INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS™

2023 WHITE PAPER

ENVIRONMENT, SAFETY, HEALTH & SUSTAINABILITY (ESHS): ENVIRONMENTAL SUSTAINABILITY OF THE SEMICONDUCTOR FACILITIES

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ACKNOWLEDGMENTS

This chapter was prepared by a group of experts representing broad spectrum of knowledge and activities associated with environmental sustainability, focusing on water and energy conservation. The Water Management forum is represented by several leading advanced semiconductor manufacturing companies, major semiconductor tool vendors, facility technology suppliers (integrators, materials, components, metrology) and consultants.

The Water + Energy management roadmap described in this narrative is based on systematic assessment, including data collection, data analysis, and modeling conducted by the forum.

The team acknowledges the contribution of the following experts in the development of the roadmap materials:

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ESHS: ENVIRONMENTAL SUSTAINABILITY OF THE SEMICONDUCTOR FACILITIES

1. EXECUTIVE SUMMARY

Growing semiconductor facilities drive increasing environmental footprint, including high energy demand, high freshwater withdrawal, carbon emission, and other GHG (Green House Gas) and waste related emissions. Whereas in the past the sustainability performance was associated with general social responsibility and cost related benefits, it is now becoming mission critical for the industry.

ESH/S IFT (Environmental, Safety, Health and Sustainability International Focus Team) comprises of a number of focus teams, driven by current ESH/S priority. This includes Environmental Sustainability of the Semiconductor Facilities (ESSF), Supply Chain, Materials Fab Process, and Product Content (circularity).

ESH/S IFT has recognized the urgency and the importance of dealing with this challenge, forming a focus team to analyze technology gaps and opportunities in the space of Environmental Sustainability of the Semiconductor Facilities. This document is a sub-chapter of ESH/S chapter and produced as an individual document to support the growing focus on this topic and help the audience with specific technology roadmap set of materials in the area. The forum operated throughout all time zones, regions, and geographies, including major semiconductor manufacturers, tool suppliers, and facility technology providers to ensure completeness of the assessment and the input into the roadmap.

The process of the roadmap development started from the analysis of the technology drivers, boundaries, and considerations. The drivers were assessed for the risk of their effect to the industry and specific technologies responsible for operating facilities within the boundaries identified.

This chapter evaluated the technology drivers, boundaries, and other considerations from the point of view of sustainable industry growth and future technology enabling. The drivers include semiconductor technology, ESG (Environmental, Social, Governance), climate change, and the growing chip demand. These drivers create both urgency and difficulty to deal with the sustainability management. The outcome of the technology gap analysis includes the following findings:

- Importance of the water, chemicals, and energy consumption requirements by the process tools
- Increasing use efficiencies of natural resources (including higher efficiency water treatment systems, energy recovery and gas recovery)
- Minimization and elimination (where possible) of hazardous chemistries
- Use holistic approach for water and energy management, ensuring organizational alignment, supporting data driven decisions with digital tools:
    - Providing effective segregation of wastewater streams
    - Maximizing water reuse
    - Minimizing energy use in brine management
    - Using renewable energy sources

To complete risk and gap analysis both site water and energy models were developed for the representative/typical 300mm semiconductor facility. The models were built with the assumption that the risks addressed would cover the needs of the entire industry.

Additionally, the forum has defined necessary KPIs (Key Performance Indicators) to measure and evaluate the performance requirements of the required solutions. Using those KPIs and the models, the roadmap target have been defined.

The nexus between the water and energy environmental performance indicators has been considered in the context of the roadmap definitions.

This work will be the basis for other activities going forward, including both SEMI standards development/update and future roadmap revisions.

2. INTRODUCTION

The semiconductor industry is facing a perfect storm of challenges in sustainability – particularly precious resources including water and energy, unprecedented growth, and a supply chain struggling with a post-Covid recovery. It is building larger than before new facilities, expanding existing ones, and /or increasing the output of currently operating ones while:

- Next generation fabs are driving an exponentially growing environmental footprint.
- Concerns of deteriorating environmental conditions including drought, flooding, hurricanes, land sliding, strong winds, snow loads, water quality deterioration, power outages and wildfires are growing. Specific occurrences are already directly impacting the semiconductor industry. In one region experiencing drought, water had to be trucked in to keep fabs running. In another, water supplies from a river are being cut by extraordinary amounts causing substantial direct pressure on chipmakers putting in new fabs to conserve water. In a different region, an unusually intense winter storm brought down power and water for days. Fabs can take many weeks to come back into production after such disruptive events.
- Geopolitical events have brought energy security concerns to the forefront.
- Environmental regulations are becoming more stringent and continue to expand their scope. PFAS (Per- and polyfluoroalkyl substances) as a group is subject for a Restriction proposal under the EU REACH Regulation for example.
- Governments and investors are scrutinizing companies' ESG commitments more closely, pressuring them to be more transparent when dealing with Environmental Sustainability performance of the semiconductor facilities.

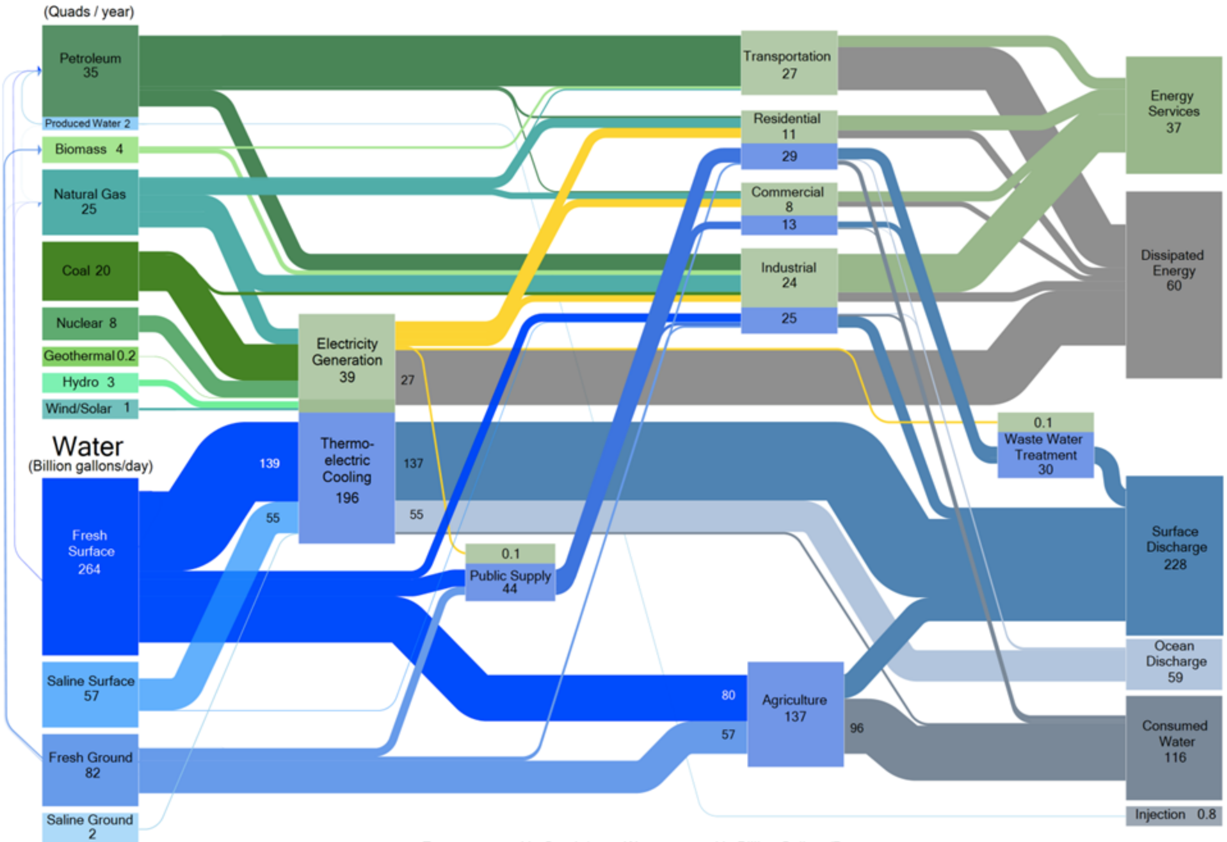
These new challenges require a clear understanding of the industry drivers and needs to motivate development of technology solutions.

The ESSF Roadmap seeks to provide the supply chain with the description of industry needs and the justification for developing new solutions for sustainable operation of facilities especially related to utilization of energy and water that will enable sustainable industry growth. Through a collaborative industry process, tangible roadmap targets for solutions in high-risk areas have been developed including rationales for these solutions anchored by key performance indicators (KPIs). The document scope includes all systems within semiconductor manufacturing facilities with meaningful water and energy footprints. Energy includes electricity, fuel, and other utilities that require significant amounts of energy to produce, including pure gases, compressed Clean Dry Air (CDA), and chemicals.

In addition to the technology roadmap definition supporting supply chain justification for the new technology development, the ESSF Roadmap is driving education and alignment within the industry on the opportunities related to the available technological solutions, allowing for improved environmental sustainability performance. Some of this information can be found in the section of Potential Solutions.

To ensure sustainability under time-to-market and cost pressures, the roadmap seeks to increase certainty and lower risk. It will allow the industry to enable facility technologies within boundaries and priorities, leverage data to manage implications of these challenges, and focus on areas of high risk. Early planning should enable streamlined decisions and lower cost of ownership. The industry will engage in extensive and continuous risk management starting from the roadmap effort and continuing into SEMI standards documents development and implementation.

Water and energy demands are strongly interdependent. A number of analyses have found that water-related energy consumption was 4.1% to 12.6% of US primary energy consumption.[1] Extracting, purifying, delivering, heating/cooling, treating and disposing of water (and wastewater) requires significant amounts of energy.[2],[3]The intrinsic interconnectivity of water and energy is shown in Figure ESHS-1 from the US Department of Energy's 2014 report on the water-energy nexus.



Energy reported in Quads/year. Water reported in Billion Gallons/Day.

Figure ESHS-1 The intrinsic interconnectivity of water and energy.[4]

The roadmap development process involves water and energy sub-teams composed of representatives of leading semiconductor manufacturers, manufacturing and facility equipment OEMs, materials suppliers, analytical labs, and consultants. The resulting document maps risks with respect to mission-critical drivers, boundaries, and other considerations; identifies critical challenges; and describes their implications for environmental sustainability, infrastructure needs and eventually costs. It also quantifies technology needs by providing parameters and KPIs for water and energy consumption. Interactions with SEMI are expected to be revived to discuss opportunities for standard updates.

3. SCOPE OF IRDS ESSF ROADMAP

The mission of the IRDS ESSF team is to enable next generation semiconductor manufacturing technology. The success depends on the ability of the semiconductor facilities to cope with both environmental sustainability challenges as well as the manufacturing yield needs. The two are related since changes driven by environmental sustainability requirements pose additional risk to the semiconductor product output. In addition to these challenges, the growing facilities pose infrastructure related concerns, requiring more energy and water to sustain operations. This means that the scope of the efforts needs to ensure the following goals are enabled:

- Environmental Sustainability, including air emissions, water conservation, wastewater compliance, etc.
- Minimizing infrastructure footprint from water and energy considerations.

To address the above, all facility and fab systems affecting water and energy consumption as well as air and liquid emissions must be included in the scope.

Semiconductor technology roadmap is focused on addressing challenges of the most constrained facilities. The assumption is that by focusing on high end and most complex technologies, there is a higher probability to enable technologies of the less complex facilities. Along these lines, the environmental conditions considered for the roadmap development are those where the higher complexity facility is built in the most challenging locations (from access to infrastructure, weather, compliance, and other points of view). Assuming that if those are addressed, the broader range of environmental conditions will be covered as well.

For the water technology roadmap, the scope includes water quantities, quality, compliance needs, and infrastructure constraints.

For the energy roadmap the focus is on, but not limited to, every type of “utility” considered by SEMI S23 ECF (energy conversion factors) definitions.[5] The energy model has provided additional detail to the S23 ECF categories:

- Exhaust (e.g., make-up air energy demand),
- UPW and Hot UPW (e.g., raw water treatment, heat recovery options),
- Air Conditioning (e.g., cleanroom HVAC energy and variable heat transfer methods).

  The energy model provides several climate zoning options as climate zones can have a significant impact on several ECFs. The energy model has added several ECF not included in the baseline S23 ECF:

  - Water (raw feed typically provided by city, local wells, etc.)
  - Hot water – boiler hot water used for heating UPW (ultrapure water) and other purposes
  - Natural Gas
  - Treated Wastewater
  - Chilled Water – low temperature cooling water provided by chillers and used for controlling temperature of PCW (process cooling water), cleanroom air, and other purposes.
  - Hydrogen
  - Oxygen.

  Additionally, consumption to various utilities to generate ultrapure water was accounted for.

This roadmap covers Scope 1 and 2 of GHG emissions of SBTs (Science Based Targets).

- Scope 1 GHG emissions that occur from sources that are controlled or owned by an organization (e.g., emissions associated with fuel combustion in boilers, furnaces, vehicles).
- Scope 2 emissions are indirect GHG emissions associated with the purchase of electricity, steam, heat, or cooling. Although scope 2 emissions physically occur at the facility where they are generated, they are accounted for in an organization’s GHG inventory because they are a result of the organization’s energy use.

This roadmap chapter is intended to provide an overview of the needs of next generation semiconductor technology with respect to the measures needed to enable the above goals.

This roadmap provides narrative in support to the enclosed excel document delivering key parameters and their values helping to specify quantitative technology targets. This report also provides an appendix with additional supporting information that is used to justify certain definitions in the roadmap table.

Given the purpose of the roadmap in defining future technology needs, it is important to emphasize that the recommendation included in the roadmap materials are suggestion for improvements rather than guidelines for design of the facility systems. Those guidelines are expected to come from the SEMI standards. As the result, the focus of the road-mapping is on the technology gap analysis. This involves the following methodology:

- Identifying drivers and risks – it is apparent that existing facilities operate and produce semiconductor products using existing technologies and approaches. What creates a risk for the future is the change in the operational or environmental sustainability resulting from internal or external drivers, such as:
  - new technology implications (tools, processes, etc.)
  - changing environmental conditions
  - changing regulations, etc.
- The risks associated with the driver must be understood in the context of the existing boundaries, such as:
  - external infrastructure
  - local environmental compliance, etc.

- Defining environmental performance criteria is required to be able to specify what is expected of technological solutions that need to be developed
- Identifying technology needs not effectively addressed by existing solutions with respect to the performance requirements and the roadmap goals helps to narrow down the definition for the next generation technologies
- While the industry is working on developing necessary solutions, the ESSF IRDS team is exploring potential workarounds for the critical challenges.
- And finally, the above assessment, along with the roadmap table, as well as auxiliary material (models, data, etc.) are included in the documentation to support technology needs (the roadmap).

3.1. WATER

Water demand reduction and influent management is essential. Drivers from manufacturing increase the total number of semiconductor device metal layers and therefore drive an increase in water demand touching the surface of the wafer, increasing the total volume of water and energy demand.

Future technologies require focus on increasing complexity of the device in pursuit of Moore's law to critical dimensions, per the More Moore roadmap.

City water (or other raw water) quality supplied to the semiconductor manufacturing site is important for the yield of the manufacturing process. As the result, the treatment systems addressing the raw water quality will drive environmental performance of the site, often requiring energy & chemicals, and producing wastewater & air emissions as by-products. Choosing sites with better water quality available reduces chemical, energy, and water use by maintaining efficiency in the makeup stream and operations.

Choice of less environmentally friendly materials in the manufacturing process or materials that are problematic for effluent treatment in facility management can result in higher complexity and higher energy/resource requirements of the wastewater management. Effluent is the product of fab operation or product of wastewater treatment/reclamation system.

It is important to start water management planning from defining most effective way of effluent segregation:

- Segregating out high concentrated wastes with subsequent disposal (ideally reuse) helps to reduce contamination and complexity of the wastewater treatment and reclamation.
- Segregating higher purity streams allows for recycling those within the process or reusing within the facility.
- Segregating streams with specific contaminants which are of concern for environmental regulatory compliance, relatively easy to treat (e.g., NMP), or difficult to treat (e.g., TMAH) often results in a more sustainable and cost-effective water management solution.

3.2. ENERGY

Energy demand reduction is also essential to enable environmentally and affordable growth of semiconductor facilities. The increasing number of layers driven by each new process technology increases the amount of energy needed as well as the amount of water and other utilities required by the manufacturing process. The energy intensity of the tools is relatively stable, but as more layers are added, this drives more tools and more cleanroom area, driving the energy demand upwards.

To counteract this, the industry needs to reduce energy demand by implementing more energy-efficient solutions on both the tools and facility systems, which includes leveraging heat recovery opportunities. A holistic approach to energy management is essential to maximize opportunities for heat recovery and energy demand reduction. There are still considerable energy savings to be gained from improving efficiency of the central thermal management systems. In addition, it is still common to encounter considerable heat sinks on various parts of the semiconductor facilities which drive large cooling demand, whereas in other locations in the same facility a heater, furnace or boiler is used to generate heat for a unit operation or process step that occurs at elevated temperature. A more coordinated approach to water and energy management is critical to ensure that energy recovery opportunities are understood, and the feasibility of heat recovery can be evaluated.

In addition to the efficient thermal management, it is important to ensure that other facility systems, which operation requires energy use are optimized to reduce energy losses in those systems' operation. This includes reducing hydraulic losses, minimizing energy for heating or cooling, as well as minimizing losses to overcome fouling like resistance in water and wastewater treatment.

Other important Net Zero strategies such as electrification of heat and the replacement of fossil fuels with green energy or green fuels like green hydrogen will be of increasing importance in the coming years.

Note: per UN.org – net zero means cutting greenhouse gas emissions to as close to zero as possible, with any remaining emissions re-absorbed from the atmosphere, by oceans and forests for instance.

4. CROSS TEAM COLLABORATION

The Water + Energy (Operational/Environmental Sustainability) team is a sub/team of IRDS ESH/S forum.

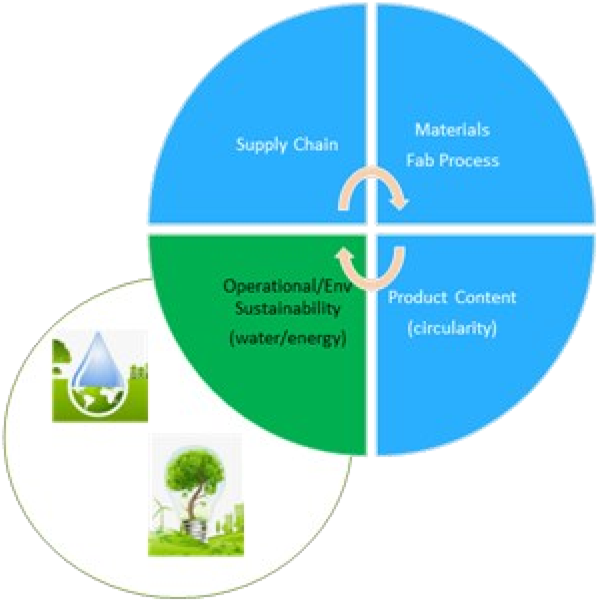


Figure ESHS-2 Water & Energy within ESH/S Organizational Structure

The roadmap development within the sub-team focuses on Water Management and Energy Conservation separately. Each area requires careful understanding of the factors determining technology needs and risks. At the same time the nexus between water and energy is very tight. Water delivery, processing, reclamation, etc. requires a significant portion of the entire site energy usage, while on the other hand, excessive use of energy leads to the significant loss of water for evaporation. This loss represents the big majority of non-recoverable demand forever lost for the watershed.

The outcome of the effort (the roadmap materials) is used as input into the development of the industry standards (e.g., SEMI F98 and SEMI F116 for water and SEMI S23 or SEMI E167/E175 for energy).

