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Environmental performance and trends of the world's semiconductor foundry industry

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Abstract

The semiconductor foundry industry faces the challenge of reducing its high environmental impact, mainly due to its energy- and water-intensive processes and significant generation of waste. To date, no other study has focused on the assessment of the environmental performance and related historical trends of this industry as a whole. Methodologically, the first step was to analyze and process a large quantity of economic, production, and environmental data, available in the Corporate Social Responsibility reports of a companies' sample, highly representative of the entire world's foundry industry (about 70% of the global revenue of the related sector). It was thus possible to calculate, using a common manufacturing index (MI) and after appropriate data processing, some key performance indicators, along a significant decade (2012–2021), marked by deep political, economic, and health crises. Some of the main findings of this study are that, over this 10-year period, the increases in technological capacity (patents), wafer production, and revenue (400%, 183%, and 172%, respectively) are matched by a significant increase in hazardous waste generation per MI (20%; 239% in absolute value) and a much larger increase in general waste generation per MI (135%; 568% in absolute value). The indicators of energy, water, and revenue per MI are substantially unchanged. A substantial decrease occurs in $GHG_{1\&2}$ emissions per MI (–32%), mainly due to significant investments in renewable energy sources. The findings of this research could help and guide upcoming sustainability policy decisions and encourage business-to-business collaboration and the adoption of better environmental production practices.

KEYWORDS
energy consumption, GHGs emissions, industrial ecology, waste generation, water consumption, wastewater

1 | INTRODUCTION

Chips are crucial and strategic components for many production sectors, especially, for the hi-tech industry (computers, smartphones, artificial-intelligence [AI] applications, blockchain technology, Internet of things [IoT], and other consumer and industrial equipment and devices) and for technologically supporting new policies for energy transition and environmental and climate mitigation programs (CRS, 2020; McKinsey, 2019; Mordor Intelligence, 2023; SIA, 2021). The semiconductor value chain is extensive, encompassing a range of specialized areas: equipment, electronic design automation (EDA) software, intellectual property (IP) cores, integrated device manufacturers (IDMs) and fabless companies, foundries, and outsourced semiconductor assembly and test (OSAT) services (Deloitte Asia Pacific, 2020; Kleinhans and Baisakova, 2020).

The foundry sector is a fundamental and preponderant part of the semiconductor manufacturing industry that focuses on the production of chips for "fabless" companies (Broadcom, Qualcomm, Nvidia, and MediaTek) that design semiconductors but do not manufacture them (Grimes & Du, 2022). Semiconductor foundry companies ("foundries" or "fabs") have the required and advanced manufacturing technology, know-how, and organizations to produce chips, providing efficient, cost-effective, and high-quality manufacturing solutions for innovative integrated circuits (ICs) (Ciani & Nardo, 2023).

A semiconductor fabless firm, despite not owning manufacturing facilities, could play a crucial role in enhancing sustainability measures such as water recycling, energy use, and waste reduction during the manufacturing process at a semiconductor foundry. Fabless companies, in fact, not having direct control over the manufacturing processes, pursue a path to sustainability working in close partnership with the foundries that manufacture their products. This involvement requires the integration of strategic planning, technological innovation, and collaboration in the whole supply chain, by adopting eco-efficient technologies and processes and investing in R&D to implement eco-design of products characterized by less resource-intensive manufacturing or easier recycling. Industry consortia could help in best practices sharing and to drive sector-wide improvements in sustainability. This could be done through contractual agreements, containing specific sustainability targets, or through partnership with a foundry company.

To improve water recycling, fabless firms could adopt more advanced water treatment technologies, such as ultrafiltration and reverse osmosis, that have been found to significantly increase the recovery rate of high-purity water from the manufacturing process (Tseng et al., 2021). These systems handle wastewater streams (e.g., from wafer back-grinding and sawing processes), reducing the need for freshwater and allowing recovered water to be used in less critical applications (such as electroplating and marking within the foundry) (Baskaran, 2017; Frost & Hua, 2019; Wu et al., 2004). Another study suggests that regression and cost analyses based on mass balance can be applied to optimize the recycling of processing water; this could be extended to the fabless firms, which could coordinate with their foundry partners (Wang et al., 2005).

In terms of energy use, fabless firms can work with foundries to adopt more energy-efficient equipment and processes, possibly supported by data analytics optimizing energy consumption at different stages of production. This could be made using renewable energy sources, investing in energy recovery systems, and implementing smart cluster within the foundry operations (Den et al., 2018). Waste and wastewater generation can be mitigated by material flow analysis to identify areas requiring minimization of resource use and maximization of recycling (Frost & Hua, 2019; Baars et al., 2022). Furthermore, the adoption of eco-design principles in semiconductor sector canreduce waste production (Faraca et al., 2023).

1.1 | Background

This industry has developed rapidly over recent years, due to the demand for advanced ICs in many highly profitable and strategic areas, enabling the rapid and comprehensive advancement of knowledge and the improvement of social welfare conditions (Khan et al., 2021; Platzer et al., 2020; Yeung, 2023).

On the other hand, the semiconductor foundry sector has significant environmental impacts; in fact, it requires a significant amount of energy, water (which can put a strain on local water resources, particularly in areas where water is scarce), and various hazardous chemicals (solvents, acids, and gases, such as sulfur hexafluoride, SF6, a powerful greenhouse factor), which could have a significant adverse impact on the environment and risk of exposure for humans (Shen et al., 2018). The related production process also generates greenhouse gas (GHG) emissions and particulate matter (PM), chemical sludge and process water, and general and hazardous waste. To mitigate these environmental effects, fabs have implemented prevention and control countermeasures: energy efficiency solutions; reduction strategies of electricity generation from fossil fuels; better water management practices; recycling programs; and more eco-friendly processes (Choi, 2018; Choi et al., 2018; Hui, 2019).

Additionally, industry organizations, such as the Semiconductor Industry Association (SIA, 2023), and government agencies, for example, the US Environmental Protection Agency (EPA, 2023a), have approved guidelines and standards to help foundries in their environmental reporting activities and to promote environmental sustainability techniques.

