron and Samsung Electronics in 2020.

Micron and Kioxia data also revealed that nearly all the market-based Scope 2 emissions were attributed to wafer fabrication facilities at an average of 93%, and the remaining share of 7% was attributed to assembly facilities. This was expected since wafer fabrication is a relatively more complex and more energy-intensive process than the wafer assembly process, as described in a study that stated the wafer manufacturing energy could be 4–13 times that of the wafer assembly's manufacturing energy [36].

3.5. Scope 3 Emissions Analysis

Scope 3 emissions are attributed to 15 categories, including purchased goods (e.g., silicon wafer, nitrogen) and capital goods (e.g., equipment used for deep ultraviolet lithography, dry etching, and chemical vapor deposition). As shown in Figure 12, for all six companies, purchased goods had the highest environmental impact; it possessed the largest share of total Scope 3 emissions at nearly 43% on average, followed by sold products (23%), sold products processing (14%), fuels (8%), capital goods (7%), downstream transportation (2%), and others (2%). Purchased goods include raw materials and chemicals purchased for semiconductor manufacturing, such as silicon wafers, photoresists, electronic gases, chemical mechanical planarization slurries, and process chemicals. The "others" category included emissions from employee commuting, upstream transportation and distribution, upstream leased assets, end-of-product life, and so on.

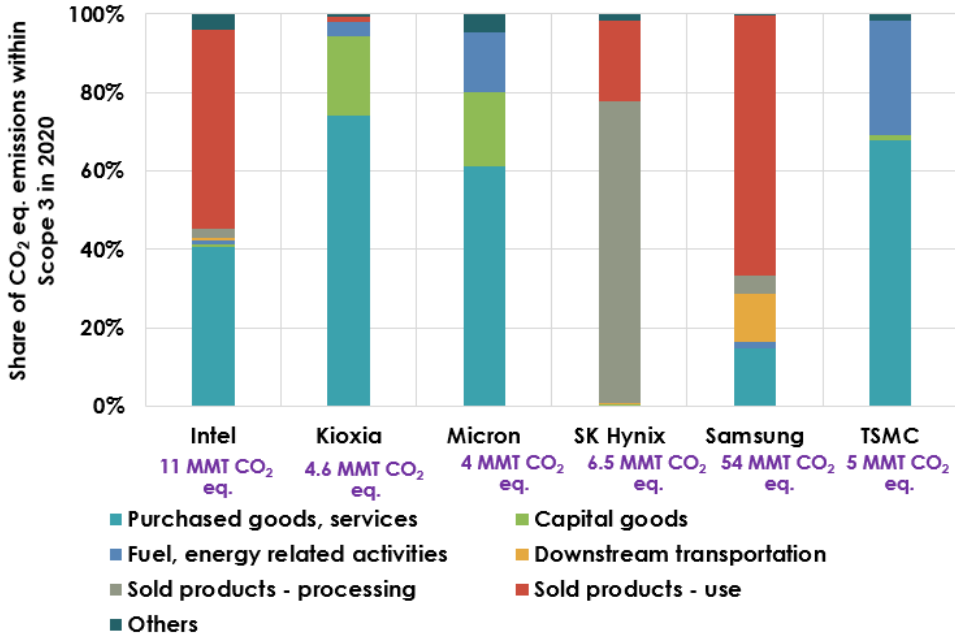

Figure 12. Breakdown of Scope 3 emissions for the six companies in 2020.

Because of the absence of a standardized methodology to estimate Scope 3 emissions, the six companies used different methodologies to determine emissions within each category. For instance, for the sold product processing category, Intel estimated the emissions based on the revenue of their top three customers and the respective customer's total Scope 1 and 2 emissions. SK Hynix estimated Scope 3 emissions based on average carbon intensity factors of semiconductors as provided by Japan Electronics and Information Technology Industries Association publications, Gartner market data on annual equipment data, and customer environmental product data. Samsung Electronics estimated Scope 3 emissions based on final product annual shipments and each product's emission factor as provided by Carbon Footprint Labeling of Korea Ministry of Environment.

