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Environmental data and facts in the semiconductor manufacturing industry: An unexpected high water and energy consumption situation

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ABSTRACT

With the expansion of the semiconductor industry, determining the huge associated water and energy consumption and accomplishing sustainable development can be key issues for this industry. This study surveyed the sustainability reports of 28 semiconductor corporations and summarized their environmental stewardship information. Overall, the total water withdrawal in 2021 was 7.89×10^8 m^3, total energy consumption was 1.49×10^{11} kWh, and total greenhouse gas (GHG) emissions were 7.15×10^7 tons CO_2 equivalent. The total Scope 1 and Scope 2 GHG emissions were 2.74 and 4.41×10^7 t CO_2 equivalent, respectively. Surface water intake, municipal water supply, groundwater withdrawal, third party supply, and external reclaimed water intake accounted for 47.0%, 35.3%, 8.5%, 5.8%, and 3.2% of total water use, respectively. Electricity, fossil fuel, renewable energy, and others accounted for 83.7%, 12.0%, 2.7%, and 1.7% of the total energy use. In 2021, average water use, energy consumption, and GHG emissions were calculated to be 8.22 L/cm^2, 1.15 kWh/cm^2, and 0.84 kg CO_2 equivalent/cm^2, respectively, based on announced data. Ultrapure water consumption was predicted to be 5.51 and 0.95×10^8 m^3 worldwide and for China, respectively. Effective sustainability strategies are supposed to be implemented to meet the considerable growth in water and energy consumption and GHG emissions for the semiconductor industry worldwide and in China.

1. Water use, energy consumption, and greenhouse gas (GHG) emissions of semiconductor industry

Semiconductors are essential for the progress of information technology, and the semiconductor industry is regarded as a key driver of economic development. Major economies worldwide, including those of the United States, China, Japan, Korea, and Europe, have attempted to expand semiconductor manufacturing capacities with great efforts. However, semiconductor manufacturing can be an industry with considerably high consumption of energy and water [1]. In semiconductor manufacturing processes, ultrapure water (UPW) is a fundamental material necessary for surface cleaning. UPW is made from conventional fresh water sources, such as tap water, surface water, and even reclaimed water, with high water loss and considerable energy input in its complex production processes [2,3]. To achieve sustainable development of the semiconductor industry, water will be one of the key restrictive factors for the development of semiconductor manufacturing because of the conflicts between high water consumption, water shortage, and water pollution.

Based on the presentation and analysis of announced data concerning water use, energy consumption, and greenhouse gas (GHG) emissions of semiconductor corporations, this study aims to reveal this neglected fact that the capacity expansion of the semiconductor industry will be accompanied by high input of water, energy, and high GHG emissions. The study surveyed the environmental stewardship of 28 semiconductor corporations [4–31], as shown in Table 1. The surveyed corporations made up the vast majority of the semiconductor manufacturing market according to information published by IC insights and the U.S. Semiconductor Industry Association [32,33].

These unexpected data and facts concerning water, energy, and GHG

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Table 1
Surveyed semiconductor corporations in this study.

Full name	Abbreviation	Headquarters location	Data source	Reference
Skyworks Solutions Inc.	SWKS	The United States	Skyworks 2021 Sustainability Report	[4]
Winbond Electronics Corp.	Winbond	China (Taiwan)	Winbond Electronics Sustainability Report 2021	[5]
Tower Semiconductor limited	TSEM	China (Taiwan)	2020 Corporate Sustainability (ESG) Report	[6]
Dongbu HiTek Co., Ltd.	DB HiTek	Korea	2021–2022 DB HiTek ESG Report	[7]
Powerchip Semiconductor Manufacturing Corp.	PSMC	China (Taiwan)	Sustainability Report 2021	[8]
Microchip Technology Inc.	MCHP	The United States	2021 SUSTAINABILITY REPORT	[9]
Vanguard International Semiconductor Corp.	VIS	China (Taiwan)	Sustainability Report 2021	[10]
Seagate Technology Corp.	Seagate	The United States	Fiscal Year 2021 Global Citizenship Annual Report	[11]
Huahong Hongli Semiconductor Manufacturing Co., Ltd.	HUAHONG	China	2021 Environmental, Social and Governance (ESG) Report	[12]
Yangtze Memory Technologies Co., Ltd.	YMTC	China	Official website	[13]
ROHM Semiconductor Co.,Ltd.	ROHM	Japan	ROHM Integrated Report 2022	[14]
Nexchip Semiconductor Corp.	NXP	Netherlands	2021 NXP CORPORATE SUSTAINABILITY REPORT	[15]
ON Semiconductor Corp.	Onsemi	The United States	2021 Sustainability Report: Creating a better tomorrow. Today.	[16]
GlobalFoundries Inc.	GFS	The United States	Corporate Responsibility Report 2022	[17]
Renesas Electronics Corp.	Renesas	Japan	Official website	[18]
Western Digital Corp.	WDC	The United States	FISCAL YEAR 2021 SUSTAINABILITY REPORT	[19]
Sony Corp.	Sony	Japan	Sustainability Report 2022	[20]
STMicroelectronics Ltd.	ST	Italy	2022 Sustainability report. 2021 performance	[21]
Texas Instruments Inc.	TI	The United States	2021 Corporate Citizenship Report	[22]
KIOXIA Holdings Corp.	KIOXIA	Japan	Sustainability Report 2022	[23]
Semiconductor Manufacturing International Corp.	SMIC	China	2021 Environmental, Social and Governance Report	[24]
United Microelectronics Corp.	UMC	China (Taiwan)	2021 UMC Sustainability Report	[25]
Infineon Technologies Corp.	Infineon	Germany	Sustainability at Infineon: Supplementing the Annual Report 2021	[26]
Micron Technology Inc.	Micron	The United States	Investing in the future: Sustainability report 2022	[27]
Intel Corp.	Intel	The United States	Corporate Responsibility Report 2021–22	[28]
Taiwan Semiconductor Manufacturing Company Ltd.	TSMC	China (Taiwan)	TSMC 2021 Sustainability Report	[29]
SK hynix Inc.	SK hynix	Korea	SK HYNIX SUSTAINABILITY REPORT 2022	[30]
Samsung Electronics Corp.	Samsung	Korea	Samsung Electronics Sustainability Report 2022: A JOURNEY TOWARDS A SUSTAINABLE FUTURE	