1.2 | Scope and aim

By the calculation and analysis of some key performance indicators (KPIs) ofthe Corporate Social Responsibility (CSR) reports data of the examined companies, it is made clear that semiconductor foundries have relevant environmental impact and generate a significant amount of organic and inorganic pollutants and waste, including hazardous waste (heavy metals, alkalis, and acids). These effects result from manufacturing processes, waste disposals, and from the use of water, energy, and various chemicals (Doble & Kumar, 2005). For a complete assessment, from an LCA (life cycle assessment) viewpoint, the effects of the use of electronic devices (e.g., electricity consumption and related GHG emission) should also be contemplated; in addition, the impact from e-waste management, which could be very difficult to recycle and hazardous to the environment if not properly disposed, would also be assessed (Julander et al., 2014; Parajuly et al., 2019).

CSR reports are a precious source of data for stakeholders to assess the performance of a company in relation to sustainability and the environment. In addition, despite certain limitations in readability and transparency, they are for some sectors, as in the case of semiconductor foundry industry, the only available source of data (Wang et al., 2018). It would be desirable for CSR reports, for better accuracy and reliability, to be certified by independent third-party bodies and/or to be arranged according to international standards, such as those issued by the Global Reporting Initiative (GRI) or the Hong Kong Stock Exchange, Ltd. (HKEx) environmental, social, and governance (ESG) rules (Caritte et al., 2015).

By reviewing scientific literature, it is possible to state that, until now, no other research has been conducted regarding the environmental trends assessment of the semiconductor manufacturing or foundry industry as a whole. This could be due to several factors: (1) complexity and multiplicity of wafer production processes that make it impossible to implement a LCA method to this industry; (2) it is a highly strategic industry, considering the strong economic, geopolitical, and military importance of its products, characterized by many technological secrets; (3) it is very difficult to get complete and reliable data for a comprehensive LCA study, even for a single fab; (4) there are no industry environmental performance standards and/or a codified list of universally accepted indicators useful to compare the activities of different fabs (Villard et al., 2015); and (5) the very few existing LCA studies published on this topic investigate only one or very few process steps of chip manufacturing (Ahmad, 2007; Boyd et al., 2010; Higgs et al., 2009; Huang et al., 2016; Kuo et al., 2022; Liu et al., 2010; Wang, 2014) or are focused only on the carbon footprint of the information and communication technology's (ICT) sector, as has been well clarified by Freitag et al. (2021).

To fill this significant gap, this study aims to investigate the production, technological capacity, and economic and environmental performance trends of several KPIs (revenue, patents, GHG emissions, energy consumption, water withdrawn and wastewater, and general and hazardous waste generation) of the world's major foundries by revenue, during a 10-year period (2012–2021): Taiwan Semiconductor Manufacturing Company Ltd. (TSMC); United Microelectronics Corporation (UMC); GlobalFoundries Inc. (GF); and Semiconductor Manufacturing International Corporation (SMIC).

2 | METHODS

This research was carried out according to the following steps: (1) data collection of several environmental items, from CSR reports; (2) calculation of a common manufacturing index (MI) using proper conversion factors (see Table 1); (3) homogenization and arrangement of the various foundries' performance data for the entire decade (see Table 2); and (4) KPIs calculation using a common MI (see Table 4); (5) graphical illustration of KPIs trends and respective discussion.

The main available sources of production and environmental data were, if not otherwise indicated, the CSR reports of the analyzed foundries (TSMC, UMC, GF, and SMIC) with their respective affiliates or subsidiaries. In fact, the only data available, regarding the production and environmental impact of these foundries, are those that can be found, albeit with preliminary homogenization processes, in the CSR reports of each company.

Regarding the accuracy of the information reported by the different companies in their respective CSR reports, it should be pointed out that all the examined CSR reports have a high degree of reliability: in fact, the reports of SMIC are certified by the Det Norske Veritas (DNV) Foundation; those of UMC are certified by the Société Générale de Surveillance (SGS); the GF's reports are prepared according to GRI standards and SMIC's reports implement the rules of the HKEx ESG Reporting Guide.

Different sources of data (TrendForce and IC Insights, as specified in Table 2) were used for revenue and patent information (Espacenet Database) of each company (EPO, 2023). Fabs' patents were searched according to the following criteria: (1) the search scope delimitation was: "Worldwide—a comprehensive collection of patent applications published from over 90+ countries"; (2) the word "semiconductor" was entered in the string of "Keyword(s) in the title or abstract"; (3) in the search string "Publication date" the various years were entered; and (4) foundries' names were entered in the string "Inventors or applicants."

It was not possible to calculate the Samsung Electronics' performance indicators because, for the years prior to 2020, environmental data, for its foundry division alone, was unobtainable from its CSR reports. In fact, Samsung Electronics, in its reports, groups management and environmental data of different business areas indistinctly: information technology and mobile communications (IM), consumer electronics (CE), and device

TABLE 1 World's major semiconductor foundries by revenue (2021).

Company	Headquarters (*a*	Fabs in operation (country codes) (*b*)	2021 World foundry revenue share (%) (*c*)	Manufacturing indexes (MIs) (*d*)	MI Conversion factor° to wfr-m^2(*e*)
TSMC	Hsinchu (TW)	TW (10 fabs), CN (2 fabs), US (1 fab), and SG (1 fab)	53	8/12-inch equivalent wafer mask layer	0.0010472 and 0.0023562[a]
Samsung Foundry	Suwon (KOR)	KOR (4 fabs), CN (1 fab), and US (1 fab)	18	8-inch equivalent wafer mask layer	0.0010472
UMC	Hsinchu (TW)	TW (8 fabs), CN (2 fabs), JP (1 fab), and SG (1 fab)	7	wafer-m^2 (wfr-m^2)	1
GF	Malta (US)	SG (4 fabs), DE (3 fabs), and US (3 fabs)	6	wafer-mm^2 (wfr-mm^2)	0.0000001[c]
SMIC	Shanghai (CN)	CN (9 fabs)	5	8-inch equivalent wafer mask layer	0.0010472[b]
PSMC	Hsinchu (TW)	TW (3 fabs)	2	wafer-cm^2 (wfr-cm^2)	0.0001[d]
HHS	Shanghai (CN)	CN (2 fabs)	2	8-inch wafer	0.031416[e]
Others	—	–	7	–	–

