

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, the sustainability of the Taiwanese electronics industry is therefore of critical interest. In this paper, we survey the environmental footprint of 16 Taiwanese electronic components manufacturers (ECM) using corporate sustainability responsibility reports (CSR). Based on data from 2015 to 2020, this study finds out that our sample of 16 manufacturers increased its greenhouse gases (GHG) emissions by 7.5% per year, its final energy and electricity consumption by 8.8% and 8.9%, and the water usage by 6.1%. We show that the volume of manufactured electronic components and the environmental footprints compiled in this study are strongly correlated, which suggests that relative efficiency gains are not sufficient to curb the environmental footprint at the national scale. Given the critical nature of electronics industry for Taiwan’s geopolitics and economics, the observed increase of energy consumption and the slow renewable energy roll-out, these industrial activities could create a carbon lock-in, blocking the Taiwanese government from achieving its carbon reduction goals and its sustainability policies. Besides, the European Union, the USA or even China aim at developing an industrial ecosystem targeting sub-10nm CMOS technology nodes similar to Taiwan. This study thus provides important insights regarding the environmental implications associated with such a technology roadmap. All data and calculation models used in this study are provided as supplementary material.

Index Terms—Sustainability, Digital, Semiconductors, Manufacturing, Electronics, Taiwan, Roadmap.

I. INTRODUCTION

OVER the last four decades, Taiwan has developed a strong ecosystem in semiconductor manufacturing, building a leadership position in packaging, foundries, 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 it is therefore not surprising that it significantly contributes to the economy of the island [3]. In fact, Taiwan’s semiconductor industry has witnessed double-digit growth for three consecutive years and is forecasted to reach more than 170 billion US dollars in 2022 [1]. The Taiwanese government heavily relies on the electronics industry for the next decades, as it plans on establishing several semiconductor initiatives and

R&D programs to support its growth [1]. In parallel, the Taiwanese government has issued a carbon reduction plan called the *Greenhouse Gas Reduction Action Plan*, with the objective of decreasing their absolute carbon footprint 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], their environmental impacts cannot be ignored. This study hence addresses the question whether the fast-paced development of the electronics industry in Taiwan is consistent with the national sustainability roadmaps.

Assessing the sustainability of semiconductor manufacturing is not only important for Taiwan itself, but also for Western economies as both the USA and the European Union (EU) are currently massively investing to relocate the manufacturing of advanced manufacturing processes on their own soil [7]. Indeed, the 2022 *European Chips Act* projects more than 43 billion Euros of investments up to 2030 [8]. It is clear that the EU aims at fostering a large digital innovation capacity based on a resilient semiconductor ecosystem. A key policy objective is to eventually bridge the gap from *lab to fab* by producing CMOS 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 [7] which revealed the increasing pressure on our production systems. However, the Association for Computing Machinery (ACM) recently 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 of ICT activities [9]. Although 195 countries have committed to strong carbon reduction targets by signing the 2016 Paris Agreement, the actual environmental impacts of electronic components over their whole life cycle is far from being thoroughly understood [10]. 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. In this context, analyzing the current Taiwanese situation can provide a good estimate of the environmental impacts associated with the development of current and future state-of-the-art electronic components, given that more than 90%

of the worldwide sub-10nm integrated circuits (ICs) are currently manufactured in Taiwan at TSMC [11], the *de facto* world leader in advanced ICs manufacturing.

In this study, we 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 multiple environmental indicators such as final energy and electricity consumption, greenhouse gases (GHG) emissions, and water consumption. Finally, we discuss the conflicting trends between the Taiwanese sustainability roadmap and the rapid electronics industry development, through a scenario analysis. In addition, we use territorial perspectives to point out the terrain-related constraints preventing the island to implement a quick ecological transition.

The rest of the paper is structured as follows. Section II presents similar studies and background while Section III depicts the methodology behind this work. Results are then presented in Section IV for each environmental indicator and compared with national and industry data. Section V discusses the link between increased production and environmental impacts, provides territorial perspectives, and details known limitations for this work. Finally, concluding remarks are given in Section VI.

II. BACKGROUND

The manufacturing of electronic components is an energy-intensive industry that heavily uses electricity, chemicals and water [4], [5]. Electronic components are manufactured on high-purity silicon substrates using pure raw materials in clean-rooms, i.e., isolated spaces in which the air is continuously cleansed [12]. Moreover, the fabrication processes often rely on perfluorocarbons (PFCs), gases that have a high global warming potential. These gases can however be abated (with abatement factors between 95–95% [5]) instead of being released in the atmosphere. Important quantities of electricity are needed to power the process tools, but also the facilities themselves (air ventilation and cleaning, water purification and cooling, ...) [13]. As an illustration, a life-cycle analysis studying the manufacturing of dynamic random access memories (DRAM) in Taiwan identifies global warming potential, non-renewable energy consumption but also the release of respiratory inorganics as major environmental impacts [14].

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. However, few works specifically look at the sustainability of this activity and the associated environmental impacts on the island. A part of the literature analyzes how individual Taiwanese semiconductor companies try to improve the sustainability of their activities. Hu et al. [15] 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. [16] propose a framework to evaluate the eco-efficiency and performance of a semiconductor company and apply it on several Taiwanese businesses. Hsu et al. [17] survey Taiwanese semiconductor companies that are part of the Dow Jones Sustainability Index (DJSI) and identify their practices for engaging with a sustainability index. Such studies however do not provide

an understanding of the overall environmental impacts of the semiconductor industry in Taiwan.

Among the rare studies that analyze nationwide the sustainability of the Taiwanese semiconductor industry, Chou et al. [3] provide the most 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].

On a broader perspective, Huang et al. [18] compute absolute environmental sustainability indicators that assess how Taiwan performs with respect to several planetary boundaries (e.g., P&N fertilizers, ocean acidification, freshwater use). This methodology is derived from the *carrying capacity* concept, i.e., the maximum environmental interference a natural system can withstand without experiencing negative changes in structure or functioning that are impossible to revert [19]. This study notably assesses the use of freshwater as high risk during the dry season in Southern and Central Taiwan, i.e., local natural boundaries regarding freshwater use are already exceeded in these parts of the island.

Incidentally, Chiu [20] provides a comprehensive history of environmental movement against high-tech pollution in Taiwan, which largely includes the electronics industry. The author shows the important advances of the civil environmental movement from 2006 to 2011 but points out difficulties for this movement to move forward without government support.

Amongst the reviewed papers, the only publication that attempts to provide a national overview of the environmental impacts of the electronics industry is Chou et al. [3]. Yet, the study only looks at GHG emissions and electricity consumption until 2016 using national aggregated data from government officials. The authors also only provide a partial insight of the sustainability of the electronics industry by comparing it to the petrochemical one, and the critical issue of the water usage is not addressed.

To overcome these limitations, we gather in this work data directly from the CSR reports of several Taiwanese semiconductor companies over the 2015-2020 period. Our data set enables a more fine-grain analysis of the evolution of the GHG emissions, electricity consumption and water usage of several Taiwanese ECMs. In addition, we use a territorial approach to account for geographical constraints regarding the stresses introduced on the production infrastructure. This particular approach eventually allows us to conduct an in-depth discussion on the sustainability of Taiwan's electronics industry.

III. METHODOLOGY

In this section, we first describe which manufacturing activities are part of the scope of this study, and we then introduce the three studied environmental indicators. We finally explain how we generated a data set for the selected indicators using the CSR reports from 16 ECMs.

A. Definition of the Study Scope

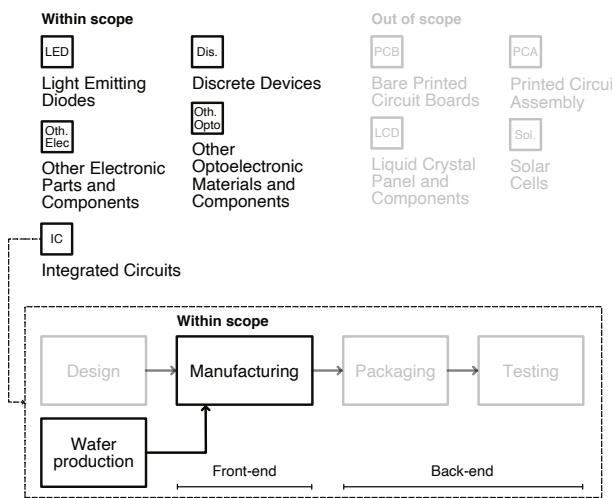


Fig. 1. Simplified view of semiconductor manufacturing processes and the scope of our study (classification based on Taiwanese Indexes of production).

Nowadays, ECMs manufacture a wide variety of electronic components with different technical specifications, which hence have different production processes. In this study, we restrict the analysis to the following categories of components, for which we were able to retrieve sufficient CSR data: integrated circuits (ICs), discrete devices, light emitting diodes (LEDs) and optoelectronic materials and components. Furthermore, these categories share similar manufacturing processes relying on the similar technologies, unlike printed circuit boards (PCBs) or liquid crystal panels (LCDs).

