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GHG emissions of semiconductor manufacturing in 2021

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Abstract

The greenhouse gas (GHG) emissions of semiconductor manufacturing represent an important share of the embodied carbon footprint of electronics systems. Manufacturing emissions are disclosed in the sustainability reports of semiconductor companies. This paper proposes a study of global semiconductor manufacturing carbon emissions, focusing on Scope 1 (direct emissions) and Scope 2 (emissions induced by consuming energy). The fifteen companies on the semiconductor market with highest 2021 revenues are considered, as well as the four main merchant foundries, over the years 2020 and 2021. As a large scale evaluation of carbon impacts, the resulting numbers compile heterogeneous figures and require a comprehensive discussion on the strengths and limitations of the evaluation. Most of the efforts on this paper are thus allocated to this discussion.

The 2021 carbon emissions for the semiconductor industry worldwide are estimated at 76.5Mtons of CO_2 equivalent, breaking down into 30.6Mtons CO_2e of Scope 1 emissions (direct emissions), and 45.9Mtons CO_2e of scope 2 emissions (emissions induced by the energy consumption of manufacturing). These numbers do not include the Scope 3 impacts, neither downwards (usage of the products) nor upwards (constructing fabrication facilities, building fabrication machines, extracting raw materials, smelting and refining materials). Between 2020 and 2021, Scope 1&2 emissions of semiconductor manufacturing have increased by 13%.

1 Introduction

The landscape of best practices in carbon emission evaluation is evolving fast and a deluge of data is available on carbon impacts of human activities at different scales. However, figures are often provided without information on their reliability, and with limited information on the method used to generate them.

When focusing on impacts of information communication technology (ICT), surveys show that the carbon footprint of ICT strongly differs depending on studies [FBLW⁺21, LPJH20]. However, a consensus is emerging on the large efforts that need to be invested in reducing this carbon footprint [MPLB⁺21]. Semiconductor manufacturing that produces integrated circuits (ICs) is also largely recognized as representing the most impacting GHG source of electronics systems, before device use phase energy consumption, printed circuit boards (PCBs) production, display production, and casing production emissions [LPJH20].

The Greenhouse Gas Protocol [Sta04] defines three scopes of emissions:

1. Scope 1 emissions: direct emissions from activity.
2. Scope 2 emissions: indirect emissions from purchased energy. Scope 2 emissions can be disclosed either *location-based* or *market-based*. This report employs location-based numbers when available, as they reflect more the present emissions of the manufacturing process. The Scope 2 disclosure choice will be discussed in Section 5.
3. Scope 3 emissions: upstream and downstream supply-chain emissions.

Scope 1 and Scope 2 emissions shall be accounted for only once, i.e. be attributed to a unique organization, while Scope 3 aggregates emissions already counted in the Scopes 1 and 2 of other

organizations. While most sustainability reports give advanced information on Scope 1 and Scope 2 emissions, information is limited on Scope 3 emissions and does not give enough insight to trace full emissions of the upstream supply chain, including raw material extraction, smelting, and refining. This paper concentrates on Scope 1 and Scope 2 GHG emissions of the semiconductor manufacturing industry in 2021, and their evolution from year 2020.

2 Related Works

GHG emission studies are released with the following scopes: information communication technology (ICT) [FBLW⁺21], integrated circuit (IC) [PDP⁺22b], Computing [GKL⁺22], Electronics [MPLB⁺21], and Consumer electronics devices [LPJH20], including packaging.

Scopes can be related to either product usage or to product technology. All these studies require evaluations of the GHG emissions of the manufacturing phase of electronics devices, including the manufacturing of ICs, and aim at providing guidance for reducing the carbon impact of products. In this context, the present study concentrates on the ICs fabrication market and aggregates the disclosed semiconductor industry GHG emission information in order to compute the carbon footprint of IC manufacturing. The closest study to the present one on integrated circuit (IC) manufacturing, from Pirson, et al., is an extensive study of the GHG emissions per cm^2 of produced silicon [PDP⁺22a][PDP⁺22b]. The present paper aims at complementing previous studies by analyzing the absolute emissions of GHG on a reference year, absolute emissions being the metric to be optimized, and drastically reduced, in the next decades. The adopted method is based on revenue and *carbon intensity*, defined as the amount of GHG emitted per dollar of revenue.

3 Goals and Scope Definition

The scope of the study is the so-called *semiconductor market* that concentrates on fabricating integrated circuits (ICs). This study does neither include flat panel display production nor photovoltaic panels productions, and concentrates on wafer-based semiconductors produced to be encapsulated in ICs. The main objective of the study is to evaluate the evolution of the sector and its GHG emissions. Another objective of the paper is to discuss the method for constructing such large-scale models, and to pinpoint the missing figures to build a complete representation of the carbon impact of the semiconductor industry.