It will be necessary to link the IRDS roadmap in the future to standards such as ISO 50001 and Carbon Footprint accounting & reduction standards.

5. CURRENT STATE OF TECHNOLOGY

5.1. ESSF—FOCUSING ON WATER & ENERGY MANAGEMENT

the future, the need to predict water and energy demand will become even more important. To ensure that this need is met the following is required:

- Accurately assessing the key focus areas and drivers,

- Anticipating future industry needs for water and energy,
- Identifying opportunities for reducing water and energy usage in the semiconductor industry by developing comprehensive water and energy models as well as relevant KPIs supporting industry commitments.

Note: the EFFS IRDS team members have collaborated extensively to develop representative digital twins of advanced semiconductor facilities which depict the key processes driving water and energy usage. These mass and energy balance models have been used to define KPIs, critical focus areas and targets for the industry based on these KPIs to achieve over the coming decade.

SEMI F98 has described a typical semiconductor facility water management scheme and offers KPIs for water conservation. EFFS has reviewed the KPIs' definitions based on the industry commitments and has proposed updates for SEMI F98, as appropriate. SEMI S23 provides ECF to help the industry to normalize energy consumption impact of different forms of utilities by developing the representative energy models. The outcome of ESSF effort may result in updating SEMI S23 document.

The current state of the technologies deployed in designing, resourcing and operating the world's High-Volume Manufacturing (HVM) Semiconductor Facilities has been challenged by several years of exponential growth in data usage, storage, and processing.

Within the scope of this section related to Water and Energy, technologies considered are facility technologies responsible for addressing industry challenges, enabling both operational and environmental sustainability.

Within this context, Semiconductor Fab Water Usage is considered throughout the complete cycle of freshwater withdrawal, purification, usage, wastewater treatment and reuse. The goal of the technologies applied is to ensure minimum environmental footprint, reliable operation, environmental regulatory compliance, operability, and other factors as found critical for the facility operation. Different facilities in the industry have different ways to address their site-specific needs and as a result have their water system set up differently. In this chapter, different set-ups are considered when developing a representative 300 mm water management model (refer to Section 6 of this report for more details on the models). The purpose of the representative model is to focus on the technology gaps and opportunities, assuming that they will be relevant to most facilities, independently of their site-specific conditions. Historically, it has been found that the existing city infrastructure may be insufficient to support advanced semiconductor site growth. The roadmap considers availability of the city infrastructure as an "open/uncertain" boundary to be resolved on the case-by-case basis. It is also expected (driven by ESG) that reclamation and reuse for process ultrapure water (UPW) is going to be necessary. This requires consideration for the technology gap analysis to ensure possibility of such application. In this case, growing UPW quality requirements (see the IRDS Yield Enhancement roadmap) must be considered.

5.2. FACILITY SYSTEMS

Water consumption in semiconductor facilities will typically fall into these five main categories:

1. Process
2. Cooling
3. Abatement
4. UPW treatment losses
5. Non-industrial use

Process use makes up the largest demand for water, with most of the water going to tools in the fab. Cooling is next, which includes managing fab heat loads (~20% of overall demand) and air separation units used to produce nitrogen gas (~3% of overall demand). This is followed by air abatement, including point-of-use abatements (~17% of overall demand) and house scrubbers (~3% of overall demand). Incoming freshwater requires extensive treatment to reach fab-level quality, and approximately 9% of water is rejected by UPW treatment processes and, due to quality, this reject water is typically not used on site. Nonindustrial uses make up the smallest portion of demand for a fab. Nonindustrial uses are not considered for the technology roadmap as they do not require special solutions and are often dealt with outside of the industrial water technology envelope. Industrial users, along with their relative water consumption levels are summarized in Figure ESHS-1.

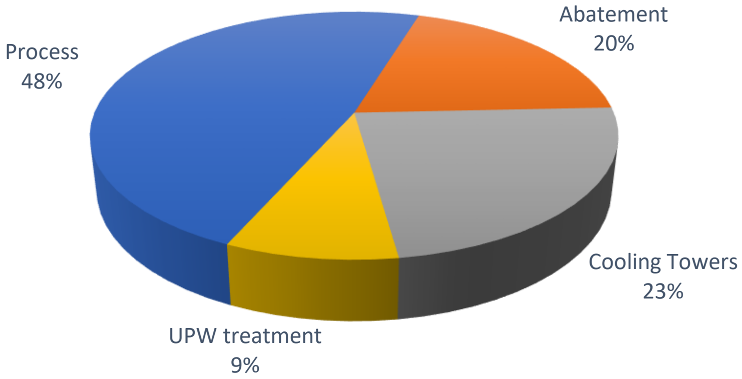


Figure ESHS-3 Typical water usage distribution for a 300 mm facility (specific ratio may vary depending on the process and climate conditions)

The more complex Fabs which are operating at the most advanced production nodes are utilizing as many as 60 elements from the periodic table and routinely use 100 or more independent utility systems to deliver the bulk of the process chemistries to hundreds of process tools.

For example, process water is used in several ways to either deliver, dilute, manage temperature, or rinse off any of those 60 elements being utilized. The water is utilized by several hundreds of different process tools, abatement units and cooling systems – each of which can be requiring its own very specific input water quality specifications and generating another slightly different set of effluent conditions.

This report provides a means of defining how to convert water usage data into meaningful water efficiency KPI's and then identify how that information can be used to identify potential reclaim, reuse, recycle and reduction opportunities. Those KPI's generated by the IRDS Water Management model (see Section 6.1) will be useful tools in the facility design and retrofit planning stages to accurately assess how the Water and Energy usage for the new or retrofitted facility can be made more efficient through the implementation of various sustainability driven solutions.

The representative 300 mm facility model used in the development of this roadmap comprises the following major systems typically utilized by the majority of advanced HVM sites:

- Ultrapure water (UPW) system, treating any freshwater to the quality of SEMI F63 or higher
- Specialty wastewater treatment systems (specific description can be found in SEMI F98 standard)
    - HFW – hydrofluoric wastewater treatment
    - SCW – slurry copper wastewater treatment
    - CCW – concentrated copper wastewater treatment
    - Ammonium wastewater treatment
- Air abatement systems:
    - Point of use scrubbers
    - General scrub exhaust (acid scrubbers)
    - Ammonium scrubbers
- Cooling towers, responsible for energy/heat dissipation
- IWW – industrial wastewater neutralization system
- Reclaim systems
    - URW – ultrapure recycle water
    - End of Pipe (EOP) Treatment – biological or other pretreatment to remove dissolved organics and other contaminants prior to reverse osmosis (RO) treatment/reclamation
        - RO Reclaim system
- Chemical and slurry recycling systems

In addition to the above commonly used systems, the current state of technology includes the following additional components/options:

- POU recycling – tool specific reuse (not shown in the model)
- Brine management solutions, commonly requiring thermal evaporation
- Note: term brine refers to the concentrated salt solutions in the facility outfall that cannot be disposed of to the environmental due to regulatory or other reasons - this becomes one of the critical challenges as described in Section #8.
- Numerous equalization, buffer, and other collection tanks, including lift stations.
- Various complexity segregation systems and schemes
- Water and wastewater metrology providing indication of the quality parameters to ensure sustainability

The freshwater supply to the industrial facility of modern semiconductor Fab(s) is typically provided via two or more redundant supply lines to ensure reliability and 100% uptime of the facility operation.

For the purpose of the representative water model, US Arizona conditions were chosen as worst case scenario for the following reasons:

1. Limited freshwater supply
2. Challenging water quality (relatively high salinity and turbidity)
3. High summer temperatures resulting in significant cooling loads and water evaporation
4. High expectations for Environmental sustainability performance

When considering technology application for reclamation and reuse, the choice needs to be made between process and non-process reuse. The representative 300 mm facility model assumes high priority is given for non-process reuse, such as cooling towers and air abatement make-up vs. process (primarily UPW), which is more sensitive to water impurities. At the same time, there is a trend for increased process reuse, requiring effective segregation and treatment of anything that may affect UPW quality and the factory yield.

Due to the increasing size and complexity of modern Fabs, the number of different types of water applications required for all of the various production tools has become quite large and the water utility capacity required for these sophisticated applications keeps increasing. The following is a partial list of the typical water conveyance, purification, treatment and reclamation systems present within a modern semiconductor campus:

- Raw Water Systems – Potable, Non-Potable Industrial Water, Fire Protection Water, Irrigation Water
- Mechanical Systems – Process Heating and Cooling, Critical Process Cooling, HVAC including Cooling Towers responsible for water evaporation, Humidification and dehumidification within MAH (make-up air handlers)
- Purified Water – Softened Water, RO Permeate, Ultrapure Water, Critical Ultrapure Water (i.e., specialized POU treatment), Hot Ultrapure Water, Functionalized UPW
- Wastewater Treatment and Waste Collection Systems – a significant number of systems handling streams containing various acids, metals, inhibitors, oxidizers, bases, organics, solvents, corrosives, specialty chemicals, etc.
- Reclaim Systems – depending on the configuration and complexity of the site there may be multiple reclaim systems of varying complexity, reclaiming up to 100% of the recoverable streams.

5.3. TOOLS

Semiconductor Wafer Fab facilities utilize many hundreds of production tools which generally fall into the following categories:

- Ion Implant
- Photomask
- Lithography
- Metal and Dielectric Deposition
- Annealing
- Planarization

- Dry Etch
- Wet Etch
- Cleaning (typically wet cleaning)
- Passivation

Within each of those tool types in HVM Fabs, the facility will typically have up to a dozen or more individual tools from different suppliers. During a wafer's time running through the entire 'Front-end' fabrication process, it will see many hundreds of individual process tools (process steps) and within every one of those steps, there will be a further consumption of chemicals, water, and energy.

The facilities' wafer-fab production engineers will usually generate a model to capture and quantify all of the process steps and tool types needed for the fab. That tool list will be used to identify every process tool needed, the tool's supplier and its specific utility requirements and drain conditions. This model is usually called the Tool Layout or utility model. The accuracy of the estimates and outputs of that model are paramount to the successful design of the facilities systems, reclaim systems and infrastructure.

There are also Back-End tools, but these are usually located at separate Assembly and Test Facilities

- Backlap
- Wafer Probe
- Dicing
- Bonding
- Packaging
- Final Test

With heterogeneous integration the complexity of the back-end is increasing together with increasing water and energy demand.

The Back-end wafer processes also require hundreds of individual tools (process steps) consuming water and energy. The Back-end manufacturing operation engineers will also be maintaining a similar model capturing and quantifying each of the steps, tool types and the utility's requirements for their Assembly and Test facility.

In recent years, these Back-End processes and facilities have started being co-located within the same campuses as the Front-end Wafer Fabs. This additional campus complexity is not an unmanageable shift, but it does add to the importance of investing in the modelling and planning for these larger and more diverse campuses.

It remains to be seen whether the industry will continue to see more of this co-location of the Front-End and Back-End processes occurring within the same campus, but where it does occur, it will always increase the variety and number of water and energy users that must be accounted for when modelling the facility and planning for any water and energy sustainability improvement programs. Co-location also creates challenges with wastewater treatment; the effects of the contaminants from back-end processing (particularly high concentrations of suspended solids) on wastewater treatment and reclaim systems need to be understood.

5.3.1. WET STATIONS

One of the typical and major users of UPW is the type of the tools responsible for wet cleans. The manufacture of integrated circuits requires contamination removal from the wafer surface and surface preparation to enable high yields. Historically, all wafer cleaning was performed in an immersion-type batch wet station, consisting of one or more chemical baths, rinse tanks, and a dryer. Immersion baths can reuse the chemical solutions for several batches of wafers, and each batch can contain up to 50 wafers. While batch wet benches are still in use, the use of single-wafer spin processors has proliferated due to better process control and reduced wafer contamination. To match the throughput of a 50-wafer batch wet bench, multiple processing chambers can be placed on one platform, providing a HVM tool that may contain up to 24 chambers.

5.3.2. DRAIN SEGREGATION

With dozens of different process steps, and hundreds of process tools and chemistries involved, a systematic approach is needed to address the challenge posed by the complexity of the facilities. While wastewater reuse and reclamation systems are designed and operated at their most efficient levels under stable influent conditions, it is important to stress the possibility of varying chemical composition of the effluent streams caused by ramp, tool quals, process upsets, and technology changes. Sustainable water reuse requires robust and proactive measures set in place to enable resilient and controllable performance.

SEMI F98 provides reference for both highly segregated and centralized water reuse schemes. Each has its benefits and choices of the specific wastewater treatment and segregation solutions requires a wholistic assessment of the best possible solution, taking into account business needs and site-specific conditions. For all facilities, the decisions and choices made regarding any reuse program will require an in-depth, site-specific review and consideration of the applicable site drivers, boundaries, and objectives.

When upgrading an existing facility or adding a new fab to a campus housing existing operating fabs, this often drives added complexity. For existing Fabs, the incremental sustainability decisions also include assessing the risks posed by installing and transitioning to any additional sets of segregated drains within the operating fab. Thorough risk assessment becomes a part of technological decisions. Decentralized solutions may be preferred in such cases.

Wet benches which have seen extensive usage in the industry for many years can be readily configured for water reuse due to the water flow path in the wet station bath. After a chemical etch, rinse or strip, the wafers are typically moved to a second bath where UPW flows upwards through the bath to rinse the wafers. Due to the flow path of the water through the bath, most of the UPW does not touch the wafers so the water passing to drain is relatively free of contaminants, making it readily suitable for reuse or reclaim with minimal treatment.

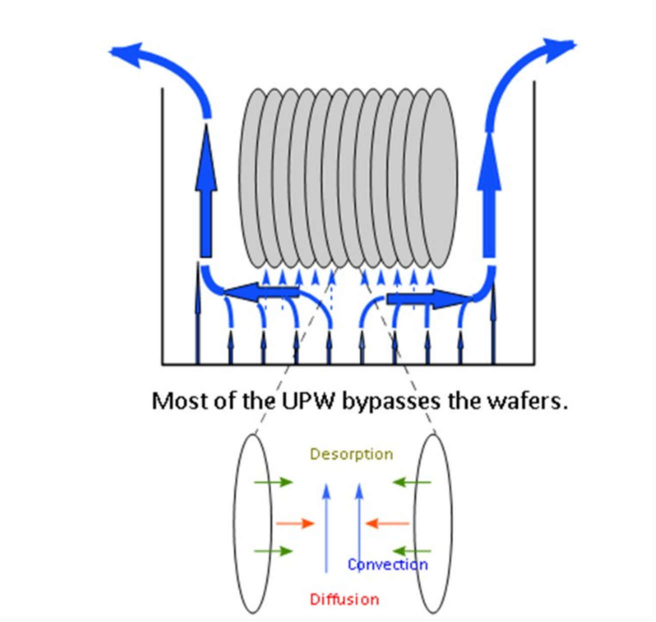
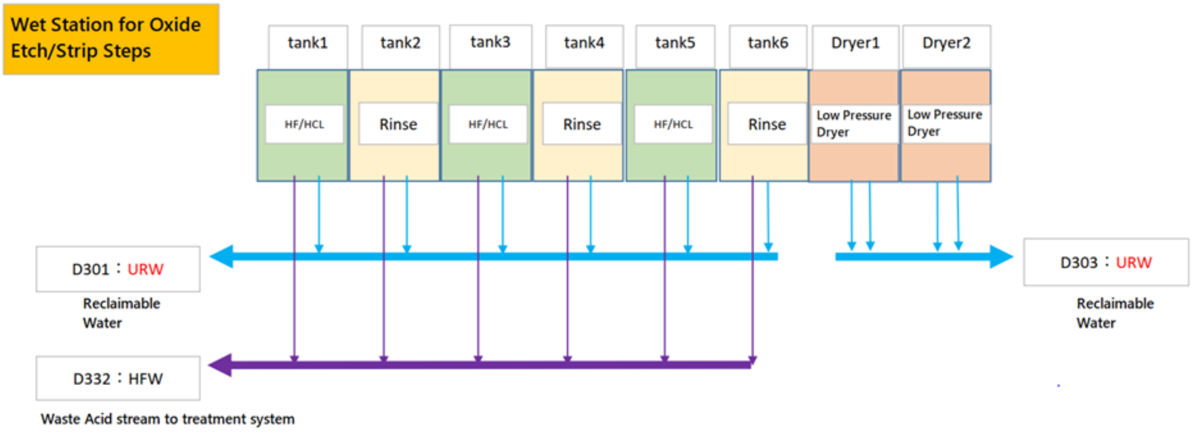


Figure ESHS-4 Schematic Showing the UPW Flow Path in a Wet Station Bath During Rinsing[6]

As a result, the rinse water from the bath can be diverted to a segregated water recovery drain after a short period. Figure ESHS-5 below shows an example drain segregation scheme on a wet station used for SiO2 layer etching or stripping. After a short rinse to the acid drain during the UPW rinse steps, the water can be diverted to a water recovery drain.



Notes: T1-2-3: main drain line is HFW, switchable to URW for bath cleans.

T2-4-6: main drain line is HFW, switchable to URW for bath cleans.

LPD: Main drain line is always URW.

Figure ESHS-5 Example Drain Segregation Scheme to Recovery Water from a Wet Etch Tool [7]

Application of the single wafer processing tools makes it difficult to reuse water unless the decisions related to the choice of the specific tool capabilities and dedicated segregated waste collection are proactively made. There are two strategies recommended for water reuse in semiconductor facility, i.e. centralized or decentralized (See SEMI F98). In the centralized approach, the main effluent waste stream is collected, treated by a centralized system, then subsequently reused. In a decentralized approach, the segregation of the waste stream is done at the tool level. Single-wafer processing chambers can dispense multiple chemistries and UPW rinses sequentially to a wafer rotating on a spin base. The various effluent coming off the rotating wafer can be collected and segregated by vertically raising/lowering the spin base relative to a splash guard that encircles the rotating wafer. This guard has layered individual drain cups connected to separated drain lines as shown in Figure ESHS-6.

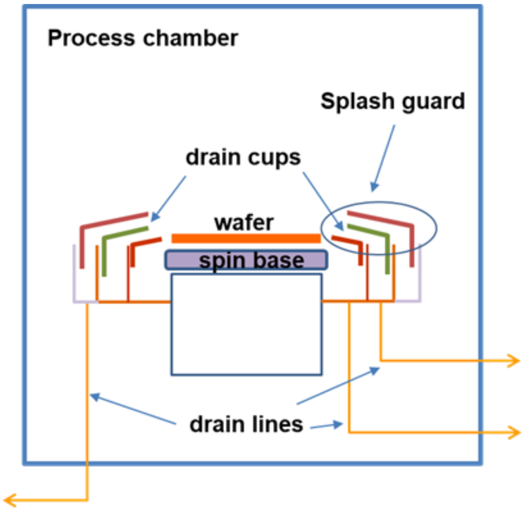


Figure ESHS-6 Schematic showing arrangement of drain cups around spin base in single-wafer processing chamber.[8]

When the process chamber is not processing wafers and in the idle state, UPW flow to the tool continues at a reduced flow to mitigate bacterial growth in the tubing to maintain tool cleanliness. This idle flow consumes a significant quantity of high-quality UPW, which could potentially be recovered and reused for other facility functions, make-up water or lower grade applications. Idle flow does not need to be continuous; only periodic flow is necessary to keep the tubing flushed. Some technology providers offer dummy dispense valves and recipes which periodically purge lines and chambers when the tool is idle; this helps to minimize the amount of idle UPW flow on a tool.

Certain aqueous process steps are performed at elevated temperatures requiring hot UPW. The UPW can be heated with a facility- or POU-supplied heater up to 80°C. Continuous flow of hot UPW is needed to maintain temperature and prevent overheating of the heating systems. When the chamber is idle, this hot UPW is often sent directly to drain. Recently, recirculated systems have been introduced which maintains a constant flow of hot UPW in a recirculation loop until needed. A schematic of this approach is shown in Figure ESHS-7.

