From Silicon Shield to Carbon Lock-in? The Environmental Footprint of Electronic Components Manufacturing in Taiwan (2015-2020)

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***Abstract*—Taiwan plans to rapidly increase its industrial production capacity of electronic components while concurrently setting policies for its ecological transition. Given that the island is responsible for the manufacturing of a significant part of worldwide electronics components (including the most advanced CMOS technology nodes), the sustainability of the Taiwanese electronics industry is of critical interest. In this paper, we survey the environmental footprint of 16 Taiwanese electronic components manufacturers (ECMs) using corporate sustainability responsibility reports (CSR). Based on data from 2015 to 2020, we find out that the sample of ECMs in this study increased its greenhouse gases (GHG) emissions by 7.5% per year, its final energy and electricity consumption by 8.8% and 8.9%, and its water usage by 6.1%. We show that the volume of manufactured electronic components and the environmental footprint compiled in this study are strongly correlated, which suggests that relative efficiency gains are not sufficient to curb the overall environmental footprint of ECMs on the island . Given the critical nature of the electronics industry for Taiwan's geopolitics and economics, the observed increase of energy consumption, and the slow renewable energy roll-out, Taiwan could face a carbon lock-in situation which will most likely prevent the achievement of carbon reduction goals and sustainability policies on the island.**

Keywords *Sustainability, digital, manufacturing, electronics, Taiwan, industrial ecology*.

Data Availability Statement: The data that supports the findings of this study are available in the supporting information of this article.

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I. Introduction

Over the last four decades, Taiwan has developed a strong ecosystem in semiconductor manufacturing, building a leadership position in advanced manufacturing, packaging, and testing of integrated circuits (ICs). The island is a key provider of electronic components for the rest of the world with more than 63% of the 2021 worldwide output value ensured by Taiwanese IC foundries and 58% of the IC packaging [1]. The electronics industry accounts on average for 30% of Taiwan's exports [2] and therefore significantly contributes to the economy of the island [3]. In fact, Taiwan's semiconductor industry has witnessed double-digit growth for three consecutive years [1] and is also supported by several semiconductor initiatives and R&D programs [1]. Meanwhile, the Taiwanese government has issued its *Greenhouse Gas Reduction Action Plan* with the objective of decreasing the absolute carbon footprint of the island at the 2050 horizon. Yet, Taiwan has been struggling with the effective implementation of this plan and actual carbon reductions are still to be realized [3]. As the production of electronic components is known to be energy and resource-intensive [4]–[6], the environmental impacts generated by the electronics industry on the island cannot be ignored. Moreover, analyzing the current Taiwanese situation can provide useful insights regarding the environmental footprint of manufacturing advanced electronics components, given that more than 90% of the worldwide sub-10nm ICs are currently manufactured in Taiwan at TSMC [7], the *de facto* world leader in advanced ICs manufacturing.

In this study, we first estimate the environmental impacts of the electronics industry in Taiwan over the period 2015-2020 with a bottom-up approach. We use the CSR reports of 16 Taiwanese electronic components manufacturers (ECMs) to gather data over several environmental indicators. Then, we address the question whether the fast-paced development of the electronics industry in Taiwan is consistent with the environmental sustainability roadmaps of the island through a scenario analysis. Furthermore, we use geographical approach to point out the terrain-related constraints preventing the island to quickly implement its ecological transition. Finally, we argue that this analysis is also of interest for Western economies, as both the Europe Union (EU) and the USA are currently trying to relocate the manufacturing of electronic components. This study comes with Supporting Information gathering all data and calculations.

II. Methods

A. Background

Over the years, Taiwan's semiconductor industry has been widely studied for its industrial development based on the Science Park model, its economic efficiency and its R&D policies. Few works specifically look at the sustainability of this activity on the island but a part of the literature analyzes how individual Taiwanese semiconductor companies try to improve the sustainability of their activities. For instance, Hu et al. [8] investigate corporate sustainability responsibility (CSR) reports of several semiconductor enterprises and link their decision making with the Sustainable Development Goals (SDG) of the United Nations. Lin et al. [9] propose a framework to evaluate the eco-efficiency and performance of a semiconductor company and apply it on several Taiwanese businesses. Hsu et al. [10] survey Taiwanese semiconductor companies that are part of the Dow Jones Sustainability Index (DJSI) and identify their practices for engaging with a sustainability index. Huang et al. [11] compute absolute environmental sustainability indicators that assess how Taiwan performs with respect to several planetary boundaries, including P&N fertilizers, ocean acidification, and freshwater use. On a broader perspective, Chiu [12] provides a comprehensive history of environmental movement against high-tech pollution in Taiwan, which largely included the electronics industry.

At a product level, a life-cycle analysis (LCA) studying the manufacturing of dynamic random access memories (DRAM) in Taiwan identifies global warming potential (GWP), non-renewable energy consumption but also the release of respiratory inorganics as major environmental impacts [13]. In fact, electronic components are manufactured on high-purity silicon substrates using pure raw materials in clean-rooms (isolated spaces in which the air is continuously cleaned) [14] and multiple processing steps which are known to heavily use electricity, chemicals and water [4], [5]. For instance, important quantities of electricity are needed to power the process tools, and the facilities themselves, e.g., air ventilation and cleaning, water purification and cooling, etc [15]. Although very interesting, these different studies do not provide an understanding of the overall environmental impacts of the semiconductor industry in Taiwan. Among the rare studies that analyze the environmental sustainability of the Taiwanese semiconductor industry, Chou et al. [3] provide the most comprehensive and up-to-date analysis regarding GHG emissions and electricity consumption . The authors conduct their analysis using official statistics and past research by comparing the semiconductor industry with the petrochemical industry, which is the other largest industry on the island. Their findings indicate that, in 2016, these industries accounted together for 27.1% of GHG emissions and 31.6% of electricity consumption in Taiwan. The conclusion of the study remarkably underlines that "for the future of Taiwan's economic development, the biggest challenge that the electronics industry face is whether it can bear the weight of its carbon emissions and electricity consumption" [3]. Yet, the study only looks at GHG emissions and electricity consumption until 2016.

