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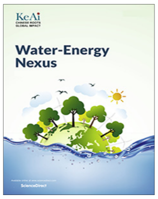

Revisiting the water-use efficiency performance for microelectronics manufacturing facilities: Using Taiwan's Science Parks as a case study

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ABSTRACT

Semiconductors are enabling technologies that drive today's information economy by producing a broad spectrum of microelectronic consumer products including computers, flat-panel displays, sensors, storage devices, and lighting devices. Manufacturing of these semiconductor devices and products is capital and resources intensive and typically operates with either a vertically integrated manufacturing mode or with a cluster of supply-chain partnering companies in the vicinity of each other. Our research group has previously reported the water recycling and reuse efficiencies of "fabs" in the Science Parks in Taiwan (Lin et al., *Res. Cons. Recycl.* 2015), which exemplify this unique cluster of tech-manufacturing fabs demanding intensive supply of water and energy. We extend our discussion by summarizing the status of water consumption of major semiconductor and optomicroelectronic plants, and the industry's collective and individual water reuse goals. Though the geographical location of fabs plays an important part of the water reuse efficiency, the industry generally displays a strong urgency to use water responsibly to maintain corporates' competitiveness and to effectively manage the risks associated with water shortage. Additionally, the examination of water and energy expenditures of semiconductor fabs indicated a close water-energy relationship in the compartment of ultrapure water production process. The energy needed to treat, recycle and reuse spent water is secondary as compared to the energy demand for manufacturing processes. Using the industrial cluster in Taiwan as an example to illustrate the potential of improve water reuse through collaborative schemes, we conducted a survey-based study to assess how the industry perceived the proposed "inter-plants" and "inter-park" schemes designed to create a reclaimed water trading mechanism in place of the existing "in-plant" practice of water reclamation. Respondents showed an overall positive perception to such schemes on the basis of reducing water and energy demands in a cost-effective manner. The cost of water supply was a dominant factor in the perceived extent of benefits.

1. Background

1.1. Global trends of semiconductor sales and investment

Semiconductors are the enabling technology of the information age. The microscopically structured devices allow data processing, storage, and communication within a "chip" or an "integrated circuit" (IC) the size of a coin. The vast majority of semiconductors demand is driven by consumer products such as the smartphone, automotive, personal computers (PC) and industrial computers. Therefore, the semiconductor industry has played a crucial role as a driver for the growth in the global economy. According to the market data of the Semiconductor Industry Association (SIA), global semiconductor sales in 2015 reached US$335.2 billion, with firms headquartered in the United States holding about half the global market share, followed by Asia-based (Japan, South Korea, Taiwan, China) companies at about 38%, and Europe-based firms at about 9%. Asia-Pacific region continues to experience rapid growth of the semiconductor market, reaching US$231 billion (about 70% of the global market) in 2015.

Depending on their functionalities, IC devices are grouped into segments by the type of product sold, including logic devices for data manipulation (27% of all semiconductor product sales), memory devices for data storage (23%), analog devices for data conversion and amplification (13.4%), microprocessor units for software execution (12.8%), and optoelectronic devices such as

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Nomenclature

Abbreviations

CMD	cubic meter per day (m^3/day)
CMP	chemical mechanical planarization
CR	concentration ratio of constituents of the recirculating water in a cooling tower
CSR	corporate social responsibility
CT	cooling tower
EIA	environmental impact assessment
ESH	environmental, safety and health
ESH&S	environmental, safety, health & sustainability
EUI	electricity utilization index
GEMI	global Environmental Management Initiative
IC	integrated circuit
IDM	integrated device manufacturing
IRDS	international roadmap for devices and systems
ISMI	international SEMATECH manufacturing initiatives
ITRS	International Technology Roadmap for Semiconductors
LCA	life cycle assessment
MF	microfiltration
MBR	membrane bioreactor
MWh	megawatt hour
PFC	perfluorocarbons
PR	water recovery rate from process-loop in a fab
PEI	production efficiency index
REACH	registration, evaluation, authorization and restriction of chemicals
RO	reverse osmosis
RoHS	Restriction of Hazardous Substances
RSD	relative standard deviation
SEMATECH	Semiconductor Manufacturing Technology
SEMI	The Semiconductor Equipment and Materials International
SIA	Semiconductor Industry Association
SIP	Science Industrial Park
TD	total wastewater discharge rate from a fab
TFT-LCD	thin film transistor – liquid crystal display
TOC	total organic carbon
TR	total water recovery rate from a fab
UF	ultrafiltration
UoP	unit of production
UPW	ultrapure water
WBCSD	World Business Council For Sustainable Development
WEEE	Waste Electrical & Electronic Equipment
WFN	Water Footprint Network
WRC	water reclamation center
WSC	World Semiconductor Council
WWTP	wastewater treatment plant

Symbols

B	unit cost
C	cost rate of water supply
G	total water demand
Q	volumetric flow rate of water
SC	cumulative unit cost of a water stream to be treated for reuse
T_1	cost of water supply to a fab
T_2	cost of wastewater treatment in a fab
T_3	cost of reuse water treatment in a fab
V	water loss to evaporation
W	intake water demand
Z	total cost
α_1, α_2, β_1, β_2	empirical cost coefficients for a power function of cost.
φ	cost function of a water reuse unit
η_t	water reuse ratio, equivalent to TR

Subscripts

chem	chemical additive
design	designed capacity
oper	operating value
i	designation for *i*th unit of water reuse process
j	designation for *j*th source of water
r	source
d	discharge

Superscripts

l	number of sources of water supply to a fab
m	number of water reuse treatment units
n	number of calculation stage in the step-categorized function of accumulative unit cost

light-emitting diode and sensors (9.9%). The semiconductor industry is generally characterized by highly fluctuating market patterns, and because of its ubiquitousness in consumer products, the market is heavily influenced by the global economy. Furthermore, the product life cycles are generally short, as new products with enhanced performance continuously emerge with greater complexity and improved chip speed. The reduction of critical feature size of a fabrication technique, as predicted by the Moore's Law, allows for greater IC density and hence improved chip performance. The size of the silicon wafer has also increased from 150 mm, 200 mm, to now 300 mm. The wafer size is of paramount importance to the profitability and productivity of semiconductor manufacturing because the number of ICs to be fabricated in a single piece of wafer increases dramatically. Moving from 200 mm wafer to 300 mm wafer manufacturing, however, required complete new design and construction of a fabrication plant (commonly shortened as just "fab"), which translates to heavy capital investment. These factors force semiconductor manufacturing companies to maintain an intense pace of constant-evolving technology and research expenditure, rendering only a handful of companies capable of operating in a mode of integrated device manufacturing (IDM) – capacity to design, fabricate, package, and branding IC products all within a vertical production chain. Firms with lesser financial resources choose to focus on either IC design ("fabless" or "fab-light" houses) or manufacturing ("foundries") IC products through contract order by IDM companies or design houses. TSMC, for example, is the world's largest foundry that possesses the capacity, delivery time, and quality of product manufacturing to maintain its sales volume and profit size.

The global semiconductor manufacturing capacities, now predominantly on products made by the 300-mm wafer technology, center in East Asia, including South Korea (26%) Taiwan (24%), Japan (18%), and China (13%) (IC Insights). According to SEMI's market forecast report (SEMI, 2015), in 2015, there were twenty-eight 300-mm wafer fabs situated in Taiwan, seventeen each in Japan and the US, twelve in South Korea, nine in China, and eleven in European and Southeast Asian countries. Despite owning only 6% of the global market share in the semiconductor industry, Taiwan is responsible for 26% of the 300-mm chip manufacturing.

