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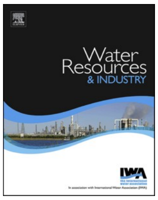

“Quantifying spatiotemporal impacts of the interaction of water scarcity and water use by the global semiconductor manufacturing industry”

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ABSTRACT

The high-tech semiconductor manufacturing sector is integral to the international electronics industry and was valued at over $400 billion USD in 2017. Intensive water use by this industry is well-documented and this work provides a spatially explicitly assessment of water use impacts by nearly 100% of global semiconductor manufacturing capacity. Both direct manufacturing water use and water use from electricity were considered as part of a facility’s total withdrawal. Manufacturing water withdrawals were estimated by using technology-specific water and electricity use data, reported at the semiconductor chip or wafer level from the life cycle literature and industry estimates. Electricity water use intensity (WUI) factors were gleaned from the literature and regional electricity WUI factors were derived for China and the U.S. Geolocation of semiconductor manufacturing facilities allowed for summation of water withdrawals at various spatial extents (i.e. watershed, country, and globally). This data was combined with calculated regional or country-level electricity water use factors to estimate total water withdrawals by a facility. Geolocation of data also allowed for calculation of watershed specific scarcity-weighted withdrawals. Scarcity-weighted withdrawals were ascertained by multiplying facility water withdrawal data by the AWaRE water scarcity characterization factor available for each of 202 watersheds associated with semiconductor manufacturing facilities. These data were used to identify and map hotspots of industry water use, which is especially important for areas of industry growth such as China. This analysis is useful as a benchmark for global semiconductor industry water withdrawals and may assist OEMs in decisions about supply chain sourcing. This could also guide semiconductor manufacturers in prioritizing locations and time periods to implement water-saving technologies or employ less water intensive electricity sources. Additionally, the spatially explicit water use data for the semiconductor sector can be used to improve existing databases of national and regional sector-specific water use coefficients that are often applied in LCA input-output studies.

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1. Background

The high-tech semiconductor manufacturing sector is integral to the international electronics industry and was valued at over $400 billion USD in 2017 [1]. Semiconductors are the silicon microchips utilized in electronics to control the flow of electrical signals. The complex transistor circuitry required to transmit these signals is layered onto silicon wafers at semiconductor fabrication plants ('fabs').

Semiconductor fabs are largely concentrated in the United States, Taiwan, China, South Korea, and Japan. These areas currently account for 83% of fab manufacturing capacity and the rapid evolution of the technology sector means that new fab facilities are being constructed at a high rate. As such, China and Taiwan are outpacing the growth rates of other industry leaders [48,2], which will result in a spatial shift in resource demands by the industry.

1.1. *Water use in semiconductor manufacturing*

Semiconductor fabrication is a water intensive process and efforts have been made by individual companies to assess the water-related risks posed by supply chain (raw materials, transportation and electricity), operations, use, and end-of-life [3]. Industry has focused on reducing water use in their operations and correspondingly, relative water use efficiency has improved over the years [4]. However, growth in absolute water use is predicted due to year-to-year increases in chip sales (2%–24% from 2016-2018) and associated production capacity, including a 41% increase in capacity for multi-layer flash memory [5]. And despite overall improving trends in water reuse efficiency, industry pursuit of Moore's Law (i.e. doubling of transistor density every two years) has led to increases in the use of higher purity water and chemicals and more complex processing steps. In addition, increases in wafer size (i.e. moving from predominantly 200 mm–300 mm, and now 450 mm), and the associated transition from batch processing to single wafer processing which requires more water per wafer, has also contributed to increased water demands by the industry [4,6].

[2,7] indicated that the use phase (i.e. use of the chips within the electronic devices) and manufacturing phase are the two most water intense stages in the life cycle of a semiconductor chip (2012). Electricity-related water from the use phase is the primary water user for most chip types and the manufacturing phase is the second largest user of water [2]. Within the chip manufacturing process, water used in the production of electricity to power the semiconductor fabs (i.e. indirect water use) is the single largest user of water; while fab feedwater (i.e. direct water use) represents another major user [2,7]. Fab manufacturing water, or 'feedwater', serves three major functions in chip manufacturing: process cooling water, production of ultrapure water to rinse the wafer between processes, and cooling water to maintain cleanroom heating, ventilation and cooling (HVAC) systems. The focus of this assessment is on fab feedwater (FW) and electricity-related water (ERW) withdrawals for the following reasons: i) as mentioned, these two elements represent the two largest water use categories in chip manufacturing [7], ii) there is precedent for manufacturing (i.e. direct or 'Scope 1') and electricity-related (i.e. indirect or 'Scope 2') resource use as the boundary for analysis within the carbon footprinting literature [8], iii) both FW and ERW withdrawals associated with a fab are likely to be spatially related and impacts may occur within the same watershed, and iv) water uses related to other processes in the life cycle of a semiconductor chip (e.g. silicon ingot processing, infrastructure/transportation) are comparatively smaller withdrawals (total just 6%, according to estimates from [7]). Another important consideration is that feedwater and electricity use are managed by the manufacturer, as opposed to embedded within the supply chain; thus, quantification of withdrawals and associated decisions related to water reduction efforts can be more easily managed within this scope [9]. Manufacturing process data from the life cycle assessment literature [2] and industry reports [4] provide estimates of water and energy use intensity, reported at the single microchip or wafer (i.e. hundreds of chips) level.

1.1.1. *Electricity-related water withdrawals*

Estimates of water use from electricity production has been examined over the last decade [10–17] as understanding of the large impact of the energy sector on water use (the water-energy nexus) has emerged. Water use data have been categorized by electricity generating type (e.g. coal, natural gas, hydroelectric) and associated cooling technologies (i.e. open loop cooling, closed loop cooling, and air cooling). [18] summarized and reported withdrawal factors by life cycle phase for ease of use in life cycle assessment (LCA) studies.

A closer examination of the application of electricity water withdrawal metrics is appropriate [19,20] and addressed here by calculating regionalized electricity water use intensity factors for two of the world's major semiconductor producing countries: the U. S. and China. In the U.S., electricity generation by fuel type for each of the country's eight major electricity trading regions (collectively known as the North American Electric Reliability Corporation or NERC) are provided by the U.S. EPA EGRID program [21], and [22] provide water use estimates for many of the country's largest electricity generating facilities. In China, provincial electricity data is supplied by the National Bureau of Statistics of China and summarized by [10–12,23] for China's six regional energy grids. For all countries except the U.S. and China, country averaged estimates of electricity mixes are provided by the International Energy Agency [24]. It should be noted that power plants commonly use freshwater resources for cooling. For example, in the U.S., it is estimated that power plants account for 40% of the nation's freshwater withdrawals [25].

1.2. *Industrial water use*

Water withdrawals are defined as "water removed from the ground or diverted from a surface-water source for use" [26]. Alternatively, consumptive water use refers to water withdrawn that is incorporated into a product or crop, or evaporated, transpired or consumed by animals or humans. Water that is withdrawn but ultimately returned to the same watershed from which it came does not count as consumptive use [26]. This study is an extension of our previous work [27] and assesses water *withdrawals* for manufacturing and electricity from fab facilities (Note: the terms water use and water withdrawals are used interchangeably in this text). Thus, this assessment does not consider a facility's efforts to recycle or return water to the watershed. And although individual companies have invested considerable effort into lowering their consumptive water use rates, reuse rates across the industry are highly variable, thus difficult to quantify on an industry-wide basis. [6] reported a benchmarking study in which only 2 out of 7 companies met the water consumption targets set by the International Technology Roadmap for Semiconductors (ITRS) with exceedances ranging from 10-50% of the target.

Water withdrawn is a good measure of *potential* water use impacts because water used in manufacturing would rarely be returned to the same water body without some loss in water quality. The appropriation of water resources due to degradation in water quality, known as 'grey water' [28], is often quantified separately from consumptive water use (i.e. 'blue water') [29]; however, as this study does not separately address water quality issues associated with semiconductor manufacturing (and the associated freshwater required to assimilate pollution), water withdrawals serve as a proxy for both consumptive and degradative uses of water [30]. However, water withdrawn may not be a good measure of actual physical scarcity of water [31] and could overestimate impacts from manufacturing water demands in a watershed. Therefore, withdrawals-based water use inventories represent a conservative approach to estimating water use impacts and should be used as a screening-level assessment of potential impacts, rather than an absolute measurement of volumetric water use.

In most countries, including the U.S., industrial water use is not understood with a high degree of spatial or temporal granularity [9, 27]. As mentioned, the water-energy nexus is vital to capture since industry is estimated to use 22% of total energy in the United States [32] and 54% of the world's total delivered energy. Although [33] reported that the electronics sector is currently considered a smaller user of water when compared to the major users (i.e. paper, primary metals, and chemical manufacturing sectors), they report that the electronics sector has the third highest energy-water ratio, further enumerating the importance of the water-energy nexus for electronics. According to the U.S. Energy Information Agency, the semiconductor subsector comprises 1.2% of U.S. manufacturing net demand for electricity [58]. This indicates that the semiconductor industry constitutes a small, but growing demand for direct water use and energy-related water use.

1.3. Water scarcity

Many areas of the globe are already reaching the limits of a sustainable supply of freshwater for human and ecosystem demands [34]. [35] and later [36], reviewed several water scarcity indices and methodologies that have been developed over the past thirty years to quantify vulnerability of water resources. These metrics have converged around two basic approaches, as defined by [36]: "water crowding" indices which are focused on per capita human water needs and "use-to-resource ratio" indices which are focused on the ratio of water withdrawals or consumption to available resources. Although there is considerable debate as to which metric, (of the almost two dozen available) is appropriate to quantify sustainable water use [36–38], this study incorporates the AWaRe (Available Water Remaining) indicator.

The AWaRe indicator is the result of a consensus-based process from the United Nations Environment Program/Society of Environmental Toxicology and Chemistry (UNEP/SETAC) Water Use Life Cycle Assessment (WULCA) group, comprised of industry, academic, government, and consulting experts, which was charged with creating a standardized water footprinting method that could be implemented in life cycle-based assessments of products, services and economies [39]. The AWaRe index utilizes data from the WaterGAP3 model which implements a global hydrology model [60] and a study simulating global industrial and domestic water use [40]. The **a**vailable **wa**ter **re**maining (aka 'AWaRe') in a watershed is calculated by assessing freshwater availability (surface + renewable groundwater) minus demand (AMD) by humans (i.e. domestic, industrial, agricultural, livestock and energy sectors) and by freshwater aquatic ecosystems, per area and by month. The AWaRe method is described by [31] and represented by the following equation, expressed in terms of volume of water remaining per month (m^3/month) within a watershed area (m^2):

$$AMD_i = \frac{Availability_{surf+renew-grdwater} - Human\ Water\ Consump_{surf+grdwater} - Environ\ Water\ Req's_{surf} * (m^3)}{Watershed\ Area\ (m^2) * month}$$

The inverse of AMD_i, or $1/AMD_i$, is used to represent the 'potential for water deprivation' in a watershed i. This potential for deprivation is then used to create a scarcity characterization factor (CF_{AWARE}) for a watershed. To calculate the CF, $1/AMD_i$ is first normalized to the world average ($m^3{}_i/m^3{}_{world\text{-}avg}$) and a dimensionless index is created by ranking each watershed against the normalized values calculated for all of the other watersheds in the world on a scale from 0.01 to 100, where 1 represents the world average and 100 represents areas that have 100 times less water available than the world average [31].