emissions in the semiconductor industry manifest the significance of sustainable development of this industry as it is a high water and energy intensive industry when ushering in its rapid growth. China is a country faced with severe water situation and carbon emission reduction pressure and plans to put great efforts into the development of the semiconductor industry in the next few decades, how to accomplish the sustainable development of the semiconductor industry is an important issue.

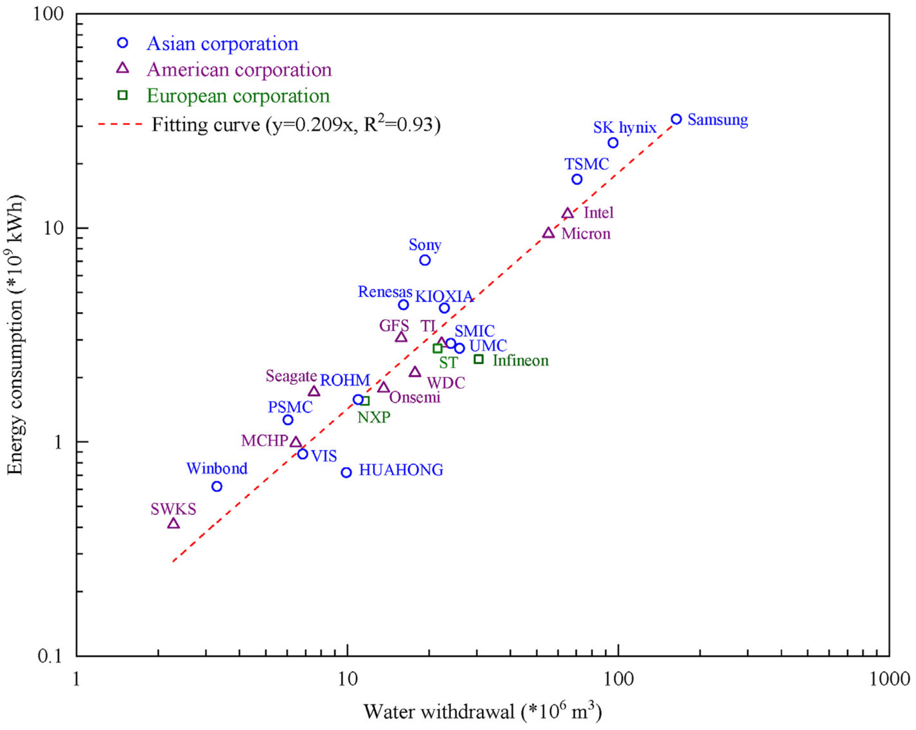

Fig. 1. The energy consumption and water withdrawal of the semiconductor corporations in 2021.

1.1. Total water use, energy consumption, and GHG emissions of semiconductor corporations

The water withdrawal and energy consumption of the 27 semiconductor manufacturing corporations are shown in Fig. 1. In 2021, water withdrawal of the semiconductor corporations was measured in units of 10^6 m^3, with a range of 2.3–163.7 × 10^6 m^3. Energy was consumed at a level of 10^9 kWh, with a range of 0.41–32.3 × 10^9 kWh. Total water withdrawal and energy consumption of the 27 corporations enumerated in this study was 7.89×10^8 m^3 and 1.49×10^{11} kWh, respectively. The median value for water withdrawal and energy consumption were 1.61×10^7 m^3 and 2.74×10^9 kWh, respectively. Five of these corporations were found to consume more than 5×10^7 m^3 of water and 9×10^9 kWh of energy annually, namely Samsung, SK hynix, TSMC, Intel, and Micron. The water and energy consumption of these corporations were mostly $<3 \times 10^7$ m^3 or 4×10^9 kWh per year (19 of 27 corporations). There was an positive correlation between water withdrawal and energy consumption, with an R^2 value of 0.93 and a ratio of 0.209 kWh (energy consumptiont)/L (water withdrawal).