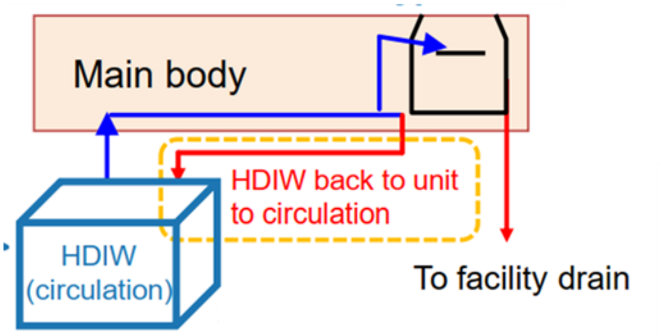


Figure ESHS-7 Hot UPW Recirculation Loop[9]

This recirculation concept is now also being deployed on ambient UPW applications where a significant amount of idle flow or bypass flow is sent to drain.

5.4. CONCENTRATED CHEMICAL WASTES

There is a concerted effort to reduce usage of chemicals at the tool level through recycling, process simplification, maintenance schedule extension, or simply chemical flow reduction. Resolve to prevent chemicals from becoming a waste in the first place is an important first step in the pursuit of long-term manufacturing sustainability.

Three categories of waste are considered in this roadmap: specialty wastes and wastewater in large quantities, hazardous wastes which are difficult to treat, and hazardous contaminants in wastewater. While each category will require a concerted approach, segregation is a critical part of the technology and suite of solutions exist for these segregated wastes.

In recent times, increased use of the following chemistries is driving need for additional segregation strategies to effectively manage them:

- Sulfuric Acid
- Phosphoric Acid
- Litho Developer (contains TMAH)
- Polar and non-polar organic solvents
- Nitric Acid
- Citric Acid

5.4.1. SPECIALTY WASTES AND WASTEWATER

Specialty wastes and wastewater are generated as part of semiconductor manufacturing or facility operations. They are either treated and reused, treated and disposed, or disposed without treatment. Common waste streams and handling methods are described below.

- HF Acid wastewater
    - May contain ozone and/or ammonia (these constituents often require additional treatment measures)

  - Treated onsite, producing calcium-based solid waste (which can be reused elsewhere outside of the semiconductor facility)[10]
- NH4-N wastewater
  - May contain hydrogen peroxide
  - Treated onsite, producing ammonium sulfate solution for offsite recycle/disposal
- Solvent wastewater
  - Contains IPA and other solvent waste (glycols, ethers, polar and non-polar photoresist, etc.)
  - May be corrosive and/or contain hydrogen peroxide
  - Collected and treated offsite
- Metal Wastewater
  - May be treated on or offsite. Solid metal may be collected for recycle (e.g. copper solid produced from concentrated waste by electrowinning)
- Concentrated sulfuric acid waste
  - May be collected in collection tanks for on or offsite reuse. Onsite reuse typically is only in waste treatment.
- Acidic or Caustic wastewater from the process or facility maintenance
  - Wastewater streams are combined and neutralized by H_2SO_4 or NaOH before discharging
- Wastewater containing suspended solids (e.g., silicon from backside grinding, SiO_2 from CMP)
  - Can be combined with acid wastewater or sent to a solids removal system with the clarified water sent for reuse
- Litho developer waste (contains TMAH)
  - May be treated on or offsite.
  - Treatment methods include biological treatment to digest the TMAH, or recovery of the TMAH in a segregated drain and treatment system for reuse offsite.
- Concentrated phosphoric acid waste
  - May be collected in collection tanks for onsite or offsite reuse. Onsite reuse typically is only as a nutrient for biological treatment.

The current state of technology describes how specific wastes are typically treated, resulting in costs and environmental impact. The technology challenges section addresses the importance of the improvement necessary for current practices driven by ESG and global environmental concerns. For example, sulfuric acid neutralization with a substantial amount of caustic and subsequent brine management implies a high energy requirement and CO_2 emission concern. This poses challenges to the conventional approach to the waste and brine management from a sustainability perspective.

5.4.2. HAZARDOUS WASTES

Industries aim to continuously improve management of hazardous substances for green manufacturing and occupational safety. Management of hazardous substances begins with full assessments of restricted substances (REACH ANNEX XVII substances, US TSCA, etc.) used in manufacturing, followed by programs to remove or reduce them and prevent introducing hazards through new materials.[11] Process adjustments (such as temperature increase), and identifying cleaner chemical alternatives are key to achieving this goal.

For hazardous wastes which are not treatable, companies will aim to remove any which can be eliminated. For example, TSMC pledged to replace 100% of NMP, and to ensure no process chemical has PFAS with more than four carbon atoms per molecule by the end of 2030.[12]. Any hazardous waste which cannot be eliminated as part of semiconductor manufacturing will be minimized and safely disposed of, typically by incineration.

In an effort to focus on challenges which need specific technological solutions, this roadmap will not consider technical solutions for chemistries which are on track for elimination.

Elimination of hazardous chemistries from the manufacturing process may have significant implications for the overall site water management. High water reuse rates of future facilities will result in generation of brine. Brine management solutions will focus on brine flow reduction and ensuring byproducts can be safely disposed into the environment.

5.4.3. HAZARDOUS CONTAMINANTS

The last category to discuss include hazardous contaminants in wastewater. These can either be treatable, such as the case with ammonium and heavy metals, or they can be not easily treatable, such as the case with azoles, a common corrosion inhibitor used in the semiconductor industry. Sites should consider a way to segregate, minimize or eliminate contaminants which risk downstream use.

5.5. WATER TREATMENT FOR RECLAMATION

Semiconductor wastewater treatment, reclaim system requirements, and configurations tended to evolve slowly and regionally for the first few decades with many of the successful practices remaining regionally known and adopted.

In the last two decades, those established regional practices and expertise have started to be slowly disseminated out into the entire global semiconductor facilities engineering community. As these regional best practices expand out into the global facilities design community, the industry is beginning to see some very well-defined sets of industry best practices.

There are many ways to design and build a water treatment system with a water reuse objective, but they all have one thing in common: each solution is a compilation consisting of a limited number of selected unit operations in series. These few unit operations will have been selected by the facility owner or the solution provider from the vast array of available technologies and devices from a diverse group of component providers.

Unit operations installed within the semiconductor wastewater treatment and reclamation systems typically include some of the following technologies:

- Separation: clarification, media filtration, micro-, nano- and ultrafiltration, reverse osmosis, electrodialysis, ion exchange, degasification, thermal distillation, crystallization, filter-press, centrifuge, etc.
- Oxidation – chlorination, ozonation, advanced oxidation, photolysis, catalysis, etc.
- Adsorption – activated carbon, zeolite, or other media.
- Absorption – absorption columns or scrubbers
- Biological – activated sludge (Membrane Bioreactor Reactor or conventional), anaerobic solvent or sludge digestion, bio-polishers (often using activated carbon or other adsorption media), moving bed bioreactors, etc.

Due to complexity of the technology choices in the context of preferred segregation strategy, the robust solution needs to take into consideration numerous factors and expertise involved.

The ability to collect and consolidate validated information in the form suitable for interpretation and decision making will impact the quality of the data available when decisions need to be made.

Further information about semiconductor wastewater Drain Segregation, treatment assessments, and related reclaim systems and programs can also be found in SEMI F98 and F116.

5.6. COOLING TOWER

Cooling towers are the single largest loss of the water from semiconductor manufacturing site.

Heat transfer to the environment utilizing cooling tower for a typical semiconductor factory is variable based on environmental conditions such as temperature and humidity. Water emission rate can reach billions of gallons per year per manufacturing site.

While evaporative losses in cooling towers are critical for environmental sustainability performance, the system provides an opportunity for the reclaim water reuse allowing for the effective site water management and reduction of water treatment chemicals.

Cooling tower drift reduction is important to minimize “non-beneficial losses”. Cooling tower type selection is an important consideration: direct contact, open evaporation, indirect contact, or closed circuit evaporative type towers can significantly change the water consumption depending upon local site conditions.

5.7. WASTEWATER METROLOGY

Fab wastewater treatment and reclaim metrology can be best considered through the two primary areas of concern which are both essential to the effective protection, performance and control of the wastewater treatment and reclaim systems. :

The influent monitoring program (influent is defined as feed to the water/wastewater treatment system).

- The effluent monitoring program (effluent is defined as product of fab operation or product of wastewater treatment/reclamation system).

An effective influent/effluent monitoring program serves to protect the water reclaim systems from encountering contaminant concentrations or operating conditions which exceed the reclaim system design limits and which might jeopardize the treatment system operations or cause undue harm to, or a premature failure in, the treatment system equipment.

The influent monitoring program will include four important aspects:

- Initial Assessments,
- On-line Monitoring,
- Off-line Measurements, and
- A steadfast and campus-wide Management of Change program.

If any of these four reclaim program facets are missing from a high-recovery water sustainability program, overall quality and stability of the reclaimed water could be put at increased risk.

The influent monitoring package will typically include several of each of the following instruments:

- Conductivity and pH
- Organics – Rapid response TOC analyzer and organic speciation by LC-OCD
- Oxidizers – Oxidation Reduction Potential (ORP) monitor or residual oxidizer colorimetric
- Solids – Turbidity monitor
- Ions – as needed for site-specific concerns, such as for: Hardness, Alkalinity, Fluoride or Copper
- Grab Samples – Site-specific sampling program (for trend analysis or triggering influent reassessments)

The output from the first set of these instruments is used by the water treatment system controls to make the ‘accept or divert’ decisions needed to manage any potential influent excursions. This first instrumentation package diverts out of spec water which could affect the stability or performance of the reclaim systems. Those diverted flows can then be separately captured, managed, or discharged as needed.

As the accepted influent water passes through the treatment systems purification steps, several more of those same instruments will be needed to monitor the efficacy and performance of each purification unit operation within the reclaim system, especially where such performance results or operational conditions might adversely impact the effective control of the treatment system and the reclaim water quality.

An effective effluent monitoring program is essential for two key purposes:

1. Making decisions or controlling wastewater segregation
2. Validating the efficacy of the treatment processes and the documenting the quality of the recovered water streams.

The effluent monitoring systems will be very similar to the influent monitoring system with the exception that the effluent monitors will most likely be 2-3 orders of magnitude more sensitive to ensure confidence in the suitability for reuse of the reclaimed water, optimize the efficacy and efficiency or the treatment processes and minimize the risk of excursions which might otherwise cause harm to the downstream water users.

The reuse water monitoring package will typically include the following:

- Conductivity and pH
- Organics – Low Range TOC analyzer and organic speciation by LC-OCD
- Oxidizers – Residual oxidizer colorimetric
- Solids – Laser Particle Counter
- Specific Ions – Likely Sodium, Silica, Boron
- Grab Samples – Site-specific grab sample program (for non-monitored elements)

Further information related to the instruments most frequently utilized within semiconductor wastewater treatment and reclaim systems and programs is available within SEMI F61, F63, F75, F98 and F116.

5.8. DATA MANAGEMENT

Modern semiconductor manufacturing facilities collect a substantial amount of data through Facility Monitoring Systems (FMS) for process control, as well as offline analytical data from grab samples. The volume of data collected presents a significant opportunity for the industry to make informed decisions and a significant amount of time and effort is invested in compiling and analyzing the data by different teams. New fault detection and diagnostics (FDD) "smart" software allows for identification of inefficiency in equipment as well as smart sequencing of multiple equipment sets e.g. chillers in a chiller plant.

Despite an overwhelming volume of data, deficiencies exist which prevent making data-driven decisions in a timely and efficient manner. Data required for water management is often owned and processed by multiple individual teams within a company, and often this data is not shared between groups. This can lead to either sub-optimal decisions being made due to incomplete or inaccurate information, or delays in the decision-making process due to not having the data quickly enough when needed. This is particularly problematic for sitewide projects where data is compiled from multiple sources.

In view of the foregoing, the existing strategies for data management are inadequate for the rapidly changing needs of the industry.

6. WATER AND ENERGY MODELS

Historically, water and energy conservation have been managed as two separate efforts. However, to ensure that an optimal solution is developed, water and energy conservation need to be collaborative efforts to ensure that an optimal, balanced solution is achieved. The models developed to support the IRDS roadmap are the result of a collaborative effort between water and energy conservation experts in the industry.

6.1. WATER MODEL

The water model has been developed to depict a logic semiconductor factory which has a significantly higher water and chemical intensity than memory factories. This model builds on the work that has already been done in SEMI F-98 which defines strategies for water management and conservation in the semiconductor industry. Using the water map developed in SEMI F-98, a representative water usage model has been developed to depict how water is used in a factory.

The model is a cloud-based digital twin of a factory and is laid out as a mass-balance based process flow diagram depicting the various users and unit operations in a semiconductor factory water system. The water model map is shown in Figure ESHS-8 and represents a 300 mm facility with a net manufacturing area (NMA) of 19,000 m^2. This represents the smallest possible 300 mm facility.

The focus of the roadmap gap/risk analysis is on technology capability. This means that independently if Publicly Owned Treatment Works (POTW) exists or not, the overall scheme should include capable wastewater treatment and reclamation set-up. This means that to meet aggressive water reuse goals the wastewater can be treated either internally or externally to the site with the effluent reused back to semiconductor site applications. As a result, the final outfall was considered for discharge to a natural water body, such as river, lake, sea, ocean, or aquifer. Natural water body discharge limits were compared to projected site outfall composition to identify compliance risks which will need a technical solution (see Appendix D).

Key water system unit operations include:

1. Water purification systems for water used in the process
2. Water reclamation systems
3. Wastewater treatment systems
4. End of pipe wastewater treatment and water recovery

Key factory water users include:

1. Wafer manufacturing process (fab)

2. Abatement systems to remove gaseous pollutants
3. Cooling tower makeup water (making up evaporative cooling losses)

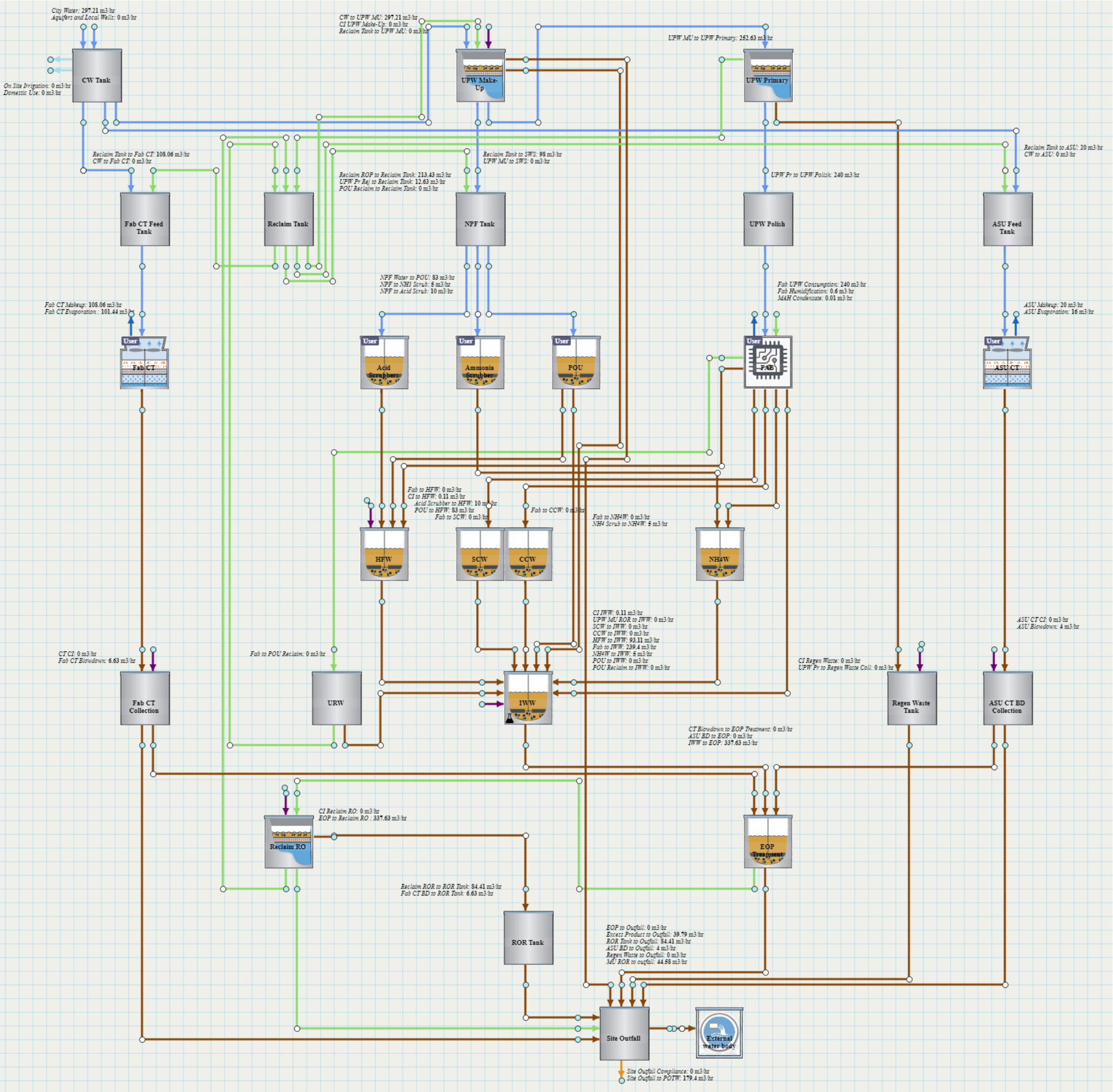


Figure ESHS-8 IRDS Water Management Application Model

See Appendix B. for IRDS Water Model key assumptions.

6.2. ENERGY MODEL

The energy model has been developed as a tool and facility system-based energy balance to depict a representative semiconductor factory. Modeling energy usage is highly complex and requires a detailed understanding of how factory tools and the facility systems supplying them operate.

The model starts with the energy and utility use of the manufacturing equipment and the associated support equipment, such as vacuum pumps and local exhaust abatement.