Display industry, dominated by thin film transistor (TFT) – liquid crystal display (LCD) in the past twenty years, has drawn comparisons with the semiconductor industry because of its prominent role in consumer tech products. Display panels, fabricated with TFT-LCD technology, have moved from early generation for notebook PC and desktop monitor, to large-screen television, smartphone, and tablet PC. The size of the display panel gets progressively larger with each new generation of product and fabrication technology. Unlike semiconductor products, however, the product turnover of TFT-LCD is much slower than semiconductor's, leaving vendors to continue building manufacturing capacity that eventually leads to oversupply and stagnant growth in the past decade. Concerning facility management, TFT-LCD industry shares many common characteristics with the semiconductor industry because of the similarities in production processing, as both look to green chemistry as the goal for chemical and byproduct management, with cost being the primary driver for improved consumables (materials, energy, and water) optimizations. Energy-saving strategies and benchmarks have also been discussed in the past (Chang et al., 2016). The major display panel manufacturers also concentrate in East Asian countries, namely South Korea (Samsung, LG), Taiwan (AUO, Innolux, CPT, Hannstar), Japan (Sharp, Japan Display), and China (BOE, CSOT, Tianma, CEC Panda).

In greening the global economy, environmental conservation directives such as Waste Electrical & Electronic Equipment (WEEE), Restriction of Hazardous Substances (RoHS), and Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) have created the effect of non-tariff international trade barriers. That is, in addition to functionality, quality, and cost, products, and services are also subject to strict environmental impact evaluation. In the long run, the demand for green products and services will grow, but so will the pressure to reduce greenhouse gas emissions and disclose environmental impact data (such as carbon and water footprints) (Wang and Chiu, 2014).

1.2. Water use characteristics of the high-tech industries

As compared to improving water consumption efficiency, high-tech manufacturing firms generally endeavor on enhancing energy efficiency because of the immediate cost benefit. Additionally, reduction of energy consumption is more accessible to benchmark (Hu and Chuah, 2003; Hu et al., 2008; Pillai, 2011), and is directly tied to the greenhouse gas emission that are widely viewed as having global consequences, as opposed to coping with water shortage issues that are perceived as more of a local concern.

As water stress is increasingly viewed as a potential constraint to economic growth, and as a threat to preserving healthy ecosystems and to promoting social justice, it can be considered part of corporate social responsibilities (CSR) to adopt policies on sustainable water use. Generally, one can discern various drivers for companies to reduce their freshwater consumption and to develop strategies for sustainable water use. Firstly, the water price increases as freshwater supply becomes scarcer. Water tariff can also escalate to cover the cost of operating and maintaining water delivery systems such as storage and treatment, as well as updating aging water infrastructures. A second driver is that many sectors need water for the production of goods or in their industrial processes. Declines or disruptions in the water supply can undermine industrial and manufacturing operations where water is needed for production, irrigation, material processing, cooling and/or washing and cleaning. The semiconductor industry, for example, uses vast amounts of purified water in fabrication plants, for washing the silicon wafers at several different stages in the fabrication process and for cooling various tools. A brief water-related shutdown at a manufacturing plant could compromise all material in production for an entire quarter. Therefore, fabs located in water-stress regions often perceive water security as one of the primary risk factors to the companies' sustainability. The third driver is a corporate's vision to maintain a positive image through being environmentally conscious and a contributor to the community. The competition for freshwater can create long-lasting tensions between industries, businesses and local communities. A fourth driver to accelerate the implementation of sustainable water practices is to reduce the risk of increasingly stringent wastewater discharge regulations. As a major water consuming industry, fabs can be profoundly affected by the decisions of local authorities in more ways than one – Reapportioning water allotments to support ecosystem functions, implementing stricter water quality standards or new regulations, and developing water markets with the reduced water-intake cap.

Society has a growing expectation that the private sector, often perceived as complicit in global water threats, should do its part, regionally and internationally, to address these challenges. Reporting on water consumption in annual sustainability reports seems to be becoming a universal trend among corporates, many of whom have noted that environmentally sound behavior can contribute to the sustained profitable growth and value creation. In doing so, corporates have the opportunity to redesign their management and operations that make their products more competitive, reduce operating and financial risk, promote efficiency improvements and create lucrative new business opportunities (Lambooy, 2011).

Increasingly stringent laws and environmental awareness affect the quantity and quality of the effluent discharge, which in return have motivated minimization of water use at the source. Collectively, these high-tech manufacturing plants worldwide have gradually improved on water consumption efficiency and water reclamation in the past two decades. Additionally, as new plants are built, they are more likely than ever before to incorporate internal water recycling techniques as a means of avoiding the high cost of environmental compliance and retrofitting later on. Industries with the implementation of sustainable practices such as water conservation or waste minimization also could put themselves in a better marketing position and a positive corporate image. Therefore, tech companies typically set their own goals on water efficiency. For example, Intel, the US-based leading semiconductor chip manufacturer, set its corporate environmental goals including reduction of water use on a per wafer basis below 2010 levels by 2020. In Intel's 2015 CSR report, the corporate used 34.1 million m^3 (Mm^3) of freshwater, another 3 Mm^3 of gray water from communities. The estimated amount of water conserved in 2015 was about 15.5 Mm^3. South Korea-based Samsung used 92.4 Mm^3 of water, including 1.23 Mm^3 recycled water in 2015, equivalent to a water "value" of 53 m^3/million KRW (equivalent to about 0.06 m^3/USD). There was significant fluctuation in these values over the past three years (12.3 Mm^3 in 2013 and 0.96 Mm^3 in 2014). Taiwan-based TSMC also committed to reducing water use per chip wafer basis to 30% below 2010 levels by 2020. The goal is ambitious due in part to the increased risk of water deficit in Taiwan. The total water consumption in 2015 amounted to 37.5 Mm^3, presenting an increase from 27.5 Mm^3 in 2011. The total water recovered also increased from 37.7 Mm^3 in 2011 to 65.3 Mm^3 in 2015, which translates to a process water recovery rate over 81%, and a per wafer-layer (using 200-mm wafer as a surrogate) basis consumption of 44.6 L, down from 59.8 L in 2011.

Table 1 illustrates the different measures of water consumption efficiency, even though most of the companies reported their performance index by the amount of water consumed per unit product produced. There has not been a consensus standard or benchmark, however, to accurately gauge the water consumption efficiency. The availability of water and energy, their infrastructures, and the weather patterns are the primary considerations in the advanced semiconductor fab locations. Many plants were built and will be built in water-stress regions such as Singapore, Taiwan, and parts of the U.S. and China. Even though water scarcity does

Table 1
Water consumption, recycling and reclamation performance of major semiconductor companies worldwide in 2015.[§]

Company	Headquarter country	Total water consumption or intake (Mm^3)	Total water reclaimed or recycled (Mm^3)	Water use efficiency index adapted
Intel[a]	USA	34.1 (intake) 37.1 (consumed, with 3.0 from city reclaimed water)	15.5	Water consumed per unit wafer produced (to 2010 level by 2020)
Samsung[b]	South Korea	92.4, with 58.4 from industrial reclaimed water)	37.0 reclaimed 11.5 reused	Water volume per unit of monetary sales (to <50 m^3/M KRW)
TSMC[c]	Taiwan	37.5	65.3 reclaimed and recycled	Water consumption per manufacturing step (30% less than 2010 level by 2020)
Qualcomm[d]	USA	0.681	0.15 reclaimed	None
Micron[e]	USA	NA	NA	Recycled rate (42% globally; >70% in Japan/Taiwan)
Infineon[f]	Germany	23.0 (including 15% from non-potable water source)	0.7 reused and 1.18 reclaimed	Water consumption per unit area of chip (33% less than WSC-reported global average)
Global Foundry[g]	USA	25.0	13.8 (55%) reclaimed	Water consumption per unit production
STM[h]	Switzerland	29.0	13.1 (45%) recycled/reused	NA

[§] Note that the phrase “recycled water” refers to water reused after treatment, “reclaimed water” to water extracted from waste in useful applications, and “reused water” as the use of water in secondary application without treatment. Recycled and reclaimed water are often used interchangeably, though recycled water generally applies water treated from segregated process effluents, whereas reclaimed water generally refers to water treated from fab wastewater to be discharged.