The manufacturing of the electronic components under study implies complex supply chains with several actors located in different countries. For instance, Figure 1 illustrates a simplified view of CMOS ICs manufacturing. The chain could be divided in two main parts, the front-end and the back-end processing. The front-end processing corresponds to the fabrication of the electronic components with a semiconductor process. Such process usually involves several hundreds of steps that modify the wafer to give it the desired electrical properties. In the back-end, the many circuits contained in a single processed wafer are cut into silicon dies and packaged in independent chips. The packaged chips are then finally tested. These stages usually take place at different geographical locations, involving transportation and operations by several companies. As a first step to map this complex ecosystem, we narrow down the scope of this study by excluding back-end processing which is generally less impacting than front-end manufacturing, as suggested by [21]. We further narrow the scope of this study by excluding design and raw material extraction as we focus exclusively on the environmental impacts of ECMs that are geographically located on the island of Taiwan. 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 supplementary material).

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	✓	✓	X	X
Foxsemicon Integrated Technology	✓	X†	-	X
Orient Semiconductor Electronics	✓	X†	-	X
Macronix	✓	X†	-	X
AUO	✓	X	-	X
Global Foundries	✓	X	-	X
Micron Memory Taiwan	✓	X	-	X
Merck Performance Materials	✓	X	-	X
Panjiti	✓	X	-	X
Lite-On Semiconductor	✓	X	-	X
Delta Electronics	✓	X	-	X
Advanced Semic. Engineering Inc.	✓	X	-	X
Tatung Corp	✓	X	-	X
Acer	✓	X	-	X
Elan Microelectronics	✓	X	-	X
Formosum Sumco Technology	✓	X	-	X
Chipbond	✓	X	-	X
Gudeng Precision	X	-	-	X
Episil	X	-	-	X
ProMOS	X	-	-	X
Taiwan Semi	X	-	-	X
Arima Optoelectronics	X	-	-	X
AWSC	X	-	-	X
SAN CHIH Semiconductor	X	-	-	X
Creative Sensor Inc.	X	-	-	X
Visir Technologies (Part of TSMC)	X	-	-	X
Episil	X	-	-	X
Creating Nano	X	-	-	X
Episil-Precision	X	-	-	X
Sun Yuan Technology	X	-	-	X
U-Car Dynatec	X	-	-	X
Ofuna Technology	X	-	-	X
Cin Phown Technology	X	-	-	X
Davicom Semiconductor	X	-	-	X
Holtek Semiconductor	X	-	-	X
Realtek Semiconductor	X	-	-	X
WiseChip Semiconductor	X	-	-	X
Unikorn Semi	X	-	-	X
Siguri Microelectronics	X	-	-	X
Mosel Vitelic	X	⊕	-	X
Kneron	X	-	-	X
Green Energy Technology	X	-	-	X
Sino-American Silicon Products	X	-	-	X
Hexawave	X	-	-	X
COUNT:	60	33	20	19
				16

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

B. Selection of the Environmental Indicators

We consider in this study three indicators that quantify the main environmental impacts of ECMs identified in Section II: GHG emissions, final energy consumption, and water usage. These indicators are nowadays often included in CSR reports. The GHG emissions of an ECM are quantified in kgCO₂-equivalent (kgCO₂eq). CSR reports follow the GHG Protocol Corporate Standard to report their GHG emissions [22]. 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 that occur in the value chain of the company, e.g., the emissions released by the refining of raw materials by a supplier. Since we conduct a territorial analysis that only comprises the environmental impacts on island of Taiwan, we exclude Scope 3 emissions

from our GHG indicator. On the contrary, since Taiwan is an island with an independent electricity grid (i.e., all the electricity is generated on the island), Scope 2 emissions are taken into account.

We will see in Section IV that most of the GHG emissions of Taiwanese ECMs are actually indirect emissions from the electricity production. It is therefore important to quantify the global energy usage (in TWh) of the industry, and in particular the electricity consumption. Our indicator combines both the final energy generated from fossil and renewable sources, as well as the energy obtained from electricity purchases. We notably discuss in Section V the proportional role of each energy source in the electronic components manufacturing in Taiwan.

Finally, our last indicator evaluates the amount of water in cubic meters (m^3) consumed by a company. Let us mention that 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. Reports rarely explicitly detail 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.

Nevertheless, even if the three aforementioned indicators already capture many aspects of the environmental impacts of semiconductor manufacturing, they fall short of providing an exhaustive picture of all environmental interference. 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 [20]. Further research on these issues is hence still needed.

C. 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 [23] and the SEMI Global industry association for electronics manufacturing and design supply chain [24]. Each database discloses a list of ECMs with their specific industrial activities. The research criteria used to identify ECMs belonging to our study scope were: "Manufacturing", "Semiconductor", "Semiconductor", "Photonics" as activity and "Taiwan" as location. A total of 60 companies fulfilled these criteria, but only 30 of them had published environmental data in CSR reports and 20 had disclosed location-based data specific to Taiwan. In the end, our sample contains 16 companies with workable data, as shown in Table I. The data set gathers mainly companies focusing on ICs, LEDs and optoelectronic components manufacturing.

After the selection of the relevant Taiwanese ECMs, we created a data set by compiling their environmental impacts using the annual CSR reports from each company. Thanks to the Global Reporting Index standards [25], compliant CSR reports now contain company-specific data about the three selected environmental indicators (GHG emissions, final energy and electricity consumption and water usage). For each company in our sample, we retrieved the values for the period 2015-2020 of the three indicators and compiled them in a database. This database is provided as Supplementary Materials. 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.

Finally, we conduct in Sections IV and V comparisons with the aggregated data from our sample with public data at the industrial and national levels provided by the Taiwanese government and by the national energy provider, Taipower.

IV. RESULTS

This section presents the aggregated data obtained from our sample of 16 Taiwanese ECMs, with respect to the three environmental indicators defined in Section III. For each indicator, the compound annual growth rate (CAGR) is given to evaluate its annual rate of increase. A CAGR of 15% over the period under study (i.e., 5 years) corresponds to a doubling of the corresponding environmental impact. The footprints of the electronics sub-sector are then compared to those of other Taiwanese sectors.

It is important to point out that, in the Taiwanese ecosystem, the company TSMC is by far the largest semiconductor manufacturer, with a revenue in 2020 of NT\$ 1,339 billions. As a comparison, the second largest EMC, UMC, only attained a revenue of NT\$ 176 billions during the same year [26]. Since the production of TSMC dwarfs those of other manufacturers, the contribution of TSMC to the aggregated indicators is shown separately from the rest of the sample to provide a more fine-grain analysis of the overall environmental trends.

A. GHG Emissions

We first present the evolution of the GHG emissions from the ECMs in our sample. Fig. 2 shows the GHG emissions belonging to the Scopes 1 and 2, i.e., the direct emissions and the indirect emissions due to purchased energy, respectively. The data shows a strong 43.3% increase of GHG emissions during the period 2015-2020 (+43.3%), 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 (i.e., Scope 2) largely dominate, with shares that vary between 75.9 and 79.4% over the years. We show next that the Scope 2 emissions originate from electricity consumption, which in Taiwan is mainly generated from highly carbon-intensive sources.

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., SF₆, NF₃, CF₄, CHF₃), that are used for processing or maintenance steps in the manufacturing processes [5]. Yet, very interestingly, it can be observed in the data that for most ECMs, Scope 2 emissions increase much faster than those of Scope 1. 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%. These trends indicate that Taiwanese ECMs tend to invest in efficient abatement systems to mitigate their direct emissions of fluorinated compounds. The latest and most efficient abatement systems reach abatement factors near 99%, whereas previous generations usually reached a 95% efficiency [5]. From these observations, it seems that a

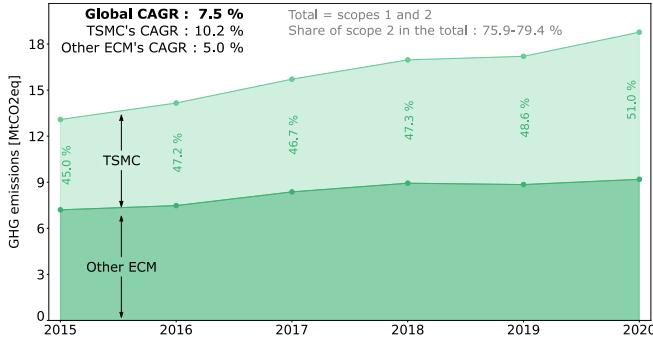


Fig. 2. GHG emissions (Scopes 1 and 2) over the period 2015–2020 for the ECMs considered in this study. The distinction is made between TSMC and the other ECMs (the percentages indicate the share of TSMC's emissions).

further decoupling of the volume of manufactured ICs from their direct GHG emissions will be very difficult and costly to achieve.