The AWaRe method and its associated scarcity CF was selected as the scarcity indicator for this work because it is i) a consensus indicator and associated with an ISO standard [31], ii) the metric is 'ecocentric' as it considers ecosystem water requirements (EWR) [36], iii) it is relatively simple to apply and communicate, consisting of a single characterization (weighting) factor to measure potential to deprive another user (human or ecosystem) of water [31,36] and iv) it has been integrated as a midpoint impact characterization factor in the major LCA software tools (e.g. GaBi and Simapro), and is thus, gaining wider use in LCA and water footprinting communities.

However, the AWaRe indicator only addresses physical water scarcity and does not take into account socio-economic water scarcity (e.g. Aqueduct) and its associated risk factors. Another point of debate regarding the use of a scarcity characterization factor, such as those employed by the AWaRe method, is that multiplying a water use inventory by a scarcity CF lacks 'physical meaning' [37].

However [38], argued that the process of transforming inventory flows and their associated potential impacts into a common unit, represented here as H_2O equivalents, is common in both LCA and footprinting methods (e.g. carbon equivalents, toxicity equivalents). Thus, in our study, the goal of the water scarcity-weighted characterization step is to transform the water use inventory (i.e. H_2O in liters) to an impact equivalent that relates the pressure exerted on the resource to the resource in question (i.e. H_2O in liter equivalents) [38]. Maps displaying the water scarcity impact data will help locate regions of potential concern and will be utilized to identify current locales with the highest potential water use impacts from semiconductor production.

This study represents the first report of total global water withdrawals for the semiconductor manufacturing industry and improves upon our prior water withdrawal estimates [27] using a bottom-up approach and application of derived regional electricity water use intensity coefficients. This study also presents facility-level estimates of FW and ERW withdrawals, addressing the need for highly granular data due to the local and regional issues surrounding water use and water scarcity. We report watershed-specific impacts by presenting scarcity-weighted withdrawals (quantified in liters of H_2O equivalents) for semiconductor fab feedwater to better understand the potential for manufacturers in a watershed to deprive other users (both ecosystems and humans) of water.

Semiconductor manufacturing and other industrial water use estimates within the literature have either been limited geographically [41], not technology specific (based on sector wide input-output assessment), use only national averages for electricity-related water use [7], and often do not address spatial variation in impacts [42]. Reporting of water withdrawals by semiconductor manufacturers, typically through their Corporate Social Responsibility (CSR) reports, is often limited in its usefulness because withdrawals are reported at a company-wide level, instead of individual facilities (where impacts are felt), and the metrics for reporting may not be easily compared with other companies due to a lack of metrics standardization within the industry [67]. Further, with the exception of a few, companies rarely report their Scope 2 indirect water withdrawals (i.e. ERW withdrawals).

2. Material and methods

2.1. Estimating facility water use

2.1.1. Semiconductor facility production data

SEMI is an industry association which tracks global semiconductor fabrication (fab) manufacturing facilities for both current and planned operations [43]. The SEMI database consists of 1129 individual production lines and its characteristics are described in detail in our previous work [27]. Most notably, the database contains information about location, integrated circuit (IC) technology node produced at the plant (e.g. 250 nm, 32 nm), wafer size (e.g. 8 inch [200 mm]), and fab production capacity, reported in wafer starts per month. In the past, a 'technology node' referred to the transistor gate length, which approximately scaled with transistor density in a microchip. Improvements in chip technology allowed for smaller gate lengths and thus, tighter packing of transistors over time (e.g. a 350 nm logic chip was state-of-the-art in 1995, compared to 45 nm in 2007). However, as the industry has reached the physical limits of size scaling, the term technology node has become uncoupled with gate length and now generally refers to a specific generation of microchip and its associated processes and design parameters. Production capacity was used as a proxy for actual production, as many of these facilities would be expected to operate at full or near full capacity, although this assumption may lead to overestimates of water withdrawals in some locations operating below capacity. The database was used to estimate total chip production (by product and per technology node) at each facility using the aforementioned parameters. Only production lines with valid wafer production data from the fourth quarter of 2016 were used ($N = 1021$).

2.1.2. Geocoding

For each production line, addresses provided by SEMI were geocoded using two software services to obtain geographic coordinates for input into a Geographic Information System (GIS). The Environmental Systems Research Institute's World Geocoder, accessed via ArcGIS Pro [44], and the GoogleMaps API, accessed through the R 'ggmap' library [45] geocoding services, were used to obtain the latitude and longitude in decimal degrees for each geocoded address. The geocoding software returns information about the estimated precision of each geocode. For each geocoded address that returned a rooftop centroid (indicating a high level of precision) we utilized the data as provided by either software ($N = 594$). If neither geocoding service provided a rooftop geocode ($N = 427$), corrections to the data were made using a manual geocoding process which included use of aerial imagery from GoogleMaps or Bing, and if needed, confirmation of the correct address by investigation of the company's website. Manual correction of geocoded data is vital to ensure accurate locations [46,47] of fab facilities which are used to estimate localized water use impacts. If manual correction of an address was not feasible, less precise location data provided by the geocoding software was used ($N = 12$). Only one facility was unable to be located and was excluded from the analysis; thus, water use analysis was conducted for 1020 fab production lines.

2.1.3. Fab feedwater (FW) use: water use by technology type

As previously described [27], the SEMI database is categorized by the product type and technology node for each production line. This includes major categories such as 'logic', 'memory', 'foundry', and 'discrete' which represent various types of semiconductor products such as CMOS (complementary metal-oxide semiconductor), DRAM (dynamic random-access memory), NAND (logic gate that stands for negative-AND), and ASICS (application-specific integrated circuits). Foundry facilities comprise a growing portion of the semiconductor manufacturing sector [48] and may produce multiple technologies; however, specific production lines will often produce one dominant product type. The use of general product categories provided by the SEMI database was determined to be adequate for purposes of water withdrawal estimation but would need to be refined with facility level data for a detailed, local assessment.

Estimates of fab FW are drawn from the LCA work of [2,49] and semiconductor industry reports [4,61-66] (see Table 1). Boyd reports comprehensive estimates of FW and electricity use for CMOS, DRAM and NAND products for technology nodes during the period 1995–2013 (350 nm–22 nm) at the chip level for a typical U.S. semiconductor facility. Feedwater estimates for other technology types (e.g. MEMS) and newer technology nodes (i.e. 2013–2016) were estimated using ITRS reports from 2001-2013 (Sematech). These industry targets were used when specific values from Boyd were not available and may represent an optimistic estimate of feedwater withdrawals. Other estimates of semiconductor chip water use from the life cycle literature were difficult to interpret due to aggregated reporting of results. Further difficulties arise from trying to pinpoint the exact kind of chip made from a foundry facility as it may manufacture a mix of technology types and nodes, so assumptions about the primary technology produced at these facilities were made by using text analysis from the SEMI database.

2.2. Electricity water use

Electricity use by each fab was calculated using technology-specific values from Boyd and where these values were not available, industry targets reported by ITRS were used. Electricity use values from Boyd, reported in kWh per chip, were normalized to kWh per cm^2 of wafer. Semiconductor fabs typically use electricity purchased from the grid, so determining the grid mix (the fuel mix and/or power sources for electricity generation in each area) of a region or country is vital to determining the water use associated with electricity consumption.

Typically, water use intensity values from electricity are based on LCA estimates of the impacts of 1 kWh of net electricity from a standard national grid mix of electricity. Because electricity use is such a large determinant of water use in a Scope 2 assessment, and often dominates water use values for technology [2], this study includes refined electricity values, estimated for China and the U.S. Regional electricity factors were calculated for the U.S. and China because of the large geographic variation in grid mixes across these two countries.

Table 1
Table of fab FW use and electricity use by technology type and node.

Approximate Technology Year	Technology Node (nanometers) - oldest to newest	Fab Feedwater Use (liters per cm^2 of wafer)	Fab Electricity Use (kWh per cm^2 of wafer)
Logic (e.g. CMOS, Bipolar, MEMs)[a]			
1995 & older	350–1000000	25.32	3.31
1996–1997	250–350	25.32	3.31
1998–1999	180–250	5.12	3.06
2000	130–180	11.27	1.33
2001–2004	90–130	21.85	1.53
2005–2006	65–90	20.63	1.49
2007	45–65	15.72	1.75
2008–2009	32–45	6.55	2.07
2010	32	7.21	2.12
2012 & newer	5–22	7.8[b]	2.12
Memory (e.g. RAM, DRAM, MRAM)[a]			
1998 & older	250–1000	0.16	0.14
1999	180–250	0.16	0.14
2000–2001	130–180	0.07	0.45
2002–2003	90–130	0.93	1.04
2004–2005	70–90	2.12	0.76
2006–2007	57–70	1.18	0.10
2008–2011	40–57	5.24	8.73
2012–2015	25–40	10.48	17.47
2016 & newer	10–22	20.96	34.93
Flash (CMOS, NAND)[a]			
2000 & older	150–400	48.55	2.07
2000–2001	120–150	48.55	2.07
2002–2003	90–120	21.24	3.03
2004–2005	65–90	12.14	2.53
2006–2008	45–65	12.73	4.24
2009–2016	14–40	7.8[b]	6.60
Other (e.g. GaAs, Sapphire, MEMs, Indium)[b]			
2000 & older	130–20000	7.0	1.4
2001–2004	90–130	7.0	1.4
2005–2007	65–90	9.0	1.4
2008–2010	40–65	8.1	1.5
2011–2015	22–40	7.0	1.0
2016 & newer	5–22	7.8	1.0

[a] [2].

[b] [4,61-66]

2.2.1. U.S. Electricity water use

Water withdrawal data from [13,22]; and [18] were used to characterize water use intensity (water withdrawal per kWh of production) for each electricity generation type. Diehl and Harris calculated detailed water withdrawal estimates in MGal/day for 1290 thermoelectric power plants in the U.S., covering a variety of fuels and cooling technologies. They also provided net generation values for each plant in megawatt hours (MWh) and these values were used to calculate water use intensity (in liters per kWh) for each thermoelectric facility. Fig. 1 depicts the locations of each thermoelectric facility in the U.S [50]. that were estimated by Diehl and Harris. An average of water use intensities (WUI) weighted by annual net generation of electricity for each facility was used to calculate an average thermoelectric WUI over the electricity trading regions in which the facilities were located. This approach is preferred over national or regional grid mixes from the LCA literature because it incorporates a large and representative amount of detailed facility level water use data. The North American Electric Reliability Corporation (NERC) is the entity responsible for coordinating and supplying electricity to various regions of the U.S. A NERC region operates as a trading region and electricity supply is mixed and redistributed within this region; thus, this is the appropriate level of spatial aggregation to calculate electricity water use intensity.