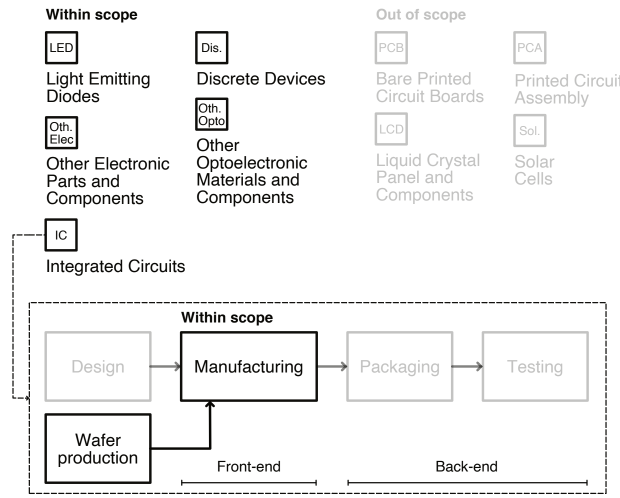

Fig. 1. Simplified view of semiconductor manufacturing processes and the scope of our study (classification based on Taiwanese Indexes of production).

To overcome these limitations, we gather data directly from the CSR reports of several Taiwanese semiconductor companies over the 2015-2020 period. This enables a more fine-grain analysis regarding the evolution of the GHG emissions, electricity consumption and water use of several Tawainese ECMs.

B. Definition of the Study Scope

The manufacturing of the electronic components implies complex supply chains with several actors located in different countries [7]. As a first step to map this complex ecosystem, we focus exclusively on ECMs that are geographically located on the island of Taiwan. In addition, we only consider the manufacturing (i.e., production phase) of electronic components to focus on the environmental impacts occurring within Taiwan, hence excluding the other life-cycle phases such as design, raw material extraction, use, or end of life [7]. Yet, ECMs manufacture a wide variety of electronic components with different technical specifications and different production processes. In this study, we restrict the analysis to the following categories of components: integrated circuits, discrete devices, light emitting diodes (LEDs) and optoelectronic materials and components. This choice was motivated by the availability of CSR data in these categories, and because they share similar manufacturing processes, unlike printed circuit boards (PCBs) or liquid crystal panels (LCDs) which are therefore left outside of the scope of this study. For the manufacturing of ICs, two main parts can be distinguished, i.e., the front-end and the back-end processing [7]. The front-end processing corresponds to the fabrication of the electronic components with semiconductor processes that usually involve several hundreds of steps to modify the silicon substrate and give it the desired electrical properties. In practice, bare silicon *wafers* with standard dimensions (e.g., 300mm wafers) are sliced from a highly purified silicon ingot and then used by the foundries for the front-end processing. In the back-end part, the many circuits contained in a single processed wafer are cut into silicon dies, tested, and packaged in independent chips. These stages usually take place at different geographical locations, involving transportation and operations by several companies. We further narrow down the scope of this study by primarily focusing on companies involved in front-end processing steps[1], as the front-end part is generally more impacting than back-end part [16], [17]. The scope of this study is summarized in Figure 1.

C. Selection of the Environmental Indicators

In this study, we consider three indicators to evaluate the environmental footprint[2] of ECMs, i.e., GHG emissions, final energy consumption, and water usage. Nevertheless, even if these indicators already capture many aspects of the environmental impacts of semiconductor manufacturing, they fall short of providing an exhaustive picture of the environmental footprint. For instance, toxicity concerns, biodiversity loss and impacts on ecosystems are not investigated in this study, as well as air pollution and wastewater, even though they represent a historical environmental problem on the island [12].

GHG emissions are quantified in $kgCO_2$-equivalent ($kgCO_2eq$) and reported accordingly to the GHG Protocol Corporate Standard [18]. This protocol classifies the emissions of a company into three scopes. Scope 1 emissions are direct emissions from owned or controlled sources, while Scope 2 emissions are indirect emissions from the generation of purchased energy, mainly electricity. Scope 3 accounts for all the indirect emissions outside of Scope 2. Since we focus on the environmental impacts occurring on the island of Taiwan, we exclude Scope 3 emissions. As Taiwan is an island with an independent electricity grid, Scope 2 emissions are taken into account. Regarding the energy consumption, we use the (final) energy usage in TWh. This combines both the final energy generated from fossil and renewable sources, as well as the energy obtained from electricity purchases. Finally, the last indicator evaluates the amount of water consumption in cubic meters (m^3). The difference between water use and net water consumption is not always clear in CSR reports, partly due to the different recovery and discharge water processes that take place in semiconductor facilities. We faced difficulties to systematically find whether water is taken from the tap, recycled, reused or reclaimed, but the reported data still provides a good insight on the water consumption of ECMs.

[1]Note that for optoelectronics companies, the distinction between front-end and back-end processing is not always clear, as pointed out in Table I. Yet, they are included in this study as they represent a non-negligible part of the environmental impacts, as shown in the Supporting Information.

[2]The term environmental *footprint* is used in this study to highlight that we quantify the environmental impacts over several indicators. Yet, as clearly mentioned in the scope definition, only the production phase is considered.

TABLE I
LISTING OF ECMS IN TAIWAN AND SELECTION OF COMPANIES CONSIDERED IN THIS STUDY.