The GHG emissions of 26 semiconductor corporations are shown in Fig. 2 (GHG emission data of YMTC was undisclosed), which were attributed to direct (Scope 1) and indirect emissions (Scope 2). The total GHG emissions of these corporations were 7.15×10^7 t CO_2 equivalent. The total Scope 1 and Scope 2 emissions of these corporations were 2.74 and 4.41×10^7 t CO_2 equivalent, respectively. Scope 1 emissions covered direct carbon emission in semiconductor production, including direct use of energy such as fossil fuels, carbon emissions from vehicles in parks, and emissions of other types of GHG necessary for production, including perfluorinated compounds, polyfluorinated carbon compounds, sulfur hexafluoride, and nitrogen trifluoride. Scope 2 emissions covered carbon emissions from indirect energy use such as grid electricity supply, steam, and district heating. The huge differences of presented value on water and energy use and GHG emissions among different corporations were mainly due to the differences of company scale and market shares.

To better understand the water and energy consumption levels of semiconductor manufacturing, relevant statistics of China announced by the National Bureau of Statistics of China were taken as a reference [34]. In 2021, the total water use in China was 5.81×10^{11} m^3 and domestic water use was 8.63×10^{10} m^3. The comprehensive water use per capita was 419 m^3 and the domestic water use per capita was 64.3 m^3 in China in 2021, with a total population of 1.41 billion. Water consumption of these corporations amounted to the total water consumption of a city with 1.88 million people or domestic water use of 12.2 million people in China. The total electricity consumption of the whole China was 8.31×10^{12} kWh in 2021 according to data provided by the National Bureau of Statistics of China. The comprehensive electricity consumptions per capita of China in 2021 were 5884.8 kWh. The energy consumption of these corporations in 2021 was equal to the total electricity consumption of a city with a population of 25.2 million people (larger than Beijing or Shanghai in China), which helps to comprehend the huge energy consumption in semiconductor industry more directly.

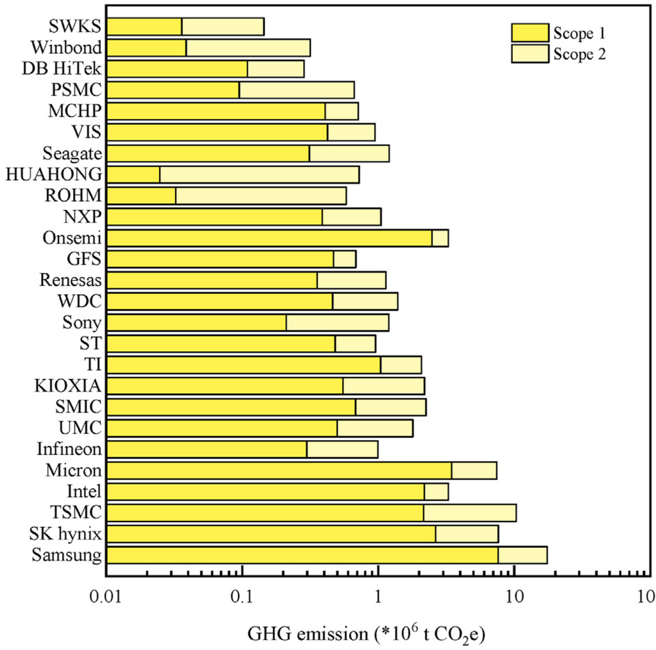

Fig. 2. The greenhouse gas (GHG) emissions of the semiconductor corporations in 2021.

1.2. Average water use, energy consumption, and GHG emissions per unit product

Water use, energy consumption, and GHG emissions per unit product of semiconductor manufacturing from 2017 to 2021 are shown in Fig. 3, with relevant information for DB HiTek, PSMC, VIS, HUAHONG, NXP, and UMC presented [7,8,10,12,15,25]. The annual mean value of water use, energy consumption, and GHG emissions per unit product announced by these six corporations were also calculated from 2017 to 2021. In 2021, average water use, energy consumption, and GHG emissions per unit area of product were 8.22 L/cm^2, 1.15 kWh/cm^2, and 0.84 kg CO_2 equivalent/cm^2, respectively, based on announced data by the corporations. That is, consumption of 2.58 m^3 of water and 361.3 kwh of energy, and emissions of 263.9 kg of CO_2 equivalent occurred in manufacturing processes of a single 8-inch wafer.