For non-thermoelectric power plants in the U.S. (i.e. hydroelectric, solar photovoltaic, and wind), estimates of water withdrawal from [18] were used and production-weighted water use intensities were calculated by averaging known production levels of thermoelectric and non-thermoelectric power within each NERC region [21] using the following equation:

$$WUI_{regional} = \sum TEWU_i * \left(\frac{PC_i}{RPC}\right) + (WUI_{solar} * RSP) + (WUI_{wind} * RWP) + \left(WUI_{hydro} * RHP\right) \tag{1}$$

where $WUI_{regional}$: U.S. NERC electricity region water use intensity (Liters/kwh); $TEWU_i$: Annual thermoelectric water use per facility (liters); PC_i: annual production capacity per thermoelectric facility (kWh); RPC: total annual thermoelectric regional production capacity (kWh); WUI_{solar}: water use intensity of solar photovoltaic power (L/kWh); RSP: regional solar electricity production as percentage of total production (%); WUI_{wind}: water use intensity of wind power (L/kWh); RWP: regional wind production as percentage of total production (%); WUI_{hydro}: water use intensity of hydroelectricity production (L/kWh); RHP: regional hydro production as percentage of total regional electricity production (%)

Each fab facility in the U.S. was then assigned an ERW withdrawal intensity associated with its derived NERC region water use intensity ($WUI_{regional}$) factor. This assignment was determined by overlaying fab locations with a map of electricity regions provided by the U.S. Electricity Information Agency (EIA). Detailed information about the production mix and net generation of each region are provided in Appendix A, Table A1.

2.2.2. Chinese electricity water use

[23]reported water withdrawals by the various thermoelectric cooling technologies (i.e. recirculating, once-through cooling, dry cooling, and seawater cooling) used across China. By understanding province-level electricity production mixes and cooling types, water use intensities by province were calculated for China using equation (2) below. Province-level water use intensities, production and cooling type data (Table A2), and sample calculations are available in Appendix A.

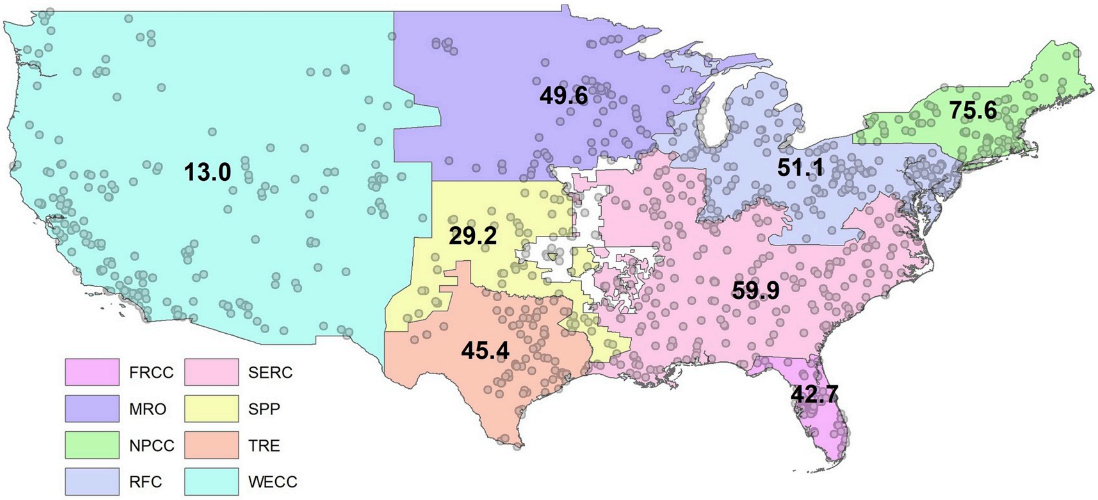

Fig. 1. Derived water use intensity factors (in L/kWh) of NERC electricity regions overlaid with the thermoelectric power plants from [22]. The boundaries of NERC electricity regions were provided by [50]. FRCC = Florida Reliability Coordinating Council, MRO = Midwest Reliability Organization, NPCC = Northeast Power Coordinating Council, RFC = Reliability First Corporation, SERC = SERC Reliability Corporation, SPP = Southwest Power Pool, TRE = Texas Regional Entity, WECC = Western Electricity Coordinating Council. The white areas of the map are classified by EIA as 'indeterminate, with various NERC memberships'; thus, a WUI was not calculated for these areas.

$$WUI_{prov} = \sum PCPC\big((RC_{coal} * WUI_{recirc}) + (OTC_{coal} * WUI_{otc}) + \big(DC_{coal} * WUI_{dry}\big)\big) + PNGPC\big(\big(RC_{ng} * WUI_{recirc}\big) + \ \big(OTC_{ng} * WUI_{otc}\big)\big) \\ + (PNPC * WUI_{nuclear}) + (PBP * WUI_{biomass}) + (PSP * WUI_{solar}) + (PWP * WUI_{wind}) + \big(PHP * WUI_{hydro}\big) \tag{2}$$

where WUI_{prov}: Chinese provincial water use intensity (liters/kwh); PCPC: Provincial coal-power capacity (kWh); RC: electricity production from recirculating cooling as percentage of total thermoelectric production in province (%); WUI_{recirc}: water use intensity of recirculating cooling operations in China; OTC: electricity production from once through cooling as percentage of total thermoelectric production in province (%); WUI_{otc}: water use intensity of once through cooling operations in China; SC: electricity production from seawater cooling as percentage of total thermoelectric production in province (%); PNGPC: Provincial natural gas power capacity (kWh); PNPC: Provincial nuclear power capacity (kWh); $WUI_{nuclear}$: water use intensity of nuclear power (L/kWh); WUI_{solar}: water use intensity of solar photovoltaic power (L/kWh); PBP: biomass electricity production as percentage of total provincial electricity production (%); PSP: solar electricity production as percentage of total provincial electricity production (%); WUI_{wind}: water use intensity of wind power (L/kWh); PWP: wind production as percentage of total provincial electricity production (%); WUI_{hydro}: water use intensity of hydroelectricity production (L/kWh); PHP: hydro production as percentage of total provincial electricity production (%)

Like the U.S., China has electricity producing regions in which electricity is mixed and redistributed; however, electricity grid mixes by region were not directly accessible. Thus, a weighted average of production capacity for each province within the electricity region was used to calculate a production capacity weighted average for the region. A map of electricity regions was adopted from [51], and using spatial overlays, each fab within that electricity region was assigned a water use intensity associated with its regional mix of electricity production (Fig. 2). This may result in error if a fab does not purchase electricity from the grid of the electricity region in which it is located.

2.2.3. Rest of world

For all other countries in which fab production takes place, country specific average grid mixes from the IEA were utilized. Average water use intensity factors [13,18] were applied per generation type to electricity production within these countries. Table 2 summarizes the water use factors associated with each generating type and Table A4 displays the water use intensities calculated for each country based on their grid mix and factors from Table 2.

2.3. Characterizing water use per facility

As developed in detail in our previous work, an estimate of global water use by the semiconductor industry can be calculated using the following basic equation [27]:

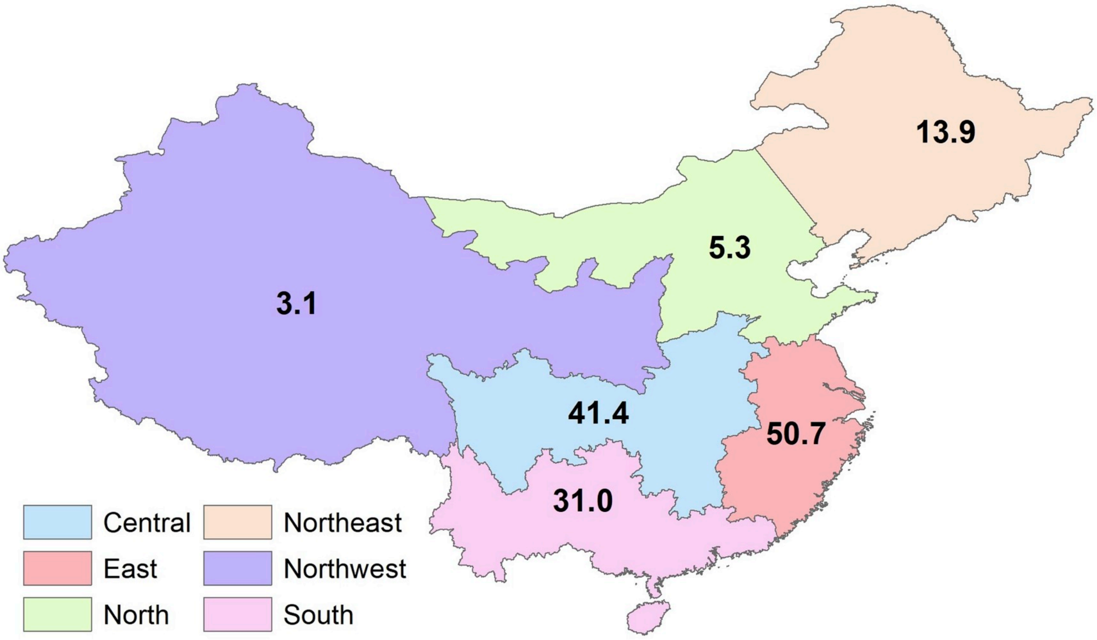

Fig. 2. Calculated water withdrawal intensity (in liters per kilowatt hour) of Chinese electricity regions. The boundaries of Chinese electricity regions were adopted from [51].

Table 2
Default water use intensity factors for each electricity generation type. All values from [18]]; except for petroleum and hydroelectric [13]].

Electricity Generation Type	Water use intensity (liters per kWh)
Coal	2.5
Natural gas	9.5×10^{-1}
Petroleum	3.9×10^{-1}
Nuclear	1.8×10^{2}
Biomass	1.7×10^{-2}
Geothermal	1.2
Solar thermal	2.9×10^{-1}
Hydroelectric	1.1×10^{1}
Solar Photovoltaic	2.3×10^{-2}
Wind	5.7×10^{-3}

$$SMGWU = \sum_{i=1}^{n} (FWW_i + EWW_i)*MWS_i \tag{3}$$

$FWW = WUI_{tech}*SA_{wafer}$

$EWW = EI_{tech}*WUI_{elec*}\ SA_{wafer}$

where SMGWU: semiconductor monthly global water use; n: the number of semiconductor facilities in Q4 of 2016 with valid production data; FWW: fab feedwater per wafer; WUI_{tech}: water use intensity of semiconductor technology at facility i (Liters/cm^2); SA_{wafer}: surface area of wafer (cm^2); EWW: electricity water per wafer; EI_{tech}: electricity intensity of semiconductor technology (kWh/cm^2); WUI_{elec}: water use intensity of electricity mix (Liters/kWh); and MWS: monthly wafer starts per facility in Q4 2016 [43]. This monthly figure was annualized to calculate total annual consumption.