4 The Semiconductor Market

We propose to analyze the semiconductor market based on its revenues. Figure 1 shows the revenues of the 15 entities with largest revenue on the *semiconductor market* in 2021¹. Samsung Semiconductor is a subsidiary of Samsung Electronics, while other entities are independent. These 15 entities together represent 65.3% of the whole semiconductor market revenue of 475.4B\$ in 2020. They represent 63.9% of the semiconductor market revenue of 608B\$ in 2021.

The semiconductor market includes integrated device manufacturers (IDMs) that design and manufacture ICs, and *fabless* companies that design semiconductor products but do not manufacture them. These fabless companies delegate fabrication of most of their products to foundries. Apart from Samsung Semiconductor that is already accounted for in the semiconductor market but also acts as a foundry for fabless companies, four companies dominate the foundry market: TSMC, UMC, SMIC and Global Foundries. The total foundry market is estimated at 87.4B\$ in 2020 and 110B\$ in 2021. Revenues of the four main foundries are displayed in Figure 2. One may note that IDMs also resort to external foundries for some of their products.

The semiconductor market aggregated revenue has raised by nearly 28% from 2020 to 2021. **The aggregated revenue of the 15 main entities of the semiconductor market has raised by 25%.** The foundries aggregated revenue, for its part, has raised by 26%.

¹source: Statista public figures - www.statista.com

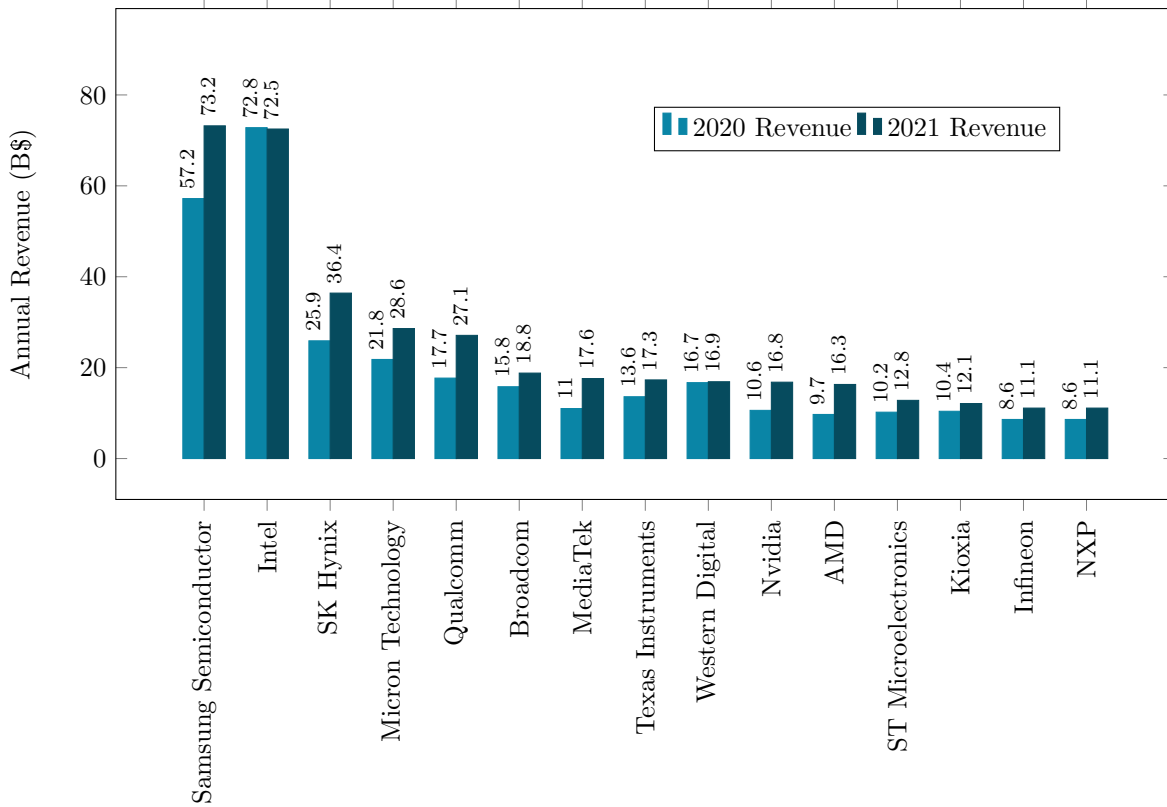


Figure 1: The 15 main semiconductor market entities by revenue in 2020 and 2021. Source: Statista public information. Remaining semiconductor market entities are estimated to represent a revenue of respectively 165B\$ in 2020 and 219.5B\$ in 2021.