Overall, the average water use and energy consumption per unit product of PSMC, VIS, UMC, HUAHONG, DB HiTek, and NXP increased from 2017 to 2020. Compared with 2017, the average water use and energy consumption increased by 15.0% and 10.2%, respectively. In 2021, the figures decreased by 10.5% and 13.6%, respectively, compared to 2020. The GHG emissions gradually fell year by year. The average GHG emissions in 2021 were 19.4% lower than those in 2017.

2. Water and energy sources of the semiconductor corporations

Water withdrawal by source of the semiconductor corporations is presented in Fig. 4. Fig. 4 (a) shows the overall composition of the surveyed corporations' water sources. Surface water intake, municipal water supply, groundwater withdrawal, and third-party supply were found to be the main water sources for semiconductor corporations. These four water source categories accounted for 47.0%, 35.3%, 8.5%, and 5.8% of the total water supply, respectively. Reclaimed water took up 3.2% of total water withdrawal. Condensation and rain water accounted for the remaining 0.3% of the total. Surface water, municipal water, third party water, and groundwater were regarded as fresh water withdrawal, which accounted for 96.5% of the total water withdrawal.

Fig. 4 (b) presents the water sources of the surveyed corporations. Fresh water intake accounted for the majority of water withdrawal according to data announced by semiconductor corporations. Seven corporations took external reclaimed water as a water source, namely, PSMC, UMC, TSMC, GFS, Seagate, Sony, and SK hynix. In the total water withdrawal of PSMC, Seagate, GFS, Sony, UMC, TSMC, and SK hynix, reclaimed water from external water reclamation plants accounted for 4.2%, 34.6%, 37.3%, 0.15%, 12.8%, 4.5%, and 7.0%, respectively [8,11,17,20,25,29,30]. TSMC constructed external water reclamation plants to supply 10000 m^3 of water per day. The Singapore factories of GFS , VIS, and UMC used NEWater as a water source [10,17,25]. NEWater is well known as high-quality reclaimed water purified from municipal wastewater and has been proven to be well-qualified water resource for industrial and domestic use with a stable water supply and quality [35]. For semiconductor manufacturing, there is still considerable growth space

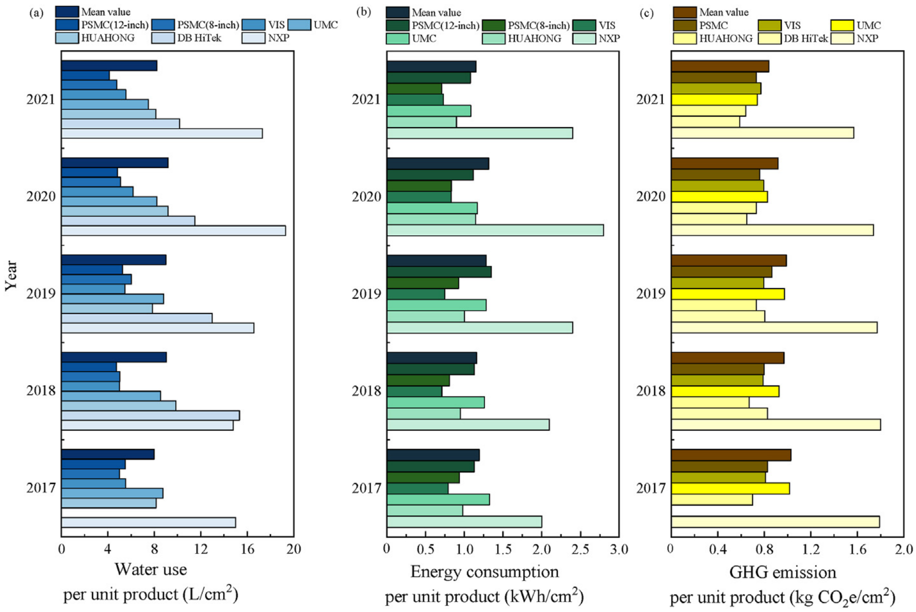

Fig. 3. The water use (a), energy consumption (b), and greenhouse gas (GHG) emissions (c) per unit product of the semiconductor corporations from 2017 to 2021.