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. Fig. 3 shows that the final energy consumption of the 16 ECMs in our sample has increased by +18.4% over 3 years¹, 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. More importantly, we observe that electricity is the main source of energy for ECMs, with shares greater than 94% of the global final energy use. As shown in Fig. 3, 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 general trend as they are achieved by non-dominant actors.

The joint analysis of both Fig. 2 and Fig. 3 indicates that the GHG emissions of the studied ECMs are strongly correlated to their electricity consumption [3]. This correlation stems from the fact that electricity in Taiwan is mainly generated from highly carbon-intensive energy sources such as coal (45.3%), natural gas (36%) and oil (1.5%) while nuclear (11.2%) and renewable energies have much smaller contributions (5.9%) [27]. An abundant access to zero-carbon electricity will therefore be needed to reduce the indirect GHG emissions of Taiwanese ECMs. This issue is discussed in more details in Section V.

C. Global Water Usage

We now present the aggregated water usage for the ECMs belonging to our data set. We report in this section global values corresponding to the entire island of Taiwan. However, contrary to the previous indicators, water-related issues should rather be considered with a territorial approach. Since water is much more difficult to transport than electricity, water shortages are often restricted to specific regions and

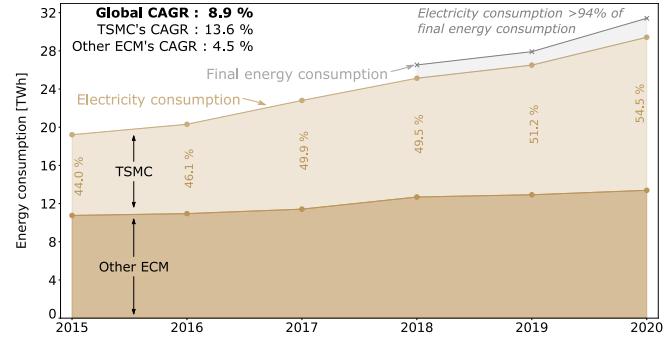


Fig. 3. Energy and electricity consumption over the period 2015–2020 for the ECMs considered in this study. The distinction is made between TSMC and the other ECMs (the percentages indicate the share of TSMC's emissions). CAGRs are given for the electricity consumption.

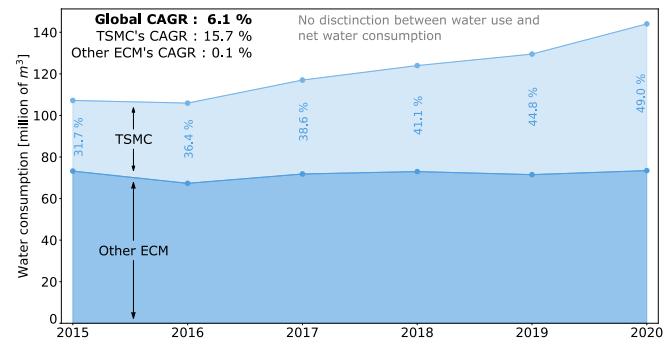


Fig. 4. Water usage over the period 2015–2020 for the ECMs considered in this study. The distinction is made between TSMC and the other ECMs (the percentages indicate the share of TSMC's emissions).

a global indicator does not convey this reality. We hence also conduct in Section V a territorial analysis of the water usage on the island of Taiwan, and its consequences for the semiconductor industry.

Figure 4 shows the amount of water consumed by the sampled ECMs. The global volume increased by +34.4% over 6 years, corresponding to a CAGR of +6.1%. This global increase comes exclusively from TSMC, which used 70.6 million m³ of water in 2020 and increased its consumption by 108% over 6 years. 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 global indicator because of TSMC's considerable increased water usage.

D. National and Industry-Wise Comparison

We finally analyze the aggregated environmental footprint of the 16 ECMs we studied by comparing it to the footprints of other Taiwanese sectors (industry, residential, services, transport, agriculture and energy) for the year 2020. This systematic comparison allows a better understanding of the importance of the environmental impacts of ECMs both at the industrial and national levels.

We first discuss the weight of electronics manufacturing in the overall Taiwanese electricity consumption. The Taiwanese Ministry of Economic Affairs reports annually the quantity of electricity consumed by each sector [28]. Fig. 5 shows the proportions of each sector in the Taiwanese electricity consumption. In addition, Taipower, the dominating electricity supplier for the electronics sub-sector,

¹Five 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

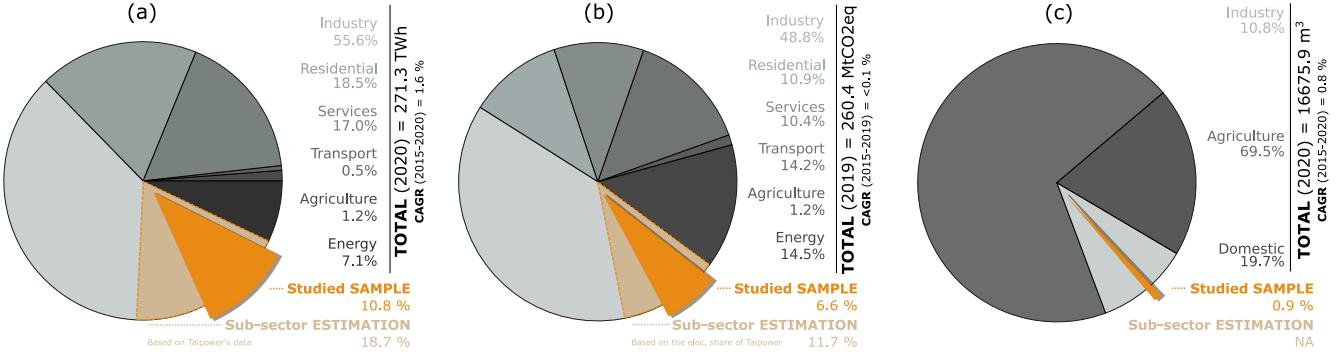


Fig. 5. National shares of (a) electricity consumption, (b) GHG emissions, and (c) water consumption in 2020 for the different Taiwanese sectors. The contribution of the ECMS from our sample belong to the electronics sub-sector, which itself is part of the industrial sector.

annually reports the electricity consumption of this sub-sector under a category named *Electronic Components Manufacturers* [29]. The industry represents 55.6% of the overall electricity consumption and, according to Taipower, its electronics sub-sector uses a striking 18.7% of the same national consumption. Our sample of 16 ECMS accounts for 10.8% of the national electricity budget, i.e., approximately a fifth of the entire sector. The important weight of our sample in the sub-sector (56 to 70%) indicates that, despite studying only 16 out of the 60 Taiwanese ECMS, our set of selected companies still represents a representative part of the targeted sub-sector thanks to major actors such as TSMC or UMC.

Regarding the emissions of GHG, the industrial sector is responsible for 48.8% of the 260.4 Mt of CO₂eq released in Taiwan during 2020. [28] In this sector, our sample of 16 ECMS represents 6.6% of the annual emissions. 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 our 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 [30]–[32]. By assuming that this correlation holds for all Taiwanese ECMS (they all rely on the same carbon-intensive electricity sources), we estimate the GHG emissions of the entire electronics sub-sector by scaling the aggregated GHG emissions from our sample, which represents 58% of the electricity consumed in the sub-sector, to the overall electricity usage disclosed by Taipower. This extrapolation yields an estimated annual share of 11.7% of the national GHG emissions. This result confirms the important responsibility of the Taiwanese ECMS in the national GHG emissions, which has also been raised in [3]. The limitations of the proposed extrapolation method are discussed in Section V-E.

Finally, Fig. 5 also shows the proportional share of the studied ECMS in the national water usage. We have no straightforward method to estimate the water usage of the entire sub-sector for this indicator. The 16 ECMS surprisingly consume only 0.9% of the national water usage, while the agricultural sector uses up to 70% of the total. Yet, as previously discussed, even if the national footprint of ECMS is only a small part of the total water consumption, their water usage is highly concentrated in a few Science Parks. We hence conduct a local territorial analysis in the next section to better assess the risks of water shortages for the

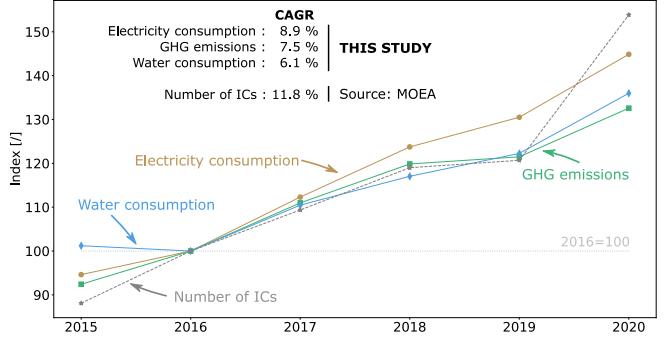


Fig. 6. Evolution of the environmental indicators obtained in this study and of the ICs manufactured in Taiwan over the period 2015–2020. All data is normalized with respect to 2016, i.e., 2016=100.