[a] 2015 Corporate Responsibility Report, Intel Corporation, 2016.

[b] Samsung Sustainability Report 2016, Samsung C&T Corporation, 2016.

[c] TSMC Corporate Responsibility Report 2015, Taiwan Semiconductor Manufacturing Co., Ltd. (TSMC), 2016.

[d] 2015 Qualcomm Sustainability Report, Qualcomm Incorporated, 2016.

[e] 2016 Micron Sustainability Report, Micron Technology, Inc., 2016.

[f] Sustainability at Infineon-Supplementing the Annual Report 2016, Infineon Technologies AG, 2016.

[g] Corporate Responsibility Report 2016, Global Foundries Inc., 2016.

[h] Sustainability Report 2015, STMicroelectronics group of companies, 2016.

not prevent the construction of fabs because other factors (e.g., supply chain, logistics, labor cost, tax exemption) may outweigh the risk of water shortage, in locations with specific water-stress concerns, fabs are inherently more conscious about securing a steady source of water supply. Therefore, corporates must recognize that water conservation is at the forefront of their sustainability practices, to both maintain the integrity of the environment and to enhance the corporate competitiveness. For instance, when encountering prolonged droughts or other unexpected water shortage events, fabs must be ready to compensate the water deficit by supplying water internally, through water-saving practices or water recycling and reuse.

Additionally, the variation in product types (e.g., logic devices, memory devices, analog devices, central processing units), even with similar fabrication techniques, differs significantly in the process complexity and the intensity of resource consumption. For example, the fabrication complexity of logic ICs is substantially higher than standard memory, requiring higher power and water demand. Consequently, fabs whose primary products are logics ICs will have higher water and power consumption per unit product (wafer) than memory ICs. In many cases, companies also consider the water and energy consumption marks an indication of their manufacturing capacity and technological competency, and thus are inclined to keep relevant information confidential.

While the flourishing growth of semiconductor, TFT-LCD and other (opto)microelectronics industries in Taiwan has been instrumental to pillaring its economy and securing job opportunities, the intense consumption of energy and natural resources has also led to public scrutiny on the environmental burden these fabs exert, especially in an island-state that is severely lacking natural energy and material feedstock. Furthermore, Taiwan faces water-stress problems despite its abundant precipitation and is vulnerable to the increasingly frequent occurrence of extreme climate episodes. Consequently, water allocation to the industry, in general, has always been scrutinized despite a minor share of distribution (10%) as compared to agriculture (72%). Notably, high-tech industry including manufacturers of integrated circuit chips, solar photovoltaic panels and devices, and display devices, are perceived as a water-intensive industry because of the extensive amount of ultrapure water (UPW) involved in rinsing and cleaning procedures in the production lines. Water use in their secondary systems (i.e., cooling tower and air scrubber) is also high, as the environment in cleanrooms is required to be maintained at high standards (i.e., moderate temperature and low airborne molecular contamination). The water used in the secondary system may not need to meet the ultra-pure water criteria; however, low concentrations in total organic carbon (TOC), as well as conductivity, are expected to avoid fouling and corrosion problems under normal operations. As a result, there have been challenging mandates developed for fabs to follow to achieve the water reclamation goals. Conversely, the capital-intensive nature of these high-tech companies also identify water deficit as part of their corporate risk management consideration, and thus compliance with the demanding water reclamation goals become a commitment that is mutually beneficial to companies and the water management agency.

Tables 2 and 3 show the water use performances for several semiconductors and flat panel fabs. The data was obtained from the company’s reports on sustainability and social responsibility. Some of the reports revealed the total volume of reclaimed water as compared to the amount of water extracted from the water supply agencies, but all of them indicated that their process-level water recycling rates were well over 85% and that the fab-level water recycling rates were at least 75% as mandated. It is noteworthy from these tables that the expression of performance index varies among the companies, depending on how companies express the “unit of production” (UoP) in their fabs. For semiconductor fabs, the UoP is conventionally represented in the total wafer area (in cm^2) manufactured over a month or a year, which can then be converted an equivalent number of 200-mm or 300-mm wafer pieces. However, the complexity of an IC design often determines the volume of water needed to fabricate the product rather than the total size of the wafer produced. The inclusion of wafer starts per year, wafer area, and the number of mask layers involved in the fabrication process would thus provide a more

Table 2
Water consumption efficiency of major semiconductor companies in Taiwan (data in 2015).

Company	Water consumption (Mm^3)	Water reclaimed (Mm^3)	Water use efficiency
TSMC[a]	37.5	65.3 (87.3% process-level recovery)	44.8 L/8″ wafer-layer
UMC[b]	14.5	27.1	85.2 m^3 UPW/m^2 wafer
Powerchip[c]	3.46	3.35 (88% process recovery rate)	NA
Winbond[d]	2.32	81% plant-level88% process-level	123 L/12″ wafer-layer
VIS[e]	4.54	6.85 (83.7% process-level recovery)	8.04 L/cm^2 @ 8″ wafer
Macronix[f]	2.57	3.42 (83.5% process-level recovery)	NA

[a] TSMC Corporate Responsibility Report 2015, Taiwan Semiconductor Manufacturing Co., Ltd. (TSMC), 2016.
[b] 2015 Corporate Social Responsibility Report, United Microelectronics Corporation, 2016.
[c] 2015 Corporate Social Responsibility Report (in Chinese), Powerchip Technology Corporation, 2015.
[d] 2015 Social Responsibility Report, Winbond Electronics Corporation, 2016.
[e] 2015 Corporate Social Responsibility Report, Vanguard International Semiconductor (VIS) Corporation, 2016.
[f] 2015 Corporate Social Responsibility Report (in Chinese), Macronix Corporation, 2016.

Table 3
Water consumption efficiency of major TFT-LCD companies in Taiwan (data in 2015).

Company	Water consumption (Mm^3)	Water reclaimed (Mm^3)	Water use efficiency
AUO[a]	27.2	120 (88% process-level recovery)	0.47 m^3/m^2 panel (reduce by another 30% by 2020)
Innolux[b]	24.2	236	0.357 m^3/m^2 panel
Hannstar[c]	3.9	NA (86% process recovery rate)	0.9 m^3/m^2
Chunghwa Picture Tubes[d]	9.8	6.20 (63% plant-level)	1.587 m^3/m^2

[a] AUO 2015 Corporate Social Responsibility Report, AU Optronics Corp., 2016.
[b] Innolux 2015 Corporate Social Responsibility Report (in Chinese), Innolux Corp., 2016.
[c] HannStar Corporate Social Responsibility Report, HannStar Display Corp., 2016.
[d] CPT Corporate Social Responsibility Report, Chunghwa Picture Tube Co. Ltd., 2016.

accurate expression of UoP. The number of mask layers is proportional to the number of steps required to produce an IC wafer and has been introduced to represent the complexity of production. Therefore, some companies (i.e., TSMC, Winbond) choose to include the total number of layers as a part of the water use efficiency index. For flat panel manufacturers, less variability on product complexity and processing techniques makes expressing water use efficiency more uniform. Most companies report their water use efficiency by the total volume of water withdrawal (or of UPW) to the total area of panel produced.

1.3. Existing international standards and management measures for water-use efficiency

1.3.1. Technology roadmap for semiconductors

The World Semiconductor Council (WSC) is an international platform that brings together industry leaders to address issues of global concern to the semiconductor industry. The WSC is mainly comprised of the SIAs of the United States, Korea, Japan, Europe, China, and Taiwan. WSC has led industry efforts to successfully achieve voluntary reduction goals in the emissions of a family of potent global-warming gases in perfluoro-compounds and to voluntarily eliminate the use of perfluorooctanyl sulfonates, a known class of persistent organic pollutants that are bioaccumulative and toxic to mammalian species. In one of the latest WSC joint statements (WSC, 2016), the organization indicated that the industry in 2015 had achieved 49% reduction in the normalized water consumption (per cm^2 of silicon wafers processed), 25% in the waste generated as compared to 2001.