°From (*d*) to a common MI (wfr-m^2).
[a](0.031416 m^2) / 30 (mask layers) = 0.0010472 (wfr-m^2) and (0.070686 m^2) / (30 mask-layers) = 0.0023562 (wfr-m^2).
[b](0.031416 m^2) / 30 (mask layers) = 0.0010472 (wfr-m^2).
[c](1 m^2) • (10^{-6} mm^2) = 0.0000001 (wfr-m^2).
[d](1 m^2) • (10^{-3} cm^2) = 0.0001 (wfr-m^2).
[e](31,416 mm^2) • (10^{-6} m^2) = 0.031416 (wfr-m^2).
Sources: Elaboration of data of TrendForce (2023) and of CSR reports (several years) of TSMC, UMC, GF, SMIC, PSMC, and HHS.

solutions (DS), which includes Samsung's foundry sector. Powerchip Semiconductor Manufacturing Corp. (PSMC), Hua Hong Semiconductor Ltd. (HSS) Group (2019), and other even smaller ones (for a total revenue share, in 2021, of about 10% of the world's revenue of the whole foundry sector) were not considered due to the unavailability of environmental data for all the years and items analysed. In any case, in 2021, the above mentioned four analyzed companies represent, excluding the share of Samsung Electronics' foundry business, nearly 90% of the global revenue of the entire sector (71% of share, if the 18% share of Samsung's Foundry is included in the overall total).

Based on the CSR reports data and information, the following items were considered for the subsequent KPIs calculation: (1) Production; (2) Revenue; (3) R&D investments; (4) Patents; (5) direct (Scope 1) and indirect (Scope 2) GHG emissions, referred to in tables and figures as GHG_1 and GHG_2, respectively; (6) Energy consumption; (7) Water (consumption and intake); (8) Wastewater; (9) General waste; and (10) Hazardous waste. Fluorinated-GHG (F-GHG) emissions were not taken into account because the related data are not always available.

Not all the companies report the amount of their Scope 3 GHG emissions. However, the results and assessments on Scope 1 and Scope 2 GHG emissions are not limited and affected by the lack of Scope 3 GHG emissions data because, as is well known, they are a category of emissions that result from activities not directly owned or controlled by the reporting organization and, furthermore, their analysis has little relevance for a paper, like this, that deals with assessing the environmental performance of companies whose production activities, and their environmental impact, are under their control.

As foundries adopt different MIs to which to refer theirperformance, as shown in Table 1, column (*d*), a preliminary homogenization was therefore necessary, calculating and using different conversion factors (CFs), in order to calculate a singular and common MI, corresponding to the total area of wafers produced in a year (wafer-m^2/y or wfr-m^2/y) and obtained by multiplying the wafers produced by the average number of layers of each wafer (AMD, 2022; Ruberti, 2022). For those fabs adopting, in their CSR reports, different MIs (e.g., "12-inch equivalent wafer mask layer," "8-inch equivalent wafer mask layer," and so on), required conversion processes were carried out, considering that: (1) on average, in a single wafer there could be about 30 mask layers (Bosch, 2023; Intel, 2011; UniversityWafer, 2023); and (2) an 11.8-in. wafer (generally indicated as 12″) and a 7.9-in. wafer (generally indicated as 8″) have, correspondingly, a radius of 150 mm (area of 70,686 mm^2) and 100 mm (area of 31,416 mm^2).

In Table 1, the main information of each company, about its MI and the respective conversion factor to the adopted MI (wfr-m^2), are summarized.

3 RESULTS AND DISCUSSION

In Table 2, all the available data, from the analyzed fabs' CSR reports, are shown.

In Table 3, the most significant correlations (Pearson's r—correlation coefficient, PCC), between the annual variations of several items, are shown.

In Table 4, the KPIs, obtained by processing the data of the various items of Table 1, are shown.

TABLE 2 Performance data of the world's major foundries.

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
(a) Production (MI)—Wafer-m^2 (in 000)[a]	773.6	898.4	1026.2	,124.1	1228.8	1404.3	1530.0	1546.9	1883.6	2193.1
(b) Revenue (US $ billion)[b]	26.34	30.49	36.17	39.28	43.78	46.30	48.65	48.95	60.36	71.73
(c) Representativeness of the sample (%)[c]	87.0 (76.1)	90.8 (85.0)	90.4 (85.2)	92.5 (87.0)	90.7 (83.0)	91.5 (83.9)	90.6 (73.7)	92.5 (74.9)	92.9 (75.6)	89.9 (73.6)
(d) R&D Expenditures (US $ billion)[b]	2.27	2.63	2.98	3.28	3.61	4.28	4.86	4.67	5.22	5.71
(e) Patents per year	2360	3808	4428	5491	6548	6942	6548	6988	7711	9102
(f) Total patents of the sample[d]	14,389	18,197	22,625	28,116	34,664	41,606	48,154	55,142	62,853	71,955
(g) GHG emissions (kt CO_2e)—Scope 1	2659	2903	3376	3417	3431	3560	3554	3419	3518	3799
(h) GHG emissions (kt CO_2e)—Scope 2[e]	5190	5698	6534	6933	7806	9039	9318	9519	10,539	11,225
(i) Total GHG emissions (kt CO_2e)	7850	8601	9910	10,349	11,237	12,599	12,872	12,938	14,057	15,024
(l) Energy consumption (GWh)[f]	10,526	11,740	13,480	15,089	16,580	19,264	20,547	21,556	24,493	27,769
(m) Water consumption (kt)	42,743	47,845	53,502	54,115	61,068	71,594	78,328	84,185	100,868	112,205
(n) Wastewater discharge (kt)[g]	47,889	53,389	54,344	61,789	68,613	74,323	80,409	86,890	99,680	107,138
(o) Water withdrawal or intake (kt)	90,632	101,234	107,846	115,904	129,681	145,917	158,737	171,075	200,548	219,343
(p) General waste generated (t)[h]	62,084	75,410	97,839	181,877	228,456	267,077	282,297	293,936	349,636	414,816
(q) Hazardous waste generated (t)	135,595	155,636	209,160	198,882	211,109	261,688	272,745	281,116	391,268	459,521
r) Total waste generated (t)	197,679	231,046	306,999	380,759	439,565	528,765	555,042	575,052	740,904	874,337