2.4. *Scarcity-weighted water use*

The AWaRe characterization factors (CFs) described in Section 1.3 have been developed for 11,050 watersheds, with the largest 34 watersheds divided into subwatersheds. These are available for download from the WULCA website as a kmz file and are provided both on a monthly basis and as an annual average [52]. By utilizing location specific information about semiconductor production, water use at various spatial extents (e.g. watershed, country, globally) could be aggregated. This data was summed at the watershed level and was weighted by the AWaRe CFs available for each watershed. This analysis resulted in 202 scarcity-weighted watersheds associated with the 1020 fab facilities. Due to the difficulty and potential error associated with allocating water withdrawn for electricity from the grid mix to a specific watershed, only fab FW withdrawals (which can be associated with an exact location or area) was considered as part of the scarcity-weighted assessment. For the purposes of this assessment, it was assumed that facilities were withdrawing water from within their own watershed to meet their manufacturing needs. All of the fab facility water withdrawals within a watershed were summed across the watershed using spatial libraries in R [53] and visualized using ArcMap 10.5.1 [54]. This work modified our previously developed equation to summarize the scarcity-weighted withdrawals for each of the watersheds that contain semiconductor facilities, and was expanded to include many more facilities and watersheds [27]:

$$SWWU = \sum_{i=1}^{m} AFW_n *WSF_{(avg)} \tag{4}$$

$AFW_n = FWW_n * MWS_n * 12$ (months)

where SWWU: Scarcity Weighted Water Use (liters of H_20 equivalents); m: the number of facilities in a given watershed; AFW_n: annual feedwater withdrawals per facility; FWW_n: Feedwater withdrawals per wafer (see equation (3)); MWS: monthly wafer starts and $WSF_{(avg)}$: the average annual water scarcity factor for that watershed.

2.5. *Temporal variability of water scarcity*

Due to the seasonal nature of water scarcity, monthly AWaRe scarcity indicators were also considered. For each of the 202 watersheds associated with fab production, the minimum annual scarcity values, as well as maximum annual scarcity values for each watershed in a year were mapped to represent best and worst-case scenarios of water scarcity. These maps identified seasonal “hotspots”: locations characterized by seasonally high water scarcity and water withdrawals by semiconductor fabrication.

3. Results

The following results describe the facility level production data and associated FW and ERW withdrawals for the 1020 semiconductor fab production lines available for analysis. Scarcity-weighted withdrawals were calculated using AWaRe scarcity characterization factors applied to each of the 1020 facilities located in 202 watersheds across the globe and are summarized and presented here. The raw data used to produce each of these graphs and maps are available along with an interactive web map [55].

3.1. Feedwater (FW) withdrawals

The annual FW withdrawals by semiconductor facilities were summarized over various spatial extents. Total annual semiconductor wafer production and total annual water withdrawals per country for the top global producers is presented in Figs. 3 and 4. The top five producers are Japan, Taiwan, South Korea, China and the United States, respectively. Japan has the largest FW withdrawals for any single semiconductor producing country, which aligns with its large wafer production numbers. Taiwan is the second largest semiconductor producer, despite having the third largest water withdrawals after South Korea and Japan. This is likely due to the type of chips being produced in Taiwan, compared to South Korea, which are dominated by newer, more water intensive chip production.

Fig. 6 is a map of fab annual FW withdrawals summed at the AWaRe watershed level. Table 3 indicates that watersheds located in South Korea, Taiwan, Malaysia, and China display the highest levels of fab FW withdrawals. Summarizing by watershed reveals potentially high impact areas that may not be apparent when delineated at the state/province or country level. Manufacturing facilities in these watersheds have the potential to cause physical shortages of water resources; however, this must be further investigated with consideration of existing watershed scarcity-related factors such as climate, ecosystem water needs, and human water use patterns.

3.2. Scarcity-weighted withdrawals

Wafer production and watershed scarcity data can be combined to gain a general understanding of how much semiconductor production is located in areas with high potential water use impacts (see Fig. 5). Table 4 summarizes the amount of total wafer production in areas considered to be water scarce by the AWaRe index, indicating that almost 13% of production occurs in very water scarce areas (60–100 times less water than the global average), and nearly half (~47%) of all semiconductor manufacturing occurs in locales exhibiting more scarcity than the global average (scarcity factor >1)

While four of the top five countries are the same as for unweighted FW withdrawals, the order of the countries changes somewhat (see Table 5). The greatest volume of weighted FW withdrawals from semiconductor manufacturing occurs in China, despite having lower wafer production numbers than Japan, Taiwan and South Korea. Scarcity-weighted withdrawals indicate potential areas of concern with relation to existing water availability for humans and ecosystems. Regional water issues in China are attributed to heavy water demands from agriculture, energy, and dense manufacturing, especially in the heavily populated and industrialized eastern provinces which comprise 47% of China's total industrial output [56].

Fig. 8 maps the interaction of existing water scarcity and semiconductor FW withdrawals across the globe at the watershed level by

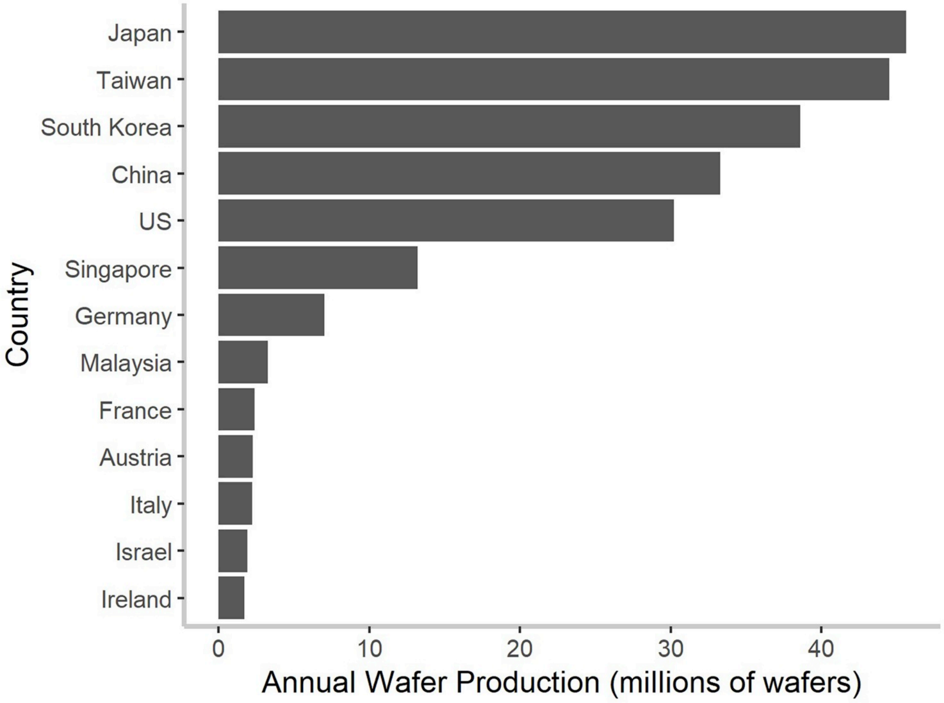

Fig. 3. Annual wafer production (in 8-inch [200 mm] wafer equivalents) by countries producing more than one million wafer starts per year.

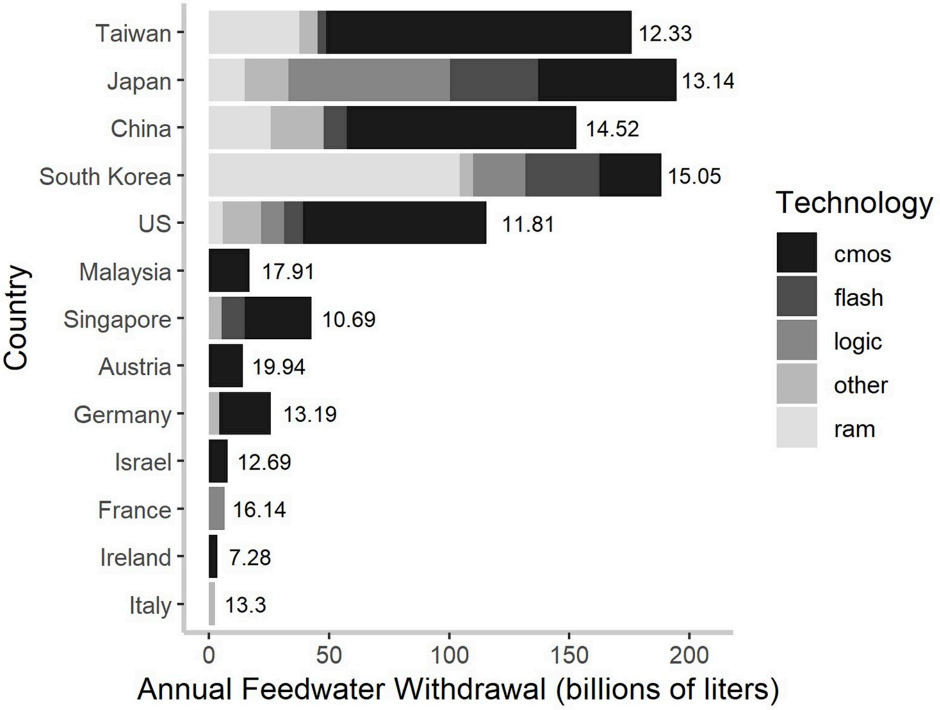

Fig. 4. Annual fab FW withdrawals by country and technology. Countries producing more than one million wafer starts per year are displayed. The value next to each bar represents the average FW withdrawal intensity (in L/cm2) for each country's semiconductor manufacturing facilities, averaged across all technology types.

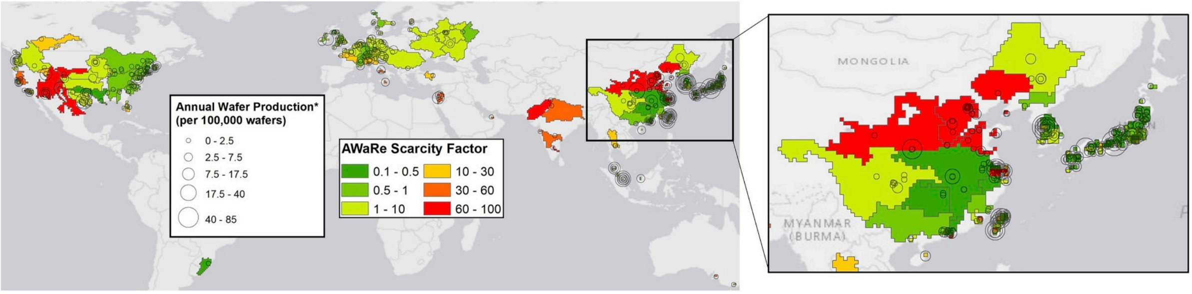

Fig. 5. Semiconductor manufacturing facility annual wafer starts overlaid on AWaRe scarcity factors, by watershed. *Wafer production normalized to 8-inch [200 mm] wafer.

summing and displaying scarcity-weighted withdrawals for each watershed. By comparing Figs. 8 and 6, one can see the spatial shift in impacts when scarcity is considered.

3.3. Temporal analysis

The AWaRe factors provided by WULCA are comprised of annual average scarcity factors and monthly scarcity factors, with the latter representing the temporal variation in water scarcity throughout the year. The figure below represents the difference in withdrawals when using a best case (minimum annual scarcity value) versus worst case (maximum annual scarcity value) scenario. In Fig. 9, the dark orange areas highlight the top 10% of watersheds that are of the most concern with regard to seasonal scarcity, representing the largest annual variation (in absolute terms) with respect to scarcity-weighted withdrawals. Fig. 10 represents the coefficient of variation (standard deviation of each watershed's annual scarcity factor normalized by mean annual scarcity). This shows areas that may display a large swing in annual scarcity, but which may not appear problematic with respect to total withdrawals.