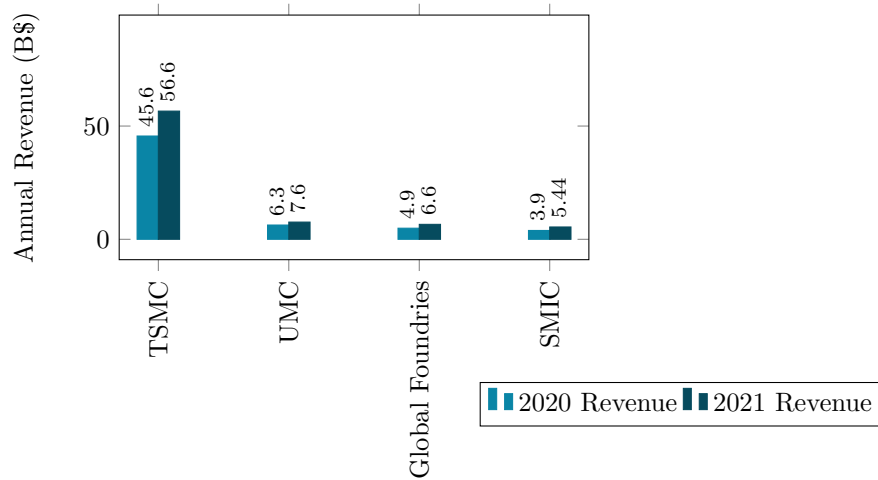


Figure 2: The foundry market four main entities by revenue in 2020 and 2021, excluding Samsung Semiconductor. Mixed source: Statista and TrendForce public information. Remaining foundry market entities are evaluated respectively 12B\$ and 15B\$ in 2020 and 2021.

5 GHG Emissions of the Semiconductor Industry

5.1 Compiling Emission Figures

The Kyoto protocol defines six families of greenhouse gases that shall be accounted for in the GHG emissions reports:

- Carbon Dioxide (CO_2),
- Sulfur hexafluoride (SF_6),
- Methane (CH_4),
- Nitrous Oxide (N_2O),
- Hydrofluorocarbons ($HFCs$),
- Perfluorocarbons ($PFCs$),

Semiconductor manufacturing produce all these six families of emissions [Boy11], and also produce Nitrogen trifluoride (NF_3) and other fluorinated GHGs. We refer to GHG emissions and impact as *carbon emissions* and *carbon impact* as it is the standard term used for characterizing them [GKL⁺22] but carbon impact covers all these families of gases converted into weight of CO_2 equivalent (CO_2e).

Companies disclose their GHG emissions in sustainability reports. The present report compiles numbers from reports up to 2022 [Sam22, Int22, SK 22, Mic22, Qua22, Bro22, Med21, Ins21, Dig22, Nvi22, AMD22, STM22, Cor22, Inf22, NXP21, TSM21, UMC21, Fou22, Cor21]. Samsung Semiconductor emissions are disclosed in the global sustainability report of Samsung Electronics but with no specific number for the Samsung Semiconductor subsidiary. Specific emissions of Samsung Semiconductor are evaluated from the revenue share of the subsidiary, corresponding to respectively 27.98% and 31.3% in 2020 and 2021 [Sam22].

Figure 3 shows the Scope 1 emissions of the 15 main semiconductor entities in kilo metric tons of CO_2 equivalent. As expected, the 5 listed fabless companies disclose much less GHG emissions in their Scope 1 than the IDMs. Fabless companies, while their business relies on externalized fabrication, may still have internal fabrication facilities. It is the case of Broadcom which foundry in Fort Collins emitted $125ktonsCO_2e$ in 2021². Similarly, Qualcomm owns fabrication facilities that manufacture radiofrequency products [Qua22]. One can also note that memory chip manufacturers: SK Hynix, Micron Technology and Kioxia tend to have larger Scope 1 carbon intensity than manufacturers concentrating on other activities. These elements are detailed in next sections.

Figure 4 shows the Scope 1 emissions of the four main semiconductor foundries. From these numbers and companies market shares, the total Scope 1 emissions of foundry market can be estimated $12.7MtCO_2e/\$$ in 2020 and $13.8MtCO_2e/\$$ in 2021.

Figure 5 shows the Scope 2 emissions of the 15 main semiconductor entities in kilo metric tons of CO_2 equivalent. These scope 2 emissions are *location-based* if data is available in sustainability reports (a † symbol is shown on the company name if data is known to be location-based). If disclosed scope 2 emissions are only *market-based* or if the type of emissions is unknown, the displayed figures are the disclosed ones.

Figure 6 shows the Scope 2 emissions of the four main semiconductor foundries. The Scope 2 emissions of the foundry market can be estimated $13.1MtCO_2e/\$$ in 2020 and $14.2MtCO_2e/\$$ in 2021. The Scope 2 emissions of GlobalFoundries are market-based while other emissions are either location-based or of unknown type.