[a] Total annual capacity of the related manufacturing facilities of TSMC, UMC, GF, and SMIC. Sum of individual companies' data after homogenization by a common MI.
[b] At current prices in each year.
[c] Based on the total revenue of the world top 10 foundries (for 2015 and 2017, on the total sales of the world top eight foundries) without (or with) the share of Samsung Foundry.
[d] Number of pre-2012 patents: 12,029.
[e] Outsourced energy such as electricity, steam, and heat.
[f] From non-renewable sources. Including electricity and natural gas. Natural gas consumption, expressed in km^3, was converted to GWh assuming a heating value of 39.4 MJ/Sm^3.
[g] The amount of wastewater is a function of tap water consumption and the amount of recycled water.
[h] The item includes: production waste (the most abundant), sludge from water treatment, and domestic waste (the smallest).
Sources: Elaboration of data of CSR reports (several years) of TSMC, UMC, GF, and SMIC; TrendForce (several years); IC Insights (several years); Statista (2022); EPO (2023).

TABLE 3 Indices of significant correlation ($r \geq 70$) between the annual changes of the management variables. Underlying data for this table are available in Table 2 of this article.

(a) Production—Revenue	0.92	(m) GHG_2 - GHGt	0.93
(b) Production—Energy consumption	0.91	(n) Energy—Water consumption	0.76
(c) Production—Water consumption	0.83	(o) Energy—Water withdrawal	0.70
(d) Production—Water withdrawal	0.80	(p) Energy—Hazardous waste	0.81
(e) Production—Hazardous waste	0.87	(q) Energy—Waste (total)	0.92
(f) Production—Waste (total)	0.92	(r) Water consumption—Water withdrawal	0.93
(g) Revenue—Energy consumption	0.79	(s) Water consumption—Hazardous waste	0.90
(h) Revenue—Water consumption	0.72	(t) Water consumption—Waste (total)	0.75
(i) Production—Water withdrawal	0.70	(u) Wastewater—Water withdrawal	0.84
(j) Revenue—Hazardous waste	0.93	(v) Water withdrawal—Hazardous waste	0.78
(k) Revenue—Waste (total)	0.88	(w) Water withdrawal—Waste (total)	0.75
(l) GHG_1 - GHGt	0.71	(x) Hazardous waste—Waste (total)	0.86

By using the graphically represented indicators of Tables 1 and 2, it was possible to outline the trends related to the main aspects about the performance of the various companies as a whole sector. Trend lines were not placed in the graphs when their R^2 had values of little significance (<0.5).

Statistical representativeness of the fabs' sample, based on the global revenue of the world's top 10 foundries, is always very high: consistently around 90% (without Samsung Foundry's share) for each year of the decade analysed (Table 2).

3.1 | Productivity and R&D investments

Foundries' wafer production and their annual revenue have grown from 2012 to 2021 at an almost constant annual rate (Table 2), with the exception of the economic stagnation which occurred in 2019.

After 2016, during which the highest profitability of wafer production was reached (over US $ 35,500/wfr-m^2), there was a definite stabilization, for all subsequent years, around an average value of US $ 32,200/wfr-m^2 (Figure 1a). This price slowdown was mainly due to a market oversupply and to increasing competition (Ross, 2019). This oversupply, at first, led to an average reduction of chips prices, and, subsequently, companies had to search new ways to differentiate their production to preserve their profit margins.

About the relationship between environmental management, production, and revenue levels, the environmental performance of a company may significantly affect its revenue. This may be a positive or negative effect depending on the company's environmental management. In fact, a good environmental performance can lead to direct economic benefits: companies that invest in cleaner technologies and energy-efficient processes tend to get reduced operating costs in the long term. Zeng et al. (2010) found that clean production practices may have an overall positive impact on a firm's financial performance. This suggests that investments in environmental sustainability may reduce costs and improve operational efficiency, leading to higher profit margins (Gotschol et al., 2014; Schaltegger & Synnestvedt, 2002).

In addition, also for 2019, R&D investments decreased: from US $4.86 billion to US $4.67 billion (Figure 1b). In fact, the semiconductor market declined in 2019 due to a combination of factors, including: (a) slowdown in the world's economic growth, which led to a reduction of overall demand for electronics and semiconductors (Gopinath, 2019); (b) United States–China and China–Taiwan tensions resulting in increased tariffs on electronics and microchips, which led to a decreased demand for these products (Chen et al., 2021; JEITA, 2019; Pufal et al., 2023); (c) a higher level of excess inventory, due to weakening demand for electronics and semiconductors (SemiMedia, 2023); (d) weak demand for chips from the automotive sector, due to declining sales and production cuts (Brown et al., 2021); (e) weak demand for chips from the smartphone sector, due to market saturation and other economic factors (Mongardini & Radzikowski, 2020); and (f) implications on the consumer market by the COVID-19 stringent political measures (Bauer et al., 2020a). These contractions were anticipated in the previous year (2018) by a significant diminution of new patents, decreasing from 6942 to 6548 (Figure 1b).

R&D investments were gradually increased throughout the decade in relation to revenue (Figure 1c). From the high value of the multiple regression coefficient (R^2) of the trend line, it may be inferred, as it is obvious for an industry with high technological innovation, that these rates will also grow in the next years. R&D expenditures also increased, albeit with some interludes of stagnation in the period 2015–2018, correspondingly with the related production slowdown (Figure 1d).

TABLE 4 Foundries' key-performance indicators (KPIs). Underlying data for this table are available in Table 2 of this article.