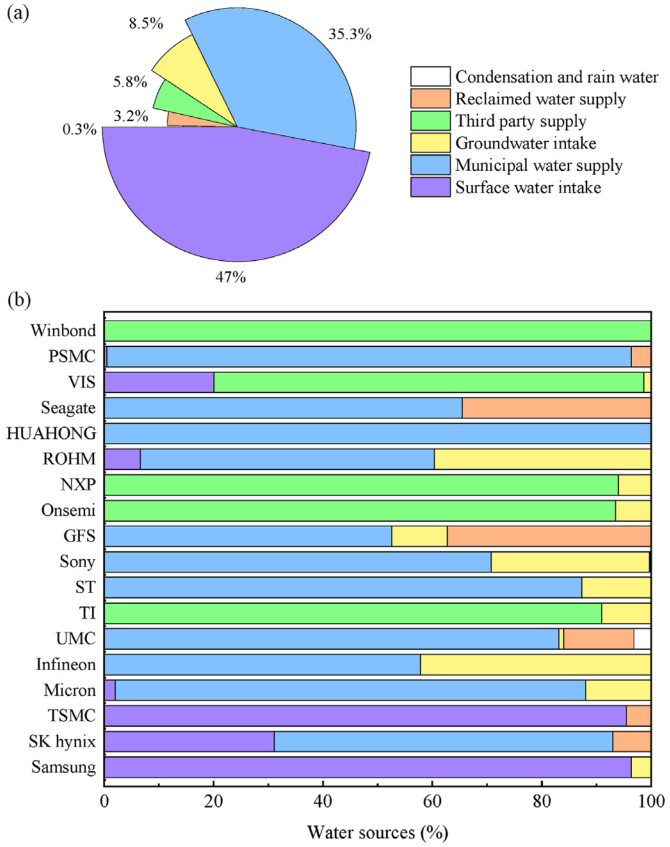

Fig. 4. The total proportion of different water sources (a) and individual water source proportion (b) of the semiconductor corporations in 2021.

and potential for the introduction of external reclaimed water to alleviate water stress [36].

The energy sources of semiconductor corporations in 2021 are displayed in Fig. 5. The energy sources of these corporations fall into seven types: electricity, fossil fuel, steam and cooling, district heating, nuclear energy, renewable energy, and other unrenewable energy. The detailed sources of electricity were not further explained in the reports of the corporations. Gird electricity and fossil fuels were the dominant energy sources for semiconductor manufacturing. Electricity and fossil fuel accounted for 95.8% of the total energy use. Meanwhile, 2.7% of the total energy use was renewable energy. The proportion of other types of energy sources was 1.7%.

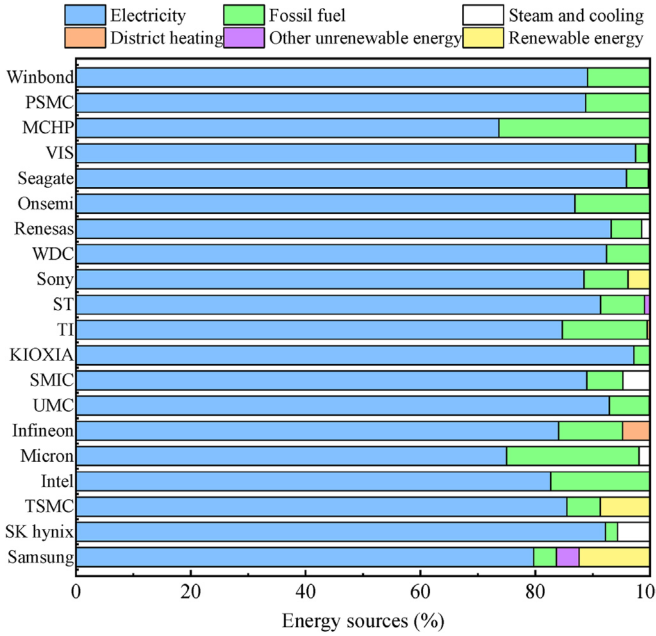

Fig. 5. The energy sources of the semiconductor corporations in 2021.

3. UPW use in the semiconductor industry

UPW is a fundamental material in semiconductor manufacturing that contains extremely small impurities to meet the strict requirements of semiconductor manufacturing [37]. The DOC limit of UPW is 1 μg/L and the resistivity limit is 18.2 MΩ. To guarantee extremely high water quality, complex technologies, including multi-stage reverse osmosis, ultraviolet irradiation, degassing membranes, multi-stage resin bed, are normally applied in UPW production processes [37,38]. Semiconductor manufacturing processes consume considerable quantities of UPW [38, 39]. Under severe water shortage stress, guaranteeing the quantity and quality of the UPW supply can be a key issue in the semiconductor industry.

Notably, nine of the surveyed corporations published their UPW usage data in 2021, as shown in Fig. 6. The total water withdrawal of these nine corporations was 4.52×10^8 m^3 and the total UPW usage was 3.02×10^8 m^3. In PSMC, VIS, and TSMC, UPW usage was larger than water withdrawal. The water withdrawal of these three corporations in 2021 was 6.03, 6.84, and 82.8×10^6 m^3, while the UPW use was 8.77, 9.07, and 109.5×10^6 m^3, respectively [8,10,29]. Owing to the well-designed UPW recycling systems, the UPW in these three corporations could be reused a few times after treatment. The process water recycling rate of these three corporations was all higher than 85%. Most corporations have set hierarchical wastewater collection and treatment systems in the production process to make the best use of internal water resources and recycle UPW or other waste resources as much as possible. Water and waste resource recycling in the semiconductor manufacturing process is undoubtably a trend for sustainable production.