²<https://ghgdata.epa.gov/ghgp/service/facilityDetail/2021?id=1008734&ds=E&et=&popup=true>

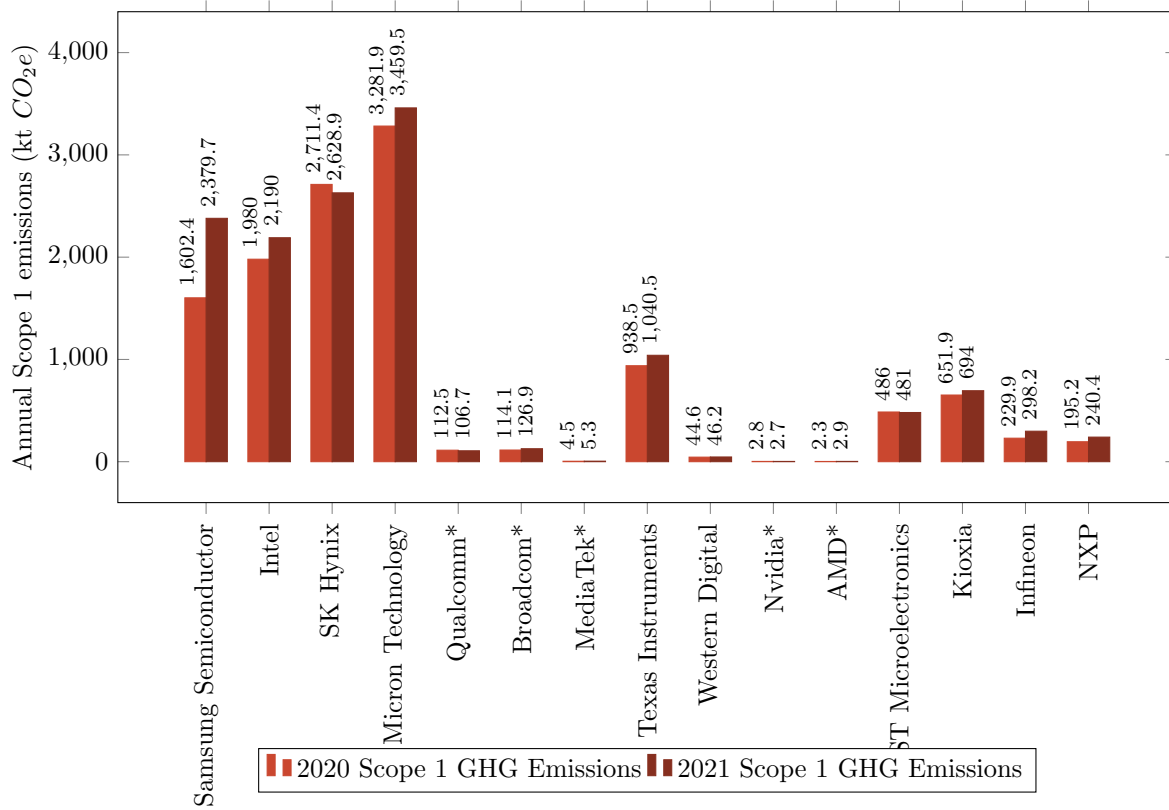


Figure 3: GHG Scope 1 Emissions of the 15 main semiconductor market entities in 2020 and 2021. Source: corporate sustainability reports. Companies marked by * are fabless.

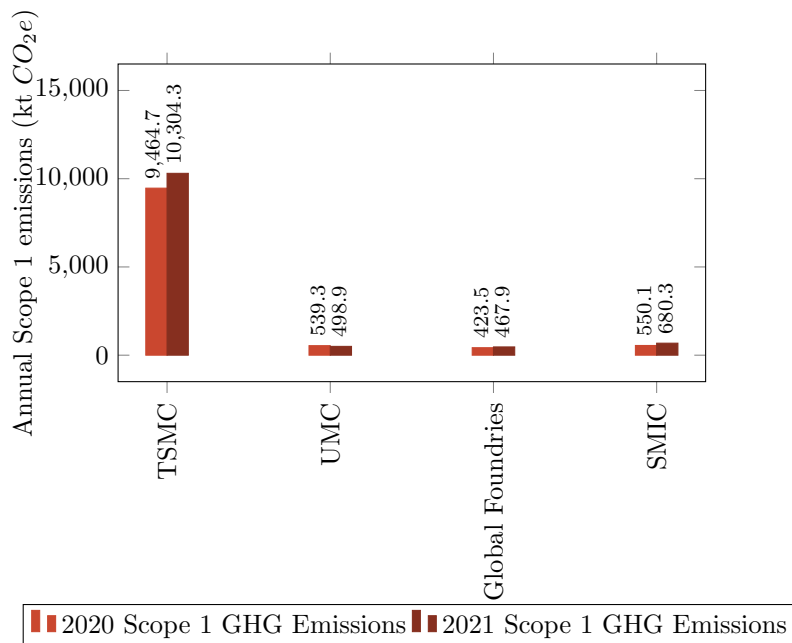


Figure 4: GHG Scope 1 emissions of the foundry market four main entities by revenue in 2020 and 2021, excluding Samsung Semiconductor. Source: corporate sustainability reports.