Energy usage coefficients have been defined for the various facilities systems by breaking them down into major components and their respective energy and utility use. This, in addition to the power and utility demand for the manufacturing equipment, allows an energy usage intensity (kWh/m^2 and kWh/wafer) to be calculated for a factory of given net manufacturing area and wafer output. The correlation between wafer output and net manufacturing area is based on input from the Facility section of the Factory Integration Chapter of IRDS.. Key inputs to the model include:

- Wafer throughput
- Tool power and utility demand
- Cleanroom area and energy consumed for recirculation air flow, temperature and humidity control, and make-up air
- UPW demand – ambient UPW and Hot UPW
- Wastewater treatment and UPW recycling/reuse as well as process water use
- Brine management and treatment
- Heat balance, process and facility cooling water loads
- Exhaust demand from process and facilities including chemicals and gases
- Nitrogen demand and energy/utilities for generating Nitrogen and purifying other bulk gases
- Compressed air demand
- Chiller and cooling tower loads
- Hot water, heating demand and heat recovery applications
- Natural Gas and other fossil fuels for Local Abatement Units, Oxidation of Volatile Organic Compounds (VOCs) and heating purposes

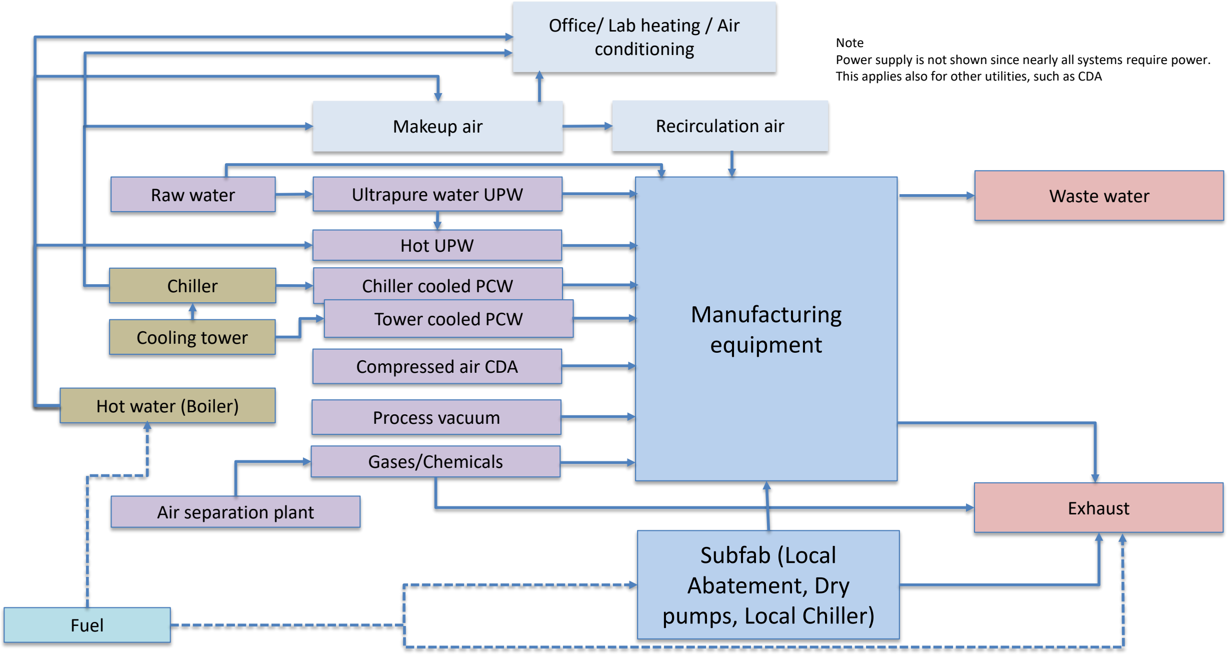


Figure ESHS-9 Factory Energy Balance Model. Source: IRDS Energy Model (see Appendix)

The inputs to the model again highlight the importance of a collaborative effort between water and energy management teams as an understanding of the factory water demands and system setup is a crucial component to characterize factory energy usage and ensuring that solutions developed to reduce energy usage properly account for the effect on factory water usage.

Key Considerations on the Energy Model

- All major facility and infrastructure systems have been considered with the model.
- It starts with the subfab where significant amount of energy is consumed for removal and treatment of the process gases and liquids, the thermal management of processes (both heating as well as cooling). The system needs to consider the balance between emissions and energy consumption to abate these gases.
- The impact of energy losses from inefficient operation of the facility systems are not covered in detail. General good practices such as green building codes or LEED ™ shall be applied.
- The ECF for power is considering the transformer losses. It is assumed that power correction systems are implemented and optimized.
- The energy needed for lighting is considered in the cleanroom section, also the use of LED is now a minimum expectation and use of occupancy and light level control considered good practice and shall be implemented wherever feasible and economically viable to extend the life of the LED fixtures.
- In the cleanroom and HVAC section both the manufacturing requirements (filter coverage, temperature, humidity control as well as contamination control requirements) are considered, e.g., overpressure. The make-up air quantity is driven by the exhaust requirements. Major improvements are possible with exhaust recycling and the minimalization of the make-up air reheating.
- Cleanroom & HVAC energy efficiency is impacted by the environmental conditions, as well as certain design decisions, such as heat recovery, direct cooling, and choice of dehumidification system. Alternate dehumidification technology such as the use of desiccant technology is starting to get consideration by some companies, but contamination and reliability concerns have so far delayed far reaching adoption.
- The fab water systems (UPW and hot UPW for process use, and softened water for abatement) are major energy users. Understanding the achievable energy efficiency requires a general water balance, which need to include the systems for recycling and reuse, the water supply to the cooling towers as well as other secondary water users such as local and central exhaust abatement systems, humidification/air washing for AMC control and others. The close linkage between Energy and Water usage demonstrates the importance of the Water and Energy teams collaborating closely to develop a representative model.

7. FRAMEWORK OF TECHNOLOGY ROADMAP

7.1. BOUNDARIES

Boundaries for site water management are typically well defined. System owners are aware of performance and capacity constraints of internal infrastructure. External capacity and local environmental compliance requirements are generally well established and understood.

Sometimes, industries can play a role in establishing boundaries with the local municipality, and accurate projected discharge loads are necessary. Providing this information to a municipality requires accurate modeling (flow and chemistry) and strategy selection. An informed approach to this situation is vital to enable new development.

7.2. DRIVERS

Facilities are balancing ESG (environmental, social, governance) commitments with the effects of climate change, increasing complexity of technology and a significant increase in demand for advanced semiconductor products. These factors are driving rising costs and diminishing resources which need to be accounted for by the company as it sets priorities and goals. The relative priorities and implications between drivers are not typically well understood (and stakeholders may not agree upon priorities). Establishing driver priority as part of a decision framework helps program owners make and justify decisions that best align with the company's long-term goals.

Water and energy usage drivers are changing, with sustainability concerns increasingly being viewed as technology enabling due to the scarcity of water supply, cost pressures and increased water and energy intensity of the semiconductor wafer manufacturing process. Due to its higher water usage, Logic is and will likely continue to be the leading driver for water management and conservation efforts in the future. Logic has a higher water and chemical intensity for the following reasons:

- It has tighter pitch size than that of other types of semiconductor products

- Advanced Flash manufacturing is transitioning to 3D structure where the pitch equivalent is almost an order of magnitude larger than that of Logic
- Logic has significantly more metal layers and higher complexity, increasing risks to yield
- Logic has less redundancy compared to Flash memory

All these factors drive considerably more water usage per wafer on Logic processes.

The key drivers on the energy side are also the complexity of the process (3D structures), which require more energy intensive process steps such as lithography, deposition and etch.

The transition to EUV lithography may initially increase the energy consumption per mask step substantially. But on the other hand, it reduces process complexity, such as the need for multiple patterning. This reduces the amount of water, chemicals and (above a certain productivity of EUV lithography tools) the integral energy needed in the process. The long-term effects of EUV on the energy intensity of the process will be better understood as more device manufacturers incorporate EUV lithography, and as progressively more layers in the process adopt this lithography technique instead of traditional Deep UV (DUV).

In production and related production support in the subfab enormous efforts have been undertaken to improve energy efficiencies, by using more efficient components, internal recycling and reuse of materials and heat by improving the overall process and process support efficiency.

The following areas are the mission critical drivers for water and energy management in Logic processes. Together, these are combining to create a perfect storm for the industry and urgent action is needed to address these challenges:

Table ESHS-1 Key Drivers for Water and Energy Management

Key Driver	**Why Important**
Semiconductor Technologies	To meet performance demands of the semiconductor market, the transistor size is reducing, and device complexity is increasing with every generation of technology. To meet the performance characteristics required, some layers on the device are now only several atoms in thickness, and innovative methods are needed to achieve the required transistor density on the chip. This is driving the industry to explore new methods, new device architectures and new materials as the limitations of traditional silicon-based materials and planar device structures are reached. **Impact:** These new materials and manufacturing methods are causing the energy, chemical and water intensity of the process to progressively increase with each technology generation.
New Materials	As the transistor size gets smaller with each technology generation, this pushes the device closer to the limits of materials traditionally used in the device structure. This has driven the industry to innovate with new materials to alleviate issues such as electromigration or charge leakage. These new materials introduce new contaminants into the wastewater which need to be understood and dealt with as these can impact compliance or the ability to treat and reuse factory wastewater. The addition of new material processing steps can also drive additional rinsing and cleaning steps which increases the UPW demand of the process.
Process/Tool Changes (i.e., EUV)	The reducing transistor size and more complex structure means that the industry is reaching the limits of what can be achieved using traditional lithography pattern masking. This is particularly problematic in the contact to gate area of the device where the structures are very complex and, in many cases, only several atoms thick. There are two ways to deal with these challenges: 1. Multi-patterning- masking and developing one part of the layer, then bringing the wafer back and developing subsequent parts of the same layer. This adds significant additional processing, with more water, energy and chemical usage required per layer and increasing the amount of freshwater and chemical demand for the process. 2. Extreme Ultraviolet Lithography (EUV) allows the complex patterns to be manufactured in fewer steps than traditional lithography, but EUV is very energy intensive, driving additional evaporative cooling loads which increases site water demand, and it also requires large amounts of hydrogen which is costly and very energy-intensive to produce. Introduction of EUV can reduce multi-patterning if compared with realizing same feature size by immersion DUV lithography. Further advancement of feature size shrinking,

Key Driver	**Why Important**
	however, can require multi EUV patterning. Effect of EUV on energy demand is currently under detailed review together with the Lithography IFT.
Many more process steps	As the industry moves away from the traditional planar devices structure and more 3D structures (e.g., Fin-FET, gate-all-around) are introduced to achieve the required transistor density on the device, this drives significantly more masking, deposition, etching and polishing steps for each wafer. This means that progressively more tools and cleanroom area are needed to support a given number of wafer starts, which drives more water, energy, and chemical demand.
Growing facility complexity and size	All the above factors drive a larger and more complex facility, as more tools and cleanroom are needed to support the required wafer output, more UPW is needed to support the process, more wastewater needs to be treated and additional wastewater segregation and treatment is needed to support the new materials needed for the new process technologies. In addition, process cooling demand is growing with each technology, driving more chiller plant capacity.
ESG – Corporate Sustainability	Whereas previously sustainability initiatives were deemed to be "nice to haves" or good for a company's public relations, sustainability concerns are increasingly being viewed as technology enabling due to the scarcity of water supply, cost pressures and increased water and energy intensity of the semiconductor wafer manufacturing process. In addition, the upcoming generation of consumers is paying close attention to the environmental footprint of the products they purchase. Semiconductor companies are therefore spending increasing amounts of time and effort marketing the environmental footprint of their products whereas previously performance of the chip was the only meaningful metric. **Impact:** ESG is now a core enabler for future semiconductor industry growth.
Water demand reduction	Water has increasingly been described as "the new oil", with up to 40% of the world's population facing water scarcity by 2035.[13] Driving down the water demand from the watershed is therefore a critical consideration to improve the semiconductor industry's environmental footprint. Water is either used directly on the wafer as a rinsing medium (UPW) or is used for cooling and abatement. The following have been identified as key focus areas to reduce water demand: 1. Reduce freshwater consumption (both in the process and in cooling and abatement) 2. Reduce evaporative cooling demands. Primarily this is driven by the factory's energy usage and is being addressed by the IRDS energy reduction roadmap, but opportunities to make the water purification and treatment systems more energy efficient to reduce their energy footprint. 3. Reduce non beneficial usage for process water- as discussed in Section 5.3, tools have idle flow purges or dummy dispense recipes for particle or bacteria excursion control, and the water is cycled to drain without touching the wafer. Reducing this non beneficial flow, or recovering it for reuse, is a key opportunity and focus area for the industry.
Water reuse	In addition to water reduction, water reuse (either reclaiming rinse water or wastewater internally or exploring reclaim water from external sources) is a key enabler to reduce the semiconductor industry's freshwater demand and enable future growth. As non-process use now comprises about half of a semiconductor facility's water demand, feeding these non-process users (cooling water and abatement) from reuse sources presents a low-risk opportunity to reduce a facility's water demand. In addition, several facilities and organizations have successfully recycled water to the front end of the UPW system in the past; [14], [15],[16], [17], [18] wider adoption of wastewater recycle to UPW presents another opportunity for the industry to reduce freshwater demand
CO_2 emission	In addition to water scarcity, greenhouse gas emissions are becoming an increasingly urgent issue for the industry to address, with the UN stating that even if carbon neutrality is achieved by 2050, we are on track to warm the planet by 1.5°C from pre-industrial times.[19] Efforts of the industry to do their part in achieving this goal will come under greater scrutiny from consumers, governmental organizations, and environmental groups. The IRDS energy reduction roadmap is key to addressing this concern. There is still considerable

Key Driver	**Why Important**
	energy saving potential in the central thermal management systems from implementing heat recovery solutions and using more energy efficient cooling methods. Other important Net Zero strategies such electrification of heat and the replacement of fossil fuels with green energy or green fuels, such as green hydrogen, will be of increasing importance in the coming years. Whilst CO_2 emissions are primarily driven by the facility's energy usage and are being addressed by the IRDS energy reduction roadmap, opportunities also exist to make the water purification and treatment systems more energy efficient, reducing their energy footprint and CO_2 emissions as a result. A key focus area is brine management which is becoming a key consideration due to the increasing amounts of acid used in semiconductor wet etch operations. Semiconductor facilities are being increasingly driven to manage and treat their brine streams onsite as they become more concentrated; this process is typically very energy intensive and is a key focus area for future improvement to reduce energy usage and the resulting CO_2 emissions.
Wastewater pollution	As the process becomes more complex, in addition to more water and more energy, more chemistry is needed as the quantity of process steps increases. This results in additional or more intensive treatment of the wastewater. In the past, much of the wastewater could be discharged or reused with minimal treatment, but as contaminant concentration increases, this drives more treatment steps to produce a stream that either meets compliance limits for discharge or is suitable for reuse or recycle. This results in an increase in the energy footprint of the facility and may reduce the amount of water available for reuse, as well as resulting in brine streams and other segregated hazardous waste streams that need to be managed and treated.
Climate Change	Climate change considerations are closely linked to ESG, with the potential impact of the semiconductor companies on the ecosystem and water shortages being exacerbated by warming climate conditions which have been discussed previously. Two examples of recent headline grabbing events highlight the challenge the industry faces: 1. Colorado River Basin water shortages: Much media attention has been directed to the aridification being witnessed in the Southwestern region of the United States of America and the impact on the Colorado River basin in particular. Images of the dramatic reduction in the water level in Lake Mead starkly bring this issue into focus.[20] With the semiconductor industry expanding its already significant presence in areas fed by the Colorado River basin with major new factory construction or expansions underway in Phoenix, AZ and Albuquerque, NM, the industry urgently needs to address water management challenges as the effects of climate change are biting deeper. 2. Taiwan droughts: severe droughts in Taiwan during 2020 and 2021, due the island only receiving 30% of its normal annual rainfall, came close to bring TSMC's factory production to a halt, with emergency measures having to be enacted to ensure the factory water supply could be maintained including a 15% reduction in its water usage.[21] However, the issue goes beyond water scarcity. As climate change drives more extremes in temperature, this is putting additional pressure on factory water and energy infrastructure due to increased heating and cooling demands to cope with these extremes. The impacts of these changes need to be understood and steps taken to increase water and energy efficiency. **Impact:** The industry needs to proactively address the effects of changing climate on their facility operations and explore ways to make the facilities more water and energy efficient, thus reducing risk of being impacted by future climate events whilst enabling sustainable expansion of the facilities.
Chip Demand	Against a backdrop of water scarcity, changing climate and increasing complexity, increasing chip demand is putting additional pressure on facilities and infrastructure. Semiconductors are finding use in more and more applications, with the automotive industry being a key driver as more computing functionality is needed to manage the various drive, environmental and entertainment systems in modern day vehicles. The growth of electric vehicles presents a particular challenge, with a typical EV requiring double the number of chips typically used in a vehicle with an internal

Key Driver	Why Important
	combustion engine.[22] The demand increase drives larger factories to meet the higher wafer demand, which in turn places more pressure on internal and external infrastructure to meet the resultant increase in water and energy demand. Finding water and energy management solutions is therefore critical to ensure that this increased product demand can be met in a sustainable manner, as well as making sure that the facilities are right sized to cope with current and projected future demands.

7.3. CONSIDERATIONS

Facility engineers and directors are challenged to make decisions that withstand the test of time, and therefore the question must be asked:

"How do we ensure our facilities are sustainable?"

It is important for sites to understand implications of the increased device complexity that comes with each new technology generation, along with the changes driven by the increased prevalence of heterogeneous integration.

- New generations of technologies imply changes to UPW demand, process chemistry, process steps and layout, along with heat loads and their respective evaporation rates.
- Heterogeneous integration implies more comingling of wastewater from front-end and back-end processes, which creates more challenges to water treatment operations and potentially impacts availability and quality of water available for reuse.

While considering established and future infrastructure, it is therefore important to develop and design systems which can be adapted as necessary to meet the needs of future technologies.

7.4. KEY PERFORMANCE INDICATORS (KPIS)

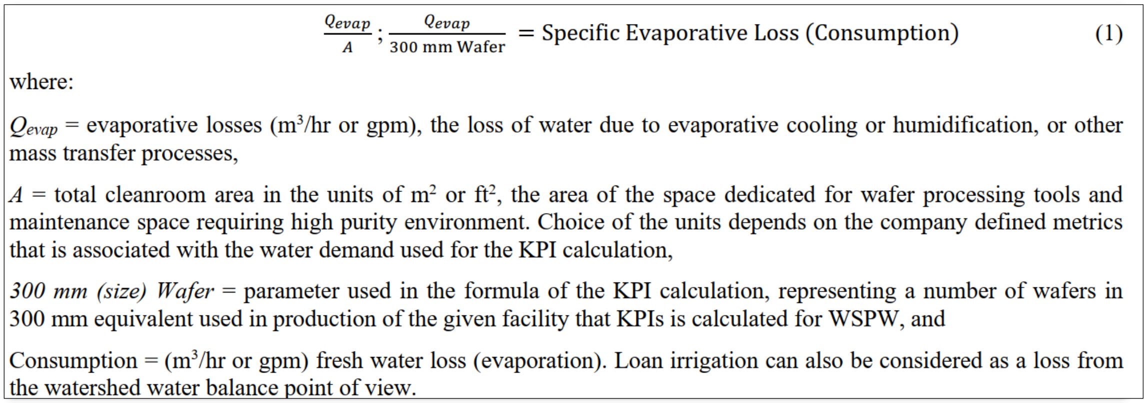
7.4.1. WATER USAGE AND EFFICIENCY KPIS

Key performance indicators have been developed by the industry for water usage and these are defined in SEMI F98. These allow companies to objectively measure their water usage and conservation against industry benchmarks and enable transparent communication of water usage, conservation, and reuse. This document uses these KPIs as a starting point for the IRDS projections, refining them as needed to provide consistency and developing a roadmap for the industry to achieve specific water conservation and reuse targets. The indicators support three primary concepts of water management: reduction, reuse, and recycling to reduce environmental impact.

7.4.1.1. TYPE 1- NORMALIZED WATER USAGE & CONSUMPTION

KPI 1 – Water Evaporative Losses

KPI-1 addresses the water loss due to evaporative cooling. This is water dispersed to the environment as evaporative losses. Reduction of losses to the environment will be managed through reduction of factory energy demand, heat reclamation technology, and outlet condensate reclamation.



$$\frac{Q_{evap}}{A};\frac{Q_{evap}}{\text{300 mm Wafer}} = \text{Specific Evaporative Loss (Consumption)} \qquad (1)$$

where:

Q_{evap} = evaporative losses (m^3/hr or gpm), the loss of water due to evaporative cooling or humidification, or other mass transfer processes,

A = total cleanroom area in the units of m^2 or ft^2, the area of the space dedicated for wafer processing tools and maintenance space requiring high purity environment. Choice of the units depends on the company defined metrics that is associated with the water demand used for the KPI calculation,

300 mm (size) Wafer = parameter used in the formula of the KPI calculation, representing a number of wafers in 300 mm equivalent used in production of the given facility that KPIs is calculated for WSPW, and

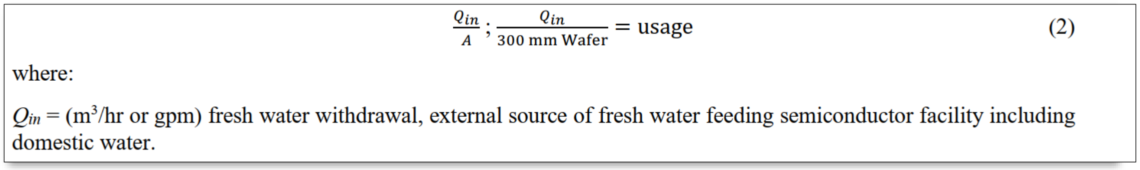
Consumption = (m^3/hr or gpm) fresh water loss (evaporation). Loan irrigation can also be considered as a loss from the watershed water balance point of view.