Company name	**CSR** data	**Taiwan** territorial data	**Within** scope	**Included** in this study
TSMC	✓	✓	✓ $^{(a)}$	✓
UMC	✓	✓	✓ $^{(a)}$	✓
Powerchip	✓	✓	✓ $^{(a,d,e)}$	✓
Vanguard	✓	✓	✓ $^{(a,b)}$	✓
Global Wafers	✓	✓	✓ $^{(f)}$	✓
Nanya	✓	✓	✓ $^{(a,e)}$	✓
Winbond	✓	✓	✓ $^{(a,e)}$	✓
Win Semiconductors	✓	✓	✓ $^{(a,e)}$	✓
Epistar	✓	✓	✓ $^{(c,d)}$	✓
Unimicron	✓	✓	✓ $^{(e)}$	✓
Innolux	✓	✓	✓ $^{(d)}$	✓
Nuvoton	✓	✓	✓ $^{(a,e)}$	✓
Lextar	✓	✓	✓ $^{(c,d)}$	✓
Everlight	✓	✓	✓ $^{(c,d)}$	✓
Optotech	✓	✓	✓ $^{(c,d)}$	✓
Wafer Works	✓	✓	✓ $^{(f)}$	✓
Siliconware Precision Industries	✓	✓	✗	✗
Foxsemicon Integrated Technology	✓	✗†	-	✗
Orient Semiconductor Electronics	✓	✗†	-	✗
Macronix	✓	✗†	-	✗
AUO	✓	✗	–	✗
Global Foundries	✓	✗	–	✗
Micron Memory Taiwan	✓	✗	–	✗
Merck Performance Materials	✓	✗	–	✗
Panjit	✓	✗	–	✗
Lite-On Semiconductor	✓	✗	–	✗
Delta Electronics	✓	✗	–	✗
Advanced Semic. Engineering Inc.	✓	✗	–	✗
Tatung Corp	✓	✗	–	✗
Acer	✓	✗	–	✗
Elan Microelectronics	✓	✗	–	✗
Formosa Sumco Technology	✓	✗	–	✗
Chipbond	✓	✗	–	✗
Gudeng Precision	✗	–	–	✗
Episil	✗	–	–	✗
ProMOS	✗	–	–	✗
Taiwan Semi	✗	–	–	✗
Arima Optoelectronics	✗	–	–	✗
AWSC	✗	–	–	✗
SAN CHIH Semiconductor	✗	–	–	✗
Creative Sensor Inc.	✗	–	–	✗
Visera Technologies (Part of TSMC)	✗	–	–	✗
Episil	✗	–	–	✗
Creating Nano	✗	–	–	✗
Episil-Precision	✗	–	–	✗
Sun Yuan Technology	✗	–	–	✗
U-Can Dynatex	✗	–	–	✗
Ofuna Technology	✗	–	–	✗
Cin Phown Technology	✗	–	–	✗
Davicom Semiconductor	✗	–	–	✗
Holtek Semiconductor	✗	–	–	✗
Realtek Semiconductor	✗	–	–	✗
WiseChip Semiconductor	✗	–	–	✗
Unikorn Semi	✗	–	–	✗
Sigurd Microelectronics	✗	–	–	✗
Mosel Vitelic	✗	–	–	✗
Kneron	⊖	–	–	✗
Green Energy Technology	✗	–	–	✗
Sino-American Silicon Products	✗	–	–	✗
Hexawave	✗	–	–	✗
COUNT: 60	33	20	19	**16**

✓ : Yes ✗: No ⊖ : not relevant †: not enough data - : not checked
(a) : IC (b) : Disc. (c) : LED (d) : Oth. Opto. (e) : Oth. Elec. (f) : Wafer

D. Data Collection

The list of ECMs selected in this study has been obtained by cross-referencing databases from two industry associations, namely the Taiwan Semiconductor Industry Association [19] and the SEMI Global industry association for electronics manufacturing and design supply chain [20]. The research criteria used to identify ECMs with industrial activities belonging to the scope of this study were: ”Manufacturing”, ”Semiconductor”, ”Photonics” as activity, and ”Taiwan” as location. A total of 60 companies fulfilled these criteria, but only 33 of them had published environmental data in CSR reports and 20 had disclosed location-based data specific to Taiwan. In the end, the sample contains

16 companies with workable data, as shown in Table I. Overall, the 16 companies selected represent 97% of the total revenues of Taiwanese IC manufacturers and 53% of the electronics industry in Taiwan [21].

After the selection of the relevant Taiwanese ECMs, we created a dataset by compiling their environmental impacts using the annual CSR reports from each company over the period 2015-2020. Thanks to the Global Reporting Index standards [22], compliant CSR reports now contain company-specific data about the three selected environmental indicators. More details are provided as Supporting Information. We selected the 2015-2020 period because environmental data reporting became more widespread for Taiwan's industry since 2015, and because CSR reports for the year 2021 were not yet available at the time of writing. Let us mention that, in the Taiwanese ecosystem, the company TSMC is by far the largest semiconductor manufacturer, with a revenue in 2021 of NT$ 1,587 billions. As a comparison, UMC (which is the second largest EMC on the island) only attained a revenue of NT$ 213 billions that year [21]. Since the production of TSMC dwarfs those of other manufacturers, its contribution to the aggregated values is shown separately from the other ECMs to provide a more fine-grain analysis of the overall environmental trends. Finally, in Sections III and IV, we also used public data provided by the Taiwanese government and by the energy provider Taipower, which is the main supplier of electricity for the electronics sub-sector. In fact, Taipower reports the electricity consumption of this sub-sector under a category named *Electronic Components Manufacturers* [23].

III. Results

A. GHG Emissions

We first present the evolution of the GHG emissions from the sample of ECMs under study. Figure 2(a) shows the GHG emissions belonging to Scopes 1 and 2 and the compound annual growth rate (CAGR) to evaluate the annual rate of increase[3]. The data shows a strong 43.3% increase of GHG emissions during the period 2015-2020, which corresponds to a CAGR of +7.5%. Although TSMC significantly contributes to the overall trend (CAGR of +10.2%), the share of GHG emitted by the other ECMs in the sample also clearly increased, with a CAGR of +5.0%.

Among the overall GHG emissions, the indirect emissions linked to energy purchases (and in particular electricity consumption) largely dominate, with shares that vary between 75.9 and 79.4% over the years. The remaining 20.6-24.1% of Scope 1 emissions are hence direct emissions released from the EMCs facilities, including on-site electricity generation and emissions of high GWP gases such as fluorinated compounds (e.g., SF_6, NF_3, CF_4, CHF_3), that are used for processing or maintenance steps in the manufacturing processes [5], [24]. Yet, it can be observed in

[3]Note that a CAGR of +15% over the period under study (i.e., 5 years) corresponds to a doubling of the corresponding environmental impact.