Kioxia, Micron, and TSMC did not report emissions related to the processing of sold products because their products were not directly sold as finished end products and were classified as intermediate products. The data regarding these emissions for these companies was unknown. Their products are sold to other downstream companies that perform further product processing before the final sale. Similarly, Micron and TSMC also did not report the emissions within the use phase category of Scope 3 emissions alluding to factors such as lack of data and stating that their products are not directly sold as end products but are sold to other downstream companies for further processing before final sale. It should be noted that the omission of these emissions conforms with the Greenhouse gas' Scope 3 guidance Corporate Value Chain (Scope 3) Accounting and Reporting Standard [12] that states that if the companies are unable to estimate emissions within the following four Scope 3 categories of downstream transportation and distribution, sold products processing, sold products end use, and end-of-life treatment of sold products, the companies may exclude them if proper justification was to be provided. Since these products were classified as intermediate products. Since the emissions data were not available for the companies, the companies excluded them. Typically, Scope 3 emissions determination can be a challenging task because of its fragmented nature across the supply chain, data reliability and accuracy, standardized methodologies, uncertainties, and privacy issues in supplier data and estimation of carbon intensities of the products [37].

3.6. Decarbonization Levers of Semiconductor Manufacturing

The measures implemented by each company in abating CO_2 eq. emissions were categorized into the four decarbonization pillars to analyze the impact of each pillar on decarbonization. As indicated earlier, the measures were only limited to abating Scope 1 and 2 emissions. The CDP data did not report any abatement measures that focused on reducing Scope 3 emissions. The abated emissions by each decarbonization pillar for each of the six companies are illustrated in Figure 13.

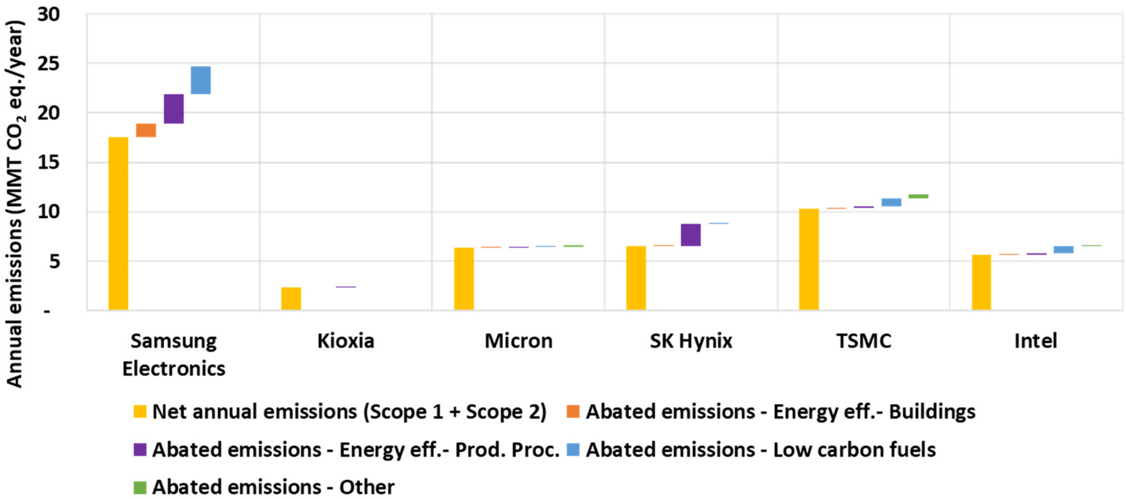

Figure 13. Net annual Scope 1 and 2 emissions of semiconductor manufacturing and abated emissions by decarbonization lever.

3.6.1. Energy Efficiency

Energy efficiency pertains to the reduction of emissions via energy performance improvements of equipment, processes, and building operations. Scope 1 and 2 emissions reductions could be achieved by improving energy efficiency for tools, equipment, cleanrooms, exhaust systems, and building operations, and by deploying operational control strategies such as turning off equipment when not in use. The CDP data for the six companies presented a breakdown of emissions related to energy efficiency in building operations and production processes.