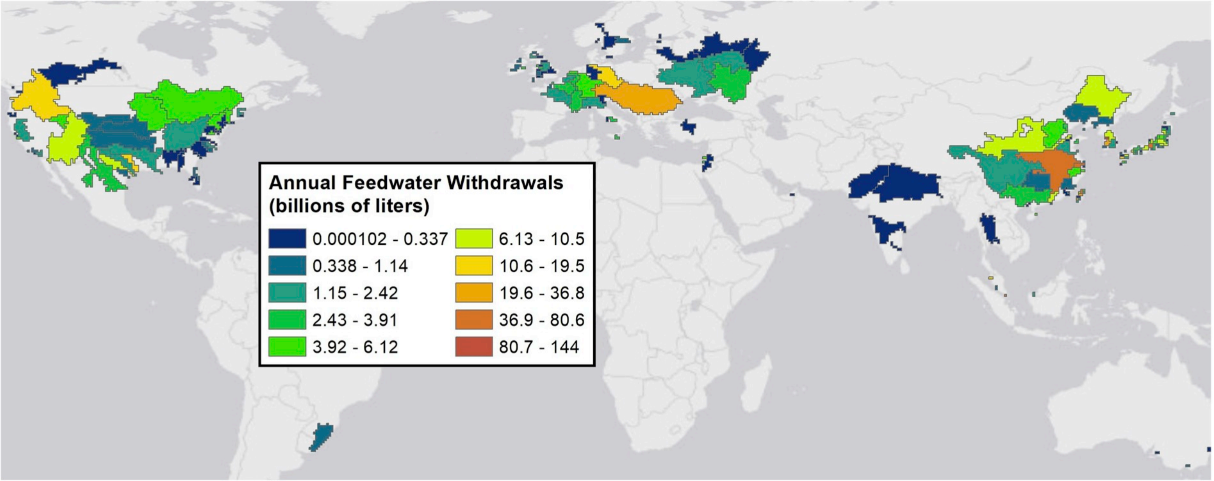

Fig. 6. Annual semiconductor manufacturing FW withdrawals summed by AWaRe watershed.

Table 3
Top five global watersheds for semiconductor manufacturing FW withdrawals.

AWaRe Watershed ID	Country	# of Fab Facilities in Watershed	Unweighted Feedwater Withdrawals (billions of liters)	AWaRe Scarcity Factor (0.01–100)
6339	South Korea	27	143.99	8.20
7282	Taiwan	47	80.60	0.52
8837	Malaysia	24	45.78	0.79
6895	China	26	45.28	67.58
6848	China	37	45.20	0.22

Table 4
Percent of total wafer production occurring in areas of various water scarcity. Description of water scarcity factors are adapted from [31]].

AWaRe Scarcity Characterization Factor	Description of Scarcity	% of Global Wafer Production
0.01–0.5	values < 1 for regions with less problems of scarcity than the world average	21.97
0.5–1	values < 1 for regions with less problems of scarcity than the world average	33.29
1–10	a value of 10, for example, representing a region where there is 10 times less water remaining per area within a certain period of time than the world average,	21.99
10–30	10–30 times less water remaining per area within a certain period of time than the world average,	5.06
30–60	30-60 times less water remaining per area within a certain period of time than the world average,	4.80
60–100	The upper cutoff of 100 affects regions where demand is higher than availability	12.89

Scarcity weighted FW withdrawals were also summarized by country and by AWaRe watershed and are represented in Figs. 7 and 8.

Table 5
Top five global watersheds for scarcity-weighted semiconductor manufacturing FW withdrawals.

AWaRe Watershed ID	Country	# of Facilities in Watershed	Weighted Feedwater Withdrawal (billions of liter equivalents)	AWaRe Avg Scarcity Factor (.01–100)
6895	China	26	3046	67.30
7405	Taiwan	19	1562	42.50
6339	South Korea	27	1181	8.20
6269	China	15	806	82.10
6825	U.S.	8	657	100

3.4. Fab electricity water use

The annual electricity-related water withdrawals by semiconductor facilities were summarized over various spatial extents. Water withdrawals for electricity consumption are not weighted, since they are not accurately attributable to a specific watershed. A country-

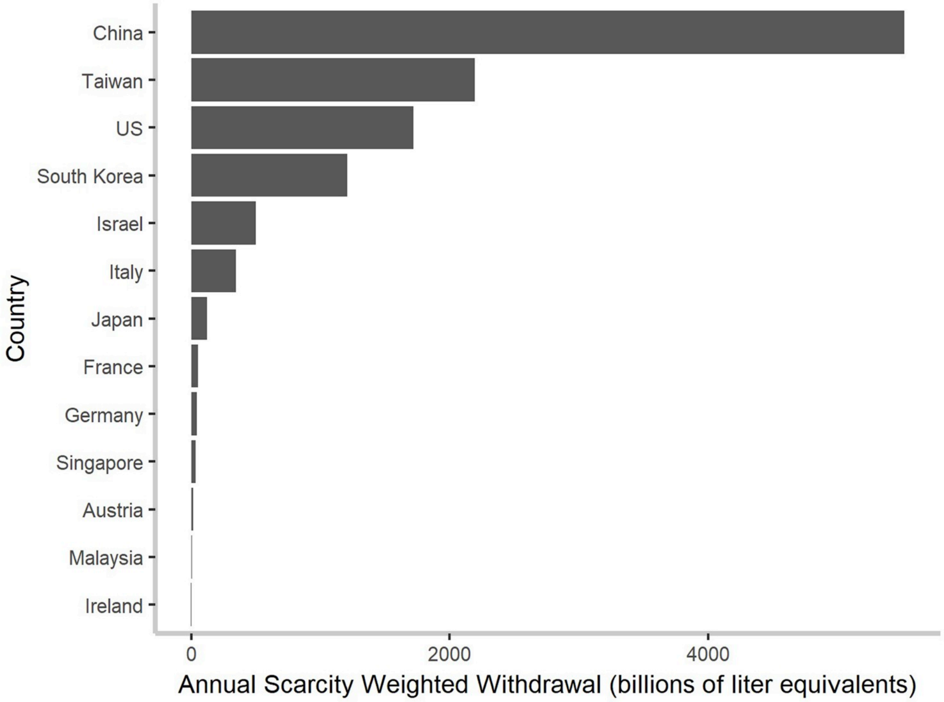

Fig. 7. Scarcity-weighted FW withdrawals by country. The withdrawal is expressed in billions of liter-equivalents to denote the transformation of withdrawal inventory data (in liters) into an impact equivalent (in liter equivalents).

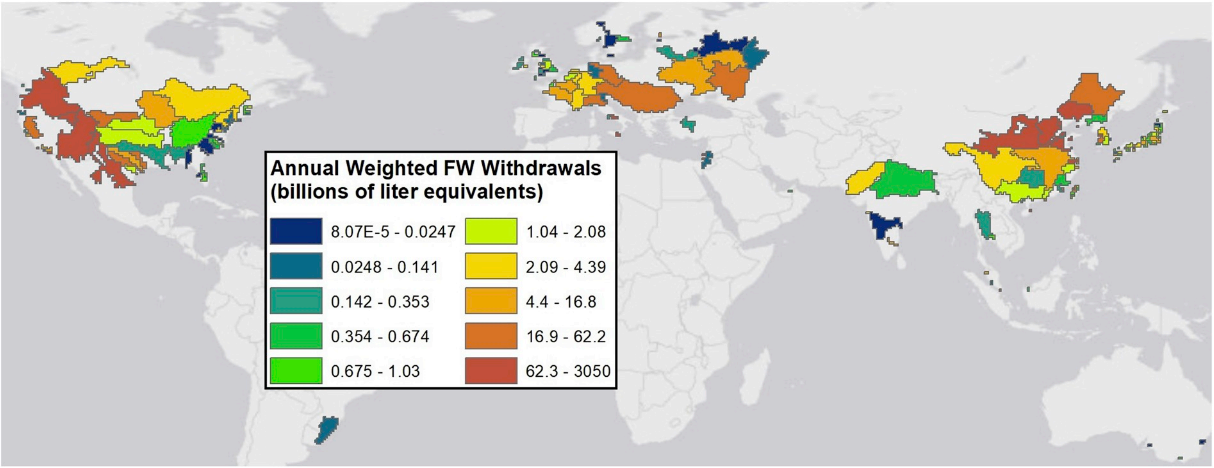

Fig. 8. Annual scarcity-weighted semiconductor manufacturing FW withdrawals summed by AWaRe watershed. The withdrawal is expressed in billions of liter-equivalents to denote the transformation of withdrawal inventory data (in liters) into an impact equivalent (in liter equivalents).

level summary of fab ERW withdrawals for the top global producers is presented in Fig. 11. This analysis indicates that South Korea has the largest ERW withdrawals for any single semiconductor producing country and China is the second largest user of ERW. China and South Korea's higher water withdrawals is due to water intensive electricity production such as coal and hydroelectric, and coal and nuclear, respectively. See the Appendix for breakdown of electricity demand by generating type for each country.

Although it is difficult to directly associate electricity use from the grid with impacts on a specific watershed, in Fig. 12 we overlay fab electricity use with water scarce areas in East Asia to draw a general picture of the relationship between water scarcity and fab ERW withdrawals in this important semiconductor manufacturing region.

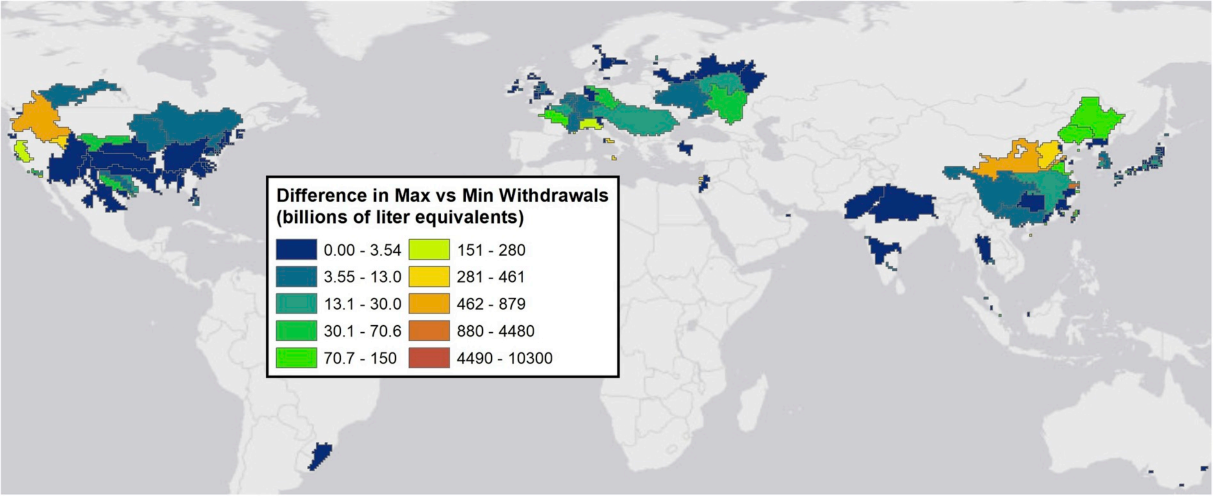

Fig. 9. Difference between maximum monthly scarcity weighted withdrawals and minimum monthly scarcity weighted withdrawals on an annual basis. This represents the difference between a best-case and worst-case scenario for water scarcity in a year, per watershed. The data is divided into deciles to better visualize variation across the dataset.