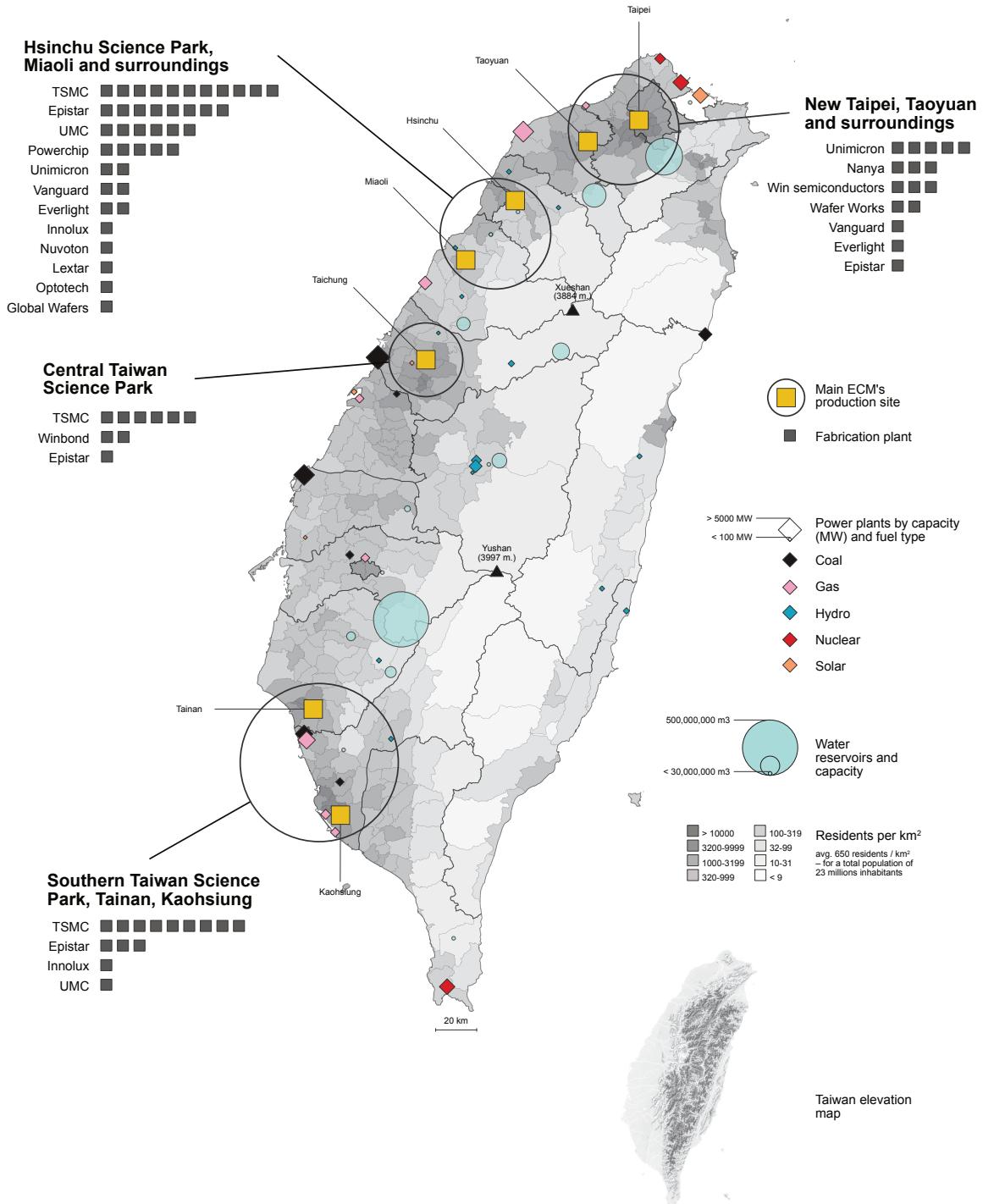
electronics sub-sector.

V. DISCUSSION AND TERRITORIAL ANALYSIS

In this section, we first compare the absolute increase of the environmental indicators highlighted in Section IV with national statistics of the production volume. We subsequently leverage the results of our study to question the fast-paced development of the Taiwanese semiconductor manufacturing sector and its consequences for the national climate roadmap. Finally, we discuss the limits of this study and we point out some blind spots in our analysis.

A. Correlations Between Environmental Indicators and Production Volume

We observed in Section IV that all three environmental indicators of 16 Taiwanese ECMS have significantly increased over the studied period. Possible explanations for these trends could reside either in an increase in the production volumes or in an increase of the resource intensity per component over the years. To obtain a better insight over these dynamics, Fig. 6 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 [33]. 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 our indicators. Albeit further work is needed to properly



Sources: water.taiwanstat.com, Taiwan Water Resources Agency, MOEA, Global Power Plant Database (2017-2018), Statistical Bureau – Republic of China, density map from Wikipedia, elevation map from Grasshopper Geography.

Sources for fabs: TSMC CSR Report 2019 ; Vanguard International Semiconductor Corporation CSR Report 2019 ; Unimicron Technology Corporation CSR Report 2019 ; UMC CSR Report 2019 ; Powerchip CSR Report 2019 ; Innolux CSR Report 2019/2020 ; GlobalWafers CSR Report 2019/2020 ; Nanya CSR Report 2019/2020 ; Winbond CSR Report 2018/2020 ; Epistar CSR Report 2018/2020 ; Win CSR Report 2018/2019/2020 ; Nuvoton CSR Report 2019/2020 ; Lextar CSR Report 2018/2020 ; Everlight CSR Report 2019/2020 ; Optotech CSR Report 2017/2019 ; WaferWorks CSR Report 2018/2020 ;

Fig. 7. Location of companies considered in this study together with power plants and water reservoirs compared to population density.

identify the main reasons behind the rise of the environmental indicators of Taiwanese ECMs, all three indicators are clearly correlated to the national production volume.

These correlations raise questions regarding the inherent sustainability of the Taiwanese electronics industry. Indeed, they suggest the impossibility of an absolute decoupling between production volume and environmental impacts, and in particular, of GHG emissions [34]. In addition, the development of advanced CMOS sub-10nm technologies could further increase the carbon intensity per component [10]. As an example, more advanced manufacturing technologies such as extreme ultraviolet lithography (EUV) are clearly expected to increase electricity consumption by approximately +50% compared to current mainstream manufacturing processes [3]. We thus discuss next whether Taiwan could sustain the development of its semiconductor industry while complying with their national carbon reduction plans.

B. Territorial Constraints of Taiwan for Electricity and Water Supply

To further study the long-term sustainability of the Taiwanese electronics industry, we now analyze the territorial constraints of Taiwan regarding renewable electricity generation and water supply. The following discussion should hence be considered with Taiwan's geography in mind. Taiwan is a small country ($36,197 \text{ km}^2$) with a mostly mountainous terrain on the eastern side of the island, as shown in Fig. 7. Because of this particular geography, most of the population is gathered on flat regions near the west coast. Even though the average population density is about 650 residents/ km^2 for a total of 23 million people in Taiwan [35], some urban regions of the island attain a population density greater than 10 000 residents/ km^2 . In additional, urban areas, energy and water sources and industries tends to be concentrated in the same areas. The Taiwanese topography suggests that the future development of renewable energies, as future industry facilities, is ultimately constrained by the remaining available space on the island.

We observed in Section IV that indirect emissions due to electricity consumption are the major source of global warming contribution from ECMs. Indeed, up to 97.5% of Taiwan's energy generation originates from imported carbon-intensive energy sources in 2020, including coal from Australia, Indonesia and Russia, crude oil from Saudi Arabia, Kuwait and US and liquefied natural gas (LNG) from Qatar, Australia and Russia [28]. Regarding specifically the production of electricity, the Taiwanese government plans to phase out nuclear power and to produce 20% of its electricity from renewable sources by 2025 [36], under the so-called *2017 Electricity Act*. Yet, renewable energy represented less than 6% of the power generation in 2020 [27], [37]. In fact, as of 2020, only 9.47 GW of renewable energy capacities have been installed in Taiwan (including 5.82 GW from photovoltaic power and 0.85 GW from onshore and offshore wind power) [37]. Renewable energies generated that year 15.12 TWh of electricity, 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. Yet, by June 2021, only 0.13 GW have been installed [36]. In addition, controversies related to the establishment of a full-scale offshore wind project have continued to occur since

mid-2017, undermining the shift towards renewable energy sources in the short term. It becomes hence extremely challenging for Taiwan to reach its 2025 targets and ultimately to decarbonize its electricity production [3], [37].