Based on the CDP data, the energy efficiency measures for all six companies on average abated nearly 5% of the company's annual CO_2 eq., with the highest emissions abatement share reported by SK Hynix at 18% and the lowest by Kioxia at 0%, as shown in Figure 13. Within abated emissions due to energy efficiency, on average, nearly 77% of contributions were due to the semiconductor manufacturing process, and the remaining 33% were due to building operations. For instance, Samsung Electronics abated 2.24 MMT CO_2 eq. emissions via process efficiency improvements in semiconductor manufacturing processes, which led to direct reductions in PFCs, thereby reducing GHG emissions. Comparatively, the emissions abated due to energy efficiency in buildings were only half those abated by process efficiency measures. As reported by abatement measures, nearly half the amount of GHG emissions was observed for process efficiency improvement measures. Utility energy optimization (automated sensing and control operations) and installation of LED lighting abated 1.32 and 0.01 MMT CO_2 eq./year in 2020, respectively.

Similarly, for Micron, building operations energy efficiencies measures, such as improvements in HVAC systems, LED lighting, and upgradation of motors and drivers, abated only 0.02 MMT CO_2 eq./year; measures related to process optimization and efficiency improvements in compressed air systems abated 0.05 MMT CO_2 eq./year. Since PFCs have a high GWP compared to CO2, as noted earlier, any abatement measures that helped reduce PFCs resulted in larger GHG emission reduction compared to energy efficiency measures, as observed for Samsung Electronics and Micron.

3.6.2. Industrial Electrification and CCUS

The industrial electrification pillar relates to the electrification of existing technologies, such as using heat pumps, microwave, and infrared technologies for process heat. Plasma-assisted chemical vapor deposition techniques are widely used in semiconductor manufacturing to deposit thin gas films such as silicon dioxide, silicon nitride, etc., onto silicon substrate or wafers at temperatures of 200–400 °C.

The reviewed CDP data for the six companies did not reveal any specific steps carried out related to the electrification of existing technologies. Similarly, for the CCUS pillar, the CDP data did not present any data related to emissions abatement. However, a study by Chen et al. indicated that TSMC has introduced a carbon capture program to encourage their CO_2 suppliers to capture CO_2 from their CO_2 purification facilities [38]. A typical CO_2 supplier to the semiconductor manufacturing company purifies the industrial grade CO_2 of 99% purity to a semiconductor manufacturing grade of 99.9% purity before supplying it to the semiconductor company such as TSMC. As part of this CO_2 purification process, some of the residual CO_2 is vented into the atmosphere via a distillation tower. TSMC provides technical assistance and encourages its suppliers to recapture this CO_2 and utilize it. This encouraged effort by TSMC enabled its CO_2 supplier to capture nearly 500 MT CO_2 in 2022 [38]. Other semiconductor companies analyzed in this study did not report any undertaken CCUS efforts. The low adoption of CCUS and industrial electrification in the semiconductor manufacturing industry can likely be attributed to the low technology readiness. This was expected because, in the global industrial sector, very few facilities have implemented CCUS technology, resulting in only 35 commercial facilities together capturing nearly 45 MMT CO_2 through this lever [39].

3.6.3. LCFFES

For the LCFFES pillar, fuels or energy sources could be delivered by using renewable energy sources such as green hydrogen, renewable natural gas, biofuels, biomass, solar thermal, etc. Hydrogen is used in semiconductor manufacturing processes such as plasma etching, annealing, epitaxy, passivation, ion implantation, and chemical vapor deposition [40]. In annealing, hydrogen assists in the rebuilding of crystal structure in the final surface layers. Hydrogen is used as a reducing agent during the deposition of new crystalline films in the steps of thin film deposition and epitaxy. The addition of hydrogen to electronic gases such as diborane (B_2H_6) and digermane (Ge_2H_6) may reduce the gases' decomposition rate thereby extending their shelf life [41]. Hydrogen could also be used in electric forklifts and other material handling systems in addition to electric plasma etching.

The RECs are tradable energy certificates that are evidence of 1 MWh of electricity provided to a semiconductor manufacturing facility being generated from renewable sources such as solar, wind, geothermal, hydropower, and biomass. The use of RECs typically abates the Scope 2 market-based emissions of semiconductor manufacturing because the electricity is sourced from renewable sources as opposed to electricity sourced from conventional fossil fuel.