Figure ESHS-10 SEMI Water Evaporative Loss KPI. Equation #1[23]

Note: Equation 1 above lists two similar indicators separated with semicolon (1st evaporative loss per cleanroom area and the other is the loss per 300-wafer produced).

KPI 2 – Water Usage

KPI-2 deals with the freshwater demand: City, rivers, streams, lakes, reservoirs, springs, aquifer and or ground water.



$$\frac{Q_{in}}{A};\frac{Q_{in}}{\text{300 mm Wafer}} = \text{usage} \qquad (2)$$

where:

Q_{in} = (m^3/hr or gpm) fresh water withdrawal, external source of fresh water feeding semiconductor facility including domestic water.

Figure ESHS-11 SEMI Water Usage KPI. Equation #2[24]

Note: Equation 2 above lists two similar indicators separated with semicolon (1st freshwater withdrawal per cleanroom area and the other is freshwater withdrawal per 300-wafer produced).

This KPI is utilized as the baseline for water conservation in either of two ways.

1. Reuse through water recycling and downcycling reducing effluent stream losses
2. Reduction of process (UPW, etc.) and non-process use (Cooling towers, waste dilution, Scrubber, and facility demands). Reduction of water and energy reduction in these use cases reduces net operations cost.

7.4.1.2. TYPE 2- WATER CONSERVATION

KPI 3 – Reuse Efficiency

The reclaim efficiency indictor sets out how much of the overall water usage at the factory is accounted for by reuse or reclaim water.

$$R = \frac{Q_D - Q_{IN}}{TACO} \times 100\% - reclaim\ efficiency \qquad (3)$$

where:

$TACO = Q_D + Q_{MAH} - Q_{EVAP} - Q_{MBDF}.$

NOTE 5: TACO is a quantitative indicator, providing a flowrate-based reference to available reuse potential.

Q_D = total industrial demand of the water systems supporting process and non-process industrial usage, including both fresh water and reclaim demand. This does not include site irrigation and domestic freshwater consumption,

Q_{MAH} = makeup air handler condensate flowrate (m^3/hr or gpm), the total flowrate of water that is condensed in all air handling units used on site, and

Q_{MBDF} = minimum brine disposal flowrate (m^3/hr or gpm), the lowest possible discharge from the site within the boundaries of the economics, rational energy use, and environmental compliance. Under certain condition and changes implemented, this parameter may change.

Figure ESHS-12 SEMI Reclaim Efficiency. Equation #3[25]

Whilst the usage and consumption KPIs are straightforward to use and are already being applied by the industry. However, Q_{MBDF} factor is supposed to be site or company specific parameter making it impossible to benchmark usage in the industry. The water reclaim efficiency indicator needs to be more intuitive, with users able to calculate the TACO (Total Available Conservation Opportunity) term in the formula with no subjective parameter included. The IRDS roadmap applies this indicator with no Q_{MBDF} factor.

In addition to the KPIs laid out in SEMI F98 standard, it is proposed to add the following KPIs to the water management roadmap to address specific water management challenges:

Table ESHS-2 Additional KPIs and Relevance

Additional KPIs	**Relevance**
Non-Beneficial Process UPW Usage	As discussed in Section 5.3, tools have idle flow purges or dummy dispense recipes for particle or bacteria excursion control, and the water is cycled to drain without touching the wafer. This comprises up to 35% of the facility UPW demand, so reducing this non beneficial flow, or recovering it for reuse, is a key opportunity and focus area for the industry. A KPI has been added to allow companies and vendors to benchmark and target this flow for their tools and processes for reduction or reclaim.
Hazardous Waste Generation	With the complexity of each successive technology increasing and transistor sizes getting smaller, in addition to more water and more energy, more chemistry is needed as the quantity of process steps (deposition, plating, polishing, etching, masking) increases. As well as driving more intensive treatment of the wastewater to render it suitable for reclaim or discharge, it also drives progressively more segregation of chemical waste to allow most of the wastewater to be treated and recovered. A KPI has been added to facilitate tracking of the amount of hazardous waste generated with each technology generation which will drive exploring better strategies to handle and treat these wastes, as well as exploring ways to reduce usage of these chemistries.

7.4.1.3. ADDITIONAL CONSIDERATIONS

Cost of Ownership

Cost of ownership of facility systems is considered non-constraining factor for future fab sustainability. However, when defining the technology needs, cost consideration is relevant as it is going to make solution adoption faster and broader.

Financially the impact of free use of water without reduction, reuse, or recycle increases cost of production. Consideration of cost profile may focus key related figures.

$$Product\ savings = \frac{C_{in}Q_D + C_{sew}Q_{sew} - C_{treat}Q_{treat} + C_{reclaim}Q_{reclaim} + C_{cap}}{n * A_{tech}}$$

Figure ESHS-13 Cost of ownership Equation #4[26]

Q_D, Total demand from facility to manufacture at product level.

C_{in}, cost fresh water supply

Q_{sew}, Total effluent waste to sewer.

C_{sew}, Cost of sewer fee to send to local municipality

C_{treat}, Cost of treatment

$Q_{reclaim}$ Reclamation or reduction in usage.

$C_{reclaim}$ Reduction or cost avoidance reducing the demand of system with intelligent controls or lowered total demand rate.

C_{cap}, Cost of capital reduction

Normalizing Water Consumption and Conservation

Normalizing water consumption and Conservation with the following methodology is recommended to create clear benchmarks to measure year over year water conservation.

Normalization should be connected to technology and use case to evaluate conservation benchmarks as water and energy intensity typically change from one technology to the next. This is typically driven by the number of layers; as the transistor gets smaller and more complex, the number of process layers increases, driving the need for more tools. With more tools, water and energy demand increases. For example, an 800-layer technology could drive double the demand of a 400-layer technology.

Normalized water consumption for production

$$\frac{Q_{evap}}{n * A_{tech}} = Evaporative\ loss\ per\ wafer\ (consumption)$$

Figure ESHS-14 Normalized Evaporative loss Equation #5

Q_{evap}, cooling and humidification water demand (m^3/hr or gpm) supplied to enable technology production.

A_{tech}, technology cleanroom area (m^2 or ft^2) the total area of the manufacturing dedicated to processing tools and maintenance requiring manufacturing space.

n, total net product estimated in flight estimated from yearly production for facility per square foot

Consumption, water loss from flow stream in (m^3/hr or gpm); multiple factors could apply (humidification, cooling towers, office facility potable water, lawn watering) all are considered as part of the cost of business and water consumption.

Normalized water demand

$$\frac{Q_{in}}{n * A_{tech}} = Usage$$

Figure ESHS-15 Normalized Water Demand Equation #6

Q_{in}, inlet water sources of fresh water of Q_{in} could consider (municipality, well, rain, remote shipped)

Total Available Conservation

Total available conservation (T) assessable by unit areas in factory communicates environmental and economic scaling factors for performance evaluation and are broken into multiple categories:

$$T = Q_D + Q_{MAH} + Q_K - Q_{EVAP}$$

Figure ESHS-16 TACO Equation #7

Q_D Total demand from facility to manufacture at product level.

Q_{MAH} Makeup air handler condensate flowrate (m^3/hr or gpm), the total flowrate of water that is condensed in all air handling units used on site.

Q_K Total of collected site containment water returned to front end of unit process source consideration: chemical mixture water reclaim, site containment collection.

Note: At the time of publication of this chapter SEMI Water Reuse Committee is balloting the change is SEMI F98 guide to remove Qmbdf from TACO.

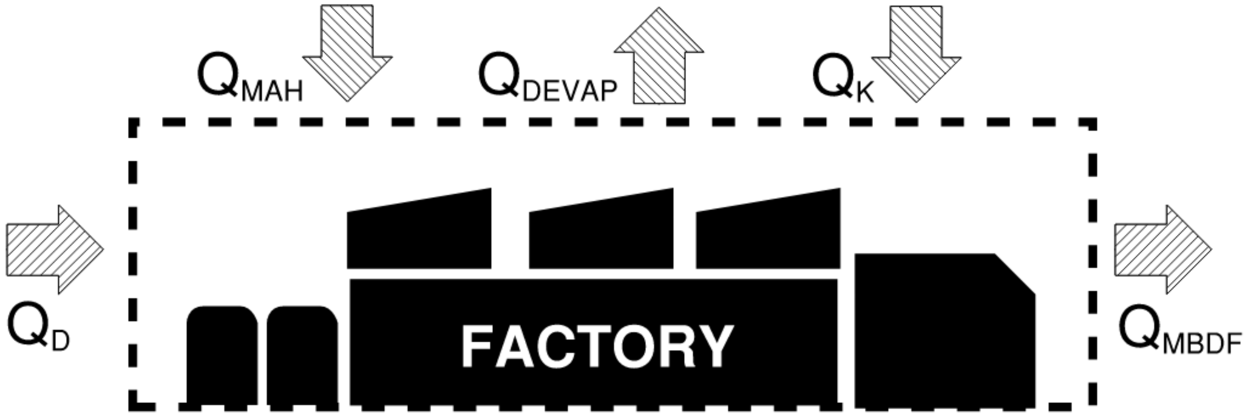


Figure ESHS-17 Process flow diagram of inlet and outlet factors

7.4.2. ENERGY EFFICIENCY KPIS

Key performance factors regarding energy efficiency need to be split in groups:

1. KPI for Manufacturing equipment: Energy and utility consumption is recipe dependent and at this point is difficult to develop. A general reduction roadmap has been proposed where key factory process is indicated.

2. KPI for key process support systems, such as vacuum pumps, local abatement and chillers: Also depend very much on processes, but a general reduction roadmap can also be provided including concepts, how energy efficiency can be improved
3. KPI for process utility and facility infrastructure systems: Detailed KPIs can be developed, but they depend still on climatic conditions and engineering decisions, equipment configurations driven by other considerations. Therefore, on one hand a reference fab has been chosen with a 19,000 m2 net manufacturing area in Chandler, Arizona and on the other hand the model allows each individual user to adopt the parameters based on their respective boundary conditions.

7.5. TARGETS

This year's roadmap effort conducted extensive analysis of the current water and energy usage intensity of the current leading-edge Logic process, as well as key drivers impacting sustainable future growth. New water usage targets have been developed based on these drivers, and sustainability goals for water and energy reductions.

Roadmap tables have been developed for both water and energy usage to drive usage reductions:

- Table ESHS-1: Water Usage KPIs and Targets
- Table ESHS-2: Energy usage KPIs and Targets

Table ESHS-1: Water Usage KPIs and Targets provides the list of water related environmental footprint of the future generations of semiconductor manufacturing technology. The parameters listed in the table include the following categories:

- Water demand – both process and non-process users.
    - The process (UPW) demand includes non-beneficial usage driven by the need to control cleanliness, as well as operation of the tool during idle time. Table ESH-1 includes both overall usage targets and a roadmap to reduce
    - Non process demand includes cooling tower evaporation and air abatement systems (general scrub exhaust and POU abatement)
- Water efficiency considering water reuse and overall water footprint
- Chemical waste generation, focusing on hazardous waste.

The table includes a target roadmap to reduce water and chemical usage for these parameters corresponding to the years of different technology generations.

7.6. VISION OF FUTURE TECHNOLOGY

A balance between corporate ESG goals and increasing size and complexity of fabs is needed within the boundaries of infrastructure, compliance, reliability, space, and safety. Projections suggest the manufacturing of more advanced production nodes will drive water and energy demand beyond infrastructure and compliance boundaries. Future technology must provide cost efficient solutions to manage these opposing drivers and boundaries. In order to do that, the industry needs a proactive way to define boundaries and priorities along with a comprehensive data management strategy to streamline logical decisions.

The ability to predict water and energy demand will become more important as water and energy availability become increasingly constrained. Anticipating future needs will enable the industry to develop solutions to conserve and recover water and energy, adapt to the changing environment, and identify key focus areas and technology needs. As the semiconductor manufacturing process becomes more complex, this puts increasing pressure on the ability of the infrastructure both internal and external to the factories to sustain the water and energy demands from the manufacturing process. As a result, sustainability goals are becoming key enablers for semiconductor industry growth.

Solutions will be necessary to ensure factories can operate in a more sustainable manner in potentially harsher environmental conditions. Future technology should address higher reclaim while minimizing CO_2 emissions and wastewater pollution. Wastewater processing technology should look to minimize or eliminate chemical consumption. Facilities management must also be made more robust to mitigate risks associated with climate change, such as water quality deterioration, droughts, severe weather events (flooding, snow, strong winds), power outages, and greater seasonal disparity effecting makeup air handler and evaporative loads.

It is necessary that the facility increases certainty and prioritize focus in the areas of the highest risk. Early planning is necessary to streamline decisions and lower cost of ownership. A holistic approach is needed to ensure reliability is maintained within a smaller environmental footprint, addressing critical challenges the industry faces. The approach to quantify risks and define technology needs follows:

- Develop a data driven decision framework
- Ensure data is complete, accurate, and validated
- Construct a Digital Twin of the site to reflect existing, target state and future state conditions
- Leverage digital twin to identify risks associated with water reuse goals for future state conditions
- Incorporate learnings to the decision framework and iterate as needed to support new technology generations

In anticipation of the challenges the industry faces, the IRDS teams have proactively developed models representing water and energy usage of a representative 300 mm fab. This model allows us to better understand and quantify implications of the pursuit of specific targets with respect to boundaries and drivers. This process also enables selection of meaningful indicators for industry benchmarks. Factory teams will be able to compare their water and energy usage against this model as a baseline.

Part of the intention of the model is to put all key performance indicators in context of a representative factory to help explain the gaps in technology with respect to boundaries and drivers. For example, when we aim to maximize overall efficiency of water systems, we understand that driving efficiency higher is traditionally associated with higher energy and chemical use, which will eventually trigger the need for brine management. The model provides a structure to quantify anticipated challenges (and risks) associated with the roadmap to better define and address the technology gap.

8. CHALLENGES

8.1. TECHNOLOGY CHALLENGES—WATER

8.1.1. TECHNOLOGY FOR EFFECTIVE AND TIMELY DECISIONS

Problem: In many aspects of technology and technology application, the decision process is not viewed as a technology challenge due to often well-defined needs. In contrast, the water management of advanced semiconductor facility under conditions of growing complexity, size, environmental concern, and other challenges has become an increasingly difficult task. Global climate challenges such as flooding/runoff, land sliding, droughts, strong winds, snow loads, water quality deterioration, make proactive decisions even harder. Fast growing semiconductor sites often outpace development of the local infrastructure. Site specific conditions that are unique for each facility make it impossible to completely synergize decision process. The amount of data necessary (though available) is so significant that the existing methodologies and tools are unable to process to enable proactive decisions. As the result, the decisions made under pressure of time-to-market when new facility is built often leads to inefficient, costly, and deficient solutions resulting in reliability, capacity, and other problems limiting ability to cope with environmental sustainability and climate issues.

Technology Need: Data management and effective decision enabling technology has been identified as one of the critical challenges. Integration of the IT tools into decision is needed to be done in the way to ensure effective environmental solutions implemented within aggressive timelines of the semiconductor site development. Holistic approach is required to ensure environmental footprint reduction is affordable and reliable. It is also important to ensure that the tools and processes enable both water and energy considerations to ensure that solutions on one side do not affect the other.

Potential Solutions: There are new solutions that have been recently developed but not widely used in the industry.

8.1.2. CHEMISTRY ENVIRONMENTAL FOOTPRINT

Problem: The increased use of chemicals and consequent increase of abatement/treatment of waste chemical stream needs are resulting in increasing environmental footprint.. These chemicals are extensively used in various stages during the fabrication of integrated circuits, from the specialty photolithography chemicals needed for the patterning of features on the chips to the bulk concentrated acids and bases used for wafer cleaning and etching processes. These bulk chemicals—*which include isopropyl alcohol, hydrogen peroxide, hydrochloric acid, ammonium hydroxide, hydrofluoric acid, nitric acid, phosphoric acid, and sulfuric acid*—are delivered to the site in large volumes and in concentrated form. With the increasing demand for computer chips, semiconductor facilities are expanding, increasing the quantity of processing equipment and requiring larger quantities of the various chemicals. Although the majority of the chemicals are not particularly harmful to the environment when adequately treated, their production, transport, and management requires significant energy, producing CO_2 emissions. For this reason, traditional treatment methods which focus solely on discharge compliance are not totally aligned with sustainability goals. Reduction of chemical consumption and waste generation is important for reduction of the environmental footprint.

Technology Need:

- A more holistic strategy is needed to ensure optimal usage of these liquid chemicals in both the facility systems and tools. This includes drain segregation at the tool level, sequencing of unit operations and enabling reuse opportunities to reduce the amount of chemistry required by the process and the amount discharged from the site. It is particularly important to consider environmental footprint implications when developing recipes and chemical applications in the manufacturing process, proactively including decisions about waste management downstream. Chemicals/waste-free cooling towers (condenser water) and wastewater treatment/reclamation are going to be particularly beneficial in the future.
- Chemical lifecycle tracking regarding segregation, measurement, treatment, and reuse is crucial. Technology will need to enable chemical management at a level beyond what is currently employed. Efforts will be necessary to refine products and identify new reuse opportunities. This process will involve establishing a regional marketplace for generators to find new or alternate downstream users. Through analysis of waste composition, developing reprocessing technology, and evaluating sales channels, individual sites can move toward a more circular economy.
- Lastly, a plan to qualify new chemicals to substitute problematic wastes and contaminants must be established. Simultaneously, a robust chemical approval process is necessary to mitigate the risk of incorporating chemicals which may impact the ability to reuse water or may impact quality of outfall, or both.

Potential Solutions:

- Existing best practices may be useful to make significant improvement. This includes optimization of the manufacturing process to reduce chemistry use in the process recipes and during idle time. Low chemicals or chemical free water and wastewater treatment solutions are available as well, but specific decisions should consider other trade-offs and risks. Some manufacturing tools come with provisions for chemical recycling that could further reduce overall demand.
- The emerging model of production is to strive toward circular economy where resources are reused to the extent possible. Effective waste segregation and collaboration with external partners may allow for reuse of the relatively high-quality chemistries. Waste renewal technologies can improve finite resource efficiency by extending the lifecycle of chemicals, decoupling environmental pressure from economic growth.
- The growing effort to employ waste valorization processes will drive technology development for individual specific wastes and their treatment byproducts. Examples of effective waste management include reuse of the following types of chemistries: sulfuric acid, ammonium sulfate, CaF2, silicon slurry, metals (such as copper and cobalt), and concentrated solvent waste (ethers, TMAH, IPA, polar and non-polar photoresist, etc.). Waste sulfuric can be used locally in wastewater treatment, reused in other industries (such as battery manufacturing), or it could be refined to electronic grade for semiconductor manufacturing. Returning waste sulfuric acid to its original purity suggests a potential circular economy with minimized sulfuric acid purchasing. Another example of waste stream reuse and upcycling utilizes the hydrofluoric acid waste stream. Calcium fluoride sludge cake has several possible reuse opportunities, such as concrete or ceramic manufacturing: however, the stream reuse value can be further enhanced by instead producing cryolite, used for electrolysis in the aluminum industry.[27] Cryolite produced is high-value and can save more than 25% of energy consumption in the process of aluminum smelting.[28]

8.1.3. UPW RECYCLING

Problem: Once non-process water demand is fully satisfied by reclaimed water, the only way to expand reclaim is to reuse water for UPW. Drivers will force the industry to apply UPW recycling, reclamation, and reuse.

Technology Need: Measures must be implemented to ensure the necessary UPW quality is maintained. Facilities are particularly sensitive to contamination risks from reused water. Evidence is needed to help facilities gain confidence that UPW level recycling will not compromise production.