4. Trend in water use, energy consumption, and GHG emissions of the semiconductor industry

4.1. *The water withdrawal, energy consumption, and GHG emissions of the semiconductor corporations from 2017 to 2021*

As shown in Fig. 7, water and energy use and GHG emissions of surveyed 28 corporations from 2017 to 2021 were summarized. Overall, the announced data of water withdrawal, energy consumption, and GHG emissions revealed a general trend of increasing from 2017 to 2021 in view of sum and average value.

The total water withdrawal was 5.24, 6.04, 6.29, 6.85, and 7.89×10^8 m^3 from 2017 to 2021, with announced data of 21, 25, 25, 25, and 27 corporations, respectively. While the average water withdrawal of these corporations was 2.49, 2.41, 2.52, 2.74, and 2.92×10^7 m^3, as shown in Fig. 7 (a). This growing trend was also shown in data on energy consumption and GHG emissions as displayed in Fig. 7 (b) and Fig. 7 (c), respectively. Compared to 2017, the sum of the water withdrawal, energy consumption, and GHG emissions of the semiconductor corporations in 2021 increased by 50.6%, 48.6%, and 32.7%, respectively, while the average of that increased by 17.1%, 24.8%, and 7.2%, respectively. The increase in water and energy use and GHG emissions mainly resulted from the production expansion and process technology improvement (also the shortening of line width). Although the surveyed average water use, energy use and GHG emissions per unit product in 2021 declined compared with 2017 as presented in Fig. 3. The increase of global demand for advanced semiconductor has led to the rising resource consumption and GHG emissions.

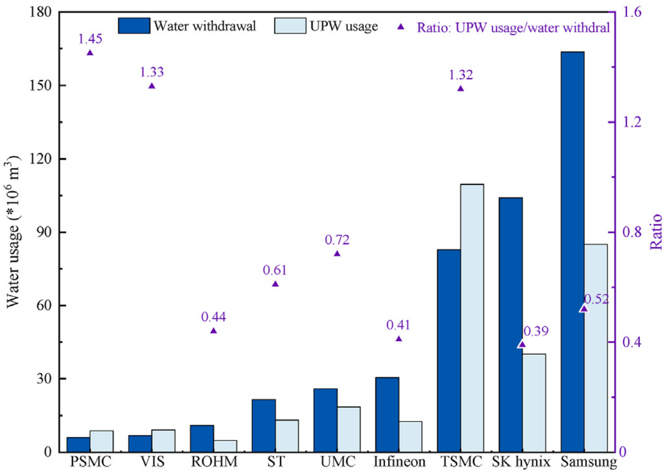

Fig. 6. The Ultrapure water (UPW) use and its ratio to water withdrawal of the semiconductor corporations in 2021.

4.2. *The calculated water consumption, UPW usage, energy consumption, and GHG emissions of the semiconductor industry from 2018 to 2022*

The calculated total water withdrawal, UPW use, energy consumption, and GHG emission in semiconductor manufacturing from 2018 to 2022 (forecast data) are shown in Fig. 8. Data on wafer capacity were accessed from information published online [32]. The total water use, energy consumption, and GHG emissions was roughly calculated by multiplying wafer capacity by the mean value per unit wafer production announced in the ESG or CSR of DB HiTek, PSMC, VIS, HUAHONG, NXP, and UMC from 2018 to 2021 [7,8,10,12,15,25], which has already been presented in Fig. 3. Water use, energy consumption, and carbon emission data for 2022 were calculated with a wafer capacity of 2022 and the average resource consumption and carbon emission value per unit product announced in 2021.

As shown in Fig. 8 (a), the water consumption of semiconductor manufacturing in 2022 is calculated to be 6.33 and 1.10×10^8 m^3 worldwide and in mainland China, respectively. In recent years, semiconductor manufacturing capacity and water consumption have increased rapidly. Compared to 2019 data, water consumption in semiconductor manufacturing in China (mainland) and the globe is predicted to increase by 53.8% and 24.5% by 2022, respectively. Based on the development trend in recent years and future investment demand of major economies worldwide, capacity and water consumption of semiconductor manufacturing is believed to usher its continuous rapid growth in China and other industrial countries.

Specifically, the total UPW use of semiconductor manufacturing is predicted to be 5.51 and 0.95×10^8 m^3 for the globe and China (mainland) in 2022, respectively, utilizing data announced by PSMC and UMC [8,25]. The average UPW consumption per unit area of wafer was estimated to be 8.27, 7.96, 8.22, and 7.16 L per square centimeter from 2018 to 2021. The calculated global UPW usage is equal to 87% of global water use in semiconductor corporations, which were predicted to be 5.51 and 6.33×10^8 m^3 in 2022, respectively. The total energy consumption of the globe and China (mainland) in 2022 is predicted to be 8.85×10^{10} kWh and 1.53×10^{10} kWh, respectively, as shown in Fig. 8 (b). The GHG emission of that is predicted to be 6.47×10^7 and 1.12×10^7 tons CO_2 equivalent in the globe and China (mainland), as shown in Fig. 8 (c).