For the six companies considered, the average annual emissions abated via LCFFES were 0.73 MMT CO_2 eq./year; the highest emissions abatement was attributed to Samsung Electronics at 2.8 MMT CO_2 eq./year due to REC purchases for their facilities located in China, the United States, and Europe (Figure 13). The lowest emissions abatement was attributed to Kioxia because the company did not report any specific measures related to the LCFFES lever. Of all the CO_2 abatement measures that encompass all the decarbonization levers, the use of RECs by semiconductor manufacturers had the most significant effect on decarbonization. For example, for Samsung Electronics, TSMC, and Intel, the shares of RECs within total CO_2 abatement were the largest at 39%, 55%, and 87%, respectively (Figure 13). This can be attributed to the relative ease of REC implementation as opposed to other complicated measures such as retrofitting existing equipment or modifying unit operations with energy-efficient and carbon-efficient measures that might affect process yield and revenue.

Other LCFFES measures aside from RECs were also deployed by companies to abate CO_2 emissions. For instance, Intel deployed solar water heaters and used biogas to generate energy that abated nearly 100 and 70 tons CO_2 eq., respectively (0.01% of Intel's annual emissions each). However, these measures possessed relatively high abatement costs of USD 227 and 308 per ton/CO_2 eq which is nearly 10 times that of the most commonly used LCFFES measure, i.e., RECs. Samsung Electronics also generated low carbon energy through the use of liquid biofuels that abated nearly 7500 tons of CO_2 eq. (0.11% of total annual emissions), while also deploying wind, solar, and geothermal technologies that together abated nearly 28,500 tons of CO_2 eq. emissions in the case of Samsung (with 0.4% of Samsung's total emissions). Table 3 provides a brief summary of CO_2 mitigation measures categorized by decarbonization lever.

Table 3. Instances of CO_2 mitigation measures categorized by decarbonization lever.

Energy Efficiency	Industrial Electrification	Low-Carbon Fuels, Feedstocks, and Energy Sources (LCFFES)	Carbon Capture, Utilization, and Storage (CCUS)
Replacement of old machines with newer higher energy efficiency equipment, installation of energy efficient LED lights, process optimization, reducing stand by power consumption in equipment, etc.	The measures related to industrial electrification were not to be found in their CDP report.	Purchase of renewable energy certificates (RECs), installation of solar photovoltaics on-site for electricity production, installation of geothermal energy generation units, deployment of biogas waste to energy equipment, etc.	The measures related to CCUS were not to be found in CDP reports.

3.7. Cost of CO_2 Abatement Technologies

Based on the CDP data of six companies, MACCs were developed to analyze the technologies based on the respective costs for abating each mass unit of CO_2 in terms of US dollars per metric ton of abated CO_2 eq. The MACCs for Intel, Samsung Electronics, and Micron are shown in Figures 14–16, respectively, and the MACCs for the remaining companies are provided in the Supplementary Materials.

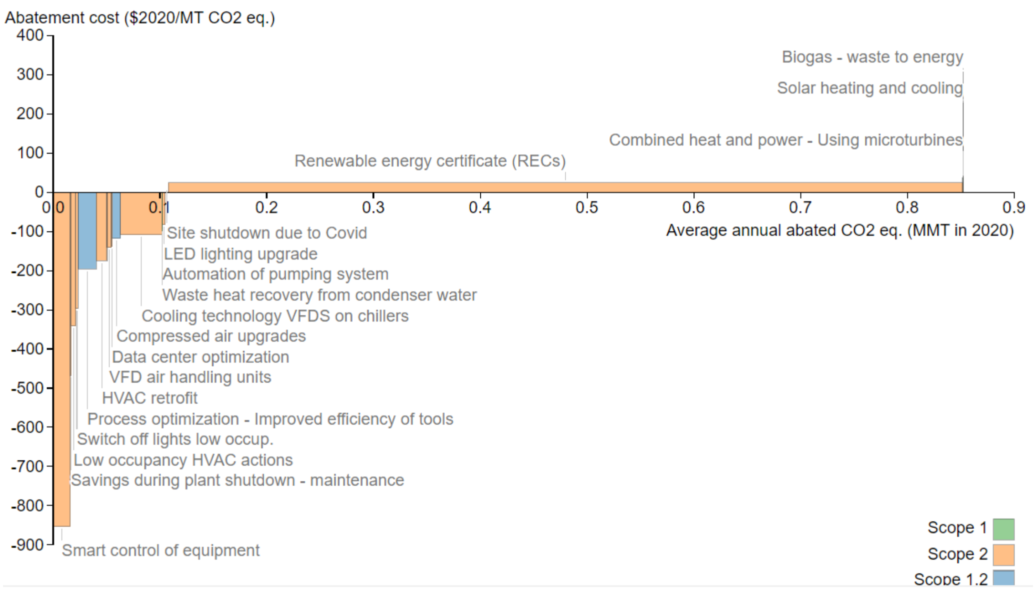

Figure 14. MACC for Intel in 2020.