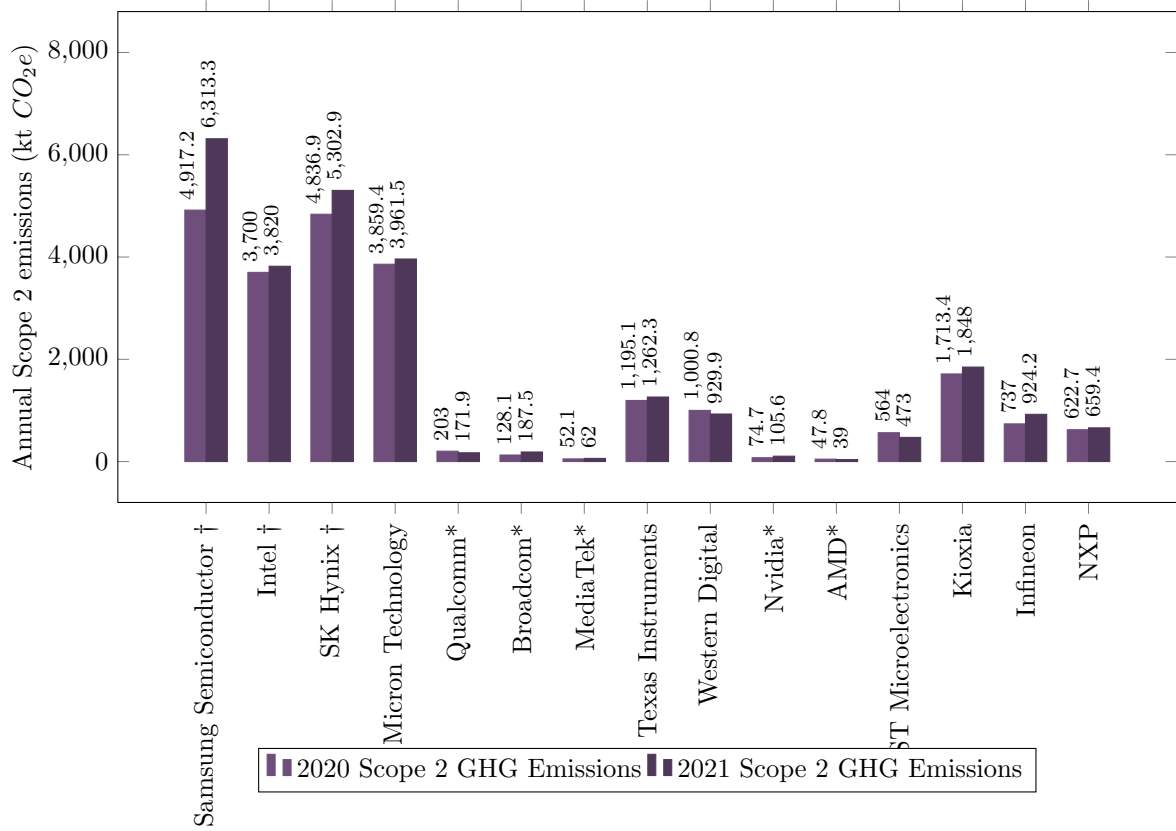


Figure 5: GHG Scope 2 Emissions of the 15 main semiconductor market entities in 2020 and 2021. Source: corporate sustainability reports. Companies marked by * are fabless. Companies marked by † explicitly specify location-based scope 2 emissions.

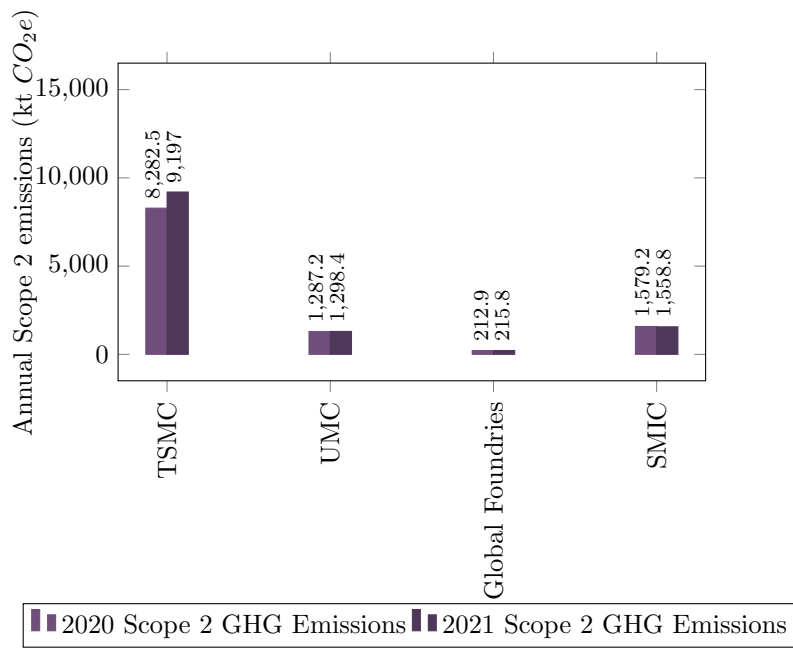


Figure 6: GHG Scope 2 emissions of the foundry market four main entities by revenue in 2020 and 2021, excluding Samsung Semiconductor. Source: corporate sustainability reports.