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Revenue/MI (USD/wfr-m^2)	34,050	33,941	35,245	34,943	35,632	32,971	31,799	31,644	32,045	32,707
R&D expenditures on revenue (%)	5.01	5.19	5.20	5.54	5.35	5.77	5.83	6.13	5.96	6.64
R&D investments/MI (USD/wfr-m^2)	2933	2930	2907	2916	2936	3047	3175	3021	2770	2605
GHG_1/MI (kg CO_2e/wfr-m^2)	3438	3231	3290	3039	2792	2535	2323	2210	1868	1732
GHG_2/MI (kg CO_2e/wfr-m^2)	6709	6343	6367	6167	6352	6436	6090	6154	5595	5119
$GHG_{1\&2}$/MI (kg CO_2e/wfr-m^2)	10,147	9574	9657	9207	9145	8972	8413	8364	7463	6851
GHG_1/revenue (kg CO_2e/1000 US $)	101.0	95.2	93.3	87.0	78.3	76.6	73.0	69.8	58.3	53.0
GHG_2/revenue (kg CO_2e/1000 US $)	197.0	186.9	180.6	176.5	177.7	194.4	191.5	194.5	174.6	156.5
$GHG_{1\&2}$/revenue (kg CO_2e/1000 US $)	298.0	282.1	274.0	263.5	256.0	271.1	264.6	264.3	232.9	209.5
Energy efficiency (MWh/wfr-m^2)	13,606	13,068	13,136	13,424	13,493	13,718	13,429	13,935	13,003	12,662
Energy intensity (MWh/US $ million)	399.6	385.0	372.7	384.2	378.7	416.1	422.3	440.4	405.8	387.1
Water consumption/MI (t/wfr-m^2)	55.3	53.3	52.1	48.1	49.7	51.0	51.2	54.4	53.6	51.2
Wastewater discharge/MI (t/wfr-m^2)	61.9	59.4	53.0	55.0	55.8	52.9	52.6	56.2	52.9	48.9
Water withdrawal/MI (t/wfr-m^2)	117.2	112.7	105.1	103.1	105.5	103.9	103.7	110.6	106.5	100.0
Wastewater intensity (t/US $ million)	1818	1751	1503	1573	1567	1605	1653	1775	1651	1494
Water intensity (t/US $ million)	3441	3320	2982	2951	2962	3151	3263	3495	3322	3058
General waste generated per MI (kg/wfr-m^2)	80.3	83.9	95.3	161.8	185.9	190.2	184.5	190.0	185.6	189.1
Hazardous waste generated per MI (kg/wfr-m^2)	175.3	173.2	203.8	176.9	171.8	186.4	178.3	181.7	207.7	209.5
Total waste generated per MI (kg/wfr-m^2)	255.5	257.2	299.2	338.7	357.7	376.5	362.8	371.7	393.3	398.7
General waste/revenue (kg/US $ million)	2357	2473	2705	4630	5218	5768	5802	6005	5792	5783
Hazardous waste/revenue (kg/US $ million)	5148	5104	5783	5063	4822	5652	5606	5743	6482	6406
Total waste/revenue (kg/US $ million)	7505	7578	8488	9694	10,039	11,420	11,408	11,748	12,275	12,189