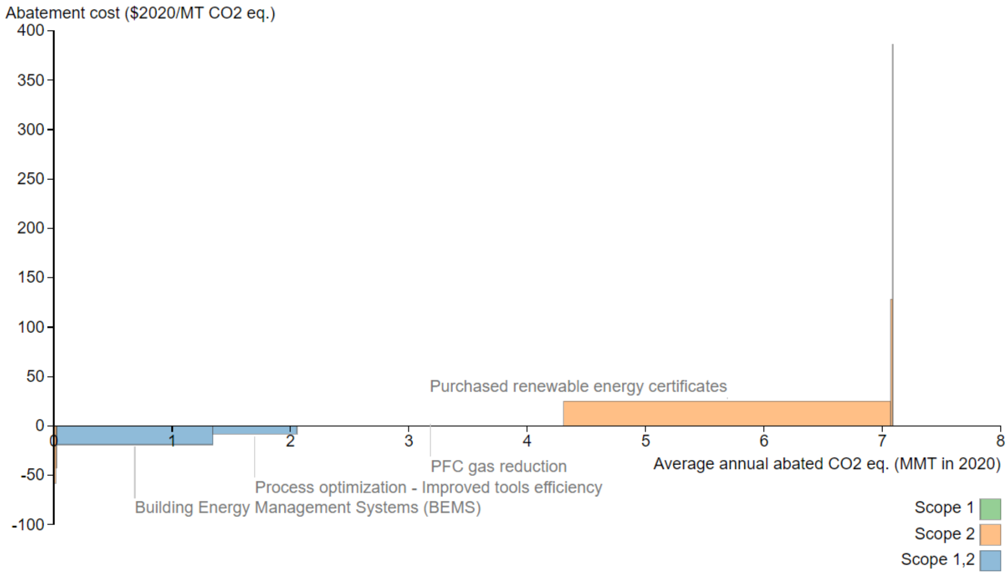

Figure 15. MACC for Samsung Electronics in 2020.

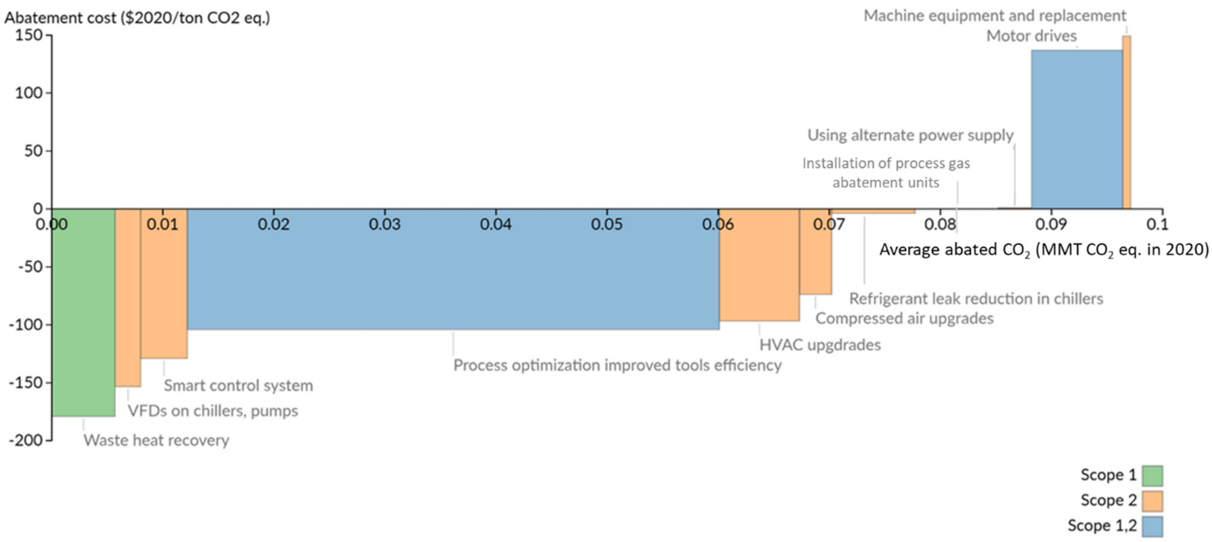

Figure 16. MACC for Micron in 2020.