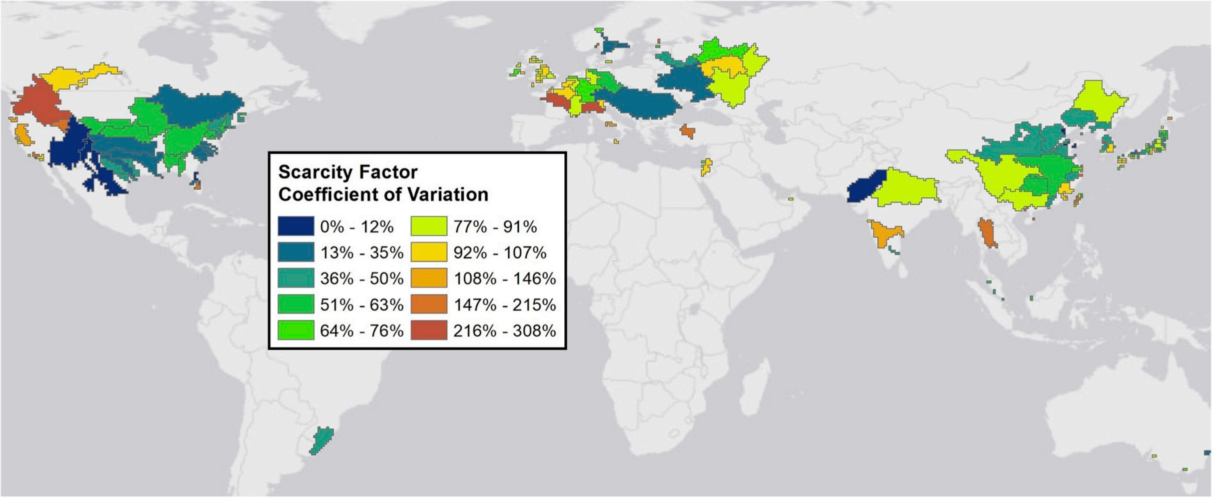

Fig. 10. Coefficient of variation (standard deviation of annual scarcity factor normalized by mean annual scarcity) of the AWaRE scarcity factor per watershed. This indicates watersheds that are likely to exhibit the largest percentage change in scarcity over the course of a year.

3.5. Total water withdrawals

The total water withdrawal for each fab is the sum of withdrawals for the fab FW and the ERW withdrawals. This metric is not scarcity weighted. The annual, total global, Scope 2 water withdrawal for semiconductor manufacturing is 2.096×10^{13} liters per year, or approximately 21 trillion liters (2.1 billion m^3) per year. As seen in Fig. 13, electricity water withdrawals dominate water use for fabs; thus, South Korea's fabs are the largest total water users. Given the relative dominance of ERW withdrawals (10–50 times more than FW withdrawals, in some cases), it is expected that South Korea and China have the largest total withdrawals.

4. Discussion and conclusion

4.1. Discussion

Current understanding of global water use emphasizes agricultural and thermoelectric demand, and less data is available about industrial water uses. Many of the industrial water use studies analyze a single facility or industry, or consider the water use of an entire industry without being spatially explicit. Thus, the methodologies are not easily applied across industries or spatial scales. The present

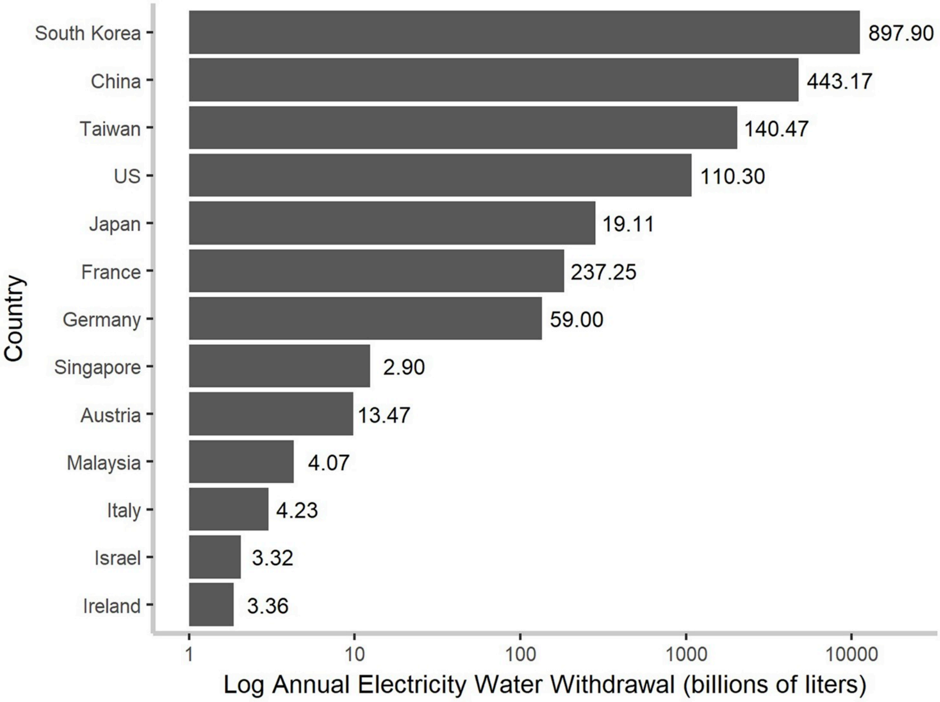

Fig. 11. Fab ERW withdrawals by country. The value next to each bar represents the average ERW withdrawal intensity (L/cm2) for each country's semiconductor manufacturing facilities.

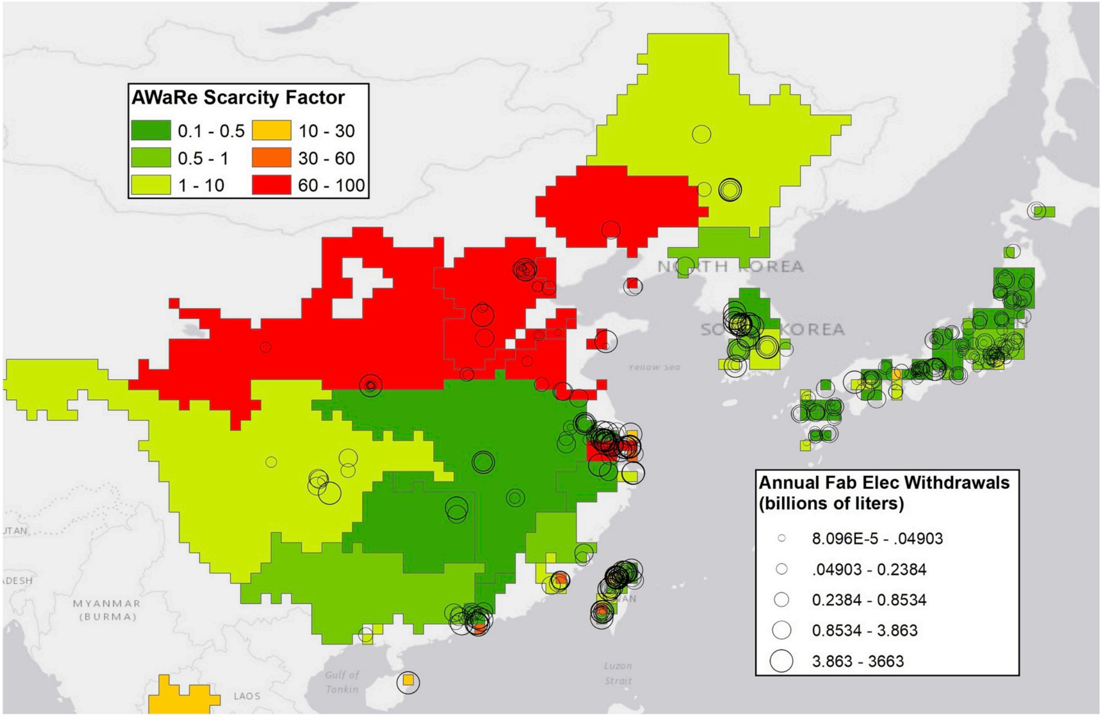

Fig. 12. Map of East Asian (i.e. Japan, South Korea, China, Taiwan) fab electricity-related water withdrawals by facility, overlaid on AWaRe scarcity factors. A map of global ERW withdrawals is available in the Appendix (Figure A1).

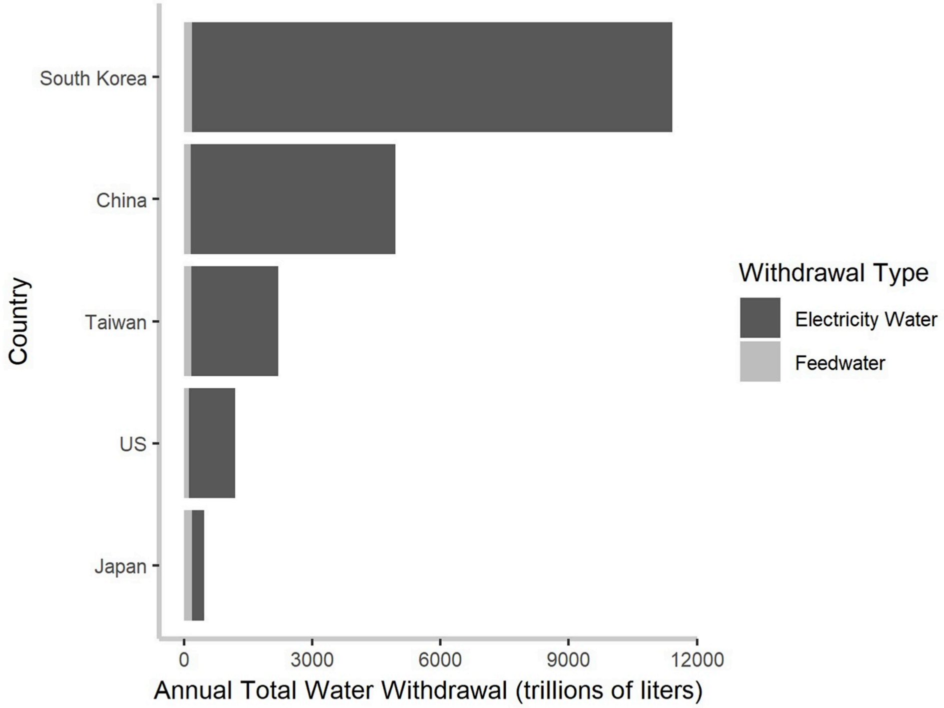

Fig. 13. Total water withdrawals (FW + ERW) by the five highest producing countries in the semiconductor manufacturing sector.

study reports total global water use by an important and growing sector, semiconductor manufacturing, and provides a methodology that could be applied to many other manufacturing sectors.