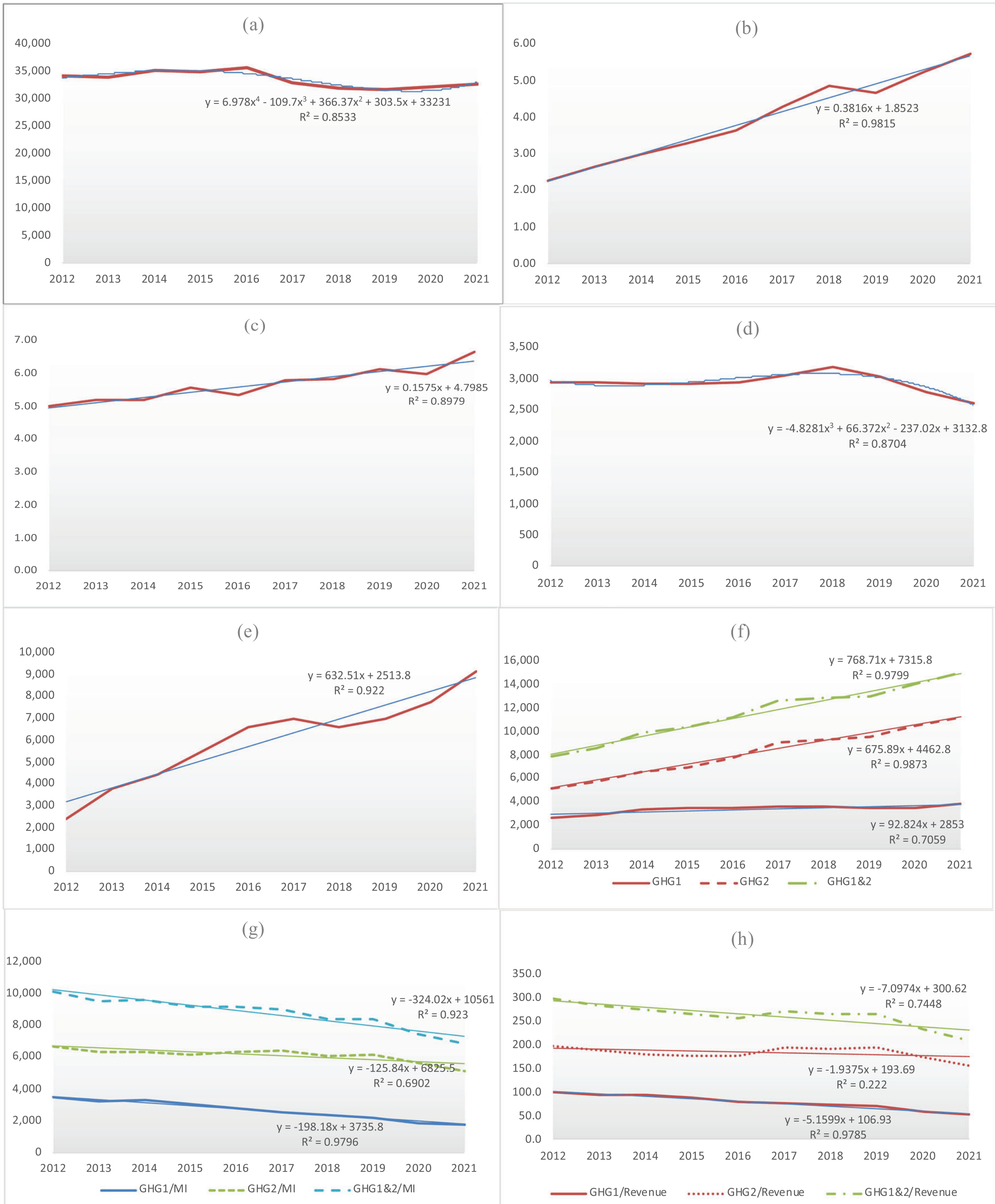

FIGURE 1 Revenue per unit of production (USD/wfr-m^2) (a); fabs' R&D expenditures (US $ billion) (b); R&D expenditures on revenue (%) (c); R&D expenditures/manufacturing index (MI) (USD/wfr-m^2) (d); patents per year (e); greenhouse gas (GHG) emissions (kt CO_2e) (f); GHG emissions/MI (kg CO_2e/wfr-m^2) (g); GHG emissions on revenue (kg CO_2e/1000 US $) (h). Underlying data for this figure are available in Tables 2 and 4 of this article.

These investments had strategic implications in the semiconductor foundry industry, characterized by rapid technological change and intense competition. Companies spent a lot on R&D to stay ahead of global competition and to develop new and advanced technologies. Specifically, some R&D areas where semiconductor foundries have invested include: (a) advanced process technologies, such as improved extreme ultraviolet lithography (EUVL), metal–organic vapor deposition (MOVD), nanoimprinting lithography (NIL), 3D nanofabrication, and so on, which have enabled high volume manufacturing (HVM) of smaller and more complex microchips; and (b) environmental sustainability, recycling, and reducing waste, to minimize their environmental impact (Chen et al., 2020; Levinson & Brunner, 2018; Schoot & Schift, 2017; Sharma et al., 2022).

Patents play another important role in the semiconductor industry, generating a competitive advantage and protecting companies' intellectual property. TSMC, known for its advanced manufacturing process, has a strong patent portfolio: about 60% (43,158 patents in 2021) of the total number of patents of all sample companies. This fab, in fact, has a long history of innovation and has invested heavily in R&D to maintain its leading position in this field. The total number of patents has steadily increased over time, with the exception of 2018, when there was a sharp decline from the previous year, due to the above-mentioned general crisis (Figure 1e).

Analyzing the correlations between the annual changes in the multiple variables (Table 3), it was found that the interrelationships between production; revenue; water and energy consumption; and gaseous, liquid, and solid waste generation were very evident. These relationships emerged because each aspect of semiconductor manufacturing was closely related to and often dependent on the other. In fact, manufacturing in the semiconductor industry is notoriously resource intensive, both in terms of energy and water, which are needed to maintain controlled environments such as cleanrooms and for the production of ultra-pure water (UPW), which is essential for washing wafers, removing debris (silica, particles, ions, etc.), and ensuring the highest-quality products (Wishnick, 2021). Den et al. (2018) stated that the semiconductor industry has shown a responsible water usage to maintain business competitiveness and effectively manage water scarcity risks. Energy consumption is correlated not only with production efficiency, but also with the environmental impact of the industry. Zhao and Feng (2021) showed a high correlation between energy consumption and exhaust emission and solid waste generation. In turn, energy use is often influenced by the need to treat and dispose of the waste generated, thus establishing a vicious cycle between energy consumed and waste generated. A company's revenue is directly affected by such dynamics as energy, water expenses, and costs for waste management and compliance with environmental regulations. All of this affects profit margins. Increased operational efficiency, which reduces water and energy consumption and minimizes waste generation, may therefore lead to revenue growth through reduced operating costs and an improved corporate identity linked to its greater environmental responsibility.

3.2 | GHG emissions

Semiconductor foundries are a significant source of GHG emissions, mainly because their processes are energy intensive (Belton, 2021). For example, Freitag et al. (2021) estimated that the current share of ITC sector emissions is between 2.1% and 3.9% of global GHG emissions.

Scope 1 and Scope 2 GHG emissions are counted within specific organizational boundaries as follows: (1) Scope 1 emissions, or direct emissions, are defined as emissions from sources owned or controlled by the organization. They include emissions from combustion in sources owned or under the organization's control, such as boilers, furnaces, vehicles, etc., and those from chemical production in process equipments that are owned or controlled by the organization. The boundary for Scope 1 is the physical location or sites controlled by the company, including buildings, manufacturing facilities, and company vehicles. (2) Scope 2 emissions (energy indirect emissions) result from the generation of purchased electricity, heat, steam, or cooling that the organization consumes. While the emissions physically occur at the facility where the energy is generated, they are accounted for in Scope 2 because they are a result of the organization's energy use. The boundary for Scope 2 includes all locations where the organization consumes purchased energy.

Total GHG emissions almost doubled over the 2012–2021 period: from 7850 to over 15,000 kt CO_2e (Table 2 and Figure 1f). This could be attributed, almost exclusively, to the increase of Scope 2 GHG emissions; while the Scope 1 component has remained basically anchored around the average value of 3400 kt CO_2e per year. Since Scope 1 GHG includes, as well known and stated above, emissions from sources controlled by a company (e.g., fossil fuels used) and GHG Scope 2 includes emissions related to energy purchased by a company, primarily for electrical consumption (by fuels burned by third parties), it means that, during the analyzed period, fabs have increasingly used electricity generated by others to power their production processes. Comparing these emissions with the production index (Figure 1 g) and revenue (Figure 1h), it can be seen that all three lines in the graph have a corresponding trend line with a negative determinant, which is more pronounced for $GHG_{1\&2}$ emissions data. This has occurred because foundries, over the years, have gradually implemented various strategies (such as using biodegradable materials and renewable energy sources, improving energy efficiency, and reducing the use of chemicals that increase GHG emissions) and invested in carbon capture and storage technologies (Crawford et al., 2021).