Potential Solution: POU-level recycle, adequate segregation, and targeted treatment will need be considered for UPW recycling. Point of use recycling will require design considerations as part of the tool itself. An adequate level of segregation will be necessary to maintain UPW quality. Recycling must consider limitations of the UPW treatment system and provide solutions necessary to compensate for those limitations. For example, UPW has limitations to treat low molecular weight neutral organic compounds, therefore this stream will need to be segregated out. Another example is segregating slurry solids that may lead to clogging of the UPW pretreatment system. Any compounds which cannot be segregated but are not expected to be adequately controlled by existing UPW systems may require targeted treatment and risk mitigation measures. A potential approach may be to define the margin of UPW quality for each categorized wet process (e.g., FEOL, BEOL, epi, CMP, scrubbing, etc.) and identify where cascade use can be implemented. The UPW IRDS team of yield enhancement forum will address risks associated with UPW recycling in the yield enhancement roadmap.

8.1.4. FAB TOOL WATER DEMAND REDUCTION

An average semiconductor manufacturing facility uses millions of gallons of water per day. Most of the water used in a fab is purified to provide UPW and supplied to the various wet processing semiconductor equipment, e.g. batch immersion, single-wafer processors, scrubbers and chemical mechanical polishing (CMP) platforms. Lower purity grade water is also used as cooling water and for point-of-use abatement of exhaust gases from various equipment. The scarcity of water caused by global warming, severe droughts, and population growth in major semiconductor manufacturing areas coupled with consumer and investor demand for better sustainability practices is putting pressure among semiconductor manufacturing facilities to reduce the overall fab water usage. Guides for water reuse can be found in SEMI F98-0521 Guide for Water Reuse in Semiconductor Industry and SEMI F116-0821 Guide for Drain Segregation for Semiconductor Manufacturing Tools to Support Site Water Reuse.

Problem: As with chemicals usage, tool water demand reduction is an important measure to support water conservation. As the process becomes more complex and more layers are added, this adds more process steps which in turn drives more tools. In the primary processing steps, which use ultrapure water (CMP and wet etch), the amount of water used per step or operation typically does not change, but as more steps and tools are added, this causes the water demand to increase, putting more pressure on the external water supply and infrastructure whilst driving more internal infrastructure, energy demand and chemical usage to purify and treat the ultrapure water supply and effluent wastewater from the fab tools. Tool water demand reduction, both on process and abatement applications, is therefore a critical need. This can be done by consistently implementing vendors' provided solution for point of use (POU) recycling or/and reduction of the non-beneficial use (i.e., rinses during idle time). Although maintaining UPW bacteria free requires use of excess UPW demand, current practices are often overly conservative resulting in significant freshwater withdrawal.

Technology Need: Process and non-process water usage reduction has been identified as an industry-critical challenge. Cooling water is addressed in Section 7.2, but the industry needs to explore ways to reduce demand from the wafer processing tools and from scrubbers and abatement. A holistic and balanced approach is needed to ensure that solutions identified do not impact process wafer yields, result in environmental compliance issues (wastewater discharge or atmospheric issues) or result in excessive energy footprint increases.

Potential Solutions: Although solutions for this problem does not require significant development of new technologies, implementation of the best practices is not trivial and needs effective assessment and data driven decisions, including validation of the respective capabilities (for example POU recycling may not be feasible due to space constraints). Tool water demand reduction may affect yield or reduce available reclaim for non-process application. The Water Management roadmap assumes gradual reduction of the non-beneficial reuse (refer to the roadmap table). Other key focus areas are exploring more water-efficient abatement systems and more aggressively optimized tool process recipes. Both solutions have been successfully demonstrated on some unit operations; wider adoption across the process is a potential opportunity but will require extensive piloting and testing to ensure that safety, wafer yield and environmental compliance are not compromised.

8.1.5. REDUCTION OF COOLING TOWER EVAPORATION

Problem: Evaporated water is considered as "water consumption", meaning that this water is forever lost to the watershed and cannot be directly recovered. In contrast with other measures, the ability to reduce evaporation helps to preserve the water resource within the watershed – a critical task from the freshwater conservation point of view. The primary ways to reduce evaporation are reducing energy management inefficiency and more energy efficient tool design, which are typically managed by different experts than those dealing with water conservation. A coordinated approach between the water and energy management teams is needed to enable success.

Technology Need:

- Water and Energy Models are instrumental in understanding of energy and water relationship, driving data driven decisions.
- Technology solutions to address this problem include energy consumption reduction in the process and facility systems, heat recovery measures, improving energy use and transfer efficiencies of the facility systems, as well as recovering water from vapor or drift (when feasible and viable)

Potential solution: Cooling tower type selection is important: direct contact, open evaporation, indirect contact, or closed-circuit evaporative type towers can significantly change the water consumption depending upon local site conditions. While technology development is still in progress, there are best-known methods that can be leveraged to drive energy efficiency, maximizing implementation of the heat recovery solutions, using variable speed drives (VFDs) on pumps and motors, allowing for high temperature heat dissipation - for example, high temperature Process Cooling Water (PCW), cooling the PCW system using cooling towers instead of chiller systems etc. In addition, process tool design needs to incorporate “green tool characteristics” e.g., best energy efficiency in components energy conversion, effective chamber volume and thermal insulation to avoid high temperature heat dissipation, which will reduce HVAC and heating module burden.

8.1.6. PFAS CONTROL[29]

Per- and poly-fluoroalkyl substances (PFAS) comprise a large group of synthetic compounds, i.e. more than 4,700, that have unique and useful properties for many industries including semiconductor manufacturing, where they find use as photoacid generators, wetting, etching and resist chemicals, articles (e.g., tubing, pipes, valves), lubricants, etc. Various substances that falls into the PFAS definitions are subject for current and proposed regulations. Some of such regulations require monitoring and managing of subjected PFAS effluent to a very low level, e.g. ng/L.[30],[31],[32]

Problem: The target concentration to support compliance at the level of nanogram per liter makes detection difficult that makes it difficult to effectively control even though treatment technologies exist but their ability to integrate into the semiconductor facility wastewater treatment and reclamation scheme has not been demonstrated. Coordinated effort across the industry is required to either eliminate or abate emissions of regulated PFAS into the natural water bodies.

If the order of the PFAS-concentration control target in the existing PFAS related regulations is carried over to more comprehensive PFAS restriction that is being proposed in EU, there are two main challenges with PFAS control, i.e. detection and removal. Currently available analytical methods for detection of PFAS compounds in wastewater are limited to only a small number of compounds due to limited chemical libraries. There is a need for the development of analytical methods that can identify and quantify all PFAS constituents that are present in semiconductor wastewaters. If this gap is not addressed, any effort to develop wastewater treatment systems may not succeed in meeting long-term requirements. Some of the current methods for detection of individual compounds include USEPA Method 537, rev 1.1 and ASTM D7979-16, while methods for detection of aggregated PFAS chemicals include particle induced gamma-ray emission (PIGE) analysis, total oxidizable precursor (TOP) assay, adsorbable organic fluorine (AOF) analysis and 19F NMR.

Information Needed: Studies and experimental analysis are needed to better understand the source and the fate of PFAS compounds in the facility water management systems and processes.

Technology solutions required: Reliable analytical methods and preferable online measurement is needed to ensure effective control. Choice and the need for new treatment solutions will depend on the success of the effort of eliminating PFAS process chemicals in the upstream process(es), as well as feasibility of the existing technology to integrate into semiconductor facility scheme to meet future discharge limits. Since PFAS compounds contain the stable C-F bond, decomposition into nontoxic, smaller molecules is problematic. PFAS compounds are resistant to hydrolytic, photolytic and oxidative reactions. Thermal reactions need to be at high temperature, e.g. digestion in molten sodium hydroxide, which make these approaches expensive. Therefore, many of the readily available technologies involve adsorption onto a media, e.g. activated carbon or membrane filtration. These technologies likewise have limitations, e.g. unable to remove the smaller molecules, and how to dispose of the media afterwards.

- Some companies target eliminating certain types of PFAS process chemicals from the manufacturing process.[33] This may eliminate the need of monitoring and control.

8.1.7. BRINE MANAGEMENT WITH LOW/NO CO_2 EMISSION (LOW OR RENEWABLE ENERGY)

Problem: Brine management is a significant, expanding challenge. The water model developed for a representative demanding case advanced logic fab (see the Modeling section) shows possible Fresh Water input with a total dissolved solids (TDS) of as high as 1,100 ppm (parts per million).

In addition to the salts coming from the city water or other freshwater sources, the TDS is contributed by both the fab processes, as well as facility systems using chemicals for regeneration, neutralization, reaction, operational control, etc. Depending on ability of the site to segregate concentrated chemicals, the site outfall chemistry may vary significantly. The representative model assumes relatively efficient segregation.

Not included in the model but present in advanced fabs are organic compounds such as isopropyl alcohol (IPA), tetramethylammonium hydroxide (TMAH), polar and non-polar photoresist, and other compounds. Concentrated organic solvents are typically segregated from other wastewaters and trucked away for either reuse or disposal. When brine management is considered, the organics are treated and removed from the effluent stream upstream to the process step to concentrate and dispose salt.

From the facility technology standpoint, a large majority of organic constituents can be effectively treated. However, salts remain the challenge to be addressed as part of the brine management solution. Cooling tower evaporation and extensive reuse driven by the industry commitment to water conservation results in the outfall TDS in thousands of parts per million. The representative model shows TDS of ~4,600 ppm in the outfall. Unless such stream can safely be discharged into the oceans, most of the locations will require brine management to avoid impact to the environment. This stream mostly contains the following ions: Sulfate SO_4^{2-}, Chloride as Cl^-, Fluoride as F^-, Na^+ (if NaOH is used for neutralization), Ca^{2+}, etc. The wastewater concentrations of many of these contaminants are too high (in some cases far too high) to be discharged into an external water body such as a river or lake.

While not always visible, management of this brine is an escalating, large-scale challenge in terms of CapEx, OpEx, water and energy conservation, and CO_2 emissions. Immense new fabs incorporating more advanced tools and processes required by future nodes will intensify the magnitude of this problem. Brine management is needed in some fab sites today. Even if selected chemicals are segregated, the water model indicates that many, if not most, fab sites will have this problem in future years. Conventional brine management technology requires highly specialized equipment very sensitive to incoming chemistry changes, is highly energy intensive with formidable capital and land costs, and has site-specific requirements. New materials introduced into processes and upcoming uncertain but stringent regulatory requirements, e.g., for certain groups of PFAS chemicals (e.g., PFOS/PFOA, their salts and related substances), exacerbate this challenge.

The concerns on certain group of PFAS chemicals may also be a driver for the brine management, as resulting ZLD (zero liquid discharge) ensures no traces of harmful chemical may end up in the environment. However, when such driver is considered, it is important to also consider other measures applied to cope with PFAS.

Information Need: emissions limits, effect of PFAS regulations (can be a driver for ZLD), quantities of chemistry (water model), new materials hitting the process, external infrastructure needs

Potential Solutions: higher recovery fouling/scaling resistant preconcentration (I.e., RO, EDR, etc.), potential alternates to thermal evaporation, metrology solutions to optimize system operation

Potential solutions: to reduce the need to concentrate high flowrates of brine resulting in high energy consumption and CO_2 emissions, the following measures can be considered:

- Optimizing segregation scheme, focusing on high salt containing ones and those with constituents that can harm brine management
- Maximizing preconcentration using best available technologies, focusing on their efficiency and robustness

8.1.8. EFFECTIVE METROLOGY FOR WASTEWATER

Problem: there are several challenges related to the monitoring effluent parameters enabling effective control of those.

- Increasing environmental concerns and regulatory requirements.
- Increasing variety and concentrations of chemistries used posing risks to growing outfall compliance requirements.
- Reliability concerns regarding the inhibitory compounds or other compounds affecting reliability of the wastewater treatment and reclamation processes
- Difficulty to operate online meters used in the corrosive and fouling-causing effluent streams

Information need: new materials entering the process, emission quantities, emissions limits or target values, potential analytical methods for compounds identified as required to control.

Technology required: developing additional online metrology, including POU metrology, which can be reliably operated under harsh conditions of the effluent streams, capable to measure broad range of compounds (both organic and inorganic) at the levels necessary for effective operations of the systems downstream and environmental compliance. With growing need for reclamation and reuse and particularly reuse for process (UPW), there is a growing need for metrology supporting such applications.

Potential solutions: until effective real time monitoring exist, well thought engineering solutions based on proactive and systematic risks analysis combined with existing metrology can provide solutions covering significant range of needs/applications.

8.2. TECHNOLOGY CHALLENGES-ENERGY

8.2.1. ENERGY MANAGEMENT

The extension of energy management programs beyond small teams from one department within the organization to organization wide with senior management support is key. Many semiconductor companies have implemented ISO 50001:2018 Energy management System Standard which provides a framework for this expansion. A traditional absence of energy usage data on significant energy using equipment to provide indicators to drive action is a key industry gap and a process needs to be developed to address this.

A key opportunity for the industry is to highlight high energy consumption equipment and tools for easy targeting and to promote for less energy users with innovation in similar functions.

The tool EPY (energy per year) can be separated into categories according to the SEMI-S23 with efforts focused to improve efficiency or find lower usage alternates with the tools and equipment falling into the higher energy tool usage categories.[34] An example categorization of energy usage could be as follows:

- EPY < 0.5M kWh/yr
- EPY 0.5M~1M kWh/yr
- EPY 1M~5M kWh/yr
- EPY >5M kWh/yr

This approach would mirror similar efforts that have been undertaken by water management teams to identify and target high water usage equipment and tools.

8.2.2. EQUIPMENT RESOURCE CONSUMPTION

The core to reduce energy and resource consumption lies in the efficiency improvement of the manufacturing equipment. The equipment drives a high factory baseload consumption with minimal variability with production throughput. Most manufacturers have set aggressive targets. Solutions to improve eco efficiency are ranging from the implementation of high efficiency components, minimization of utilities requirements, reduction of idle time usage, to the implementation of improved monitoring and control strategies, such as the use of digital eco efficiency twins, idle and sleep mode communication.

8.2.3. SUBFAB COMPONENTS RESOURCE EFFICIENCY

The core to reduce energy and resource consumption lies in the efficiency improvement of the manufacturing equipment. The equipment drives a high factory baseload consumption with minimal variability with production throughput. Most manufacturers have set aggressive targets. Solutions to improve eco efficiency are ranging from the implementation of high efficiency components, minimization of utilities requirements, reduction of idle time usage, to the implementation of improved monitoring and control strategies, such as the use of digital eco efficiency twins, idle and sleep mode communication.

Efficiency improvements have been continuously implemented for the direct equipment support components such as dry pumps, local exhaust abatement and local chillers and heat exchangers, just to name a few components.

Also here, improved monitoring and control strategies, such as idle and sleep mode communication, synchronization of operation with the process chambers has already, and will drive further improvements in the future.

8.2.4. HEAT RECOVERY FROM HIGH AND LOW TEMPERATURE SOURCES

Examples for direct heat recovery (80°C+) are the main compressors of the compressed air system and the air separation plant. The use of heat pumps and other thermal recovery solutions for medium and low temperature heat sources have been started and require future research and improvement, e.g., the development of energy efficient heat pumps for low temperature heat sources (25-35°C). Implementation of such heat recovery solution require improved control for start-up and transitions.

8.2.5. HOT UPW AND CHEMICAL RECYCLING AND RECOVERY

Producing hot UPW (HUPW) consumes a significant amount of energy, producing substantial levels of CO_2. Compared to other utilities, HUPW has an extremely high ECF of 92.2, whereas the UPW ECF is 9 and other utilities are below 0.3.[35] Minimizing the energy required for HUPW by local recycle or by maximizing heat recovery can therefore have a significant impact on facility energy demand. The potential for heat recovery from hot UPW and process chemicals have been identified and first solutions have been developed and implemented as shown in Figure ESHS-7. These solutions can be proliferated more widely across the industry.

8.2.6. GREEN ENERGY INSTEAD OF FOSSIL FUELS; ALTERNATIVE ENERGY SOURCES

Replace fossil fuels with green power or green fuels is ongoing everywhere in the industry. This ranges from using power for heating and combustion processes, as well as the use of alternative green fuels, such as hydrogen as energy source, especially with the focus on hydrogen recycling. On site energy generation using renewable energy sources such as Solar PV and Wind can be used to off-set fossil fuel-based energy from utilities. Fabs may also partner with large renewable energy sources not directly located at the fab site.

8.2.7. REDUCE FACILITY POWER CONSUMPTION BEYOND CONTINUOUS IMPROVEMENT

Available options and implemented for many years in a few fabs need continual reassessment include, e.g., the use of Tower cooled instead of chiller cooled PCW, the balance between sending the heat to cooling tower/dry coolers versus retaining the heat for heating purposes may depend on infrastructure, local climatic conditions and water scarcity; the reduction make-up air flow rate by extensive exhaust recycling, e.g., using it for chemical and gas rooms after verification like PCW example will require infrastructure change.

8.2.8. GHG EMISSION IN COMPARISON WITH ENERGY INPUT

GHG are still a major source of scope 1 emission of a fab. The improvement of abatement efficiencies from 80 towards 95% to 99% is needed in the near-term future.

8.2.9. SCOPE 3 FOOTPRINT REDUCTION IN COMPARISON WITH ENERGY INPUT

Besides Scope 1 and 2 more efforts are needed to improve Scope 3 in the near future. This includes the Scope 1 and 2 of the companies in the supply chain, but also the energy needed to manufacture process materials such as chemicals and gases. In-situ, on-site and off-site recycling and reuse can reduce this burden on carbon footprint. Analysis of Scope 3 will drive partnership across the supply chain to action improvements.

8.2.10. INCORPORATING GREEN TOOL CHARACTERISTICS IN PROCESS TOOL DESIGN

Process tool design needs to incorporate “green tool characteristics” e.g., best energy efficiency in components energy conversion (like RF generator and other less efficient components), effective chamber volume to avoid excess energy, as well as chemical usage for wafer processing leading to extra waste generation, and effective thermal insultation design to avoid high temperature heat dissipation, which will reduce HVAC and heating module burden.

8.2.11. CONTINUOUS IMPROVEMENT CHALLENGES – ENERGY

Long term challenges regarding energy efficiency are based on the continuously changing process requirements and the expected growth rate of the semiconductor industry

To maintain the balance between GHG emissions the work on solutions for Green Abatement will remain a challenge for my years to come.

Very similar to this will be the balance between water and chemical recycling vs. the acceptable energy consumption.

Many materials are becoming or are already limited in availability. This will include certain rare gases, which will need to be segregated, collected and recycled/reused, Also, this will require additional energy.

9. CONCLUSIONS AND RECOMMENDATIONS

Growing semiconductor facilities drive increasing environmental footprint, including high energy demand, high freshwater withdrawal, carbon emission, and other GHG and waste related emissions. Whereas in the past the sustainability performance was associated with general social responsibility and cost related benefits, it is now becoming mission critical for the industry. The nexus between the environmental performance indicators is getting more and more obvious. This chapter evaluated the technology drivers, boundaries, and other considerations from the point of view of sustainable industry growth and future technology enabling. The drivers include semiconductor technology, ESG, climate change, and the growing chip demand. These drives create both urgency and difficulty to deal with the sustainability management. The outcome of the technology gap analysis includes the following findings:

- Importance of the water, chemicals, and energy consumption requirements by the process tools
- Reduction of inefficiencies of the use of the natural resources (including higher efficiency water treatment systems and energy and gas recovery)
- Minimization and elimination (where possible) of hazardous chemistries
- Use holistic approach for water and energy management, ensuring organizational alignment, supporting data driven decisions with digital tools
    - Providing effective segregation of the wastewater
    - Maximizing water reuse
    - Minimizing energy use in brine management
- Using renewable energy sources
- Ensuring sustainability and energy efficiency considerations are incorporated when designing tools

For next steps, the Water and Energy forum will continue focusing on the areas of the technology challenges as defined in this chapter. More detailed definition of the technology needs and of the challenges should help to address those needs. There is an increasing importance in collaborative development that will require tighter interaction between the roadmap group within ESH/S and other forums external to it.