One of the primary contributions by the SIAs is the drafting and publication of the International Technology Roadmap for Semiconductors (ITRS) that had served as the global roadmap for the semiconductor industry since 1998, revising the technology goals and parameters every two years until 2015. In its previous editions, ITRS roadmap contains an Environmental, Safety and Health (ESH) subsection concerning chemical, process, equipment and facility management. For example, in the 2013 edition, the facility technology criteria on water conservation were to attain a short-term goal in total fab water consumption of 7.8 L/cm^2 of wafer for 300 mm and 450 mm fabs (7.6 L/cm^2 for 200 mm fabs) and a long-term goal (in 2020) of 5.5 L/cm^2 and 4.8 L/cm^2 for the respective fab categories. Additionally, the process UPW consumption was to attain 6.5 L/cm^2 (in 2014) and further reduced to 5.0 L/cm^2 (in 2020). The overall goal was to achieve a fab recycle and reclamation rate over 50% (of total water use) in 2014 and over 75% in 2020.

The industry in the past decade, however, has seen a rapid evolution from device physics through manufacturing, driven by factors such as the Internet of Things, mobile devices, green technologies, and big data. As a result, many in the industry agreed that a new approach to a technology roadmap was needed, and reformed the ITRS roadmap into ITRS 2.0.[1] ESH objectives such as energy and water consumption, greenhouse gas emissions, and contaminated waste reduction, are viewed as an integral part of the facilities integration objective that must be considered along with other factory operation objectives. This transformation entails parallel consideration of chemical and materials management, process and equipment management, and facility management. The overarching aim is to move the manufacturing in the existing plants closer to green technologies, which can be integrated into the design and construction of future facilities. To this end, water recycling and reuse need to be optimized along with the energy saving goal, whether the water recycling opportunities arise from UPW production, wafer cleaning and fabrication processes, and facility-support installations and operations.

1.3.2. The Semiconductor Equipment and Materials International (SEMI)

SEMI is another prominent international industry association serving the manufacturing supply chain for the microelectronics (mainly semiconductors and flat panel display) industries. Significant functions of SEMI are to facilitate the development of the industrial manufacturing through organizing regional trade events and to conduct industry research and to report market data. SEMI also publishes technical guidelines to aid equipment suppliers to evolve with the advance manufacturing standards. Only a handful

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[1] In 2016, as the design of new transistors no longer follows geometric scaling rules and heterogeneous integration to the existing three-dimensional device structure with reduced power consumption, another revised set of criteria was developed and formed the basis of the International Roadmap for Devices and Systems (IRDS) under the sponsorship of IEEE Rebooting and Computing. ESH is now named ESH & Sustainability (ESH&S) to cover a broader sense of resource management matched with product yield efficiency.

of SEMI guidelines are relevant to water treatment and purification, briefly described as follows:

- SEMI F98-0305 "Guide for Treatment of Reuse Water in Semiconductor Processing" applies to water systems designed for reuse of water in semiconductor manufacturing facilities, including directing streams to the front end of an UPW system, to cooling systems, scrubbers, thermal processes, and to irrigation systems, depending on the quality of the water. This Guide can be used to integrate water reuse into the design elements and functionality of water systems.
- SEMI F61-0301 "Guide for Ultrapure Water System Used in Semiconductor Processing" applies to ultrapure water systems used in semiconductor manufacturing facilities for supplying high purity water for chemical dilutions, wafer processing, and other manufacturing processes.
- SEMI F63-0213 "Guide for Ultrapure Water Used in Semiconductor Processing" provides UPW quality parameters and background information for the decision-making process related to new or retrofit facilities that manufacture semiconductors with line widths of 65 nm and smaller. SEMI works with ITRS to assess the semiconductor industry's future UPW technology requirements.

1.3.3. International SEMATECH

SEMATECH started as a government-subsidized, U.S.-based consortium that eventually expanded into an international partnership. The consortium focuses on engaging research and development to advance semiconductor manufacturing through forming a collaboration with both industry and research institutions. SEMATECH also hosts many leading technology conferences and trading events and owns the International SEMATECH Manufacturing Initiative (ISMI) that is responsible for the development and implementation of international nanoelectronics manufacturing roadmaps and standards.

1.4. Life-cycle analyses and water footprint

A life cycle assessment (LCA) is the quantification of the environmental impacts of a given product or service caused or necessitated by its existence. LCA identifies the environmental impacts incurred at different stages in the value chain. Since the influential paper by Williams et al. (2002), who conducted a thorough materials inventory study on the production process of IC chips (32 MB DRAM) and reported that a single chip would consume 1.6 kg of fossil fuel, 72 g of chemicals, 32 kg of water, and 700 g of pure N_2 gas, the environmental impact of microchip production has drawn increasingly more attention. For example, a LCA study for a semiconductor fab suggested that the global warming potential from direct and indirect greenhouse gases (GHGs) and energy consumption from production processes are the major contributors to the environmental impact (Liu et al., 2010). Hence, using low greenhouse-potential perfluorocarbons (PFCs) substitution and electricity saving are effective ways to decrease environmental impacts. Another study examined the environmental impact of four wafer fabs with respect to two metrics – the production efficiency index (PEI) and the electricity utilization index (EUI) (Hua et al, 2013). The study showed that the GHG emissions declined from 601 g to 367 g (39% reduction) in PEI between 1999 and 2007, and from 28.9 g to 13.7 g (53%) in EUI. Notably, these LCA studies invariably concluded that power consumption and GHG emissions have the greatest measurable impacts on the environment.

While useful, the impact of water consumption is undermined by many of the LCA tools as water supply generally does not involve the same intensity of resource extraction and chemical addition as power generation, yet the societal and ecological impacts can be just as significant. Several tools exist for corporates to evaluate their water consumption in the context of a life-cycle framework, including those developed by Corporate Water Accounting, Water Footprint Network (WFN), World Business Council For Sustainable Development (WBCSD), and Global Environmental Management Initiative (GEMI). These tools have the capacity to couple corporate water use, discharge, and facility information with watershed data, thus allowing companies to identify risks and develop strategies to meet the their needs. However, the general lack of database and measurable impacts appear to hinder the development of a standard methodology for evaluating water footprint (Morrison et al., 2010).

Coincidentally, published information on evaluating the impact of water consumption in fabs has been scarce, as there has not been a widely available tool similar to the LCA tools and carbon footprint tools. Intel disclosed the methodology they used to assess water footprint that followed a parallel approach with the standardized carbon footprint assessment, including the direct water usage for microchip manufacturing (Scope 1), indirect usage for electricity production (Scope 2), and the usage in its supply chain for manufacturing (Scope 3) (Cooper and Pafumi, 2010; Cooper et al., 2011). The study reported that Scope 1 represented 66% of the total water footprint assessment of the corporate, while water used in energy generation accounted for about 28% and water use of tier-one suppliers took about 6%. The salient feature of the methodology is the determination of water used to generate the power consumed by the corporation as a whole. The water use intensity varies significantly among the energy sources, ranging from about 505 m^3/MWh for biomass-based energy to nearly zero for wind and photovoltaic energy (for reference, the water intensity for coal-based energy about 1.8 m^3/MWh). Consequently, a decision to purchase renewable energy generated wind turbine and photovoltaic systems not only reduces the carbon footprint, but also help lower the water footprint. Conversely, a decision to purchase hydropower, geothermal power, or biomass-derived power may benefit carbon reduction but increase water footprint.