The MACC for Intel depicts costs and CO_2 abatement volumes for 18 technological options. The highest abatement cost of 308 USD/t CO_2 was incurred by waste to energy biogas technology, and the lowest cost (highest cost benefit) of −408 USD/t CO_2 eq. was incurred by the turning off equipment when not in use. The high initial investment of USD 180,000 required for a biogas plant, along with its low abated CO_2 annual volume of only 70 MT CO_2 eq./year, contributed to an abatement cost of 308 USD/t CO_2 eq. Conversely, only simple process control changes were required in turning off equipment, which required only a fraction of the initial investment (USD 13,000) and possessed 230 times larger potential CO_2 abatement volume (16,000 MT CO_2 eq./year) than biogas installation. Thus, the cost of the LCFFES measure (a biogas plant) was higher than that of the energy efficiency measure (turning off equipment when not in use).

Of the 18 technological options that Intel implemented for CO_2 abatement, 13 technologies were observed to be economically attractive and generated economic benefits owing to their implementation, as indicated by their negative CO_2 abatement cost of −55 to −408 USD/t CO_2 eq. Implementing these technologies abated nearly 12% of combined Scope 1 and 2 emissions for Intel and generated cost savings from reduced energy consumption.

Other cost-effective options to reduce CO_2 emissions for Intel were based on increasing energy efficiency which resulted in energy savings and reduced CO_2 emissions. This suggests that despite attractive economic benefits of energy efficiency measures such as installation of variable flow drives (VFDs) on chillers, turning off equipment when not in use, HVAC retrofits, and installation of VFDs on air-handling units, these emissions together resulted in lower CO_2 emission reductions. On the contrary, LCFFES options such as the purchase of RECs resulted in the largest CO_2 emissions reduction at 88% of combined Scope 1 and 2 emissions but with an economically unattractive cost of 25 USD/t CO_2 eq. (cost burden). The abatement cost of 25 USD/t CO_2 eq. was estimated based on a 2022 analysis by Burkacky et al. since the CDP data did not disclose the investment costs incurred from the implementation of RECs [28]. The other cost expenses incurred by Intel to reduce CO_2 emissions ranged from 49 to 308 USD/t CO_2 eq.; the lower cost is for microturbines used in combined heat and power applications, and the higher cost is for a biogas waste to energy plant.

The MACC for Samsung Electronics is depicted in Figure 15. To abate the largest volume of CO_2, like Intel, Samsung Electronics relied on acquisition of RECs that possessed a CO_2 abatement cost of 25 USD/t CO_2 eq. This measure aided in reducing nearly 40% of combined Scope 1 and 2 emissions (Figure 15). Following RECs, nearly one third of the reduction in CO_2 eq. emissions was attributed to the reduction of PFCs in semiconductor manufacturing processes. The costs associated with the PFC reduction were negligible, as reported by Samsung Electronics' CDP disclosure, which made the option an economically attractive preference. Other economically attractive options to reduce CO_2 abatement were attributed to energy efficiency measures, such as building energy management systems, process optimization, geothermal, and LED lighting, which reduced approximately 29% of the total Scope 1 and 2 emissions. These energy efficiency measures possess economically attractive values ranging from −5 USD/t CO_2 for process optimization to −40 USD/t CO_2 eq. for LED lighting upgrades, as shown in Figure 15.

The MACCs for the three remaining companies are provided in the Supplementary Materials. For the six companies considered, most of the emission reduction strategies were centered on reducing Scope 2 emissions with relatively fewer strategies devoted to reducing Scope 1 emissions. The CDP data did not reveal any quantified data on reducing Scope 3 emissions, likely because of the challenging nature of its estimation and lack of information on economically feasible strategies to mitigate GHG emissions.