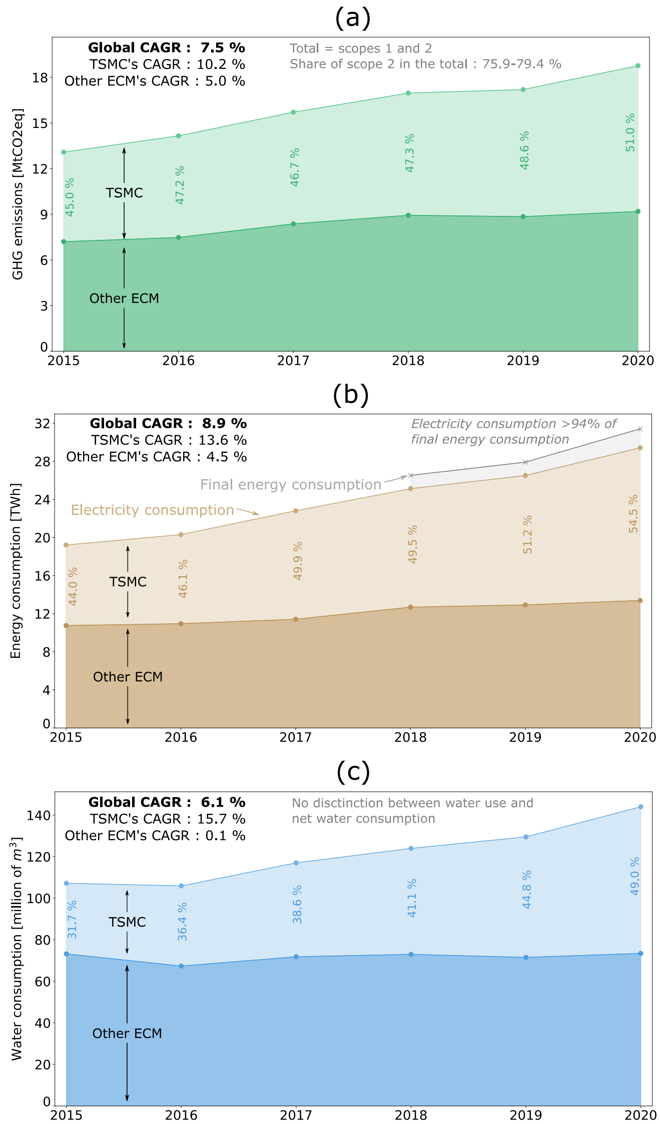

Fig. 2. Absolute environmental impacts for the ECMs considered in this study, over the period 2015-2020. The distinction is made between TSMC and the other ECMs (the percentages indicate the share of TSMC's emissions). (a) GHG emissions (Scopes 1 and 2). (b) Energy and electricity consumption. CAGRs are given for the electricity consumption. (c) Water consumption. Underlying data are available in Table *Summary* of Supporting Information S1.

the Supplementary Information that for most ECMs, Scope 2 emissions increase much faster than those of Scope 1. In fact, Scope 2 emissions of TSMC increased by 72% over the studied period, whereas its Scope 1 emissions grew only by 37%. For UMC, Scope 1 emissions even decreased by 13% while Scope 2 emissions increased by 10%. This could be explained by different factors, such as the use of more efficient abatement systems to mitigate the direct emissions of fluorinated compounds, the use of process recipes with less GHG emissions, or even GHG emissions with lower GWP. In fact, equipment continue to evolve with the latest and most efficient abatement systems reaching destruction removal efficiency (DRE) between 95% and 99% for the most critical gases [24]. Nonetheless, reaching higher DRE

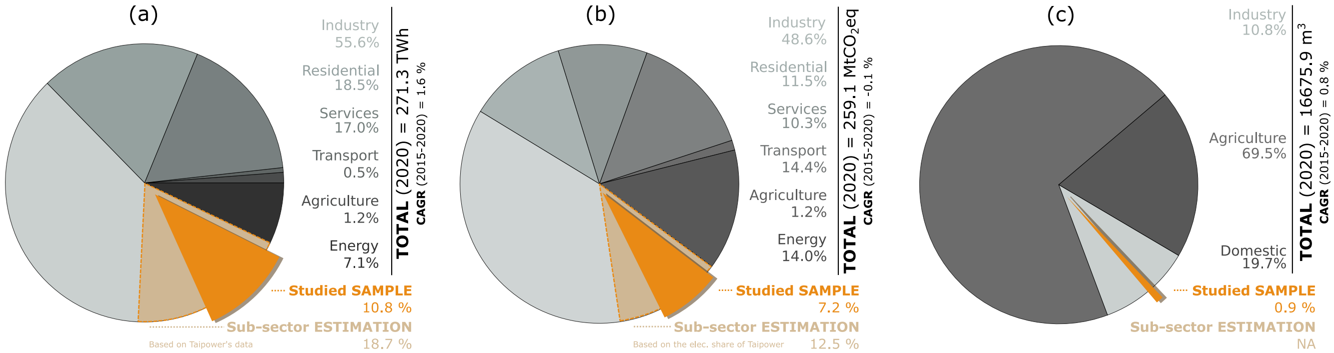

Fig. 3. Shares of (a) electricity consumption, (b) GHG emissions, and (c) water consumption in 2020 for the different Taiwanese sectors. The contribution of the sample of ECMs belongs to the electronics sub-sector, which itself is part of to the industrial sector. Underlying data are available in Tables *Summary*, *Energy*, *GHG*, and *Water* of Supporting Information S1.

may require higher energy consumption (depending on the abatement system that is used), hence increasing Scope 2 emissions.

B. Energy and Electricity Consumption

Since indirect emissions due to energy purchases dominate the overall GHG emissions of Taiwanese ECMs, it is also crucial to study the evolution of their energy consumption. Figure 2(b) shows that the final energy consumption of the 16 ECMs in the sample has increased by 18.4% over 3 years[4], corresponding to a CAGR of +8.8%. In particular, TSMC accounts for more than half of the energy consumption among the sampled ECMs and has increased its final energy consumption by 90% over the last five years. Similarly to Pirson et al. [6], we observe that electricity is the main source of energy for ECMs, with shares greater than 94% of their final energy use. As shown in Figure 2(b), the total electricity consumption has increased by 53.3% over the studied period, yielding a CAGR of +8.9%. This trend is observed for all but two ECMs: only Lextar and Nuvoton have slightly reduced their electricity consumption between 2015 and 2020, respectively with -29% and -8%. Unfortunately, these improvements have no effect on the overall trend, as they are achieved by non-dominant actors. The joint analysis of both Figure 2(a) and Figure 2(b) indicates that the GHG emissions of the studied ECMs are strongly correlated to their electricity consumption [3].