2. Water reclamation in fabs

2.1. Water reuse performance in Taiwan's Science Parks

The Science Industrial Park (SIP) in Northern Taiwan, administered and incepted in the early 1980's, harbors various clusters of tech companies and represents a type of synergistic supply chain model for the production of IC chips and computing and display devices that are enormously capital-intensive. The rapid growth of the industry in the 1990's and the continual demand for more energy and water supply to sustain the growth at the time also led to a compromise between the industry, the Park's administrative office, and the environmental protection agency. As documented in its environmental impact assessment (EIA) reports, the SIP was asked to achieve a mandated level of water recycling and reuse efficiency. Similar outcomes had since been followed as other science parks in the southern and central Taiwan developed. Over the years as the fabrication technologies evolved and fabs were newly built or renovated, numerous versions of water flow balance have been revised to accommodate the water consumption and reuse by newer processes. As of 2018, the average daily water consumptions by the main campuses in the northern, central, and southern Taiwan SIPs were about 137, 106, and 125 thousand cubic meters per day (kCMD), respectively. In principle, three key indices developed for evaluation of water use performance for a plant included the process recovery rate (PR), total plant recovery rate (TR), and total plant discharge rate (TD). These values were calculated based on the water flow balance chart collected from the fabs, whose simplified version is shown in Fig. 1a. The recovery rates are defined as total reclaimed water over total water demand (i.e., available for using), and higher recovery rate represents improved water use efficiency. On the other hand, the discharge rate is defined as total discharged water from the fab's wastewater treatment facility over total water demand, and it is expected to have the rate as low as possible. The definition and the variability of the performance as determined by the three indices across the SIPs have been reported in details in an earlier publication of our group (Lin et al., 2015). The study clearly shows that the fabs with greater water demands performed significantly better across the indices than those with lesser water demand (Fig. 1b). For example, The average values of PR, TR, and TD for fabs using greater than 5000 CMD of water (a sample size of 24 fabs) were 82.3%, 74.8%, and 65.2%), as compared with the values (59.4%, 59.0%, and 61.4%, respectively) from fabs whose water demand ranged between 100 and 500 CMD (sample size of 14 fabs). The difference was also reflected by the ratio of the used water recycled back to the pure water system (for ultrapure water production and other non-potable uses) to that to the secondary (facility support) water system. The values of this ratio were 3.9 and 1.7, respectively, for the same water demand groups. The last set of data implies that fabs with greater water demand identify that the stringent water recycling requirements (i.e., PR and TR values) can only be achieved by reclaiming the spent water to a water quality level superior to the city water they receive. Therefore, an imaginary "drop" of water can be recycled several times before being discharged out of the fab. Conversely, with lesser opportunity to reuse the spent water for manufacturing processes, fabs with smaller water demand tend to direct the recycled water to facility-supporting purposes before discharging. Other factors, such as the age of the fab facility and the type of manufacturing processes and products, also play a role in the difference in water use efficiency. The size of water demand, however, proved to be the most critical factor.

Fig. 1d and e shows the average water recycling performance of the fabs in Central Taiwan SIP over the most recent three year based on the data accumulated since our last report. The semiconductor fabs, in average, have continued to improve the PR and TR values, reaching a PR value of 90% and a TR value of 83% in 2017. Those values for the optoelectronic fabs were slightly lower and appeared to have stagnated at a PR of 83% and a TR of 78%. Additionally, the variability of these values for the optoelectronic fabs in each year was markedly greater than those for the semiconductor fabs. The larger variability for the optoelectronic fabs is primarily attributable to the great diversity of products manufactured in both individual fabs and across the industry. Besides TFT-LCD, fabs manufacturing solar panels, light-emitting diodes, and other light-emitting devices are all grouped into this sector. The manufacturing processes for these products do not use as much water as TFT-LCD production, thereby may not have as much capacity and incentive to perform as well. Nevertheless, the sustained performance for fabs consuming large amount of water to achieve >85% PR and >80% TR suggests that the viability to recycle and reuse water at a high level by implementing an effective water management strategy.

Data can be further broken down to recycle stream level for benchmarking purposes. For plant operators, examining the recycling and reuse ratio can help identify opportunities to improve water consumption efficiency. For instance, the ratio between UPW production flow and the feed water flow gives a guideline of the UPW efficiency; a ratio too low (e.g., <0.65) indicates low productivity, a ratio too high (>0.8) may implicate a high risk of system loads and unjustified energy consumption. Furthermore, a ratio of the direct recycling of process effluent (C5 in Fig. 1a) and of the regenerated water (C3) to the feed water flow can also shed light to the water management strategy to be optimized. A ratio of reuse for processes and for facility operations is also reflective of water reuse performance. For the administrators, a change of water recycling and reuse ratio beyond ordinary fluctuations in the globalized data (i.e., collective water flow balance chart) may signify an event that merits attention. One way to effectively set a benchmark value is to examine the relative standard deviation (RSD) of a water-recycling ratio for fabs in the same group. Fig. 1(f) and (g) exemplify the RSD of the annual water recycling ratios for process and facility uses corresponding to the semiconductor fabs and optoelectronic fabs. As seen in the case of the semiconductor group, a decreasing RSD mean value over a definitive period signifies that the performance by the members in the group tends to gravitate to a mean value of water recycling ratio. These mean values can then be justifiably viewed as the benchmarks for all members (fabs) to follow. Conversely, an increasing RSD value over time suggests a widened variability among members in the group to achieve a water-recycling ratio. This scenario can be seen in the case of the optoelectronic group. The causes of the event warrant a closer investigation by the administrators.

2.2. General guidelines for designing fabs' water reclamation

Despite ample experience of water reuse, reclamation, and treatment of microelectronics fabs, there remain to be stiff challenges from the viewpoints of both environmental protection and water resource efficiency (Global Water Intelligence, 2012). For example, as semiconductor devices continue to get smaller, the manufacturing processes inherently become more complicated to pursue process chemistries to achieve smaller line-width devices. Consequently, the wastewater streams will continue to change and become more chemically complex. The knowledge on the environmental toxicity, analytical capability, and contaminant separation will have to evolve to keep up with the change in the manufacturing chemistries. Several challenges likely to be encountered by fabs include:

- Separating different waste streams: Water recycling and reuse require substantial investment in either complex waste stream segregation with subsequent treatment or sophisticated end-of-pipe solutions. The industry needs to find the best way of separating different wastewater streams to maximize water reuse on site.
- Increase in water reclamation by extracting clean water from waste stream increases chemical concentration in the waste streams, posing environmental compliance difficulty. Dilution with external water to comply with the concentration-based discharge limits is not a sustainable solution. A long-range solution such as reduction in chemical uses and a cost-effective process to concentrate chemical waste remains technically challenging. Increasing water recycling will also likely increase energy and possibly chemical consumption.
- Managing large volume flow rates: Some of the new fabs have been built within existing manufacturing facilities, which increases the total volume of wastewater generated on site. Consequently, new solutions for managing high volumes of wastewater are needed.
- Increase in energy consumption intensifies cooling load and inevitably evaporates more water during the cooling process. The energy consumption and the extent of in-plant water reclamation need to be analyzed to understand the water-energy nexus of fabs.