However, semiconductor manufacturing companies are undertaking efforts to reduce their Scope 3 emissions by increasing the energy efficiency of their products in the use phase. For example, Intel processors were able to attain an energy efficiency of 1.5× for their 11th-generation processors with respect to their 2019 baselines as the company's sustainability report [42]. In 2021, Micron also introduced advanced DRAM products (used in 5G products) that were 15% more power efficient than previous-generation products [43].

3.8. Limitations and Future Recommendations

This study analyzes the Scope 1, 2, and 3 GHG emissions from a macro-level standpoint for six companies as reported to CDP by these companies in 2020 while also focusing on the efforts undertaken by these companies to mitigate them along with their costs. However, such kind of analysis may strongly depend on the reporting year as each company's efforts and costs may vary by reporting year. Therefore, future work could be focused on gathering and analyzing such data for additional years. Although Scope 3 was observed to be the largest source of annual GHG emissions in semiconductor manufacturing processes, detailed-level analyses focusing only on Scope 3 strategies are not discussed in this work due to the lack of information and data. Such information will be truly valuable as those strategies will eventually drive the sustainability of semiconductor manufacturing processes.

4. Conclusions

In this work, GHG emissions data of six semiconductor manufacturing companies were gathered from the publicly accessible Carbon Disclosure Project's (CDP) website for 2020. The six companies considered in this study were Samsung Electronics, TSMC, Micron, SK Hynix, Kioxia, and Intel, which together possessed nearly 58% of the global wafer manufacturing capacity in 2020. The analysis presented in this work revealed that Samsung Electronics had the highest CO_2 eq. emissions of all the six considered companies at a value of 71.6 MMT in 2020—approximately 4 to 12 times, on average, higher than the other companies—while Kioxia had the lowest CO_2 eq. emissions at 3.4 MMT.

Analyses presented in this work also revealed that Scope 3 emissions had the largest share in total annual emissions at an average of 52%, followed by Scope 2 (32%) and Scope 1 (16%). Indirect emissions (i.e., Scope 2 and 3) due to purchased electricity, heat, raw material, processing of products, and so on far exceeded the direct emissions (i.e., Scope 1) of manufacturing and assembly. Except for TSMC and SK Hynix, the breakdown of Scope 1 emissions for all companies showed that the Scope 1 emissions share was dominated by PFCs at an average share of 45%, followed by CO_2 (16%), NF_3 (15%), N_2O (9%), other HTFs (7%), HFCs (6%), and SF_6 (2%).

For the six companies considered, most of the emissions reduction strategies focused on reducing Scope 2 emissions, with relatively fewer strategies devoted to reducing scope 1 emissions. None of the strategies were devoted to reducing Scope 3 emissions, likely because of the challenging nature of its estimation, reduction strategies, and lack of information on economically feasible strategies to mitigate GHG emissions.

Marginal abatement cost curves (MACCs) were also developed to analyze the technologies and their respective costs for abating each mass unit of CO_2 in terms of US dollars per metric ton of abated CO_2 eq. The use of renewable energy certificates (RECs) had the largest effect on decarbonization focused on reducing Scope 2 emissions, followed by deployment of PFC reduction technologies. Technology-specific marginal abatement cost of CO_2 was also estimated and varied from –416 to 12,215 USD/t CO_2 eq., mainly depending on the technology deployed.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16010218/s1.

Author Contributions: Conceptualization, S.N.; Methodology, P.N. (Prashant Nagapurkar) and S.N.; Formal analysis, P.N. (Prashant Nagapurkar); Investigation, P.N. (Prashant Nagapurkar); Resources, P.N. (Paulomi Nandy) and S.N.; Writing—original draft, P.N. (Prashant Nagapurkar) and P.N. (Paulomi Nandy); Writing—review & editing, P.N. (Prashant Nagapurkar), P.N. (Paulomi Nandy) and S.N.; Visualization, P.N. (Prashant Nagapurkar); Supervision, S.N.; Project administration, S.N.; Funding acquisition, S.N. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by the US Department of Industrial efficiency and decarbonization office, Washington, DC, USA under contract DE-AC05–00OR22725 with the US Department of Energy (DOE).

Data Availability Statement: All data have been sourced from CDP (Carbon Disclosure Project) website.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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