10. APPENDICES

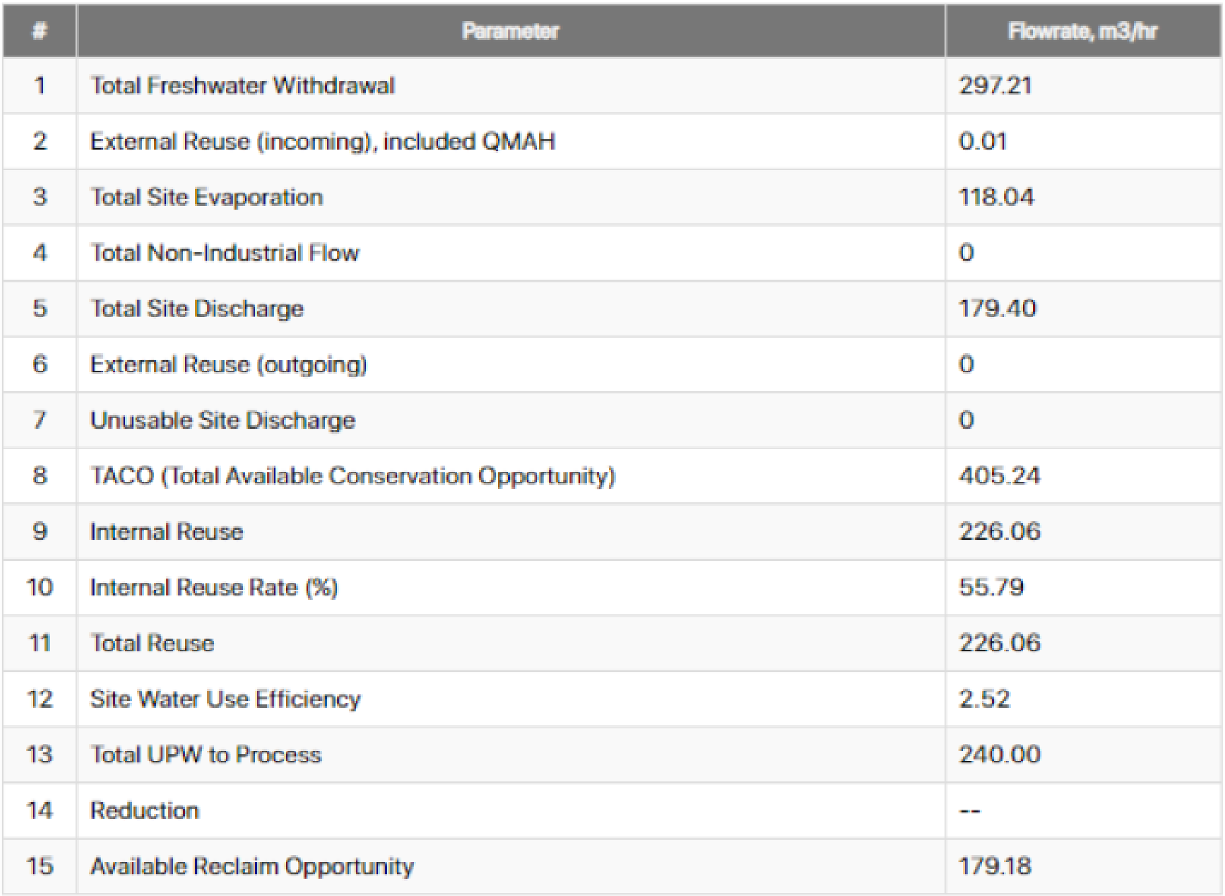
10.1. APPENDIX A—DOCUMENT ACRONYMS

AOF	Adsorbable organic fluorine
CapEx	Capital expenditure
CMP	Chemical-mechanical planarization
ECF	Energy conservation Factors
EDI	Electro-deionization
EDR	Electro-dialysis Reactor
ESG	Environmental, social and governance
ESH/S	Environment, safety, health and sustainability
GHG	Greenhouse gas
HF	Hydrofluoric acid
HFW	Hydrofluoric waste
IFT	International Focus Team (see ORG chart on IEEE IRDS site https://irds.ieee.org/)
IPA	Isopropyl alcohol
KPI	Key performance indicator
LC-OCD-OND	Liquid Chromatography with Organic Carbon Detector and Organic Nitrogen
NMA	Net manufacturing area
OpEx	Operational expenditure
PCW	Process cooling water
PFAS	Per and polyfluoroalkyl substances
POD	Point of discharge
POTW	Publicly owned treatment works
POU	Point of use
Reclaim Water	The product of water reclamation
RO	Reverse osmosis
SCW	Slurry copper waste
SEMI	Semiconductor Equipment and Materials International (organization)
TACO	Total available conservation opportunity
TMAH	Tetramethylammonium hydroxide
TOC	Total Oxidizable (Organic) Carbon
TOP	Total oxidizable precursor
UPW	Ultrapure water
UPW Recycle	The process of reclamation and reuse of water for UPW production
VOC	Volatile Organic Compounds
VSD, VFD	Variable speed drive, Variable frequency drive
Water Reclamation	A process of extracting/purifying water from wastewater for subsequent secondary use
Water Recycling	The process that leads to water reuse at the system where it was originally used
Water Reuse	The secondary use of water with or without treatment
ZLD	Zero liquid discharge

10.2. APPENDIX B—WATER MODEL KEY ASSUMPTIONS

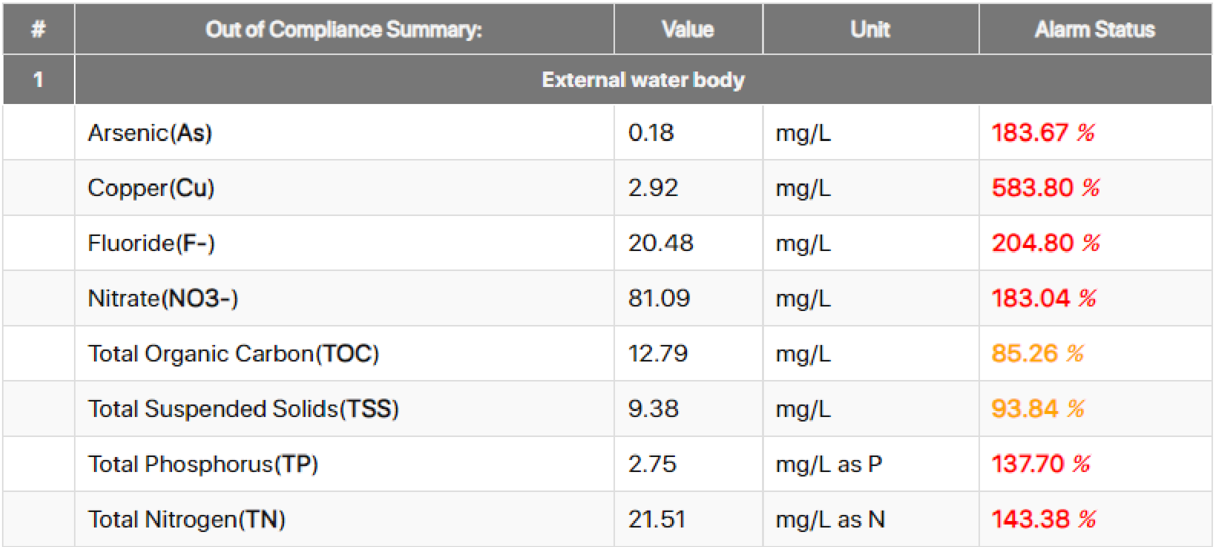
1	The model represents a 300 mm facility with a net manufacturing area (NMA) of 19,000 m^2 (200,000 ft^2). This represents the smallest possible 300 mm facility.
2	The facility is in the area that is constrained by available water resources.
3	The facility utilizes a centralized end-of-Pipe (EOP) biological treatment followed by a reclaim RO system.
4	Reclaim water fully satisfies cooling towers' and scrubbers' demand. Reclaim water sources include product water from this EOP RO and the 2nd pass UPW RO reject.
5	Domestic water use and irrigation are not included in the model
6	Utility demand for the baseline model is based on ISMI benchmarking study.
7	Due to the difference in the technologies as well as productivity, wafer throughput of different fabs, the utility consumption is normalized to the m2 of net manufacturing area, not including labs and testing/probing
8	POU abatement units' number is 500
9	Climate conditions are based on the average summer weather for southern US climate, i.e., AZ Phoenix area
10	No significant evaporation or water lost from POU and scrubbers
11	No infrastructure limitations included
12	The facility is inland located and must deal with brine management.
13	River chemistry based on 12 different credible source waters in the Phoenix area to represent worst representative case by using higher values of different source qualities. Conductivity was used as a reference and sodium/chemistry reduced to meet worst case conductivity (1400 ppm TDS) and rebalanced for ions. Conductivity, calcium, chloride, copper, magnesium, nitrate, sulfur and TOC were the high norm based on existing data. These were reduced to worst case "average" not peak worst case.
14	The industrial wastewater (IWW) composition is based on a dataset of five independent sources. It is representative of a worst-case effluent.
15	3:1 TOC to COD ratio is assumed
16	Site agnostic data used for reactor effluent setpoints
17	UPW is configured as a chemical-free double pass RO.
18	The focus of the roadmap gap/risk analysis is on technology capability. This means that independently if POTW exists or not, the overall scheme should include capable wastewater treatment and reclamation set-up. This means that to meet aggressive water reuse goals the wastewater can be treated either internally or externally to the site with the effluent reused back to semiconductor site applications. As a result, the final outfall should be considered for discharge with no additional treatment and should be suitable for discharge to a natural water body, such as river, lake, sea, ocean, or aquifer.
19	The cooling tower demand is based on Phoenix, AZ summer weather data along with the following Assumptions: CT approach temperature is 6 deg F 0.005% drift RAH DB SP = 72 F RAH RH SP=59% Heat recovery assumed to cover air compressor and ASU load. Non-Cleanroom (CR) HVAC uses the cooling towers for heat rejection and are accounted for in "misc. loads" Chiller efficiency value is based on AHRI 550 performance data
20	Cooling tower blowdown is based on 200-hour chemical residence time

10.3. Appendix C—IRDS 2022 Water Model Management Snapshot- 300 mm Facility, 19,000 m2 NMA



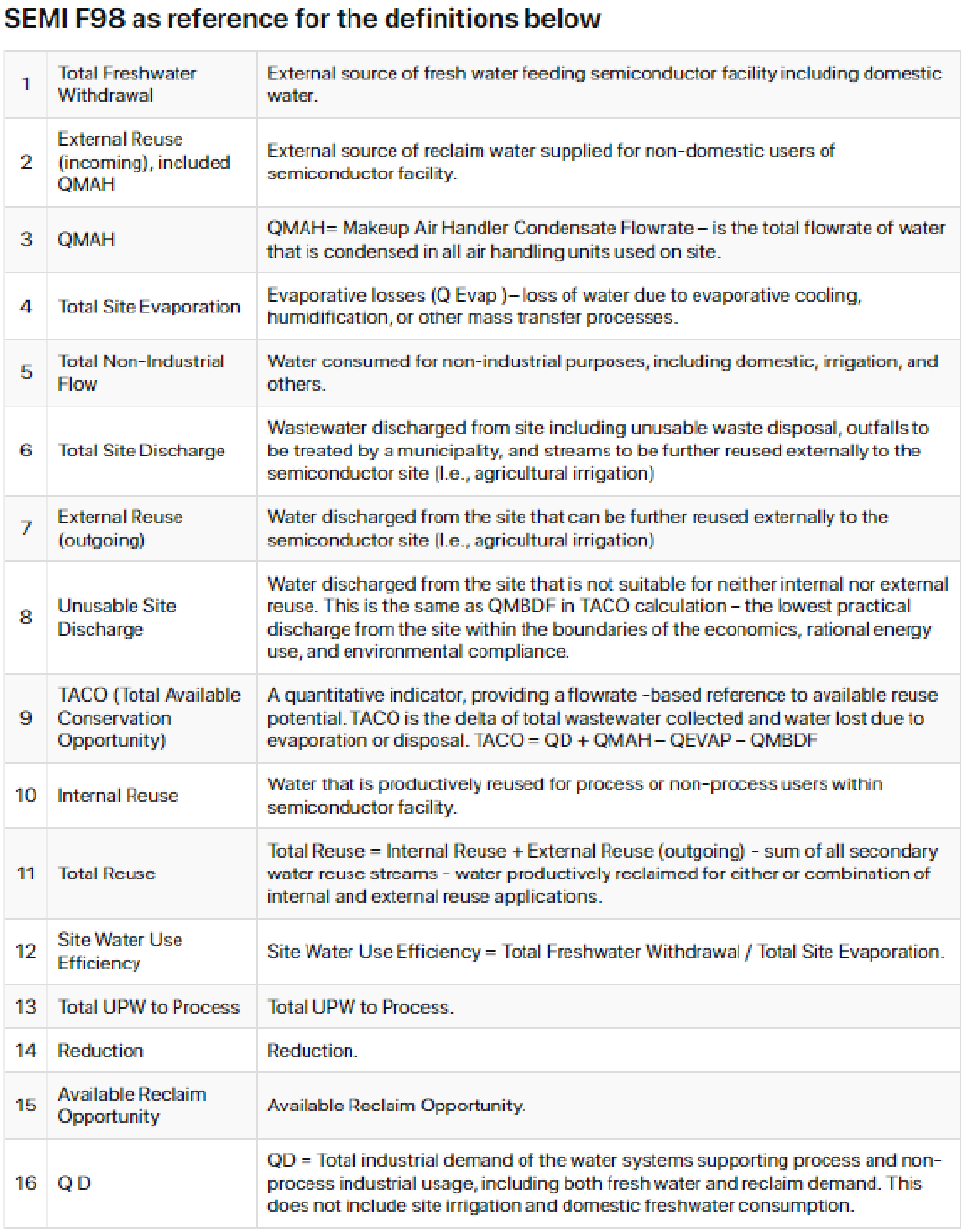
#	Parameter	Flowrate, m3/hr
1	Total Freshwater Withdrawal	297.21
2	External Reuse (incoming), included QMAH	0.01
3	Total Site Evaporation	118.04
4	Total Non-Industrial Flow	0
5	Total Site Discharge	179.40
6	External Reuse (outgoing)	0
7	Unusable Site Discharge	0
8	TACO (Total Available Conservation Opportunity)	405.24
9	Internal Reuse	226.06
10	Internal Reuse Rate (%)	55.79
11	Total Reuse	226.06
12	Site Water Use Efficiency	2.52
13	Total UPW to Process	240.00
14	Reduction	--
15	Available Reclaim Opportunity	179.18

10.4. Appendix D—IRDS Water Model 2022 Compliance risks (Site Agnostic)



#	Out of Compliance Summary:	Value	Unit	Alarm Status
1	**External water body**			
	Arsenic(**As**)	0.18	mg/L	183.67 %
	Copper(**Cu**)	2.92	mg/L	583.80 %
	Fluoride(**F-**)	20.48	mg/L	204.80 %
	Nitrate(**NO3-**)	81.09	mg/L	183.04 %
	Total Organic Carbon(**TOC**)	12.79	mg/L	85.26 %
	Total Suspended Solids(**TSS**)	9.38	mg/L	93.84 %
	Total Phosphorus(**TP**)	2.75	mg/L as P	137.70 %
	Total Nitrogen(**TN**)	21.51	mg/L as N	143.38 %

10.5. APPENDIX E—SEMI F98 REFERENCE DEFINITIONS FOR SUMMARY REPORT



SEMI F98 as reference for the definitions below

1	Total Freshwater Withdrawal	External source of fresh water feeding semiconductor facility including domestic water.
2	External Reuse (incoming), included QMAH	External source of reclaim water supplied for non-domestic users of semiconductor facility.
3	QMAH	QMAH= Makeup Air Handler Condensate Flowrate – is the total flowrate of water that is condensed in all air handling units used on site.
4	Total Site Evaporation	Evaporative losses (Q Evap)– loss of water due to evaporative cooling, humidification, or other mass transfer processes.
5	Total Non-Industrial Flow	Water consumed for non-industrial purposes, including domestic, irrigation, and others.
6	Total Site Discharge	Wastewater discharged from site including unusable waste disposal, outfalls to be treated by a municipality, and streams to be further reused externally to the semiconductor site (I.e., agricultural irrigation)
7	External Reuse (outgoing)	Water discharged from the site that can be further reused externally to the semiconductor site (I.e., agricultural irrigation)
8	Unusable Site Discharge	Water discharged from the site that is not suitable for neither internal nor external reuse. This is the same as QMBDF in TACO calculation – the lowest practical discharge from the site within the boundaries of the economics, rational energy use, and environmental compliance.
9	TACO (Total Available Conservation Opportunity)	A quantitative indicator, providing a flowrate -based reference to available reuse potential. TACO is the delta of total wastewater collected and water lost due to evaporation or disposal. TACO = QD + QMAH – QEVAP – QMBDF
10	Internal Reuse	Water that is productively reused for process or non-process users within semiconductor facility.
11	Total Reuse	Total Reuse = Internal Reuse + External Reuse (outgoing) - sum of all secondary water reuse streams - water productively reclaimed for either or combination of internal and external reuse applications.
12	Site Water Use Efficiency	Site Water Use Efficiency = Total Freshwater Withdrawal / Total Site Evaporation.
13	Total UPW to Process	Total UPW to Process.
14	Reduction	Reduction.
15	Available Reclaim Opportunity	Available Reclaim Opportunity.
16	Q D	QD = Total industrial demand of the water systems supporting process and non-process industrial usage, including both fresh water and reclaim demand. This does not include site irrigation and domestic freshwater consumption.

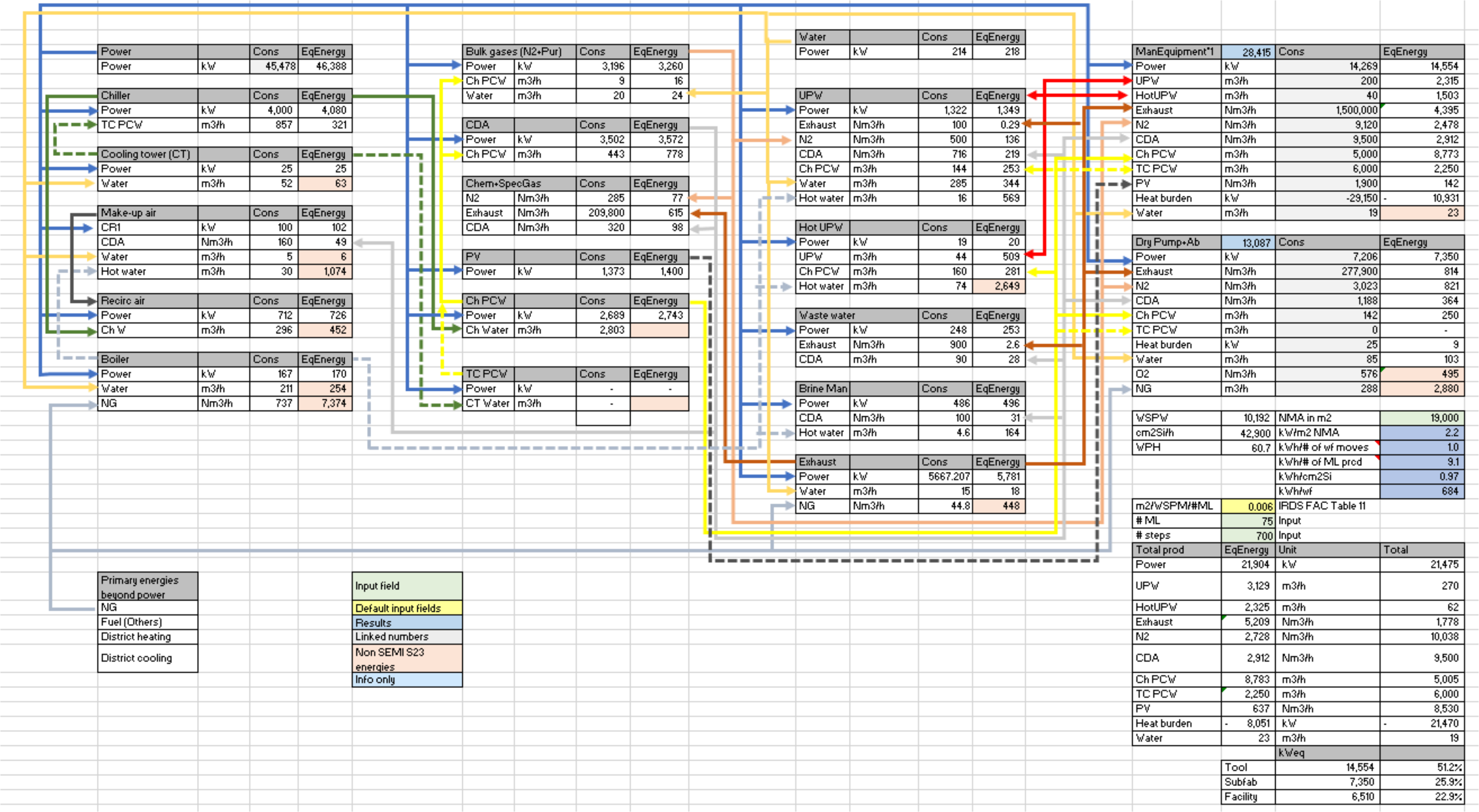
For further details related to Appendix E, refer to SEMI F98.