C. Water Usage

In this section, we present the aggregated water use for the ECMs under study. Figure 2(c) shows that it increased by 34.4% over 6 years, corresponding to a CAGR of +6.1%. However, in this case the growth comes exclusively from TSMC, which increased its consumption by 108% over the period under study. This highlights that even though three EMCs have reduced their water consumption between 2015 and 2020 (namely Innolux with -16%, Unimicron with -20%, and Winbond with -48%), these savings have almost no effect on the aggregated value because of TSMC's considerable increased water usage.

[4]Five ECMs did not report their final energy consumption from 2015 to 2017, but well their electricity consumption. We hence show the total final energy consumption only for the period 2018-2020.

D. Comparison with the environmental footprint of Taiwan and Taiwanese sectors

We finally compare the aggregated environmental footprint of the 16 ECMs with the environmental footprint of other Taiwanese sectors for the year 2020. This comparison allows for a better understanding of the environmental footprint of ECMs at the industrial level, but also with respect to the whole island of Taiwan. Figure 3(a) shows the proportions of each sector in the Taiwanese electricity consumption, based on annual reports from the Taiwanese Ministry of Economic Affairs [25] and Taipower. The industry represents 55.6% of the total electricity consumption on the island, with the electronics sub-sector using 18.7% of the same total consumption, according to Taipower. The sample of 16 ECMs accounts for 10.8% of the island electricity budget. The important weight of the sample in the sub-sector (56 to 70%) indicates that, despite studying only 16 out of the 60 Taiwanese ECMs, the set of selected companies still represents a significant part of the targeted sub-sector thanks to major actors such as TSMC or UMC.

Regarding the GHG emissions, the industrial sector is responsible for 48.6% of the 259.1 Mt of CO_2eq released in Taiwan during 2020 [25]. In this sector, the sample of 16 ECMs represents 7.2% of the annual emissions, as depicted in Figure 3(b). Since there are no official statistics for the GHG emissions specific to the electronics sub-sector, we propose the following method to extrapolate the carbon footprint of the sub-sector from the sample. We previously observed that the studied ECMs have GHG emissions strongly correlated to their electricity consumption, since the Scope 2 of these companies outweighs their Scope 1 emissions [26]–[28]. Therefore, we assume that GHG emissions of all Taiwanese ECMs are strongly correlated with their electricity consumption and we estimate the GHG emissions of the entire electronics sub-sector by scaling the aggregated GHG emissions from the sample according to its share in the overall electricity consumption of the sub-sector disclosed by Taipower,i.e., 57.9%. This extrapolation yields an estimated share of 12.5% of Taiwan's GHG emissions. This confirms the important responsibility of the Taiwanese ECMs in the GHG emissions of the island, which has also been acknowledged in [3]. The limitations of the proposed extrapolation method are discussed in the Supporting Information, together with all data and calculations.

Finally, Figure 3(c) also shows the proportional share of the studied ECMs with respect to Taiwan's total water usage. The 16 ECMs surprisingly consume only 0.9% of the water usage on the island, while the agricultural sector uses up to 70% of the total. Because we see no relevant method to extrapolate the water usage of the entire sub-sector with currently available information, we rather do not provide any extrapolation. Nevertheless, this is not expected to change the conclusion regarding the water footprint of ECMs on the island.

IV. Discussion

A. Correlations Between Environmental Indicators and Production Volume

We observed in Section III that all three environmental indicators of 16 Taiwanese ECMs have significantly increased over the period under study. Possible explanations for these trends could reside in an increase in the production volume and/or in an increase of the resource intensity per component over the years [29]. To obtain a better insight over these dynamics, Figure 4 depicts the normalized evolution of the three aggregated indicators and of the number of manufactured ICs in Taiwan from 2015 to 2020, according to data from the Ministry of Economic Affairs [30]. We focus specifically on the manufacturing of ICs because it was not possible to match perfectly the scope of our study with the available data from the Ministry of Economic Affairs. Nevertheless, Table I points out that a significant share of companies under study are specialized in IC manufacturing. We observe that the number of ICs produced in Taiwan follows an upward trend which is very similar to the trend of the indicators in this study. Albeit further work is needed to properly identify the main reasons behind the rise of the environmental indicators of Taiwanese ECMs, all three indicators are clearly correlated to the production volume. These correlations raise questions regarding the (environmental) sustainability of the Taiwanese electronics industry. Indeed, they suggest the impossibility of an absolute decoupling between production volume and environmental impacts (in particular GHG emissions) [29].

B. Territorial Constraints of Taiwan for Electricity and Water Supply

In this section, we use a geographical approach to highlight how the territorial constraints of the island can impede the long-term sustainability of the Taiwanese electronics industry. More specifically, we further analyze the electricity generation and water supply in Taiwan, given their central role for ECMs. The following discussion should hence be

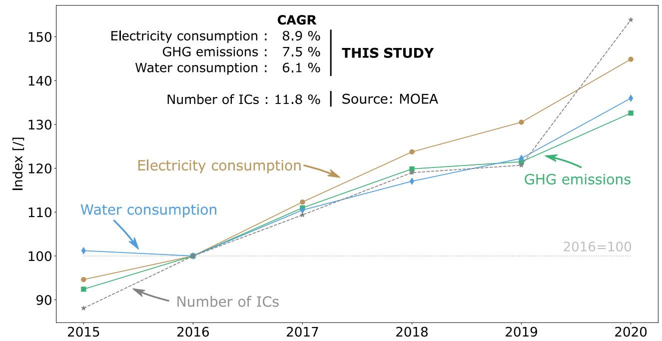

Fig. 4. Evolution of the environmental indicators obtained in this study and of the ICs manufactured in Taiwan over the period 2015-2020. All data is normalized with respect to 2016, i.e., 2016=100. Underlying data are available in Table *Summary* of Supporting Information S1.

considered with Taiwan's geography in mind. Taiwan is a small country (36,197 km^2) with a mostly mountainous terrain on the eastern side of the island, as shown in Figure 5. Because of this particular geography, most of the population is gathered on flat regions near the west coast, with a density around 650 residents/km^2 for a total of 23 million people in Taiwan [31]. Consequently, urban areas, industries, as well as energy and water sources tend to be concentrated in the same areas.