Compared to the sum of water withdrawal and energy consumption announced by the 28 surveyed corporations shown in Fig. 7, the calculated water and energy consumption is lower, particularly energy consumption. This difference may be attributed to the uncertainty in the calculation of the average value. The average water and energy consumption data are speculated to be underestimated compared with those in actual semiconductor manufacturing. Water and energy consumption increase along with rinse times because of the increase and complication of manufacturing procedures in more advanced manufacturing process [3]. Water and energy consumption per unit product was not announced or unavailable in corporations that utilized more advanced processes, including TSMC, Intel, and Samsung. Thus, the estimated average water and energy consumption value can be lower than the actual value. In addition, other water use or energy consumption, not in semiconductor manufacturing, was concluded in the published data, which could also result in the discrepancy between the estimated and surveyed values. The predicted ratio of UPW use to water withdrawal is markedly higher than the calculated value based on the announced data in the reports of nine corporations displayed in Fig. 6. In the case of UPW use, only PSMC and UMC announced the UPW usage per unit product. Available and accessible data here are used to make estimation but not perfect prediction.

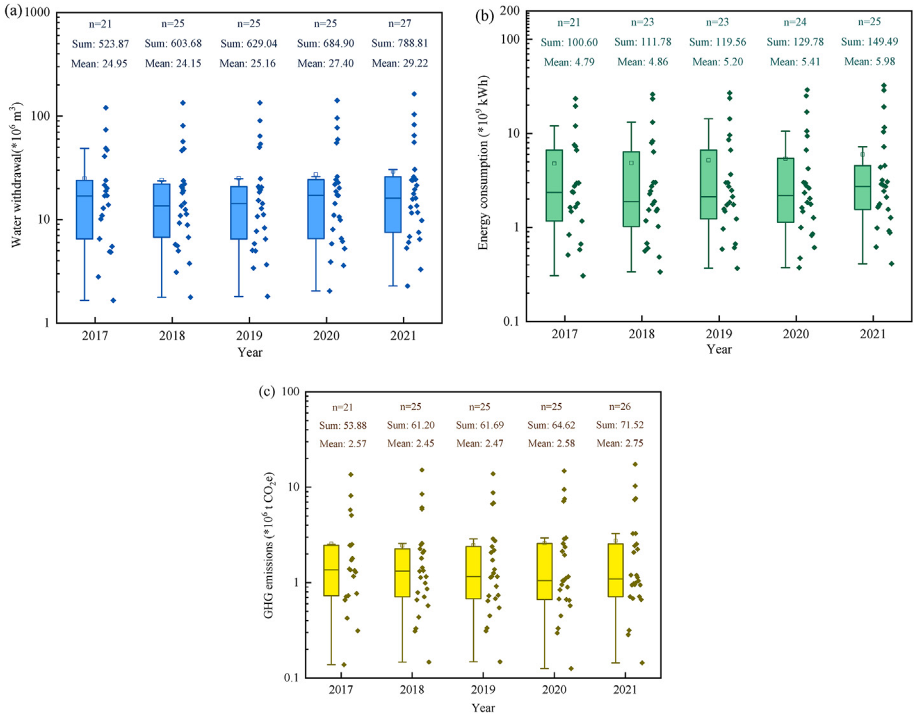

Fig. 7. The water withdrawal (a), energy consumption (b), and greenhouse gas (GHG) emissions (c) of the semiconductor corporations from 2017 to 2021.

5. Summary and future developments

Overall, the annual water consumption in semiconductor manufacturing could be significantly high. The surveyed value were 7.89 $\times$ 10^8 m^3 in 2021. The global energy consumption and GHG emissions in 2021 were surveyed to be 1.49 $\times$ 10^{11} kWh and 7.15 $\times$ 10^7 t CO_2e, respectively. The water use, energy consumption, and GHG emissions experienced a period of rapid growth with the expansion of semiconductor manufacturing industry worldwide in the recent years. To a great degree, the development of semiconductor will lead to significant consumption of resource and emissions of GHG.

Most of the surveyed corporations have proposed their sustainability strategies in the sustainability reports and have been summarized in previous study. Water strategies, including water recycling, water reuse, and external reclaimed water supply, could be crucial for the sustainable development of the semiconductor industry [40]. Many corporations have already taken steps on water and resource recycling to accomplish sustainable development. Singapore factories of GFS, UMC, and VIS have already taken NEWater made from municipal wastewater as water source and TSMC has the plan to construct several external water reclamation water plants to cut fresh water use and one of the plants have already finished in 2021, supplying 10000 m^3/day of reclaimed water [10,25,17,29]. Among the treatment technologies utilized in water recycling systems of semiconductor production parks, reverse osmosis is regarded as one of the most important and commonly used ones, which has been already widely used in advanced treatment for municipal and industrial wastewater [41,42]. In consideration of the facts that high-quality reclaimed water supply used as a water source for semiconductor industry parks has been partly accepted worldwide, reclaimed water deserves a place in the future water system construction of the semiconductor industry parks.