10.6. APPENDIX F—IRDS WATER MODEL 2022 OUTFALL COMPOSITION

Chemistry Element	Unit	Lab Result
Aluminum (Al)	mg/L	2.4
Antimony (Sb)	mg/L	0.03
Arsenic (As)	mg/L	0.2
Barium (Ba)	mg/L	5.9
Boron (B)	mg/L	0.7
Cadmium (Cd)	mg/L	0.06
Calcium (Ca)	mg/L	274
Chromium (Cr)	mg/L	0.7
Cobalt (Co)	mg/L	0.08
Copper (Cu)	mg/L	2.9
Iron (Fe)	mg/L	5.8
Lead (Pb)	mg/L	0.8
Lithium (Li)	mg/L	3.0
Magnesium (Mg)	mg/L	63
Manganese (Mn)	mg/L	1.7
Molybdenum (Mo)	mg/L	0.2
Nickel (Ni)	mg/L	0.03
Potassium (K)	mg/L	38
Selenium (Se)	mg/L	0.6
Silver (Ag)	mg/L	0.1
Sodium (Na)	mg/L	1236
Strontium (Sr)	mg/L	3.4
Tin (Sn)	mg/L	2.8
Titanium (Ti)	mg/L	0.07
Tungsten (W)	mg/L	1.9
Vanadium (V)	mg/L	0.05
Zinc (Zn)	mg/L	0.4
Ammonium (NH4+)	mg/L	4.1
Bromide (Br-)	mg/L	1.3
Chloride (Cl-)	mg/L	693
Fluoride (F-)	mg/L	20
Nitrate (NO3-)	mg/L	81
Phosphate (PO4 X-)	mg/L	0.8
Sulfate (SO4 2-)	mg/L	2573
Alkalinity (ALK)	mg/L as CaCO3	515
Total Nitrogen (TN)	mg/L as N	22
Total Organic Carbon (TOC)	mg/L	13
Total Phosphorus (TP)	mg/L as P	2.8
Total Silica (TSi)	mg/L as SiO2	43
Total Suspended Solids (TSS)	mg/L	9.4
Total Dissolved Solids (TDS)	mg/L	5061

10.7. APPENDIX G—ENERGY MODEL SNAPSHOT

Summary Energy Balance



Power		Cons	EqEnergy
Power	kW	45,478	46,388

Chiller		Cons	EqEnergy
Power	kW	4,000	4,080
TC PCW	m3/h	857	321

Cooling tower (CT)		Cons	EqEnergy
Power	kW	25	25
Water	m3/h	52	63

Make-up air		Cons	EqEnergy
CR1	kW	100	102
CDA	Nm3/h	160	49
Water	m3/h	5	6
Hot water	m3/h	30	1,074

Recirc air		Cons	EqEnergy
Power	kW	712	726
Ch W	m3/h	296	452

Boiler		Cons	EqEnergy
Power	kW	167	170
Water	m3/h	211	254
NG	Nm3/h	737	7,374

Bulk gases (N2+Pur)		Cons	EqEnergy
Power	kW	3,196	3,260
Ch PCW	m3/h	9	16
Water	m3/h	20	24

CDA		Cons	EqEnergy
Power	kW	3,502	3,572
Ch PCW	m3/h	443	778

Chem+SpecGas		Cons	EqEnergy
N2	Nm3/h	285	77
Exhaust	Nm3/h	209,800	615
CDA	Nm3/h	320	98

PV		Cons	EqEnergy
Power	kW	1,373	1,400

Ch PCW		Cons	EqEnergy
Power	kW	2,689	2,743
Ch Water	m3/h	2,803	

TC PCW		Cons	EqEnergy
Power	kW	-	-
CT Water	m3/h	-	

Water		Cons	EqEnergy
Power	kW	214	218

UPW		Cons	EqEnergy
Power	kW	1,322	1,349
Exhaust	Nm3/h	100	0.29
N2	Nm3/h	500	136
CDA	Nm3/h	716	219
Ch PCW	m3/h	144	253
Water	m3/h	285	344
Hot water	m3/h	16	569

Hot UPW		Cons	EqEnergy
Power	kW	19	20
UPW	m3/h	44	509
Ch PCW	m3/h	160	281
Hot water	m3/h	74	2,649

Waste water		Cons	EqEnergy
Power	kW	248	253
Exhaust	Nm3/h	900	2.6
CDA	m3/h	90	28

Brine Man		Cons	EqEnergy
Power	kW	486	496
CDA	Nm3/h	100	31
Hot water	m3/h	4.6	164

Exhaust		Cons	EqEnergy
Power	kW	5667.207	5,781
Water	m3/h	15	18
NG	Nm3/h	44.8	448

ManEquipment*1	28,415	Cons	EqEnergy
Power	kW	14,269	14,554
UPW	m3/h	200	2,315
HotUPW	m3/h	40	1,503
Exhaust	Nm3/h	1,500,000	4,395
N2	Nm3/h	9,120	2,478
CDA	Nm3/h	9,500	2,912
Ch PCW	m3/h	5,000	8,773
TC PCW	m3/h	6,000	2,250
PV	Nm3/h	1,900	142
Heat burden	kW	-29,150	- 10,931
Water	m3/h	19	23

Dry Pump+Ab	13,087	Cons	EqEnergy
Power	kW	7,206	7,350
Exhaust	Nm3/h	277,900	814
N2	Nm3/h	3,023	821
CDA	Nm3/h	1,188	364
Ch PCW	m3/h	142	250
TC PCW	m3/h	0	-
Heat burden	kW	25	9
Water	m3/h	85	103
O2	Nm3/h	576	495
NG	m3/h	288	2,880

WSPW	10,192	NMA in m2	19,000
cm2Si/h	42,900	kW/m2 NMA	2.2
WPH	60.7	kWh/# of wf moves	1.0
		kWh/# of ML prod	9.1
		kWh/cm2Si	0.97
		kWh/wf	684
m2/WSPM/#ML	0.006	IRDS FAC Table 11	
# ML	75	Input	
# steps	700	Input	

Total prod	EqEnergy	Unit	Total
Power	21,904	kW	21,475
UPW	3,129	m3/h	270
HotUPW	2,325	m3/h	62
Exhaust	5,209	Nm3/h	1,778
N2	2,728	Nm3/h	10,038
CDA	2,912	Nm3/h	9,500
Ch PCW	8,783	m3/h	5,005
TC PCW	2,250	m3/h	6,000
PV	637	Nm3/h	8,530
Heat burden	- 8,051	kW	- 21,470
Water	23	m3/h	19
		kWeq	
	Tool	14,554	51.2%
	Subfab	7,350	25.9%
	Facility	6,510	22.9%

Primary energies beyond power
NG
Fuel (Others)
District heating
District cooling

Input field
Default input fields
Results
Linked numbers
Non SEMI S23 energies
Info only

Legend

Power	→
NG	→
N2	→
Exhaust	→
Ch PCW	→
CDA	→
Water*2	→
BG	⇢
TC PCW	⇢
Chilled water	→
PV	⇢
Hot water	⇢
Others	→
UPW/Hot UPW	→

Abbreviations

BG … Bulk Gases

CDA … Compressed dry air

ChW … Chilled water

Cons … Consumption

CT … Cooling tower

DT … Delta temperature

HEX … heat exchanger

NG … Natural gas

NMA … Net manufacturing area

PCW … Process cooling water

Ch PCW … Chiller cooled PCW

TC PCW … Tower cooled PCW

PVac … Process vacuum

UPW … Ultrapure water

WSPM … Wafer starts per month

WSPW … Wafer starts per week

WW … Waste water

WW Cu … Copper waste treatment

WW HF .. Fluoride waste treatment

Summary of ECFs by System

	Unit		ECF SEMI	DT	ECF calc
Power	kW/	kW	1.00		1.02
UPW	kWh/	m3	9.00		11.57
Hot UPW	kWh/	m3	71.70		37.58
Exhaust	kWh/	km3	3.70		2.93
N2 incl BG	kWh/	m3	0.25		0.27
CDA	kWh/	m3	0.15		0.31
Ch PCW	kWh/	m3	1.35	5	1.75
TC PCW	kWh/	m3	0.38	5	0.38
Pvac	kWh/	m3	0.06		0.07
Heat	kW/	kW	0.29		0.38
Water	kWh/	m3			1.21
Hot water	kWh/	m3			35.79
NG	kWh/	m3			10.00
WW neutra	kWh/	m3			1.86
WW HF	kWh/	m3			2.96
WW Cu	kWh/	m3			2.72
Ch Water	kWh/	m3			5.00
Hydrogen	kWh/	m3			4.50
Oxygen	kWh/	m3			0.86

Flow and Energy Demand by System

	Unit	Man Eq.	Dry Pump+ Ab	Water	UPW	Hot UPW	Waste water	Brine Man	Exhaust	Bulk gases (N2+Pur)	CDA	PV	Ch PCW	TC PCW	Chiller	Cooling tower (CT)	Make-up air	Recirc air	Boiler	Total
Power	kW	14,269	7,206	214	1,322	19	248	486	5,667	3,196	3,502	1,373	2,689	-	4,000	25	100	712	167	21,475
UPW	m3/h	200				44								-						200
HotUPW	m3/h	40																		40
Exhaust	Nm3/h	1,500,000	277,900		100		900													1,777,900
N2	Nm3/h	9,120	3,023		500															12,143
CDA	Nm3/h	9,500	1,188		716		90	100									160			10,688
Ch PCW	m3/h	5,000	142		144	160				9	443							296		5,142
TC PCW	m3/h	6,000	-												857					6,000
PV	m3/h	1,900																		1,900
Heat	kW	-29,150	25																	- 29,125
Water	m3/h	19	85		285				15	20						52	5		211	104
Hot water	m3/h				16	74		5									30			-
NG	Nm3/h		288						45										737	288
WW neutra	m3/h																			-
WW HF	m3/h																			-
WW Cu	m3/h																			-
Ch Water	m3/h												2,803							-
Hydrogen	Nm3/h																			-
Oxygen	Nm3/h		576																	576
Power	kWeq	14,554	7,350	218	1,349	20	253	496	5,781	3,260	3,572	1,400	2,743	-	4,080	25	102	726	170	21,904
UPW	kWeq	2,315	-	-	-	509	-	-	-	-	-	-	-	-	-	-	-	-	-	2,315
HotUPW	kWeq	1,503	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1,503
Exhaust	kWeq	4,395	814	-	0	-	3	-	-	-	-	-	-	-	-	-	-	-	-	5,209
N2	kWeq	2,478	821	-	136	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3,300
CDA	kWeq	2,912	364	-	219	-	28	31	-	-	-	-	-	-	-	-	49	-	-	3,276
Ch PCW	kWeq	8,773	250	-	253	281	-	-	-	16	778	-	-	-	-	-	-	519	-	9,023
TC PCW	kWeq	2,250	-	-	-	-	-	-	-	-	-	-	-	-	321	-	-	-	-	2,250
PV	kWeq	142	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	142
Heat	kWeq	- 10,931	9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	- 10,922
Water	kWeq	23	103	-	344	-	-	-	18	24	-	-	-	-	-	63	6	-	254	126
Hot water	kWeq	-	-	-	569	2,649	-	164	-	-	-	-	-	-	-	-	1,074	-	-	-
NG	kWeq	-	2,880	-	-	-	-	-	448	-	-	-	-	-	-	-	-	-	7,374	2,880
WW neutra	kWeq	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
WW HF	kWeq	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
WW Cu	kWeq	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ch Water	kWeq	-	-	-	-	-	-	-	-	-	-	-	14,014	-	-	-	-	-	-	-
Hydrogen	kWeq	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Oxygen	kWeq	-	495	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	495
Total		28,415	13,087	218	2,870	3,458	283	690	6,246	3,300	4,349	1,400	16,757	-	4,401	89	1,231	1,245	7,799	41,502

11.REFERENCES

---

[1] C. a. C. N. Carter, "Energy-Water Nexus: The Water Sector's Energy Use," Congressional Research Service, 24 January 2017. [Online]. Available: https://sgp.fas.org/crs/misc/R43200.pdf. [Accessed October 2022].

[2] G. e. a. Klein, "Wikipedia Article on Water-energy nexus," California Energy Commission, 17 June 2020. [Online]. Available: https://en.wikipedia.org/wiki/Water-energy_nexus. [Accessed October 2022].

[3] J. K. Szinai, "Evaluating cross-sectoral impacts of climate change and adaptations on the energy-water nexus: a framework and California case study," UC Berkeley, 16 December 2020. [Online]. Available: https://iopscience.iop.org/article/10.1088/1748-9326/abc378. [Accessed October 2022].

[4] M. P. a. B. V. D. Bauer, "The Water-Energy Nexus: Challenges and Opportunities," US Department of Energy, June 2014. [Online]. Available: https://www.energy.gov/sites/prod/files/2014/06/f16/Water%20Energy%20Nexus%20Report%20June%202014.pdf . [Accessed October 2022].

[5] SEMI, "Guide for Conservation of Energy, Utilities and Materials Used by Semiconductor Manufacturing Equipment," *SEMI S23 ,* February 2022.

[6] J. DeGenova, "Ultrapure Water Recycle in the Semiconductor Industry," University of Arizona, Tucson, 1999.

[7] S. S. S. Co., URW Drain Segregation Scheme on a Wet Station, SCREEN Semiconductor Solutions Co., 2021.

[8] L. SCREEN Semiconductor Solutions Co, *2022,* October.

[9] L. SCREEN Semiconductor Solutions Co, *2022,* October.

[10] S.-P. W. e. al, "TSMC Launches the First Hydrofluoric Acid Waste Regeneration System, Creating NT$ 400 Million in Benefits Yearly," TSMC, 19 November 2021. [Online]. Available: https://esg.tsmc.com/en/update/greenManufacturing/caseStudy/55/index.html. [Accessed 20 December 2022].

[11] QC 080000: Framework for Assessment and Reduction of Hazardous Substances, International Electrotechnical Commission.

[12] TSMC ESC Committee, *TSMC Sustainability Report,* Hsinchu 300-78, Taiwan, Hsinchu 300-78: Taiwan Semiconductor Manufacturing Company, 2021.

[13] P. Clark, 14 July 2014. [Online]. Available: http://ig-legacy.ft.com/content/8e42bdc8-0838-11e4-9afc-00144feab7de.

[14] J. DeGenova, "Ultrapure Water Recycle in the Semiconductor Industry," University of Arizona, Tucson, 1999

[15] R. P. T. M. J. D. R. V. J. a. D. M. R. Robert P. Donovan, "Performance of a Treatment Loop for Recycling Spent Rinse Waters," Sandia National Laboratories, Alburqurque, 2000.

[16] "Mie Plant Green Factory Promotion Efforts- Wastewater recycle system achieves a 40% reduction in water volume by regenerating and recycling industrial wastewater," Do Eco!, Yokohama, 2008.

[17] L. Peters, "Ultrapure Water: Rewards of Recycling," Semiconductor International, 1998.

[18] J. D. a. F. Shadman, "Recovery, reuse, and recycle of water in semiconductor wafer fabrication facilities," Environmental Progress, 2006.

[19] United Nations, "UN News," 9 May 2022. [Online]. Available: https://news.un.org/en/story/2022/05/1117842.

[20] S. F. a. I. P. John Kapetaneas, "Historic Lake Mead drought leads to disturbing discoveries on dried up ground," ABC News, 27 October 2022. [Online]. Available: https://abcnews.go.com/US/historic-lake-mead-drought-leads-disturbing-discoveries-dried/story?id=92124028. [Accessed 20 December 2022].

[21] OCHA, 22 September 2022. [Online]. Available: https://reliefweb.int/report/china-taiwan-province/how-lack-typhoon-affected-lives-5-facts-taiwan-drought.

[22] "Electronics Sourcing," 4 May 2022. [Online]. Available: https://electronics-sourcing.com/2022/05/04/how-many-chips-are-in-our-cars/. [Accessed 20 December 2022].

[23] SEMI, F98-00-0521: Guide for Water Reuse in Semiconductor Industry, 2021, May.

[24] SEMI, F98-00-0521: Guide for Water Reuse in Semiconductor Industry, 2021, May

[25] SEMI, F98-00-0521: Guide for Water Reuse in Semiconductor Industry, 2021, May

[26] SEMI, F98-00-0521: Guide for Water Reuse in Semiconductor Industry, 2021, May

[27] TSMC ESC Committee, *TSMC Sustainability Report,* Hsinchu 300-78, Taiwan, Hsinchu 300-78: Taiwan Semiconductor Manufacturing Company, 2021.

---

[28] S.-P. Wu, Y.-S. Lin, J. Liu and C.-C. Chang, "TSMC Launches the First Hydrofluoric Acid Waste Regeneration System, Creating NT$ 400 Million in Benefits Yearly," 19 November 2021. [Online]. Available: https://esg.tsmc.com/en/update/greenManufacturing/caseStudy/55/index.html.

[29] U. E. P. Agency, "PFAs Explained," US Environmental Protection Agency, 28 Apr 2022. [Online]. Available: https://www.epa.gov/pfas/pfas-explained. [Accessed 28 Dec 2022].

[30] US-EPA, "Long-Chain Per-fluoroalkyl Carboxylate and Perfluoroalkyl Sulfonate Chemical Substances; Significant New Use Rule," US Environmental Protection Agency. In 40 CFR 721 ed., 2015;Vol. 80 FR 2885, pp 2885–2898, 2015.

[31] UN, "Report of the Conference of the Parties to the Stockholm Convention on Persistent Organic Pollutants on the work of its ninth meeting," United Nations, Geneva, 2019.

[32] EU, "Annex XVII TO REACH: Conditions of restriction; Council of the European Union," European Chemicals Agency, Helsinki.

[33] TSMC ESC Committee, *TSMC Sustainability Report,* Hsinchu 300-78, Taiwan, Hsinchu 300-78: Taiwan Semiconductor Manufacturing Company, 2021.

[34] SEMI, "Guide for Conservation of Energy, Utilities and Materials Used by Semiconductor Manufacturing Equipment," *SEMI S23 ,* February 2022.

[35] UN, "Report of the Conference of the Parties to the Stockholm Convention on Persistent Organic Pollutants on the work of its ninth meeting," United Nations, Geneva, 2019.