We observed in Section III the correlation between GHG emissions and electricity consumption, which stems from the fact that electricity in Taiwan is mainly generated from highly carbon-intensive energy sources such as coal (45%), natural gas (36%) and oil (2%) while nuclear (11%) and renewable energies have much smaller contributions (6%) [32], [33]. On the topic of electricity production, the Taiwanese government plans to phase out nuclear power and to produce 20% of its electricity from renewable sources by 2025 [34], under the so-called *2017 Electricity Act*. Yet, with only 9.47 GW of renewable energy capacities installed in Taiwan (including 5.82 GW from photovoltaic power and 0.85 GW from onshore and offshore wind power) [33], 15.12 TWh of electricity were generated in 2020 whereas the sole electronics sub-sector consumed 50.73 TWh. Due to the limited usable space on the island, the Taiwanese government mainly counts on offshore wind turbines in the future, with a target capacity of 5.7 GW by 2025. However, only 0.13 GW have been installed as of June 2021 [34]. The Taiwanese topography hence impedes the future development of renewable energies on the island, which suggests that it will be extremely challenging for Taiwan to decarbonize its electricity production [3], [33].

Analyzing Taiwan's geography is also crucial to understand the water management and the water storage infrastructure on the island. Since water is much more difficult to transport than electricity, water shortages are often restricted to specific regions and an aggregated value at the island level does not convey this reality. In fact, although ECMs do not represent a significant part of Taiwan's water intake at first sight, the industry rely on a limited number of reservoirs located in places of very high population density as depicted

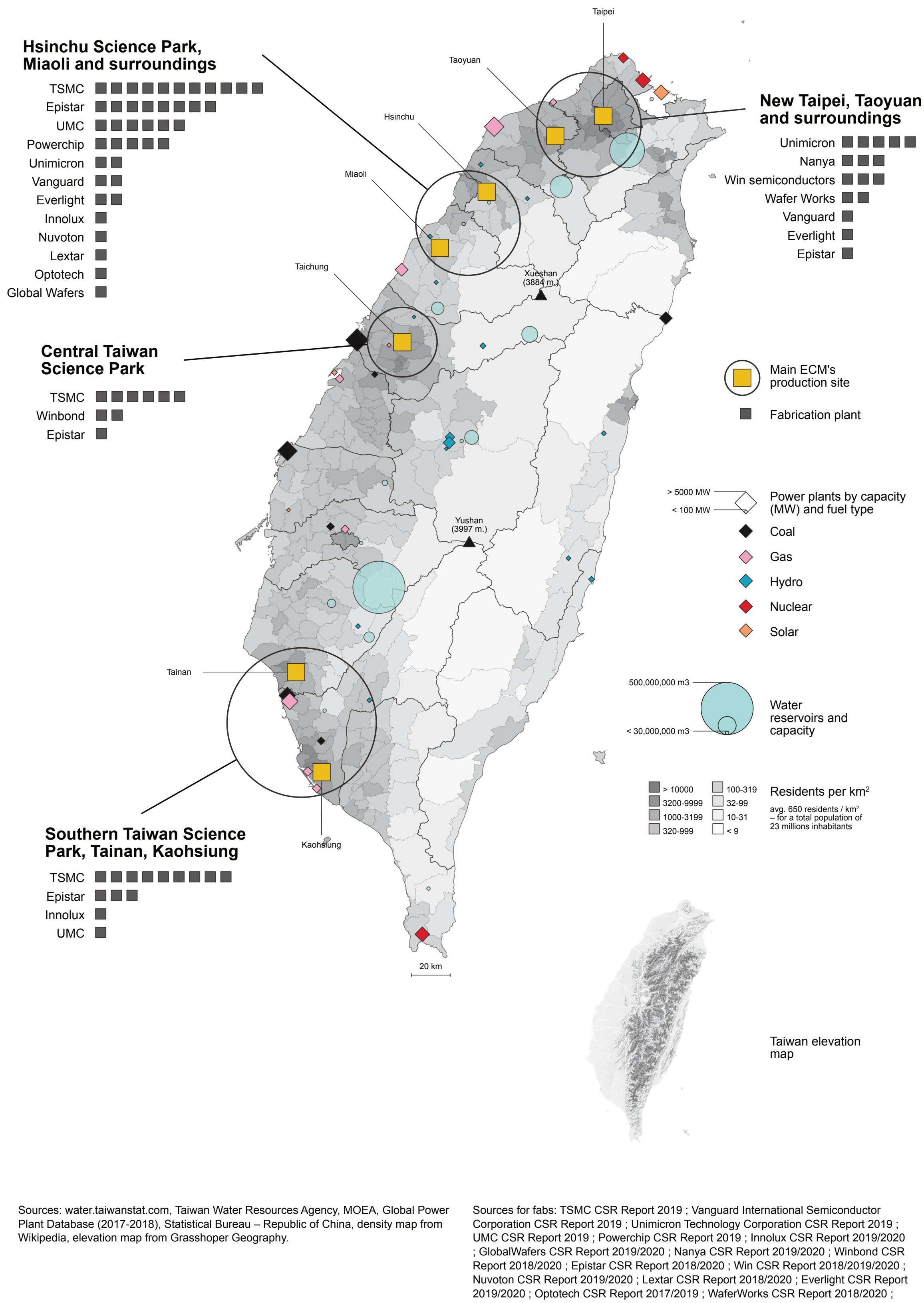

Fig. 5. Location of companies considered in this study together with power plants and water reservoirs compared to population density.