The increasing production of electronics will likely represent a growing share of the global water demand by the semiconductor industry. Thus, this study enhances the current understanding of water use by semiconductor manufacturing operations around the globe. We report annual water use for nearly 100% of semiconductor manufacturing capacity in Q4 2016 and identify Scope 2 (electricity-related) water withdrawals as more significant than Scope 1. Production data indicates a high level of water use in South Korean, Chinese, Japanese, U.S. and Taiwanese electronics manufacturing sectors. However, we have also segmented semiconductor manufacturing capacity with respect to water scarce locations, using watershed-level scarcity characterization factors provided by the AWaRe index. This analysis indicated that almost 13% of production occurs in very water scarce areas, and nearly half (∼47%) of all semiconductor manufacturing occurs in locales exhibiting more scarcity than the global average. This study also examined areas that undergo seasonal scarcity, which is not captured by annual average scarcity values that are often reported. Manufacturers should consider the variability in water use impacts on ecosystems and humans that may occur seasonally.

This study presents a method for applying regional electricity water withdrawals and LCA/industry water use coefficients to calculate industry-wide, global, scarcity-weighted withdrawals. The granularity of the present analysis allows for summary of data at various spatial extents. The regional electricity water use factors calculated for the US (using plant specific data) and China (using provincial production data) provide more accurate withdrawal data for large countries that may exhibit regionally variable electricity production and water scarcity. The derived regional electricity water use factors used in this study can be applied to other industrial sectors.

4.2. Limitations

This work does not provide a complete picture of water use by all users (industrial, commercial and residential) within a watershed area; thus additional studies of global water withdrawals by other industrial sectors, at the same spatial granularity as this one, are vital to a better understanding of water use and potential impacts. Withdrawals-based estimates were used here as a conservative estimate of water use, given that degradative consumption (water used to dilute pollutants to an acceptable level) was not included in the analysis.

This study also does not provide a complete water footprint for the semiconductor industry, as it focuses on manufacturing water use and excludes the significant ERW withdrawals attributed to the use phase of these semiconductor chips. Additionally, while some basic benchmarking was conducted against limited available data, more complete benchmarking of facility level data against these LCA based estimates should be completed.

Scarcity-weighted water withdrawals (quantified in liters of H_2O equivalents) are not a direct measurement of physical water scarcity, thus estimates provided here serve as a screening level indicator of the potential of this industry to deprive other users (ecosystems or humans) of clean water, resulting in regulatory or reputational risk. This study does not explicitly address the operational risks to the manufacturer associated with the withdrawal of feedwater in a water scarce area.

4.3. Conclusions

This study may serve as a benchmark for global withdrawals by the semiconductor industry and could be used by industry or regulatory bodies to set withdrawals-based standards. Additionally, the spatially explicit water withdrawal data for the semiconductor sector can be used to improve existing databases of national and regional water use coefficients that are often applied in LCA input-output studies [42,57].

Industry leaders such as Intel and Taiwan Semiconductor Manufacturing Company (TSMC) have shown that large reductions in fab water use can be achieved with the appropriate investments in water-saving technologies. And although these water savings are vital for reducing localized water impacts, this study indicates that in the case of semiconductor manufacturing, the most efficient way to reduce overall manufacturing water withdrawals (and associated regional watershed impacts) is through reduction in fab electricity use. Reductions in electricity water use can also be achieved by using less water intensive sources of electricity, such as solar PV and wind, which is especially important during seasons of higher water scarcity.

Large electronics OEMs can use this location-specific data to determine water use impacts of operations from this energy and water intensive component within their supply chain. Specifically, the rise in semiconductor manufacturing growth in certain regions in China may enhance water scarcity in areas that are already water stressed, due to existing demands by industry, agriculture and domestic users. Supply chain decisions, such as sourcing semiconductor chips from less water stressed areas, may be a potential approach to reducing the overall water footprint of electronic products and managing the associated regulatory or reputational risk.

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Appendix A

Table A.1Net generation, fuel mix, and water use intensity for U.S. NERC electricity regions.

NERC Region	Net generation (TWh)	% of Region's Electricity Provided By Fuel Type [EPA 2014]									Water use intensity (L/kWh)
		Thermoelectric						Non-thermoelectric			
		Coal	*Oil*	*Gas*	*Nuclear*	*Biomass*	*Geo-thermal*	*Hydro*	*Wind*	*Solar PV*	
Florida Reliability Coordinating Council (FRCC)	220	21.6	0.8	61.4	12.7	2.0	0.0	0.1	0.0	0.1	42.67
Midwest Reliability Organization (MRO)	227	60.2	0.3	3.9	11.9	1.7	0.0	5.5	16.3	0.0	49.57
Northeast Power Coordinating Council (NPCC)	244	3.9	1.7	41.2	32.3	4.0	0.0	13.2	2.4	0.2	75.55
Reliability First Corporation (RFC)	947	50.3	0.6	15.7	28.6	1.0	0.0	0.7	2.3	0.1	51.10
SERC Reliability Corporation (SERC)	1090	42.2	0.5	25.4	26.1	2.0	0.0	3.0	0.4	0.1	59.88
Southwest Power Pool (SPP)	226	53.5	1.6	26.0	3.8	1.1	0.0	1.5	12.3	0.0	29.23
Texas Regional Entity (TRE)	368	33.4	0.1	44.9	10.7	0.3	0.0	0.1	9.9	0.1	45.41
Western Electricity Coordinating Council (WECC)	741	27.5	0.1	30.1	7.9	1.5	2.1	21.9	6.4	2.0	12.97

Table A.2Chinese provincial electricity production capacity, fuel mix, and water use intensities. Weighted averages based on production capacity were used to create regional averages.

Province	Chinese Elec. Region	Provincial Production Capacity (TWh)	% of Provincial Production Capacity for Each Energy Type [10]							% of Thermoelectric Production Using Various Cooling Types (C [23].				Provincial Average Water Use Intensity	Capacity Weighted Regional Average WUI (L/ kWh)
			Coal	*Natural gas*	*Biomass*	*Nuclear*	*Hydro*	*Wind*	*Solar*	*Recirculating Cooling*	*Once-through Cooling*	*Dry Cooling*	*Sea-water Cooling*		
Chongqing	Central	109.78	76.7%	0.0%	1.1%	0.0%	21.9%	0.4%	0.0%	66.6%	33.4%	0.0%	0.0%	46.89	51.33
Henan	Central	303.14	94.2%	0.0%	1.3%	0.0%	3.1%	1.4%	0.0%	96.0%	4.0%	0.0%	0.0%	7.71	
Hubei	Central	272.93	37.2%	0.0%	0.4%	12.8%	49.5%	0.1%	0.0%	40.6%	59.4%	0.0%	0.0%	105.69	
Hunan	Central	205.68	52.0%	0.0%	0.9%	17.0%	30.1%	0.0%	0.0%	35.8%	64.2%	0.0%	0.0%	117.27	
Sichuan	Central	364.37	22.4%	0.0%	1.2%	0.0%	75.9%	0.4%	0.1%	98.5%	1.5%	0.0%	0.0%	11.01	
Anhui	East	288.7	95.3%	0.0%	2.1%	0.0%	1.6%	1.0%	0.1%	75.7%	24.3%	0.0%	0.0%	33.39	77.69
Fujian	East	215.21	46.0%	7.0%	1.1%	22.8%	21.1%	2.0%	0.0%	9.1%	13.3%	0.0%	77.6%	120.51	
Jiangsu	East	448.52	71.2%	17.7%	1.3%	7.3%	0.1%	2.2%	0.2%	42.2%	49.3%	0.0%	8.6%	83.85	
Jiangxi	East	118.88	53.2%	2.1%	3.0%	29.4%	10.4%	1.7%	0.2%	63.5%	36.5%	0.0%	0.0%	101.71	
Shanghai	East	149.84	75.2%	22.6%	1.1%	0.0%	0.0%	1.0%	0.1%	7.7%	75.9%	0.0%	16.4%	117.79	
Zhejiang	East	385.59	61.3%	16.0%	1.3%	13.8%	7.0%	0.5%	0.1%	23.9%	7.2%	0.0%	68.9%	56.78	
Beijing	North	48.72	56.4%	37.6%	2.5%	0.0%	1.0%	1.9%	0.5%	90.7%	9.3%	0.0%	0.0%	14.28	8.31
Hebei	North	301.93	93.3%	1.4%	1.4%	0.0%	0.2%	3.6%	0.2%	65.2%	4.0%	12.3%	18.5%	8.59	
Shandong	North	479.07	92.9%	0.0%	1.9%	3.9%	0.1%	1.2%	0.0%	80.7%	1.2%	0.5%	17.6%	11.08	
Shanxi	North	380.12	98.2%	0.0%	0.5%	0.0%	1.1%	0.3%	0.0%	35.9%	3.4%	60.8%	0.0%	7.27	
Tianjin	North	126.24	77.2%	21.5%	1.2%	0.0%	0.0%	0.1%	0.0%	65.1%	0.2%	0.0%	34.6%	2.90	
W. Inner Mong.	North	227.37	87.0%	0.0%	0.3%	0.0%	0.8%	11.8%	0.1%	46.0%	2.6%	51.4%	0.0%	5.57	
E. Inner Mongolia	NE	227.37	87.0%	0.0%	0.3%	0.0%	0.8%	11.8%	0.1%	46.0%	2.6%	51.4%	0.0%	5.57	19.37
Heilongjiang	NE	138.78	88.4%	0.0%	2.1%	0.0%	2.4%	6.9%	0.3%	78.2%	21.8%	0.0%	0.0%	30.14	
Jilin	NE	100.25	63.3%	0.0%	5.6%	0.0%	9.1%	21.8%	0.2%	81.5%	11.5%	7.0%	0.0%	17.51	
Liaoning	NE	183.66	74.7%	0.0%	2.2%	15.2%	2.7%	5.0%	0.2%	62.6%	0.1%	1.9%	35.4%	29.32	
Gansu	NW	121.4	54.5%	0.0%	1.5%	0.0%	22.2%	21.0%	0.8%	55.5%	0.0%	44.5%	0.0%	3.37	3.15
Ningxia	NW	141.67	91.9%	0.0%	0.4%	0.0%	1.3%	5.7%	0.7%	42.3%	0.0%	57.7%	0.0%	1.26	
Qinghai	NW	90	46.9%	0.0%	0.0%	0.0%	48.8%	1.3%	3.0%	100.0%	0.0%	0.0%	0.0%	6.60	
Shaanxi	NW	274.98	92.4%	0.0%	1.1%	0.0%	4.5%	1.5%	0.5%	45.8%	0.0%	54.2%	0.0%	1.69	
Xinjiang	NW	272.03	88.1%	0.0%	0.0%	0.0%	6.6%	5.3%	0.0%	82.8%	1.2%	16.0%	0.0%	4.12	
Xizang	NW	9.91	3.8%	0.0%	0.0%	0.0%	94.6%	0.0%	1.6%	100.0%	0.0%	0.0%	0.0%	10.72	
Guangdong	South	469.69	55.1%	15.0%	0.4%	19.5%	9.1%	0.9%	0.0%	21.0%	12.2%	0.0%	66.8%	84.48	55.63
Guangxi	South	198.14	63.4%	1.6%	1.5%	7.1%	25.7%	0.8%	0.0%	17.9%	48.0%	0.0%	34.0%	110.23	
Guizhou	South	215.65	79.3%	0.0%	2.9%	0.0%	16.4%	1.4%	0.0%	98.5%	1.5%	0.0%	0.0%	5.61	
Hainan	South	20.56	82.5%	0.0%	5.8%	0.0%	7.3%	3.4%	1.0%	11.4%	0.0%	0.0%	88.6%	2.78	
Yunnan	South	264.07	31.0%	0.0%	1.2%	0.0%	67.2%	0.4%	0.1%	100.0%	0.0%	0.0%	0.0%	8.30	

Sample calculation for provincial electricity WUI: $\sum PCPC((\%RC_{coal}*WUI_{recirc})+(\%OTC_{coal}*WUI_{otc})+(\%DC_{coal}*WUI_{dry}))+PNGPC((\%RC_{ng}*WUI_{recirc})+(\%OTC_{ng}*WUI_{otc}))+(PNPC*WUI_{nuclear})+(Biomass*WUI_{biomass})+(PSP*WUI_{solar})+(PWP*WUI_{wind})+(PHP*WUI_{hydro})$ For Shanghai Province, the calculation would be as follows:

Shanghai Province WUI = 0.752*((.077*2.37)+ (.759* 95.5) + (0*0.334)) + 0.226((.077/(.077 + .759))*2.75) + (0.759/(.077 + .759)*34.07)) + (0*178) + (0.011*0.0172) + (0.01*0.0227) + (0.001*.0057) + (0*11.245).