The ways of semiconductor corporations to accomplish sustainable development are diverse based on the local situations. Besides resource recycling and reuse in semiconductor industry parks, some corporations, including Intel and Micron, have got involved with community or watershed water ecosystem protection beneficial to the local water source conservation, ecosystem restoration, and agricultural development [27,28].

Furthermore, with the announcement of the CHIPS and Science Act of 2022 by the federal government of the United States [43], the major economies in the world will focus on improving production capacity and promoting technique localization for semiconductor manufacturing to guarantee national economic development and security. The industry chain migration or relocation of semiconductor manufacturing means the transition of resource consumption pressure, which needs further and full attention, particularly the economies faced with severe water and resource pressure. Notably, although production capacity and water use of China mainland is estimated to be 16% of globe by 2022, there is a huge growth potential and space for semiconductor industry development in China. As a country faced with severe water shortages and resource pressure [44], China needs to fully notice and determine appropriate strategies to alleviate the conflicts between water shortages and semiconductor industry development.

Overall, development of the semiconductor manufacturing industry is supposed to be based on risk assessment of local environmental and ecological situations and the principles of process optimization management should be regarded. The formulation and implement of sustainability strategies in the semiconductor industry is supposed to be paid more attention in the years to come.

6. Data source and analytical methods

This study investigated the environmental stewardship information of 28 semiconductor corporations announced in Corporate Social Responsibility (CSR) reports or Environmental, Social, and Governance (ESG) reports of 2021 or recent years. Detailed information of surveyed corporations is referred to Table 1. Only sustainability report of TSEM in 2021 was not published and information of TSEM in previous years was provided. The included corporations are: Samsung, DB HiTek, and SK hynix from Korea; TSMC, UMC, PSMC, VIS, and Winbond from Taiwan of

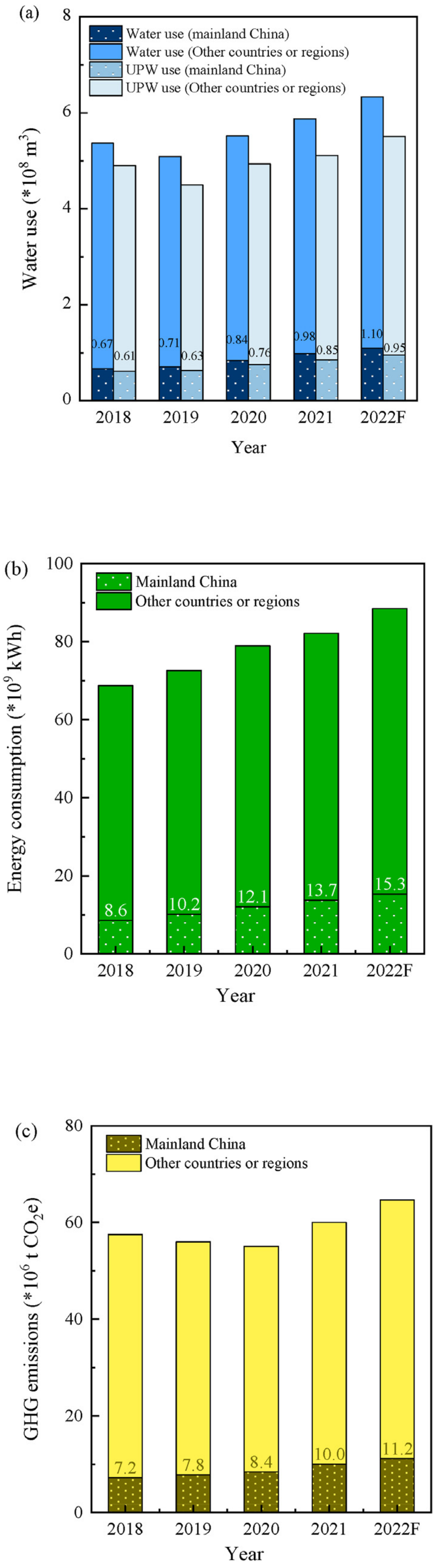

Fig. 8. The calculated annual water consumption and ultrapure water (UPW) usage (a), energy consumption (b), and greenhouse gas (GHG) emissions (c) of the semiconductor industry worldwide and for China from 2018 to 2022 (forecast).

China; Shanghai HUAHONG, SMIC, and YMTC from mainland China; Sony, KIOXIA, ROHM, and Renesas from Japan; Intel, Micron, TI, Onsemi, SWKS, MCHP, Seagate, WDC, and GFS from the United States (the U.S.); NXP, ST, and Infineon from Europe; and TSEM from Israel [4–31]. The selection of surveyed corporations in this study was referred to published information of IC insights and the U.S. Semiconductor Industry Association [32,33]. The surveyed corporations made up the vast majority of the semiconductor manufacturing market according to public information.

Declaration of competing interest

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

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