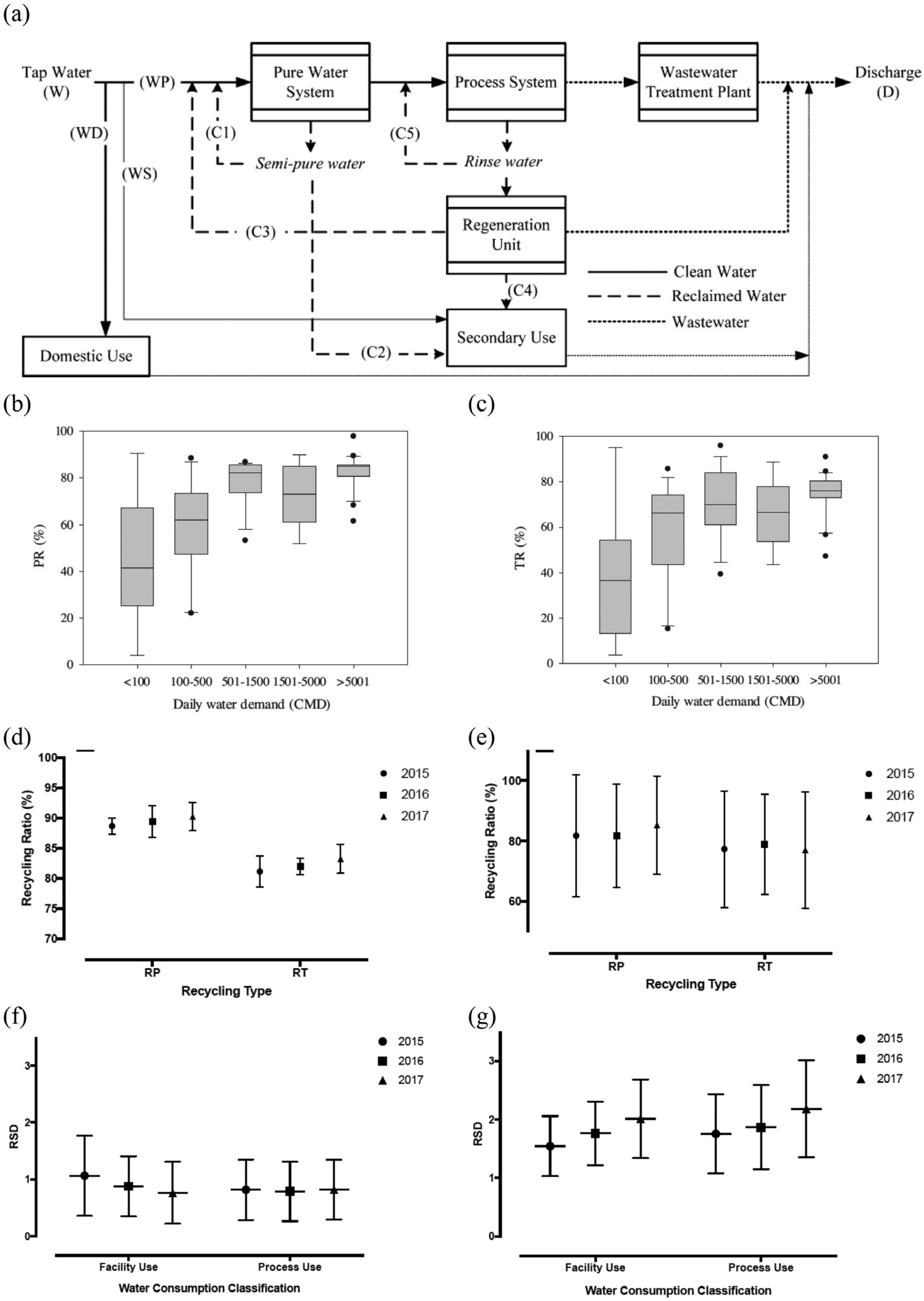

Fig. 1. (a) Water flow balance chart by which the values of PR, TR, and TD are determined (WP: water consumption for processes; C1: reject or effluent recycle back to pure water production system; C2: reject or effluent recycle for secondary water use; C3: rinse water from process system recycle back to pure water production system after the regeneration unit; C4: rinse water send to secondary water use after the regeneration unit; C5: rinse water direct reuse in process system.) The PR (b) and TR (c) values for fabs with the various water consumption size groups. The PR and TR performances over the past three years for the IC fabs (d) and optoelectronic fabs (e). The relative standard deviation of the annual water recycling ratios for process and facility corresponding to the semiconductor fabs (f) and optoelectronic fabs (g) over the same period of time are indicative of the trends of water recycling performances. (Parts (a) through (c) are reproduced from Lin et al., 2015, with the permission of the copyright holder (Elsevier)).

2.3. Process waste stream reclamation and treatment

The semiconductor manufacturing process uses a wide range of slurries and chemicals, including hydrofluoric acid for cleaning and etching photosensitive components following the photolithographic process. Other chemicals such as ammonium hydroxide, hydrogen peroxide, hydrochloric acid, sulfuric acid or phosphoric acid are commonly used in rinsing operations. The wastewater includes mixtures of these chemicals, together with other contaminants that result from the manufacturing processes, such as traces of nickel, copper, cobalt, titanium, fluoride, silica, ammonia, and many other organic and inorganic compounds. The complexity of the wafer fabrication processes leads to the generation of wastewater that are highly contaminated with chemicals and particles. Successful treatment or reclamation of the waste streams thus required robust effluent segregation systems. In general, several universal waste streams have been treated separately, including:

- Chemical mechanical polishing (CMP): The CMP is an essential process in semiconductor fabrication for polishing metal and oxide surfaces using slurries containing well-dispersed nano-sized particles. The resultant wastewater can be treated by flocculation and sedimentation to remove slurry particles. Copper can then be precipitated as copper hydroxide and removed with the slurry particles. However, any method of precipitation produces copper-containing sludge that would be handled as a hazardous waste, which could incur a significant cost depending on the local environmental regulations. More advanced treatment processes such as coagulation followed by microfiltration (MF) or ultrafiltration (UF) have been developed to separate agglomerated particles from water (Su et al., 2014; Testa et al., 2011). Reverse osmosis (RO) are often needed if the treated water is to be reused.
- Fluoride-bearing stream is commonly treated by calcium fluoride precipitation, flocculation, and solid/liquid separation. Fluoride removal by precipitation as calcium fluoride is one of the most distinct processes for removal of high fluoride concentration from fluoride-bearing wastewater. Calcium salts, such as calcium chloride and calcium hydroxide, may be used to precipitate fluoride as insoluble calcium fluoride salt (Aldaco et al., 2007; Huang and Liu, 1999).
- Low organic rinse water: Streams containing a low level of total organic carbon (TOC) comprises a significant fraction of the wastewater produced in a typical fab, as they come primarily from rinse waters (second and final rinses and organic-free rinses) that account for approximately 40% of the total UPW consumption. The main chemicals in the rinse water include acids (H_2SO_4, H_3PO_4, HF, HCl), ammonia and ammonium fluoride (NH_4OH, NH_4F), hydrogen peroxide (H_2O_2), and traces of organics. Much of the collected rinse water is already cleaner than the municipal supply water it replaces. This stream of water can be either directly reused with no additional treatment as a partial replacement for the municipal water supply used in a facility, or treated before reintroduction to the UPW system.
- High organic rinse water: Rinse water containing organics generated from several cleaning processes, and organic baths are recovered by advanced monitoring and control devices followed by activated carbon filters and various organic removal steps. Biological processes such as activated sludge and membrane bioreactor (MBR) are commonly applied to remove the organic content of the wastewater (Den et al., 2002; Xiao et al., 2014). However, because the stringent requirement of TOC in the water to be reused at either the process or facility level, the reclamation cost of the organic waste stream is often difficult to justify.

2.4. Facility water reclamation and reuse

While most of the attention concerning in-plant water-saving opportunities in fabs has focused on the production end, facility-supporting units can potentially be a significant source of water consumption. In particular, cooling towers (CTs) – an installation that takes advantage of the thermal capacity of water to reduce and control the temperature of an indoor environment – are typically the most significant point of water consumption in industrial facilities accounting for about 15% to 30% of total water use, and should be considered as a major area of water-saving strategy. CTs use and lose water in several ways, including evaporation, drift or mist, blowdown, and leaks or overflows. As a result, make-up water is needed to compensate for these water losses to maintain the necessary refrigeration. Although manufacturers' specifications provide standard operating parameters for a facility operator to follow as a guideline, many plant engineers accumulate their own experience to optimize the parameters. Fig. 2 shows the correlation plots of refrigeration tons and make-up water rate for plants in two SIP campuses in Taiwan. Evaporation loss represents 80–95% of the make-up water for these plants. Linear regressions based on the data can be calculated.