One of the leading strategies has been the optimal application of control technologies, which have integrated the efficient use of exhaust gas destruction equipment, particularly for critical processes such as etching and thin-film deposition (Zhu et al., 2023). Another major key factor has been the semiconductor industry's voluntary commitment to reduce emissions of perfluorinated compounds (PFCs) since 2010 through collaboration among manufacturers, both with each other and with fabless firmssharing knowledge on effective techniques and strategies (Illuzzi & Thewissen, 2010). This is an excellent example of what can be accomplished through collaboration. In addition, improved techniques for measuring GHG emissions have enabled more accurate estimates, facilitating the rapid development of targeted and effective reduction technologies and strategies (Lee et al., 2023). Lastly, pollution taxes and/or subsidies has stimulated semiconductor factories to reduce their GHG emissions (Chi & Hsu, 2017).

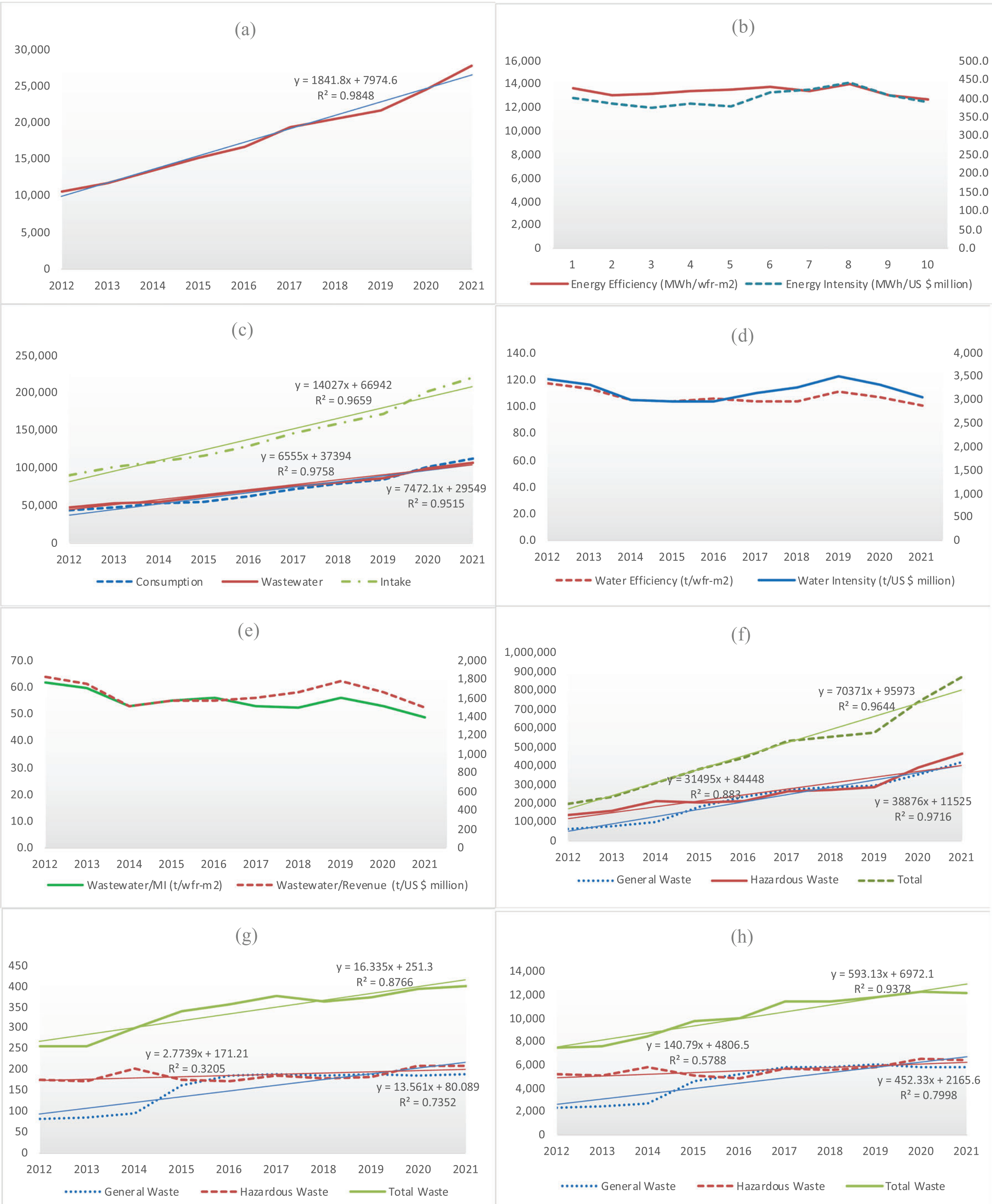

FIGURE 2 Energy consumption (GWh) (a); energy efficiency and intensity (b); water use (kt) (c); water efficiency and intensity (d); wastewater on manufacturing index (MI) and on revenue (e); waste generated (t) (f); waste generated per MI (kg/wfr-m^2) (g); waste generated per revenue (kg/US $ million) (h). Underlying data for this figure are available in Tables 2 and 4 of this article.

3.3 | Energy efficiency and intensity

Semiconductor foundries consume relatively high energy per MI in their manufacturing processes. This huge energy consumption, which nearly tripled from 2012 to 2021 (Figure 2b), was related to the need for high temperatures, high-precision air, and humidity control in large clean rooms. Other reasons were the related large-scale manufacturing processes, considering that leading foundries' scale production is about 100,000 (wafer starts per week (WSpW) (Bauer et al., 2020b; Burkacky et al., 2023a). Energy efficiency could also be expressed through energy intensity, calculated as units of energy divided by revenue. This indicator measures the capacity of a company to "convert" energy into revenue: high energy intensity reveals high inefficiency (and high costs) in "converting" energy into revenue. The decrease of energy use per unit of revenue—except in 2020 and 2021, when the global foundry industry had a slowdown in the rate of increase in energy efficiency (12,662 MWh/wfr-m^2 in 2021) and intensity (387 MWh/US $ million in 2021), after a long period of almost constant growth (from 2013 to 2019) (Figure 2a)—was due to moreefficient manufacturing processes and the use of renewable energy (Favino, 2023). Additionally, the industry has also investigated alternative manufacturing technologies, such as those based on molecular and nanoscale engineering (e.g., directed self-assembly or DSA and block copolymer or BCP technologies), which may lead to the development of more energy-efficient manufacturing processes in the future (Chen & Xiong, 2020; Mullen & Morris, 2021). These efforts may also mitigate the impact of increasing demand for semiconductors both on energy use and GHG emissions. Energy efficiency, related to the energy used per unit of production, remained essentially unchanged around the average value of 13,350 MWh/MI (Figure 2b).