Analyzing Taiwan's geography is also crucial to understand the water management and the water storage infrastructure present on the island. Even if ECMs do not represent a significant part of the national water intake, they rely on a limited number of reservoirs located in places of very high population density as depicted in Fig. 7. For instance, TSMC's factories in Hsinchu Science Park use 10.3% of the daily supply from Baoshan and Second Baoshan reservoirs whereas those located at STCP (Southern Taiwan Science Park) use 5.3% of the daily supply from Nanhua and Zengwen reservoirs [30]. This concentration has already led to supply issues during droughts. In 2020, the island faced a drought caused by the absence of typhoons in the previous year. If ECMs were already facing stress in the water-intensive production chain, this drought seriously amplified the crisis in this key sector of the island. Indeed, TSMC relied that year on hundreds of water trucks to maintain its water supply while several restrictions where being taken at the national level [38]. In this sense, Taiwanese ECMs share a liability regarding water supply due to the increasing and spatially concentrated demand in the Science Parks.

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 total GHG emissions 2050 target for Taiwan is about 125 MtCO₂e, as illustrated in Fig. 8. This could be seen as the available Taiwanese carbon budget in 2050. Yet, the Taiwanese roadmap is based on linear reductions over 30 years, which is significantly least demanding than the exponential reduction in the roadmap that has been negotiated in the Paris Agreement for the 1.5°C target, i.e., a reduction of -7.6%/year if started in 2020 [39].

To contribute to the national target, Taiwanese ECMs will have to mitigate their GHG emissions. We study three scenarios depicted in Fig. 8 to assess the coherency of the GHG evolution from the electronics sub-sector with 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 [40], [41]. Nevertheless, the Taiwanese roadmap draws a GHG reduction roadmap up to 2050 which motivates a long-term projection in this case. Here, we only use conservative assumptions to design these scenarios. 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 use the 2020 values from our sample of 16 ECMs, and not the extrapolated value for the whole sub-sector.

The first scenario aims at illustrating the GHG emissions that would result from a *business as usual* (BAU) policy. It assumes that the GHG emissions of ECMs will increase at the same pace than observed for the sample under study over the period 2015-2020, i.e., with a CAGR of 7.5%. This scenario illustrates that maintaining the current pace of development is incompatible with the national climate

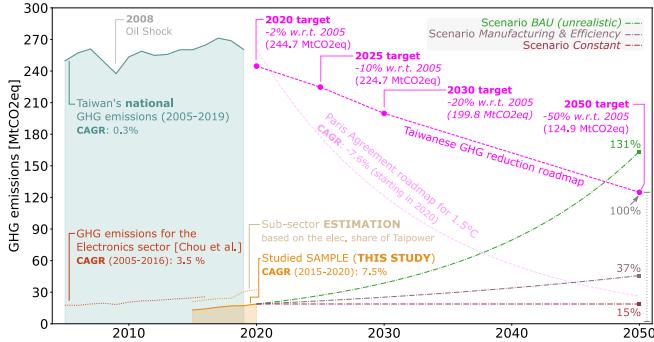


Fig. 8. Scenario analysis for ECMs' GHG emissions in Taiwan from 2020 to 2050. Perspectives regarding the national GHG emissions and the Taiwanese carbon reduction roadmap. The share of each scenario with respect to the total carbon budget in 2050 is given on the bottom right.

targets. The carbon footprint of the ECMs sample would indeed surpass the total carbon budget of Taiwan in 2050. Furthermore, 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.

The second scenario called *manufacturing & efficiency* assumes the evolution of GHG emissions as depicted by Chou et al. [3] for the electronics sector over the period (2005-2016), i.e., 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. This scenario illustrates that the carbon footprint of the sample would reach up to 37% of the available carbon budget, 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 ECMs in our sample would represent about 15% of the total carbon budget in 2050.

The results in Fig. 8 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, our analysis clearly highlights the difficult upcoming political arbitrations that will be needed if ECMs cannot decrease their GHG emissions.

D. Towards a Potential Carbon Lock-in

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 a economical context of returns to scale, both public institutions and private actors (which constitute, with the deployed technological infrastructure, a *techno-institutional complex*) drastically inhibit the competitiveness and roll-out of low-carbon alternatives [42].

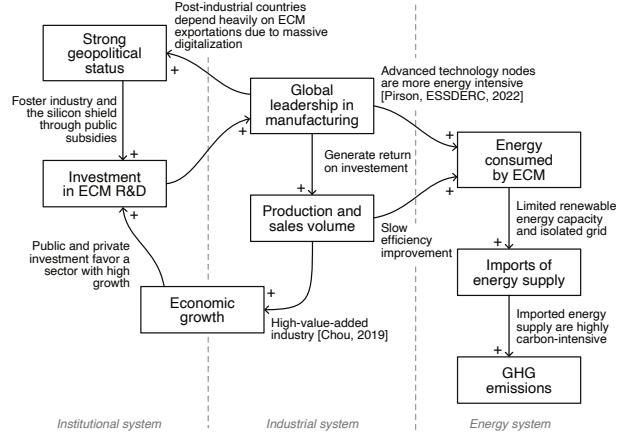


Fig. 9. Illustration of the techno-institutional complex fostering a lock-in on carbon-intensive energy sources.

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 [43]. 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 [44]. 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 [45]. Yet, the technological path towards advanced sub-10nm technologies also implies new industrial processes such as EUV, which in turn are likely to increase the environmental footprint and energy consumption of the industry (the energy consumption from EUV processes is more than ten times that of deep ultraviolet (DUV) processes [30]). At the same time, the territorial 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, as shown in Fig. 9, it becomes apparent that the Taiwanese electronics industry is fated to remain a major contributor of GHG emissions.

From this analysis specific to Taiwan, lessons can be learned for other countries that want to develop a sub-10nm industry, such as the European Union through the Chips Act or the USA. While Taiwan suffers from carbon-intensive energy sources and a constrained territory, the European Union could place 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. Anticipation is therefore critical to have a better understanding of the environmental burden generated by semiconductor manufacturing. Finally, the growth rate of the semiconductor industry 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.

E. Limitations of this Study

This study focuses mostly on companies responsible for the front-end IC processing of the chip production chain. Further analyses should however also include remaining activities such as printed circuit board (PCB) manufacturing, the back-end processing and the manufacturing of other electronic components. The activities of the companies surveyed are sometimes unclear and it is possible that some companies fall outside the original scope but still remain within the Electronics Components Manufacturers sector and therefore do not affect the results or the purpose of this study. Further research should include more component types and a more extensive production chain, i.e., design, packaging, processing, testing. For the same reasons, the extrapolation done in Section IV-D assumes that the GHG emissions of all Taiwanese ECMs are due to the generation of electricity, but it is impossible to verify the soundness of this hypothesis without reviewing all companies of the sub-sector.

Moreover, only 16 companies out of the 60 surveyed issue CSR reports with useful data, while more than 100 companies could be reviewed if all production phases were included. Obtaining data from all semiconductor manufacturers present in Taiwan is still problematic for two reasons: either the environmental data is simply not reported, or the data provided is not location-based (this is the case for AU Optronics, Macronix, Global Foundries, Micron, Merck, Delta, Lite-On Semiconductor, Panjit or Foxsemicon). The disclosure of data specific to their Taiwanese operations would significantly increase the coverage of this study. We also observed that data present in older CSR reports are sometimes changed or updated in more recent editions. Such changes raise fundamental questions about the meaning or validity of the data contained in the CSR reports. In addition, some data among the ones recovered do not report values over a sufficient number of years or report values in a non standardized format. These limitations illustrate the important improvements in CSR reporting that could be achieved to allow a more effective processing and understanding of the environmental impacts of companies. Yet, in a field that suffers from a chronic lack of open and accessible data, it is important to note that this study is possible only thanks to the open data policies set up in Taiwan. Encouraging transparency and open-data policies could foster higher quality research and allow a more accurate identification of the environmental footprint of industrial activities.

Even though this study includes 16 companies of various sizes and covers half of the electricity consumption of the sub-sector, TSMC largely influences the results. On average, this company represents half of all studied environmental impacts. Further, most of the observed growth in the indicators originate from TSMC. Due to high-level reporting of the environmental data in the CSR reports of the company, it is however difficult to clearly identify whether these increases are due to yield changes, technological changes

(e.g., the use of EUV for nodes below 10 nm) or the increase of production volumes. More granular data and interviews would be required to obtain a more precise picture. Nevertheless, TSMC is clearly the world leader in the manufacturing of sub-10nm nodes [11], which totally justifies its inclusion in this study. When taking TSMC out of the analysis, we note that the rest of the companies show a slower growth rate for the three environmental indicators.