As water circulates through the cooling system and a portion is evaporated in the cooling tower, the concentration of solids increases until it reduces efficient performance. The threshold "concentration ratio" (CR) (expressed in conductivity) is the ratio of total dissolved solids in the blowdown water to that in the make-up water. The CR widely accepted in cooling tower operation ranges from two to six. Our survey results indicate that plants' operators initially rely on manufacturer's specification to set the blowdown conditions, typically using a safe CR as the indicator to start bleed-off regardless of the make-up water quality. We recommended a baseline conductivity of the blowdown water at 1800 μS/cm, which represents a CR in the range between 6 and 9 for tap water (conductivity typically between 200–300 μS/cm) and of >10 for RO brine water. Table 4 is the calculated plant-wide water recycling rates if the CR is increased from the existing value (column) to a higher value (row). The water-potential depicted in the table is derived from the assumption of a 100 RT (capacity in refrigerating ton), cooling temperature from 30 °C to 25 °C, and a fixed air flow rate. Water losses only due to evaporation (due to temperature difference) and bleed-off frequency are considered. It should be noted that these values are highly variable, as factors such as ambient conditions (humidity, temperature, and pressure) can cause significant deviations. Evaporation loss is also highly contingent on the intensity of air convection. As a rule-of-thumb, these values illustrate the potential to save a large amount of water by increasing the operating CR. For example, with a relatively clean feed water with an electrical conductivity of 200 μS/cm, operating with a CR greater than 10 is typically acceptable without concerns over scaling problem. This approach would save potentially as much as 64% as compared to operating at a CR of 1.5. Even with feed water having a conductivity of 500 μS/cm (e.g., reclaimed water), operating at CR of 5 would still result in a 58% water-saving potential. Operating at a CR greater than 10 is still feasible, although the benefit of water-saving potential starts to taper off and the risk of scaling and other contamination-related problems may escalate.

The use of reclaimed water as CT make-up water has the advantage of conserving tap water and reducing operating cost, but it also poses risks to reduce the cooling efficiency and even damage the installation attributed to the constituents in the reclaimed water. Reclaimed water typically has characteristics of low pH, low calcium hardness and low alkalinity that can contribute to scaling and corrosion of pipelines and metal surfaces of the

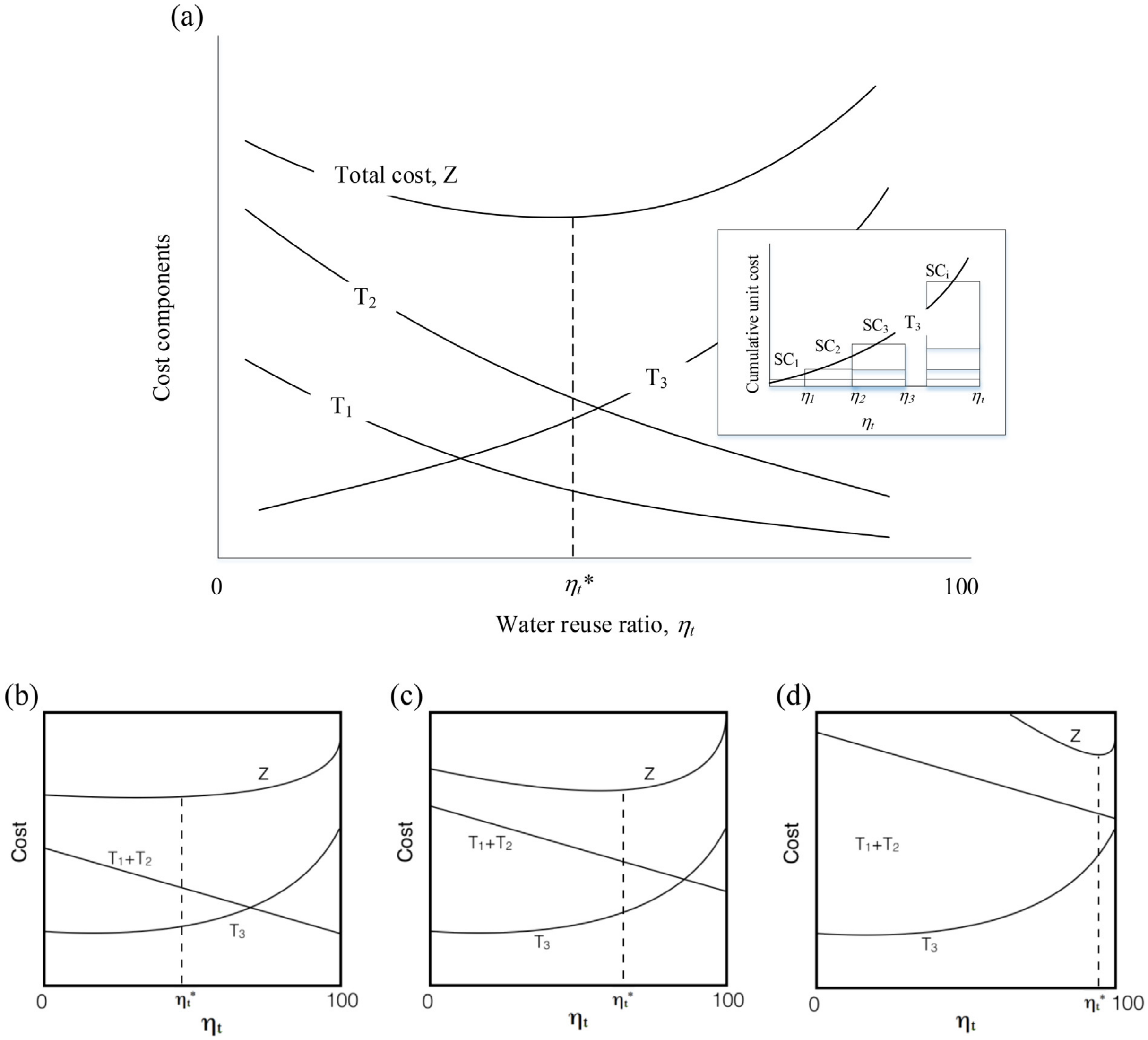

Fig. 2. (a) Conceptual curves for water cost versus water reuse ratio to determine the optimal cost based on the cost components. Graphical representation of cost effectiveness of reusing water in fabs when water tariff was (b) low; (c) medium, and (d) high.

Table 4
Water-saving potential by increasing the existing CRs to higher CRs.

Existing CR	Target CR										
	2.0	2.5	3.0	3.5	4.0	5.0	6.0	7.0	8.0	9.0	10
1.5	33%	44%	50%	53%	56%	58%	60%	61%	62%	63%	64%
2.0		17%	25%	30%	33%	38%	40%	42%	43%	44%	45%
2.5			10%	16%	20%	25%	28%	30%	31%	33%	34%
3.0				7%	11%	17%	20%	22%	24%	25%	26%
3.5					5%	11%	14%	17%	18%	20%	21%
4.0						6%	10%	13%	14%	16%	17%
5.0							4%	7%	9%	10%	11%
6.0								3%	5%	6%	7%

equipment. Moreover, contents of organic carbon in reclaimed water can also cause microalgae-growth related protein foaming problem (i.e., biofouling). Consequently, the water quality of a recycled stream as the make-up water for CTs needs to be carefully monitored and control, particularly of its pH and alkalinity, conductivity, hardness, and organic carbon content. One study reported the occurrence of iron and copper leaching from parts of a CT system of a fab due to the high corrosion potential of the reclaimed make-up water, even in the presence of chemical corrosion and scaling inhibitor. Among the several methods (increasing recirculating rate to maintain a higher pH value, dosing with sodium carbonate to maintain alkalinity, and replacing with tap water with a higher pH value), the addition of sodium carbonate provided the optimal results considering the cost and ease of operation. The system was also modified with the addition of sprinklers and covers to reduce the formation of foams.