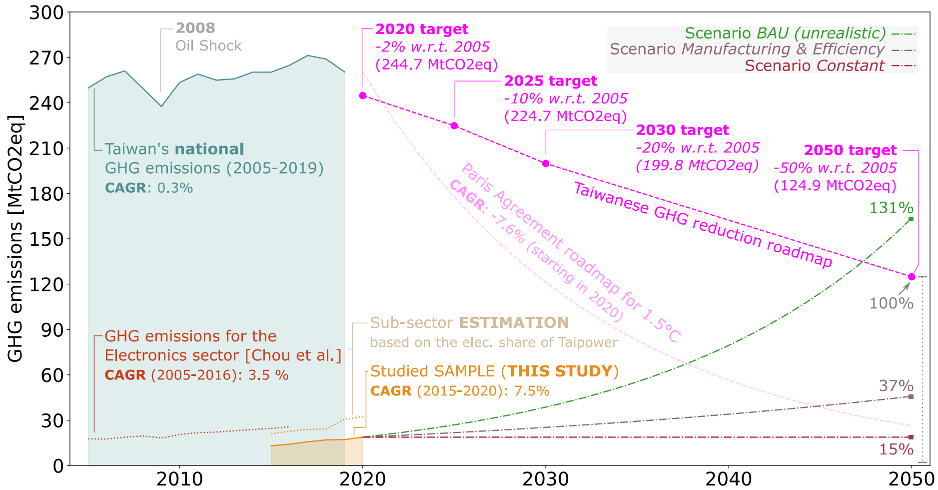

Fig. 6. Scenario analysis for ECMs' GHG emissions in Taiwan from 2020 to 2050. Perspectives regarding Taiwan's GHG emissions and the Taiwanese carbon reduction roadmap. The share of each scenario with respect to the total carbon budget in 2050 is given on the bottom right. Underlying data are available in Table *Pathways* of Supporting Information S1.

in Figure 5. For instance, TSMC's factories in Hsinchu Science Park use about 10% of the daily supply from Baoshan and Second Baoshan reservoirs whereas those located at Southern Taiwan Science Park use slightly more than 5% of the daily supply from Nanhua and Zengwen reservoirs [26]. If ECMs were already facing stress in the water-intensive production chain, the 2021 drought seriously amplified the crisis in this key sector of the island. As an example, TSMC relied that year on hundreds of water trucks to maintain its water supply while several restrictions where being taken in Taiwan [35]. This could be seen as an early sign of the incoming risks for this high-tech industry. In that sense, Taiwanese ECMs share a liability regarding water supply due to the increasing and spatially concentrated demand in the Science Parks as further discussed in [36]. Moreover, let us mention that the water footprint of the electronics industry goes beyond water use: pollution and contamination of watercourses, supply sources and waste treatment have been a problem in Taiwan since the 1980's [12] and are still recurring today with heavy metal contamination of rivers near industrial areas [37].

C. *Perspectives With Respect To Taiwan's Climate Roadmap*

While Taiwan's GHG emissions ranged from 238 to 271 MtCO2e between 2005 and 2019, the country plans to decrease GHG emissions compared to 2005 by 20, 30, and 50% in 2025, 2030, and 2050, respectively. Consequently, the 2050 GHG emissions target is about 125 MtCO2e for Taiwan (steeper reductions will be needed if reductions are delayed), as illustrated in Figure 6. Yet, Figure 6 also shows that the Taiwanese roadmap is significantly least demanding than exponential reduction pathways to reach the 1.5°C target [38]. Nonetheless, Taiwanese ECMs will have to mitigate their GHG emissions to contribute to Taiwan's climate targets. In this section, we study three simplified scenarios to explore how the evolution of the GHG emissions from the electronics sub-sector can impact the Taiwanese climate roadmap. In general, projections for the environmental footprint of electronics rarely look ahead by more than 15 years mainly because of the high uncertainty regarding the evolution of technology and uses [39], [40]. Nevertheless, the Taiwanese roadmap proposes a GHG reduction pathway until 2050 which motivates a long-term projection in this case. We do not assume improvements or degradation of the efficiency of manufacturing processes, since such hypotheses strongly depend on the type of products that are considered. In addition, the scenarios consider values from the sample of 16 ECMs for the year 2020, and not the extrapolated value for the whole sub-sector, which is a conservative approach.

The first scenario aims at illustrating the GHG emissions that would result from a *business as usual* (BAU) policy. It assumes that both the demand for Taiwanese electronics (i.e., production volume) and the GHG emissions of EMCs will increase at the same pace than observed for the sample under study over the period 2015-2020, resulting in an overall CAGR of 7.5% for the GHG emissions. Even if this scenario is clearly unrealistic[5], it illustrates that maintaining the current pace of development is incompatible with Taiwan's climate targets. The carbon footprint of the ECMs sample would indeed surpass the total carbon budget of Taiwan in 2050.

The second scenario called *manufacturing & efficiency* assumes the evolution of production volume and GHG emissions as depicted by Chou et al. [3] for the electronics sector over the period (2005-2016), i.e., an overall CAGR of 3.5%. In addition, this scenario also assumes best-effort improvements by Taiwanese electricity suppliers such that the carbon intensity of electricity decreases by 0.6%/year, as suggested in [3]. We apply these improvements only on Scope 2 as they are associated with electricity consumption.

[5]It is extremely unlikely that Taiwan could continue to produce an ever-growing number of components at an exponential pace when considering practical constraints, especially when considering the energy consumption.

This scenario illustrates that the carbon footprint of the sample would reach up to 37% of the available carbon budget for 2050, which is significantly higher than today.

Finally, the last scenario considers that the ECMs keep their absolute carbon footprint unchanged from 2020 onward, independently of the evolution of the production volume and the electricity carbon intensity. In this *constant* scenario, the emissions from the sample of ECMs would represent about 15% of the total carbon budget in 2050.

Generally, the results in Figure 6 point out the inconsistency between the GHG emissions from the electronics sub-sector and Taiwan's GHG roadmap. Indeed, following the different scenarios, at least 15% to 37% of the 2050 carbon budget would be allocated to the manufacturing of electric components. These percentages should even be revised upwards when considering the entire sub-sector. In all cases, this analysis clearly highlights the difficult upcoming arbitration that will be needed if ECMs cannot decrease their GHG emissions.

D. Towards a Potential Carbon Lock-in in Taiwan

The previous discussions suggest that there is a very low likelihood for Taiwanese ECMs to fully decarbonize their manufacturing in a foreseeable future. We finally argue that this sub-sector is likely to suffer from a *carbon lock-in*. A carbon lock-in describes a situation where, in an economical context of returns to scale, both public institutions and private actors drastically inhibit the competitiveness and roll-out of low-carbon alternatives [41].