Sample calculation for regionally averaged WUI, weighted by the production capacity of each province in the electricity trading region.

Table A.3Weighted production capacity of each province in the ‘East’ electricity trading region.

Province	Electricity Region	Provincial Production Capacity (TWh)	Prov Weighting Factor (Prov Capacity/Total Regional Capacity)
Anhui	East	288.7	0.18
Fujian	East	215.21	0.13
Jiangsu	East	448.52	0.28
Jiangxi	East	118.88	0.07
Shanghai	East	149.84	0.09
Zhejiang	East	385.59	0.24
	Total Regional Capacity	**1606.74**	1.0

East Region WUI $= (\text{Anhui}_{\text{WUI}}{*}\text{Anhui}_{\text{WeightFactor}}) + (\text{Fujian}_{\text{WUI}}{*}\text{Fujian}_{\text{WeightFactor}}) + (\text{Jiangsu}_{\text{WUI}}{*}\text{Jiangsu}_{\text{WeightFactor}}) + (\text{Jiangxi}_{\text{WUI}}{*}\text{Jiangxi}_{\text{WeightFactor}}) + (\text{Shanghai}_{\text{WUI}}{*}\text{Shanghai}_{\text{WeightFactor}}) + (\text{Zhejiang}_{\text{WUI}}{*}\text{Zhejiang}_{\text{WeightFactor}})$.

East Region WUI $= (33.39\ {*}0.18) + (120.51{*}0.13) + (83.85{*}\ 0.28) + (101.71{*}0.07) + (117.79{*}0.09) + (56.78{*}0.24)$.

East Region WUI $= 77.69$ L/kWh.

Table A.4Electricity grid mix, total production capacity [24]] and water use intensities for each semiconductor producing country (except China and U.S.).

Country	Coal	Oil	Gas	Biofuels	Waste	Nuclear	Hydro	Geo-thermal	Solar PV	Solar Thermal	Wind	Tide	Other	Total Elec Prod (GWh)	WUI (L/kWh)
Australia	62.9%	2.7%	20.8%	1.4%	0.0%	0.0%	5.3%	0.0%	2.4%	0.0%	4.5%	0.0%	0.0%	252360	2.378
Austria	7.8%	1.3%	11.9%	6.3%	1.6%	0.0%	62.2%	0.0%	1.4%	0.0%	7.4%	0.0%	0.0%	65299	7.304
Belarus	0.1%	1.1%	97.9%	0.4%	0.1%	0.0%	0.3%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	34082	0.969
Belgium	6.0%	0.3%	32.3%	6.6%	3.0%	36.9%	2.0%	0.0%	4.3%	0.0%	7.9%	0.0%	0.6%	70648	66.421
Brazil	4.7%	5.0%	13.7%	8.4%	0.0%	2.5%	61.8%	0.0%	0.0%	0.0%	3.7%	0.0%	0.1%	581652	11.731
Bulgaria	45.8%	0.4%	3.8%	0.6%	0.0%	31.2%	12.5%	0.0%	2.8%	0.0%	2.9%	0.0%	0.0%	49228	58.181
Canada	9.8%	1.2%	10.0%	1.9%	0.0%	15.1%	56.8%	0.0%	0.4%	0.0%	3.9%	0.0%	0.8%	670851	33.626
Czech Republic	52.3%	0.1%	2.7%	5.6%	0.2%	32.0%	3.7%	0.0%	2.7%	0.0%	0.7%	0.0%	0.1%	83892	58.668
Denmark	24.5%	1.1%	6.3%	11.4%	5.8%	0.0%	0.1%	0.0%	2.1%	0.0%	48.8%	0.0%	0.0%	28947	0.689
England	22.6%	0.6%	29.5%	7.8%	1.9%	20.7%	2.7%	0.0%	2.2%	0.0%	11.9%	0.0%	0.0%	339095	38.057
Finland	12.8%	0.3%	7.6%	16.0%	1.2%	33.9%	24.4%	0.0%	0.0%	0.0%	3.4%	0.0%	0.4%	68598	63.433
France	2.1%	0.4%	3.5%	0.7%	0.7%	77.0%	10.4%	0.0%	1.3%	0.0%	3.7%	0.1%	0.1%	568454	138.169
Germany	43.9%	1.0%	9.7%	6.9%	2.0%	14.2%	3.8%	0.0%	6.0%	0.0%	12.2%	0.0%	0.3%	646888	26.872
India	75.3%	1.7%	4.9%	1.8%	0.1%	2.7%	10.0%	0.0%	0.4%	0.0%	3.1%	0.0%	0.0%	1383004	7.871
Ireland	26.0%	1.4%	43.6%	1.4%	0.5%	0.0%	3.9%	0.0%	0.0%	0.0%	23.2%	0.0%	0.0%	28387	1.504
Israel	45.8%	0.7%	51.6%	0.1%	0.0%	0.0%	0.0%	0.0%	1.7%	0.0%	0.0%	0.0%	0.0%	64226	1.641
Italy	16.0%	4.7%	39.2%	6.0%	1.7%	0.0%	16.6%	2.2%	8.1%	0.0%	5.2%	0.0%	0.2%	282994	2.686
Japan	33.0%	9.8%	39.4%	3.3%	0.7%	0.9%	8.8%	0.2%	3.4%	0.0%	0.5%	0.0%	0.0%	1041343	3.837
Korea	42.8%	2.3%	22.2%	0.4%	0.1%	29.8%	1.0%	0.0%	0.7%	0.0%	0.2%	0.1%	0.3%	552876	54.427
Latvia	0.0%	0.0%	49.8%	13.9%	0.0%	0.0%	33.6%	0.0%	0.0%	0.0%	2.7%	0.0%	0.0%	5533	4.254
Malaysia	42.3%	1.2%	46.6%	0.5%	0.0%	0.0%	9.3%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%	150123	2.545
Netherlands	38.7%	1.3%	42.3%	2.7%	3.3%	3.7%	0.1%	0.0%	1.0%	0.0%	6.9%	0.0%	0.1%	110070	7.971
Norway	0.1%	0.0%	1.8%	0.0%	0.3%	0.0%	95.9%	0.0%	0.0%	0.0%	1.7%	0.0%	0.2%	145021	10.799
Russia	14.9%	0.9%	49.6%	0.0%	0.3%	18.3%	15.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1067544	35.211
Scotland	22.6%	0.6%	29.5%	7.8%	1.9%	20.7%	2.7%	0.0%	2.2%	0.0%	11.9%	0.0%	0.0%	339095	38.057
Singapore	1.2%	0.7%	95.0%	0.4%	2.5%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	50415	0.932
Slovakia	12.4%	1.4%	6.0%	6.1%	0.2%	56.3%	15.4%	0.0%	1.9%	0.0%	0.0%	0.0%	0.4%	26903	102.265
Slovenia	29.0%	0.1%	2.7%	1.8%	0.1%	37.4%	27.1%	0.0%	1.8%	0.0%	0.0%	0.0%	0.0%	15100	70.346
Sweden	0.8%	0.2%	0.3%	5.6%	1.8%	34.8%	46.6%	0.0%	0.1%	0.0%	10.0%	0.0%	0.0%	162058	67.120
Switzerland	0.0%	0.1%	1.0%	0.8%	3.4%	34.1%	58.9%	0.0%	1.7%	0.0%	0.2%	0.0%	0.0%	67720	67.292
Taiwan	45.4%	4.2%	32.4%	0.1%	1.2%	12.0%	3.7%	0.0%	0.4%	0.0%	0.6%	0.0%	0.0%	264114	23.206
Thailand	19.5%	0.6%	71.4%	4.1%	0.3%	0.0%	2.7%	0.0%	1.3%	0.0%	0.2%	0.0%	0.0%	177760	1.465
Turkey	29.1%	0.8%	37.9%	0.5%	0.0%	0.0%	25.6%	1.3%	0.1%	0.0%	4.5%	0.0%	0.2%	261783	3.989
United Arab Emirates	0.0%	1.2%	98.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%	127366	0.938
Wales	22.6%	0.6%	29.5%	7.8%	1.9%	20.7%	2.7%	0.0%	2.2%	0.0%	11.9%	0.0%	0.0%	339095	38.057

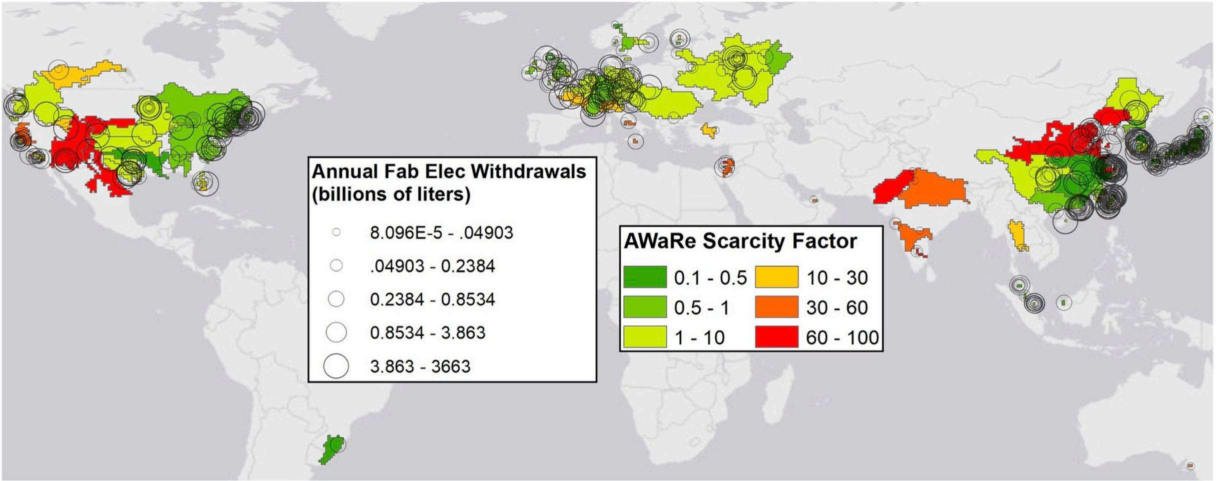

Fig. A.1. Map of global fab ERW withdrawals by facility, overlaid on AWaRe scarcity factors.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wri.2019.100115.

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