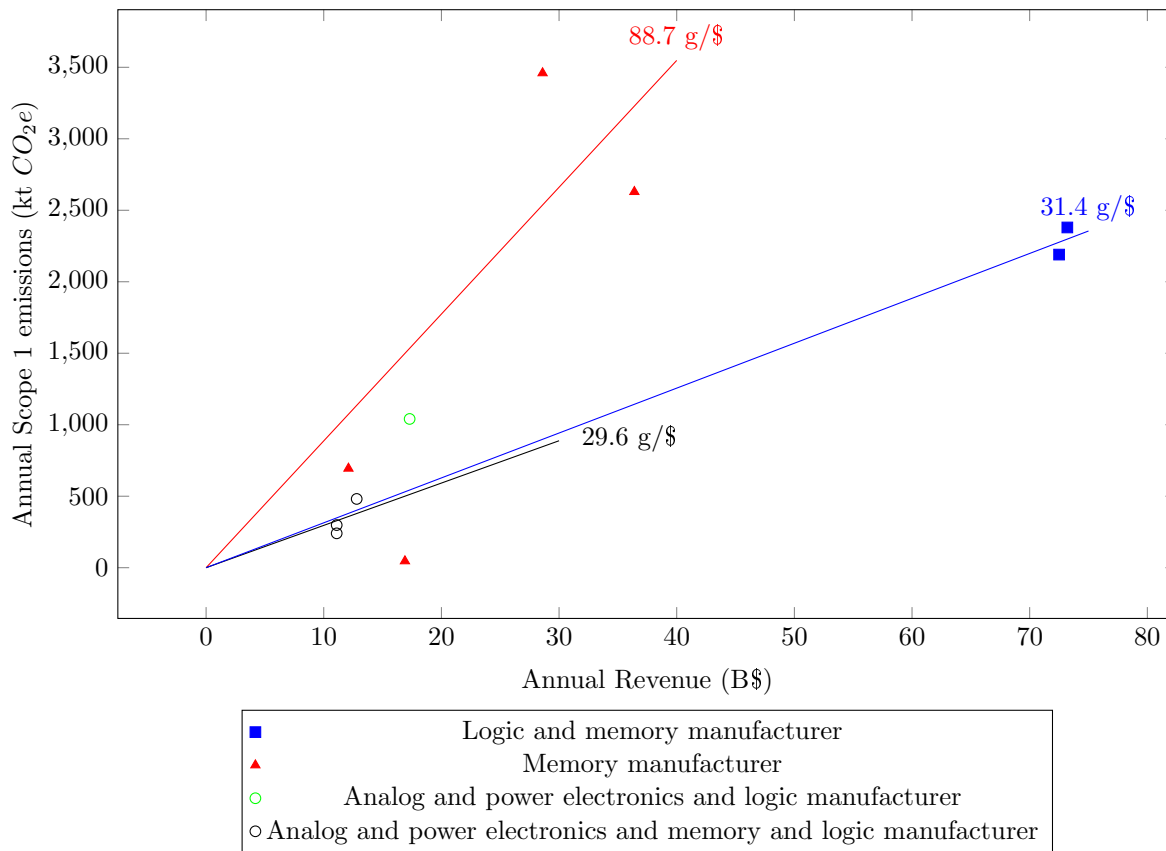


Figure 7: GHG Scope 1 carbon intensity of the 10 main integrated device manufacturers (IDMs) in 2021, relative to the types of products. Source: corporate sustainability reports.

5.2 Consolidating Figures of the Semiconductor Manufacture Impacts

5.2.1 Carbon intensity of manufacturing and integration of IDM and foundries impacts

Using the Greenhouse Gas Protocol, fabless companies disclose in their Scope 1 the GHG emissions of their facilities and company vehicles. They do not include in Scope 1 the employee commuting emissions, business travels or capital goods. Thus, analyzing Scopes 1 and 2 is not sufficient to evaluate IC design carbon impacts versus IC manufacturing carbon impacts. However, studying manufacturing emission intensity provides some interesting trends, as displayed in Figures 7 and 8 on respectively Scope 1 and 2 emissions.

A trends appears in Figure 7. Memory ICs manufacturers tend to have a larger Scope 1 carbon intensity than logic ICs manufacturers. Intel and Samsung Semiconductor fabricate both memory and logic chips, so this data is however not sufficient to clearly distinguish technologies. Western Digital claims $46kt$ of CO_2e Scope 1 emissions for a 2021 revenue of $16.9B\$$. Such a low carbon intensity of $2.7g/\$$ is specific to the company and not compiled into the carbon intensity regression. Types of memories (Flash, RAM, NVM) and markets should be distinguished to better understand memory manufacturing carbon intensity. This particular study is kept out of the scope of this paper.