We first point out that the Taiwanese geopolitics and economy are mostly centered around its electronics industry. The Taiwanese *silicon shield* is a well-described geopolitical strategy against the ambitions of mainland China on the island. This strategy relies on being a worldwide leading supplier of electronic components, enabling to seek the military protection of the United States [42]. To reach this crucial leading position, the Taiwanese government fostered the electronics industry by creating the original model of Science Parks, and keeps to heavily subsidizing it [43]. In return, leading Taiwanese ECMs have also committed substantial investments, e.g., TSMC is investing up to 44 billion USD in 2022 to increase production and R&D efforts [44]. Indeed, the technological path towards advanced sub-10nm technologies implies new industrial processes such as EUV lithography and the development of more processing steps to continue technology scaling. From an environmental perspective, the footprint of the industry is hence likely to increase if both growth of production volume and aggressive scaling are pursued at the same time. In fact, even if EUV lithography replace several key processing steps of deep ultraviolet (DUV) processes needed to achieve the same critical dimensions, the energy consumption from EUV processes is more than ten times that of DUV processes [26]. The development of advanced CMOS sub-10nm technologies is hence expected to increase electricity consumption compared to current mainstream

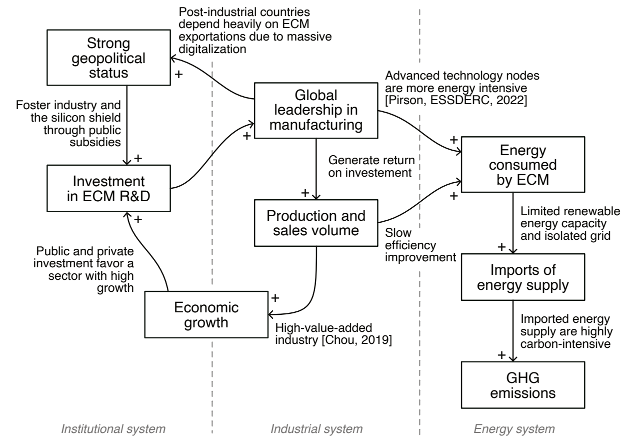

Fig. 7. Illustration of the techno-institutional complex fostering a lock-in on carbon-intensive energy sources.

manufacturing processes [5], [6], [45]. At the same time, the geographical analysis previously discussed showed the difficulties for Taiwan to conduct a large-scale deployment of renewable energies in the short and medium-term. We therefore expect that a further grow of the production volume of ECMs will require increasing imports of high-carbon energy supplies. When considering these interactions together, it becomes apparent that the Taiwanese electronics industry could remain a carbon-intensive activity for the moment, as illustrated in Figure 7.

E. Perspectives for semiconductor manufacturing relocalization

Assessing the sustainability of semiconductor manufacturing is not only important for Taiwan itself, but also for Western economies. Indeed, both the USA and the EU are currently massively investing to relocate advanced manufacturing processes on their own soil [46], while committing at the same time to strong carbon reduction targets. With investments about 40+ billion Euros in the context of the 2022 *European Chips Act* [47], it is clear that the EU expects to eventually produce chips in European foundries in order to secure its electronics supply chain and boost its competitiveness through digitalization. This is further supported by the recent chip shortage [46], which revealed the increasing pressure on current production systems and the technological dependence of Western economies. Nevertheless, the Association for Computing Machinery (ACM) stressed the striking lack of environmental considerations in the EU Chips Act, the important risk of rebound effects and the absence of consideration for the carbon emissions linked to the unrestrained growth in demand for computation [48]. It is therefore of critical interest to understand to which extent engaging into the relocalization of electronics manufacturing industry could impact the EU carbon reduction plans, especially if it focuses on the manufacturing of advanced semiconductor technologies [6]. From this analysis specific to Taiwan, lessons can be learned for other countries that want to develop a sub-10nm industry. While Taiwan suffers from carbon-intensive energy sources and a constrained territory, the European Union could establish its future industry in places where power is less carbon-intensive and can also disperse its plants to avoid concentrated needs of resources such as water and energy. Nevertheless, such advanced foundries will undoubtedly require qualified professional staff in sufficient numbers which tends to favor locations close to metropolitan centers rather than in remote places. Last but not least, having this industry relocated in Europe will likely come together with strict environmental legislation and constraints, which strongly supports the need for an in-depth monitoring of the environmental impacts. Finally, the growth rate of the semiconductor industry's environmental footprint observed in Taiwan (in particular at TSMC) should also question the technological choice of CMOS technology nodes to be manufactured. More research has to be done on this matter.

V. Conclusions

In this study, we first show that the absolute environmental impacts of the electronic components manufacturing industry in Taiwan are on the rise for each indicator over the period 2015-2020, despite the (relative) efficiency improvements claimed by the industry and the strong efforts to develop state-of-the-art manufacturing technologies. An increasing trend is observed for final energy consumption, electricity consumption, GHG emissions, and water consumption, with a CAGR of respectively 8.8%, 8.9%, 7.5%, and 6.1%. Then, we use a geographical approach to account for constraints regarding the stresses introduced on the production infrastructure and how they impact the sustainability of Taiwan's electronics industry. Through a scenario analysis, we highlight the conflicting trends between the ECMs' growing carbon footprint and the carbon neutrality roadmap outlined by the Taiwanese government up to 2050. As a quick switch to low-carbon energy sources still seems out of sight on the island, and because of the high energy intensity of the manufacturing processes, Taiwanese semiconductors components are therefore expected to remain with a relatively high carbon footprint for a long time. In fact, we argue that Taiwan could be in a carbon lock-in situation, which raises serious concerns regarding its ability to succeed in its ecological transition.

This study can be seen as a first attempt to lay the foundations for an urgent work of monitoring for the environmental footprint of ECMs. In fact, this study already gathers enough data to cover a significant part of the ECM industry on the island of Taiwan, i.e., 56 to 70%. Yet, further work could build upon this work to extend the scope, improve the accuracy, and include more companies. We also point out that the open-data culture in Taiwan is a real opportunity to develop an in-depth understanding of ECMs' environmental footprint, albeit ECMs' CSR reports should provide more details in the reporting of their environmental impacts.

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Supporting Information

Supporting information is linked to this article on the JIE website. Supporting Information S1 provides all the data and calculations used in the article, i.e., a list of the companies assessed, their GHG emissions (Scopes 1 and 2), water usage, and energy consumption reporting from 2015 to 2020, the production index of ICs in Taiwan, additional details on the carbon reduction pathways, and finally known limitations of this study.

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