3.4 | Water use and wastewater production

Semiconductor foundries require huge amounts of water for their manufacturing processes (Wishnick, 2021). Water consumption in 2021, which has more than doubled since 2012, was nearly 220 kt, almost equal to the average daily water consumption of 28.9 million US citizens (EPA, 2023b) (Figure 2c).

This water is used for cleaning (as deionized UPW, ultrapure water), for cooling equipment and for air conditioning (HVAC [heating, ventilation and air conditioning]) systems, for heating ventilation, and other purposes (Multani, 2020). The amount of water withdrawal for these purposes changes significantly depending on the complexity of a process. Some foundries, like TSMC, use recirculated water systems in combination with alternative water sources (such as rainwater or wastewater) to minimize their water withdrawal, but other fabs still use large amounts of freshwater with a significant impact on local water resources (Den et al., 2018; TSMC, 2023).

Over the years, the amount of water intakes, in relation to MI and revenue, has remained basically stable around the average value of 107 t (metric tons)/wfr-m^2 and 3200 t/US $ million (Figure 2d). Since 2017, the two corresponding trend lines diverge: that of the water withdrawal/MI ratio is clearly lower than that of the water/revenue ratio. This is due, fundamentally, to the lower unit profitability of wafers produced related to the performance of the revenue/MI ratio.

Semiconductor foundries generate a significant amount of wastewater during manufacturing processes, which may contain various chemicals and hazardous substances. The treatment and disposal of this wastewater is fundamental to safeguard the environment and public health. Typically, in the foundries, wastewater treatment involves physical, chemical, and biological methods to remove contaminants and pollutants before discharge (Wang et al., 2023). Some foundries also implement closed-loop systems, such as zero liquid discharge (ZLD) systems, to minimize wastewater discharge and reduce its environmental impact (Burkacky et al., 2023b; Gandhi, 2020; Makini, 2015).

Wastewater generation has slightly decreased. In fact, the relative trend line has a negative determinant ($m = -0.9523$) (Figure 2e) because some companies, such as TSMC, have implemented systematic and resolute programs for water reuse and recycling. TSMC, in fact, for every year of the period, has a wastewater/MI index that is constantly about 60% of the corresponding average of the all examined companies.

3.5 | Waste generation

Foundries generate chemical, electronic, and hazardous substances. Hazardous waste generation is due to the use of toxic chemicals in the manufacturing process: additives, photoactive compounds, polymer, salts, etc., which are mainly used in photolithography, in the liquid or gaseous phase. They, sometimes secretly, may include solvents, acids, and heavy metals that could be harmful to the environment and human health if not properly managed (Kim et al., 2018).

The total amount of waste has more than quadrupled over the decade: from 198 kt, in 2012, to 874 kt, in 2021 (Figure 2f). This is due in part to the increase of production (almost tripled) and in part to the increased manufacturing complexity of the new wafers (with smaller technology nodes), which required much more water per unit. The most relevant aspect, however, is not only the fact that hazardous waste has more than doubled in absolute values since 2012, but that the corresponding trend line has shown a conspicuous increase since 2019.

General and hazardous waste generation per MI has also strongly increased, over the years, in relation to wafers produced and annual revenue (Figure 2g,h). Since 2017, however, there is a settling trend in the rise of the trend lines of waste generated per MI and waste generated per revenue, due to the commissioning of new and modern plants and/or to the startup of more technologically advanced production lines.

Added to this, there is the consideration that, in the semiconductor manufacturing sector, the environmental impact of waste may be more severe, mainly due to the increased use of materials with uncertain long-term environmental effects. In particular, the relationship between the amount of these materials and the related environmental impact is not so evident. For instance, the impact could be exponential and not linear to the increase in the amount of waste. The chemical waste management in the semiconductor industry is very complexfor the various toxic components involved. This highlights the need of addressing these environmental challenges through comprehensive strategies for reducing the use of hazardous materials, improving waste treatment technologies, and implementing strict environmental safety measures and protocols (Shen et al., 2018).

To reduce waste generation, some semiconductor foundries have implemented sustainability practices: a strategy to reduce the use of hazardous chemicals; recycling waste products; waste minimization processes, like the reduced use of test wafers; adopting new techniques (such as more advanced NIL and EUVL), and improving energy efficiency (CRS, 2020; Mullen & Morris, 2021). For the future, this sector will have to search and develop alternative production processes to reduce waste generation and promote sustainability (Englund et al., 2023; Shen et al., 2018).

4 | CONCLUSIONS

In absolute value, all the main indicators of the examined sample of foundry companies have shown decidedly growing trends for the entire period. In fact, since 2012, increases in wafer production (183%), revenue (172%), and technological capacity (400% more patents) have been matched by corresponding increases in resource use and environmental impacts, in terms of energy consumption (164%), water use (163%), and by more than proportional increases in general waste (568%) and hazardous waste (239%) generation. These negative findings have been partly counterbalanced by unitary GHG emissions, relating to the values of MI and revenue, having markedly decreasing trends (about −30%). This is due to the increased use of renewable energy sources, such as photovoltaic and wind power, which are very helpful in improving energy efficiency and reducing carbon footprint.

The increase in waste generation is the most notable of these facts, and it is even more remarkable considering that general waste and hazardous waste are, among all these, the only two factors whose trends have significantly grown also in relation to fabs' MI and revenue. It is, therefore, critical for this industry to reduce its environmental impact and promote more sustainable practices to mitigate the negative effects of microchip production.

The findings of this research could help and guide upcoming sustainability policy decisions and stimulate the adoption of better environmental production practices, for instance, by encouraging the development and implementation of waste reduction technologies, improving better wastewater management, providing incentives for better efficient production practices, promoting renewable energy investments, and establishing new benchmarks or promoting technological innovations.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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