Scope 2 impacts strongly depend on the energy mix of the country where foundries are installed. The carbon intensities of companies Scope 2 emissions are thus consistently more varied. The world average carbon intensity of energy production is $0.47kgCO_2e$ per kWh , while it is $0.06kgCO_2e$ per kWh in France, $0.40kgCO_2e$ per kWh in Korea, $0.41kgCO_2e$ per kWh in Germany, $0.50kgCO_2e$ per kWh in the United States, and $0.64kgCO_2e$ per kWh in China [Ash23]. The trend in Scope 2 emissions is still that of a larger emissions of memory manufacturers but deviations are larger.

From the preceding numbers, we propose two methods for evaluating the global carbon footprint of the semiconductor market.

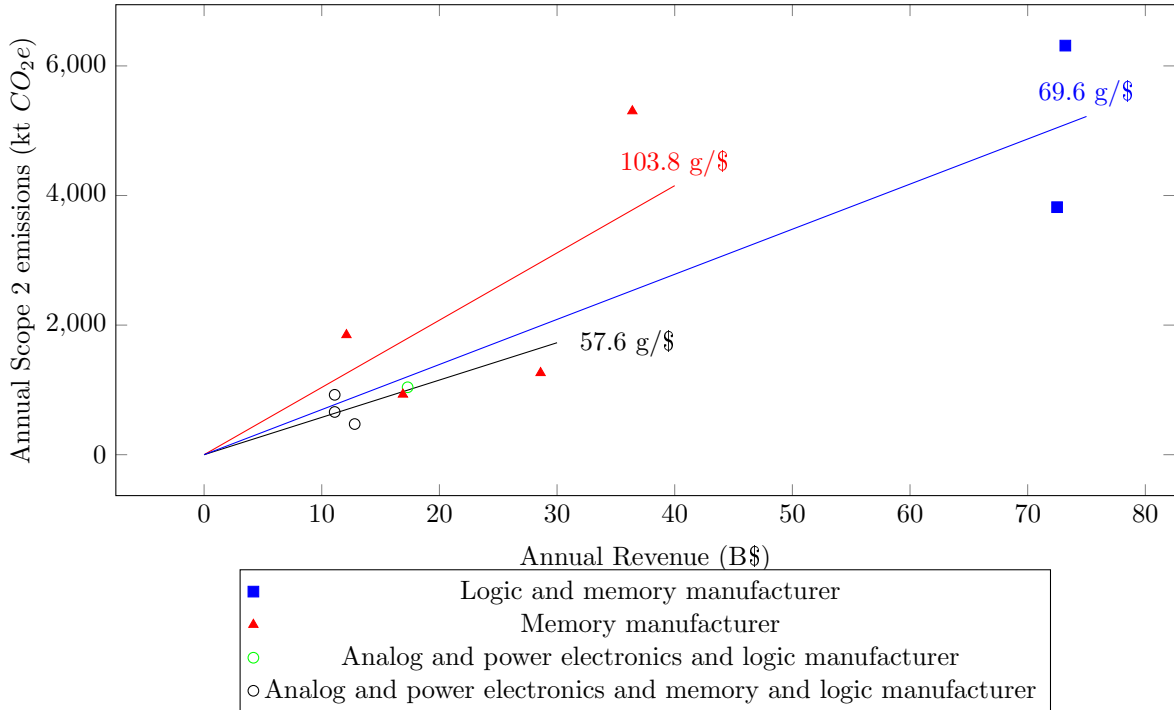


Figure 8: GHG Scope 2 carbon intensity of the 10 main integrated device manufacturers (IDMs) in 2021, relative to the types of products. Source: corporate sustainability reports.

5.2.2 Consolidating Global Figures from Carbon Intensities

Relying on carbon intensities, amounts of Scope 1&2 emissions of semiconductor manufacturing can be consolidated, combining figures from IDMs, fabless companies and foundries. Qualcomm, Broadcom, Mediatek, NVidia and AMD can be hypothesized to present similar carbon intensity as Samsung Semiconductor and Intel, i.e. $31.4gCO_2e/\$$ in Scope 1 and $69.6gCO_2e/\$$ in Scope 2. Indeed, the target markets of these companies are the closest. Fabless companies induce externalized fabrication emissions, disclosed by external foundries in their Scope 1 and Scope 2. Their aggregated emissions can then be evaluated at $3,034ktCO_2e/\$$ Scope 1 and $6,725ktCO_2e/\$$ Scope 2 in 2021, as a share of foundries in 2021. These emissions would appear in the upstream Scope 3 of the fabless companies. Following the same method, fabless total externalized fabrication emissions can be evaluated at $1.780ktCO_2e/\$$ Scope 1 and $4.161ktCO_2e/\$$ Scope 2 in 2020.