Regarding the GHG emissions, the reported CSR data are usually well detailed for the Scopes 1 and 2. Nevertheless, few companies report the use of self-produced renewable energy on their facilities. In the case of TSMC, this represents only 6.8% of the company's electricity consumption in 2019 [30] but the company increased its renewable energy self-consumption by 818% in 5 years, up to 918 GWh. Beyond Scopes 1 and 2, the general lack of data and standardized reporting regarding the Scope 3 hinder an in-depth understanding of the emissions throughout the entire value chain, although this could hide significant impacts. For instance, TSMC indicates that it has increased its Scope 3 emissions by 63% between 2015 and 2020 [30].

VI. CONCLUSION

In this study, we show that the absolute environmental impacts of the electronic components manufacturing industry in Taiwan are on the rise over the period 2015-2020. An increasing trend is observed for each indicator, with a CAGR of 8.8%, 8.9%, 7.5%, and 6.1% for final energy consumption, electricity consumption, GHG emissions, and water consumption, respectively. It is clear that total absolute environmental impacts keep increasing on the island, despite the (relative) efficiency improvements claimed by the industry and the strong efforts to develop state-of-the-art manufacturing technologies.

Through a scenario analysis, we also highlight the conflicting trends between the ECMs' growing carbon footprint and the carbon neutrality roadmap outlined by the Taiwanese government up to 2050. As these companies are a keystone of the island's industrial, commercial and geopolitical policies, it raises a serious challenge for Taiwan to succeed in its ecological transition. To meet its targets, Taiwan could rely on a better efficiency from new production processes and a heavy decarbonation of its electricity supply. However, even TSMC's footprint indicates that the most advanced machinery might not be sufficient to curb the total GHG emissions in the coming years, especially if both the production volumes and the environmental impacts of advanced CMOS technology nodes continue to grow [10]. A quick switch to low-carbon energy sources still seems out of sight for an economy that relies mainly on imported carbon-intensive energy sources such as coal, crude oil and LNG. Other options could be to cap production volumes and number of plants, maintaining the most resource-efficient processes and rapidly stabilizing or reducing energy consumption in absolute values. Yet, this would have direct economic effects in conflict with the objective of the government who clearly wants to maintain and strengthen the economic outputs. Furthermore, the electronics industry is one of the major geopolitical assets of the island, referred as the *silicon shield*, for its use as a deterrent against possible Chinese ambitions [43].

Overall, Taiwan's carbon neutrality roadmap will have to deal with an industry that is likely to increase its GHG

emissions by 3.5 to 7.5% per year. Facing such trends, it is unlikely than Taiwan will be able to both maintain its current industrial development and its carbon neutrality roadmap. As a consequence, Taiwanese semiconductors components will remain with a relatively high carbon footprint for a long time. In addition, the electronics industry itself is facing the increasing pressure of its environment. The recent drought caused by the absence of typhoons in 2020 and the water restrictions put in place in 2021 can be an early sign of the incoming risks for this industry.

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

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SUPPLEMENTARY MATERIAL

The supplementary material includes all the data and assumptions used in this study.

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VII. SUPPLEMENTARY MATERIAL

Listing of electronic components manufacturers (ECMs) in Taiwan

Company name	Fab location in Taiwan	CSR Data available	Taiwan-related data available	Within scope	Included	Specification
TSMC	Fab02, Fab03, Fab05, Fab12, Fab16	Yes	Yes	Yes	Yes	Logic / IC, Semiconductors, Passive electronic component manufacturing, optoelectronic materials and components, Other electronic component manufacturing.
UMC	Fab02, Fab08-N (Hsinchu); 1	Yes	Yes	Yes	Yes	Power management IC, Sensors / Image Sensor / Integrated Memory (CPLD, DRAM, Flash, Low Power DRAM, HGS, LCD Driver IC (Cpds), SLC, NAND DRAM, Flash Memory, Specialty DRAM / Mobile DRAM, 12-inch GaN devices, LED (Oeko))
Powerchip	Fab01, Fab02, Fab03, Fab08 Yes	Yes	Yes	Yes	Yes	Power management IC, Sensors / Image Sensor / Integrated Memory (CPLD, DRAM, Flash, Low Power DRAM, HGS, LCD Driver IC (Cpds), SLC, NAND Display Drivers IC, Power management IC, Discrete components, 8-inch DRAM)
Vanguard	Fab1, Fab2 (Hsinchu); Fab3 (Taiwan)	Yes	Yes	Yes	Yes	Power management IC, Sensors / Image Sensor / Integrated Memory (CPLD, DRAM, Flash, Low Power DRAM, HGS, LCD Driver IC (Cpds), SLC, NAND Display Drivers IC, Power management IC, Discrete components, 8-inch DRAM)
Global Wafer	Fab, Fab2 (Linkou); Fab3 (New Taipei City)	Yes	Yes	Yes	Yes	Power management IC, Sensors / Image Sensor / Integrated Memory (CPLD, DRAM, Flash, Low Power DRAM, HGS, LCD Driver IC (Cpds), SLC, NAND Display Drivers IC, Power management IC, Discrete components, 8-inch DRAM)
Nanya	Memory Product Foundry (Taichung)	Yes	Yes	Yes	Yes	Power management IC, Sensors / Image Sensor / Integrated Memory (CPLD, DRAM, Flash, Low Power DRAM, HGS, LCD Driver IC (Cpds), SLC, NAND Display Drivers IC, Power management IC, Discrete components, 8-inch DRAM)
Winbond	Fab A, Fab B (Tainan); Fab C (Tainan); Fab D (Tainan); Fab E (Tainan); Fab F (Tainan); Fab G (Tainan); Fab H (Tainan); Fab I (Tainan); Fab J (Tainan); Fab K (Tainan); Fab L (Tainan); Fab M (Tainan); Fab N (Tainan); Fab O (Tainan); Fab P (Tainan); Fab Q (Tainan); Fab R (Tainan); Fab S (Tainan); Fab T (Tainan); Fab U (Tainan); Fab V (Tainan); Fab W (Tainan); Fab X (Tainan); Fab Y (Tainan); Fab Z (Tainan)	Yes	Yes	Yes	Yes	Power management IC, Sensors / Image Sensor / Integrated Memory (CPLD, DRAM, Flash, Low Power DRAM, HGS, LCD Driver IC (Cpds), SLC, NAND Display Drivers IC, Power management IC, Discrete components, 8-inch DRAM)
Win Semiconductor	Epistar	Yes	Yes	Yes	Yes	Power management IC, Sensors / Image Sensor / Integrated Memory (CPLD, DRAM, Flash, Low Power DRAM, HGS, LCD Driver IC (Cpds), SLC, NAND Display Drivers IC, Power management IC, Discrete components, 8-inch DRAM)
Ummtron	Shantou, Suzhou, Beijing, Zhaojiabang, Zhuhai, Taiwan	Yes	Yes	Yes	Yes	Power management IC, Sensors / Image Sensor / Integrated Memory (CPLD, DRAM, Flash, Low Power DRAM, HGS, LCD Driver IC (Cpds), SLC, NAND Display Drivers IC, Power management IC, Discrete components, 8-inch DRAM)
Immax	Zhuhai, Taiwan	Yes	Yes	Yes	Yes	Power management IC, Sensors / Image Sensor / Integrated Memory (CPLD, DRAM, Flash, Low Power DRAM, HGS, LCD Driver IC (Cpds), SLC, NAND Display Drivers IC, Power management IC, Discrete components, 8-inch DRAM)
Nuvoton	Hsinchu plant	Yes	Yes	Yes	Yes	Power management IC, Sensors / Image Sensor / Integrated Memory (CPLD, DRAM, Flash, Low Power DRAM, HGS, LCD Driver IC (Cpds), SLC, NAND Display Drivers IC, Power management IC, Discrete components, 8-inch DRAM)
Luxtar	T01 (Hsinchu)	Yes	Yes	Yes	Yes	Power management IC, Sensors / Image Sensor / Integrated Memory (CPLD, DRAM, Flash, Low Power DRAM, HGS, LCD Driver IC (Cpds), SLC, NAND Display Drivers IC, Power management IC, Discrete components, 8-inch DRAM)
Everlight	Yuanshi Plant, Shulin Plant, Tongxiao Plant, Hsinchu	Yes	Yes	Yes	Yes	Power management IC, Sensors / Image Sensor / Integrated Memory (CPLD, DRAM, Flash, Low Power DRAM, HGS, LCD Driver IC (Cpds), SLC, NAND Display Drivers IC, Power management IC, Discrete components, 8-inch DRAM)
Optebeam	Yinggepu, Longtan	Yes	Yes	Yes	Yes	Power management IC, Sensors / Image Sensor / Integrated Memory (CPLD, DRAM, Flash, Low Power DRAM, HGS, LCD Driver IC (Cpds), SLC, NAND Display Drivers IC, Power management IC, Discrete components, 8-inch DRAM)
Wellspace Works						
Siltronix	Dafeng, Chungshan, Zhonghe, Hsinchu, Kaohsiung	Yes	Yes	No	No	IC packaging, processing, testing
Siltronix Precision Industries	Fab02, Fab05, Fab1 (Hsinchu); Fab3 (Gushan); Fab5, Fab6, Fab7 (Tainan)	Yes	Yes	No	No	IC packaging, processing, testing
Foxconn Integrated Technology	Fab3, USA, Germany, Singapore	Yes	Yes	No	No	IC packaging, processing, testing
Orient Semiconductor Electronics	Macronix	Yes	Yes	No	No	IC packaging, processing, testing
AUO	Fab 3.0, LSD (Gushan); Fab 5, Fab 6, Fab 7 (Tainan)	Yes	Yes	No	No	IC packaging, processing, testing
GlobalFoundries	Micron Memory, Taiwan	Yes	Yes	No	No	IC packaging, processing, testing
Pangl	Micro Performance Materials	Yes	Yes	No	No	IC packaging, processing, testing
Winbond	Koohsiung	Yes	Yes	No	No	IC packaging, processing, testing
Lite-On Semiconductor	Plant 1 (Keelung) / Plant 2 (Hsinchu)	Yes	Yes	No	No	IC packaging, processing, testing
Delta Electronics	Advanced Semiconductor Engineering Inc. (ASE Group + SiMIC)	Yes	Yes	No	No	IC packaging, processing, testing
Taiung Corp	Hsinchu, Zhonghe, Talian, Kaohsiung	Yes	Yes	No	No	IC packaging, processing, testing
Acer	Kuang-Fu, Li-Hsin (Taoyuan), Fushan	Yes	Yes	No	No	IC packaging, processing, testing
Elan Microelectronics	Taiwan	No	No	No	No	IC packaging, processing, testing
Formosa Sumitomo Semicon	Taiwan	No	No	No	No	IC packaging, processing, testing
Chicoboard	Taiwan	No	No	No	No	IC packaging, processing, testing
Guiding Precision	Taiwan	No	No	No	No	IC packaging, processing, testing
PHONOS	Davidson Facility, 6A, 6B (Hsinchu); Fab4 (Taichung)	No	No	No	No	IC packaging, processing, testing
Taiwan Semicon	Lige, Ilan	No	No	No	No	IC packaging, processing, testing
Almi Optoelectronics	Hsinchu	No	No	No	No	IC packaging, processing, testing
AWSL	Taiwan	No	No	No	No	IC packaging, processing, testing
SAN CHIH Semiconductor	Taiwan	No	No	No	No	IC packaging, processing, testing
Creative Sensor Inc.	Wuxi Creative Sensor (Taichung)	No	No	No	No	IC packaging, processing, testing
Visera Technologies (Part of TSMC)	Headquarters Phase 1 (Hsinchu)	No	No	No	No	IC packaging, processing, testing
Episil	-	No	No	No	No	IC packaging, processing, testing
Creating Nano	-	No	No	No	No	IC packaging, processing, testing
Episil-Precision	-	No	No	No	No	IC packaging, processing, testing
Sun Yuan Technology	-	No	No	No	No	IC packaging, processing, testing
U-Car Display	-	No	No	No	No	IC packaging, processing, testing
Orluna Technology	-	No	No	No	No	IC packaging, processing, testing
Cin Phown Technology	-	No	No	No	No	IC packaging, processing, testing
Davcom Semiconductor	-	No	No	No	No	IC packaging, processing, testing
Holek Semiconductor	-	No	No	No	No	IC packaging, processing, testing
Reawink Semiconductor	-	No	No	No	No	IC packaging, processing, testing
WiseCip Semiconductor	Hsinchu	No	No	No	No	IC packaging, processing, testing
Unknown Sem	Peiping, Chungchih, Hsinchu	No	No	No	No	IC packaging, processing, testing
Signtec Microelectronics	No	No	No	No	No	IC packaging, processing, testing
Netac Vitec	No	No	No	No	No	IC packaging, processing, testing
Kortron	No	No	No	No	No	IC packaging, processing, testing
Green Energy Technology	No	No	No	No	No	IC packaging, processing, testing
Sato-American Silicon Products	No	No	No	No	No	IC packaging, processing, testing
Hexwave	No	No	No	No	No	IC packaging, processing, testing
COUNT	60	33	33	17	17	16