If we add-up these figures, and consider that the 15 considered companies revenues correspond to respectively 65.3% and 63.9% of the whole semiconductor market revenue in 2020 and 2021, we obtain the evaluations in Table 2. These figures are composed of much extrapolation that reduces their reliability. The next section proposes another method for aggregating numbers.

Table 1: GHG emissions of the semiconductor market in 2020 and 2021, evaluated from carbon intensities and market shares.

Year	Semiconductor Market with Foundries		
	Scope 1	Scope 2	Total
2020	21.65 MtCO ₂ e	42.59 MtCO ₂ e	64.24 MtCO ₂ e
2021	26.19 MtCO ₂ e	51.30 MtCO ₂ e	77.49 MtCO ₂ e

5.2.3 Consolidating Figures from Combining Semiconductor Market and Foundry Market

An alternative method to consolidate semiconductor market figures consists of aggregating the emissions of the foundry market. One can hypothesize that all emissions from fabless entities within the top 15, as well as all emissions from entities outside the top 15, are produced by the foundry market. Table 2 gathers the emissions obtained by consolidating figures in this way. One can observe that Scope 1 emissions are evaluated 16% to 24% higher with this new method, while Scope 2 emissions are evaluated 4% to 11% lower. **We choose this method as the final result of this paper, as it is employing very limited extrapolation.** However, the differences between the two models show that large-scale figures must be handled with care.

Table 2: GHG emissions of the semiconductor market in 2020 and 2021, evaluated from adding up the impact of foundries to the impact of IDMs and fabless companies.

Year	Semiconductor Market with Foundries		
	Scope 1	Scope 2	Total
2020	26.84 <i>MtCO_{2e}</i>	40.96 <i>MtCO_{2e}</i>	67.8 <i>MtCO_{2e}</i>
2021	30.56 <i>MtCO_{2e}</i>	45.93 <i>MtCO_{2e}</i>	76.5 <i>MtCO_{2e}</i>

One consistent conclusion of both models is that the carbon footprint of semiconductor manufacturing is raising. The selected model evaluates the growth of GHG emissions at about 13% from 2020 to 2021.

6 Discussion

6.1 Limitations of the Current Study and Future Work

This discussion aims at identifying some required future works for analyzing the semiconductor manufacturing impacts.

GHG emissions of the semiconductor market are related to designing and producing a large variety of products. Even if semiconductor-based products are central to these companies, the considered emissions must also be understood product per product. For instance, Texas Instruments produces analog and digital ICs, which GHG emissions are likely to vary much from one process to another. Similarly, Intel does not only produce semiconductors but also computers, servers and network solutions. Process and product-related studies such as [PDP+22b] are required on each family of products, for design and manufacturing decisions to be reliable.

This report is based on markets and revenues. GHG emissions accounting requires companies to determine organizational boundaries [Sta04] that determine which organization should include each specific Scope 1 and Scope 2 emissions so as to avoid double counting. Such boundaries can be complex and must be well understood to produce a market analysis like the one of this document. There is a risk of under- or over-estimating figures by misunderstanding the organizational boundaries of the source sustainability report.

Scope 2 market-based GHG emission figures reflect in a single number the impact of the energy consumed, by a facility and the investment made by the manufacturing company in renewable energies. As a consequence, market-based GHG emissions are not sufficient for evaluating present carbon emissions of manufacturing facilities. For this reason, the present study displays location-based Scope 2 figures, when available.

One may note that the Scope 2 reported emissions of semiconductor manufacturing companies do not include the electricity transmission and distribution (T&D) losses [Sta04], as these transmission and distribution-related energy losses are already counted in the electric utility companies reports that own or control the T&D operation. However, these losses would not appear if that specific energy would not be consumed by the semiconductor manufacturing facilities. Some hidden impacts thus remain, that are difficult to track. These impacts can only appear in Scope 3 emissions of semiconductor manufacturing companies.

Finally, exploring impacts of upstream Scope 3 emissions will require to combine different sources of information and cross-check results in order to build reliable evaluations. The present GHG emissions study is based on semiconductor industry outputs, based on revenues generated by these outputs. Considering inputs (purchased raw materials and machines) would have certainly resulted in different figures. Such complementary studies are necessary to build up the full picture of electronics carbon impacts.

7 Conclusion

This paper has provided a summary of Scope 1 and Scope 2 GHG emissions of the semiconductor manufacturing industry in 2021, based on the study of sustainability reports of 19 companies. Understanding such impacts is vital for establishing methods and tools to reduce carbon emissions in the next decades. Results demonstrate a growth in the GHG emissions of semiconductor manufacturing. The consolidation of Scope 3 emissions figures is a challenge, and will be necessary to understand carbon reduction objectives and levers.

8 Acknowledgment

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