* The term "Electronic Components manufacturers" (ECMs) can include: semiconductor manufacturing, optoelectronic materials and components, Other electronic component manufacturing.

https://www.semicon.org/wa/list_of_semiconductor_member_firms.aspx?Category=Manufacturing

https://www.semicon.org/research_member_directory/search.aspx?Category=%5B50-65%5D&Country=%5B601-650%5D&saz (Criterion : Category = Semiconductor, Photronics o + Criterion : Semiconductor, Photonics o + Criterion : Device manufacturing o + Country = Taiwan)

Notes

Sources

https://en.wikipedia.org/w/index.php?title=List_of_semiconductor_manufacturers&oldid=910000000

Summary of results										
Year	2015		2016		2017		2018		2019	
	GHG emissions (Unit : metric tons CO ₂ e)									
THIS STUDY - GHG Emissions (Sc1+2)	13 085 218	14 158 364	15 712 523	16 969 393	17 200 259	18 770 908				7.5%
Industry GHG emissions	126 330 000	127 590 000	131 210 000	132 950 000	127 070 000	ND				
THIS STUDY - share of Industry GHG emissions (%)	10.4	11.1	12.0	12.8	13.5	ND				
National GHG Emissions	260 200 000	264 740 000	271 220 000	268 850 000	260 400 000	ND				0.0%
THIS STUDY - share of National GHG emissions (%)	5.0	5.3	5.8	6.3	6.6	ND				
THIS STUDY (SECTOR) - share of National GHG emissions (%)	8.1	8.6	8.8	9.0	11.7	ND				
Final energy consumption (Unit : GWh)										
THIS STUDY - final energy consumption	18 947	20 395	25 131	26 515	27 904	31 403				8.8%
Industry final energy consumption	294 101	297 016	297 418	302 286	299 450	312 579				1.2%
THIS STUDY - share of industry final energy consumption (%)	6.4	6.9	8.4	8.8	9.3	10.0				
National final energy consumption	774 059	780 075	775 570	788 370	761 440	769 250				-0.1%
THIS STUDY - share of national final energy consumption (%)	2.4	2.6	3.2	3.4	3.7	4.1				
THIS STUDY (SECTOR) - share of National final energy consumption (%)	3.9	4.2	4.9	4.8	6.5	7.0				
Electricity consumption (Unit : GWh)										
THIS STUDY - electricity consumption	19 217	20 309	22 807	25 131	26 805	29 421				8.9%
Industry electricity consumption	134 700	136 590	141 111	148 861	147 675	150 742				2.3%
THIS STUDY - share of industry electricity consumption (%)	14.3	14.8	16.2	16.9	17.9	19.5				
National electricity consumption	250 019	255 420	261 394	266 868	265 720	271 247				1.6%
THIS STUDY - share of national electricity consumption (%)	7.7	8.0	8.7	9.4	10.0	10.8				
THIS STUDY (SECTOR) - share of National electricity consumption (%)	12.3	12.8	13.3	13.4	17.7	18.7				
Water consumption (Unit : m ³)										
THIS STUDY - water consumption	107 207 300	105 927 409	117 015 590	123 979 533	129 511 532	144 040 335				6.1%
Industry water consumption	160 100 000	162 900 000	165 400 000	166 800 000	167 135 000	1 803 190 000				2.1%
THIS STUDY - share of industry water consumption (%)	6.7	6.5	7.1	7.4	7.7	8.0				
National water consumption	16 025 000 000	16 546 000 000	16 645 000 000	16 713 000 000	16 739 280 000	16 675 930 000				0.8%
THIS STUDY - share of National water consumption (%)	0.7	0.6	0.7	0.7	0.8	0.9				
Indexes of environmental impacts and manufacture of electronic parts and components										
2016=100	2015	2016	2017	2018	2019	2020				
THIS STUDY - GHG Emissions (Sc1+2)	92.4	100.0	111.0	119.9	121.5	132.6				
THIS STUDY - Electricity consumption	94.6	100.0	112.3	123.7	130.6	144.9				7.48%
THIS STUDY - Water consumption	101.2	100.0	110.0	117.0	122.3	126.0				8.88%
Manufacture of Integrated Circuits	88.1	100.0	109.4	119.0	120.7	153.9				6.08%
Representativeness of study based on Taipower data	ND	62.3	65.8	70.2	56.3	57.9				11.80%
Year	2015	2016	2017	2018	2019	2020	(min)	(max)	(average)	
Autoproducers share of national electricity generation	16.40	16.44	16.17	15.22	15.53	16.00				
Independent power producers share of national electricity generation	15.55	14.97	14.37	15.81	15.93	15.78				
Taipower share of national electricity generation	68.05	68.59	69.46	68.97	68.54	68.22				
Share of Taipower ECm electricity consumption	ND	62.34	65.82	70.23	56.31	57.94				

62.5

70

56

56

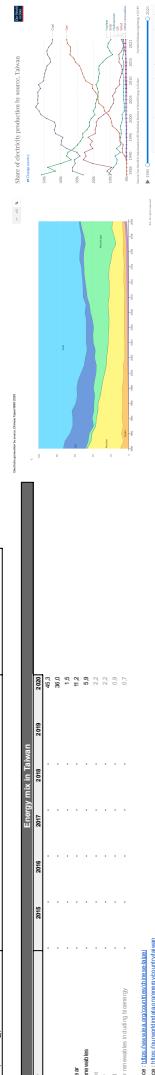
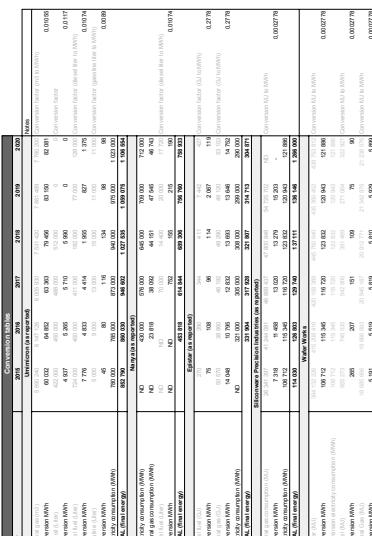
Sources MOEA, Energy Statistics Handbook, 2020 p.83-84; Taipower Open Data, 台湾电力公司_歷年營業量(用油別) (<https://data.gov.tw/dataset/35392>)https://www.moeaopeo.gov.tw/ECW/main/content/wHandMenuFile.aspx?file_id=1411https://www.moeaopeo.gov.tw/ECW/main/content/ContentLink.aspx?menu_id=1540

Taipower produces about 70% of the electricity on the island but it is the main electricity vendor for ECms. We therefore consider Taipower's electricity to represent 100% of the sub-sector.

Taiwan national energy Consumption
-GW

The Bureau of International Energy Consumption Analysis and Projections (BIECP) is responsible for reporting more often than annually to Congress on energy consumption by country. BIECP is a part of the U.S. Energy Information Administration (EIA), which is part of the U.S. Department of Energy (DOE). BIECP's primary responsibility is to provide timely, accurate, and reliable information on energy consumption and its impact on the global environment.

Taiwan national energy consumption



Water consumption of selected electronic components manufacturers										
Unit : m3	Year	2015	2016	2017	2018	2019	Water consumption	2020	Diff 2015/2020 (%)	Source
TSMC		34 000 000	38 600 000	45 200 000	51 000 000	58 000 000	70 600 000	108	108	TSMC CSR Report 2019-2021
Innolux		24 190 000	22 950 000	26 040 000	21 830 000	20 210 000	20 415 000	-16	-16	Innolux CSR Report 2019-2020
Unimicron		13 061 106	13 140 482	14 614 868	15 306 000	15 007 898	15 500 000	-20	-20	Unimicron CSR Report 2019-2020
UMC		13 830 000	14 456 000	14 900 000	14 910 000	14 810 000	12	12	12	UNIC CSR Report 2019-2020
Powerchip		3 678 689	ND*	ND*	1 451 197	1 487 624	1 560 296			Powerchip CSR Report 2019-2020
Vanguard		4 540 000	4 750 000	4 860 000	4 990 000	4 980 000	6 560 000			Vanguard CSR Report 2019-2020
GlobalWafers		545 997	3 639 324	3 684 318	5 468 000	4 960 000	4 324 000			GlobalWafers CSR Report 2019-2020
Nanya		2 198 960	2 244 759	3 092 814	3 022 362	3 258 386	3 368 954			Nanya CSR Report 2015-2016-2019-2020
Winbond		2 320 000	2 340 000	2 830 000	945 000	979 000	1 216 000			Winbond CSR Report 2017-2018-2020
Epistar		450 000	420 000	410 000	380 000	370 000	370 000			Epistar CSR Report 2018-2020
Win Semiconductor		ND*	ND*	253 101	214 044	208 239	255 063			Win CSR Report 2018-2019-2020
Nuvoton		387 000	420 000	442 000	440 000	395 000	401 000			Nuvoton CSR Report 2019-2020
Lexar		ND*	ND*	ND*	98 470	83 750	76 410			Lexar CSR Report 2016-2017-2018-2020
Everlight		ND*	ND*	ND*	994 490	874 770	849 600			Everlight CSR Report 2019-2020
Optitech		1 194 967	1 272 536	1 336 185	1 422 818	1 402 261	1 402 261			Optitech CSR Report 2017-2019
Wafer Works		1 570 607	1 713 984	1 836 660	2 168 502	2 166 502	2 133 853			Wafer Works CSR Report 2018-2020
Subtotal		107 207 300	105 927 409	117 015 590	123 979 533	129 511 632	144 040 335	34		
All ECUs except TSMC		73 207 300	67 327 409	77 815 590	72 979 533	71 511 532	73 440 355			

ND = No Data

(*) - CSR department contacted but didn't answer

CSR reports are sometimes unclear about their reporting, it is difficult to understand if they're reporting water intake, water consumption including recycled water or their net water consumption. The numbers presented here should rather viewed as water intake or water footprint.

Domestic water consumption in Taiwan										
Unit : m3	Year	2016	2017	2018	2019	Water consumption	2020	Diff 2015/2020 (%)	Source	
National water consumption		16 025 000 000	16 546 000 000	16 645 000 000	16 713 000 000	16 739 280 000	16 675 930 000	4	4	Utilization of Water Resources (2016-2019) https://www.wra.gov.tw/News.aspx?n=2653&sns=908&CSn=0
Industry water consumption		1 601 000 000	1 629 000 000	1 654 000 000	1 668 000 000	1 671 380 000	1 803 190 000	13	13	https://www.wra.gov.tw/News_Content.aspx?n=2345&s=734
Industry share of national consumption		10.0	9.8	9.9	10.0	10.0	10.8			
THIS STUDY – Water consumption of:		107 207 300	105 927 409	117 015 590	123 979 533	129 511 632	144 040 335	34,4		
Share of industry water consumption		6.7	6.5	7.1	7.4	7.7	8.0			
Share of national water consumption		0.7	0.6	0.7	0.7	0.8	0.9			
Other sectors										
Agriculture water consumption		10 497 740 000	11 096 030 000	11 200 240 000	11 189 000 000	11 363 500 000	11 592 470 000	10	10	
Industry water consumption		1 601 000 000	1 629 000 000	1 654 000 000	1 668 000 000	1 671 350 000	1 803 190 000	13	13	
Domestic water consumption (household)		3 142 230 000	3 183 410 000	3 147 140 000	3 155 610 000	3 195 510 000	3 280 270 000	4	4	

Indexes of Industrial Production in Taiwan

Year	2016=100					2020 Notes	Sources
	2015	2016	2017	2018	2019		
Manufacture of Integrated Circuits							
Manufacture of Discrete Devices	88.1	100.0	109.4	119.0	120.7	153.9 <i>SCOPE</i>	
Packaging and Testing of Semi-conductors	96.0	100.0	109.3	128.3	124.3	130.0 <i>SCOPE</i>	
Manufacture of Electronic Passive Devices	99.8	100.0	103.8	108.3	116.6	123.8 <i>OUT OF SCOPE</i>	
Manufacture of Bare Printed Circuit Boards	94.9	100.0	109.4	151.0	104.9	120.7 <i>SCOPE</i>	
Manufacture of Liquid Crystal Panel and Components	99.6	100.0	108.7	109.7	107.4	120.1 <i>OUT OF SCOPE</i>	
Manufacture of Light Emitting Diodes (LED)	110.7	100.0	117.7	113.5	102.5	108.4 <i>OUT OF SCOPE</i>	
Manufacture of Solar Cells	118.6	100.0	91.2	84.0	69.0	64.5 <i>SCOPE</i>	
Manufacture of Other Optoelectronic Materials and Components	110.1	100.0	83.4	74.0	46.2	44.5 <i>OUT OF SCOPE</i>	
Manufacture of Printed Circuit Assembly	105.8	100.0	88.8	84.5	83.3	82.5 <i>SCOPE</i>	
Manufacture of Other Electronic Parts and Components (Not Elsewhere Classified)	95.2	100.0	101.2	102.9	138.0	193.9 <i>OUT OF SCOPE</i>	
Manufacture of Electronic Parts and Components (overall)	95.6	100.0	108.2	114.0	114.1	136.3	MOEA