2.5. Cost elements of in-plant water reuse

The cost-benefit analysis aims to identify the most economically efficient measures while addressing the current and future water needs. Pan et al. (2011) reported the cost-benefit analysis for a 200-mm wafer semiconductor fab in China and identified seven potential reclamation points of processing water, namely RO reject, UF reject, multimedia filtration backwash, online analyzer drain, ion-exchange backwash, inorganic wastewater, and organic wastewater. The life-cycle costs (i.e., construction, operating, maintenance, labor, overhaul costs) and the unit-volume costs were evaluated. The cost ranged from as low as $64/m^3 for reclaiming UF reject water to as high as $560/m^3 for recycling organic wastewater. Based on the cost analysis, >60% process spent water could be reclaimed with a payoff period less than ten years when the tap water cost is $0.58/m^3, and >85% recycled rate when the tap water cost is $0.95/m^3. Recently, our group applied the multi-constraint linear programming method to optimize water reclamation strategy for a wafer packaging fab in Taiwan and found that the water reclamation costs ranged between $0.30/m^3 (UF) and $1.07/m^3 (MBR + RO system). If the water tariff were to be elevated to $1.00/m^3 as compared to the existing fixed flat rate at $0.40/m^3, then the overall water consumption cost would have been reduced by 27% (Lu et al., 2018).

A typical industrial plant has three general cost categories for water management, namely the cost of intake water (T_1), the cost of wastewater treatment (T_2), and the cost of reuse water treatment (T_3). The costs incurred from in-plant transport and distribution are considered part of the design and operation of either the wastewater or reuse facility. Liaw and Chen (2004) modeled the cost function of water to locate a cost-effective water reuse ratio through the minimization of the objective function in Eq. (1):

$$\mathrm{Min}\,Z = T_1 + T_2 + T_3 \tag{1}$$

$$T_1 = \sum_{j=1}^{l} C_j Q_j \tag{2}$$

$$T_2 = \alpha_1 Q_{design}^{\beta_1} + \alpha_2 Q_{oper}^{\beta_2} + kQ_{oper} + C_{out}Q_{out} \tag{3}$$

$$T_3 = \left\{ \left[\sum_{i=1}^{m-1} SC_i(\eta_1 - \eta_{i-1}) \right] + SC_m(\eta_m - \eta_{m-1}) \right\} G \tag{4}$$

$$\text{where} \quad SC_i = \sum_{i=1}^{m} C_i\ , \quad C_{i+1} \geqslant C_i, \quad i = 1 \ldots n \,\text{and}\, 1 \leqslant m \leqslant n \tag{5}$$

Eq. (1) simply states that the total cost (Z) is the summation of aforementioned water-related cost components. Eq. (2) states the cost of intake water considers all prices from various water sources (e.g. tap water and reclaimed water) where C_j and Q_j is the average fixed cost rate and volumetric flow from water source j, and l is the number of sources. Eq. (3) states that the cost of wastewater treatment may include capital costs, electrical power costs, chemical additives cost, and off-plant discharge fees at site. In the equation, Q_{design} and Q_{oper} represent the designed capacity and the actual operating flow of a fab's treatment plant, respectively; α_1, β_1, α_2, β_2 are constants that describe the power function of costs to the wastewater flows to be treated, k is the average cost of chemical additives, and C_{out} is the average unit cost of discharge of treated wastewater with a flowrate Q_{out}. Both T_1 and T_2 decrease with water reuse rate increases. The cost of reuse water treatment, depicted in Eqs. (4) and (5), is calculated by integrating a step-categorized function of cumulative unit costs. In Eq. (4), SC_i is the cumulative unit cost of a stream that leaves ith reuse treatment units, whereas in Eq. (5), C_i is the average cost of water reuse incurred at treatment unit i. In those equations, m is the number of stages to incrementally improve the water reuse ratio (η), and n is the number of reuse treatment units in the system. Therefore, Eq. (4) is composed of the cumulative costs incurred in the previous stages and the cost incurred in the current stage. The cumulative unit cost (SC) is then multiplied by the total water demand (G) to obtain the total cost of water reuse. The concept of the cost model is graphically illustrated in Fig. 2a. The inset of Fig. 2a shows the progression of water reuse stages and the cumulative cost associated with it. At the optimal water reuse ratio from water conservation strategies, the total water cost can be controlled at a minimum by reducing wastewater and intake water costs and promoting appropriate water reusing.

Hsia Lo (2010) adopted a similar approach to rationalize water reuse rate for fabs but furthered the model by directly linking the cost components with the aforementioned water reuse rates for process-level (η_p) and facility-level (η_t). For example, T_1, T_2, and T_3 can be expressed regarding the fab-level water reuse rate, η_t:

$$T_1 = P_r W = P_r[(V - G)\eta_t + G] \tag{6}$$

$$T_2 = P_d W = P_d(W - V) = P_d[(G - V) - \eta_t(G - V)] \tag{7}$$

$$T_2 = a \times e^{b\eta_t} \tag{8}$$

where G represents the total water demand, W is the intake water demand, and V is the water loss to evaporation. Unlike Eq. (3), this model assumes T_1 and T_2 linearly decreases with increasing η_t, and that the cost of water reclamation projects follows an exponential function with η_t. Hence the total cost of water components becomes

$$Z = P_t[(V - G)\eta_t + G] + P_d[(G - V) - \eta_t(G - V)] + ae^{b\eta_t} \tag{9}$$

By taking derivative of Eq. (9) and setting $dZ/d\eta_t$ to zero, one can locate the optimized water reuse rate with respect to cost effectiveness. This equation would be:

$$\eta_t{*} = \frac{1}{b}\ln\frac{(p_r + p_d)(G - V)}{ab} \tag{10}$$

The relationship between cost and reuse rate expressed in Eq. (10) is reflected in Fig. 2(b) through (d). T_1 and T_2 generally decrease with enhanced water reuse rate attributing to the reduction of water intake demand and discharge flow volume. Consequently, with a small value in the water tariff, the optimum water reuse rate (η^*) would be also low (Fig. 2(b)); as water tariff increases, the value of η^* also increases (Fig. 2(c)). At a high water tariff, η^* becomes greater than unity, indicating that cost would not be a limiting factor to the reuse rate (Fig. 2(d)).

Other than illustrating a model to estimate the cost to attain a water recycling goal, the underlying message implied by the cost model was that the current water supply and discharge costs in Taiwan does not incentivize fabs to set an aggressive in-plant water reclamation goal from the sole viewpoint of economics, though regulatory enforcement, corporate image, and long-term corporate competitiveness are also factor that drive the companies to comply with the ambitious standards. Consequently, additional cost-driven schemes revolving around the idea of trading and sharing reclaimed water while meeting the water conservation goal within the regulatory framework will provide an alternative solution to the challenge. These schemes will be discussed in Section 4.

3. Water and energy correlation in fabs

The energy intensity of recycling water is inherently high because of the low water quality. Frequently, recycling schemes are perceived as greener or more sustainable alternatives to conventional water supplies derived from surface or groundwater sources. However, when sustainability is a driver for implementation, it entails a broader examination of other life-cycle components such as the energy needed to attain water recycling goals. To date, there has been plenty of literature discussing the correlation between water supply and energy consumption in various scales (global, national, regional), for benchmarking purposes and crosscutting the socio-economic impacts of both water and energy in different parts of the world (Wakeel et al., 2016; M. Lee et al., 2017; S.-H. Lee et al., 2017; Sanders and Webber, 2012; Park et al., 2008; Darwish et al., 2015). Most of the data acquired to make these analyses were based on the energy intensity in water treatment plants or reclamation plants equipped with a broad spectrum of water purification processes. The trade-off between saving water and spending energy is not well defined and often is geographically dependent. For example, regions with high water deficit risks or with considerably higher water supply cost than energy cost are naturally more amenable to use reclaimed water. Furthermore, recycled water can be reused for drastically different purposes; some regions allow and even encourage aquifer recharge, some prefer to use for agricultural irrigation to boost food security, some allow only landscaping and other non-human contact purposes. Each of the reuse purposes bears different trade-off considerations. For those that would enable potable use, higher energy consumption becomes a trade-off for reduced health and demand risks (Institute for Sustainable Futures, 2013).

The concept of "matching treatment with risk" also applies to water reuse scheme in fabs, where reclaimed water can be directed to replace tap water for UPW production, facility installations (e.g., CT, central exhaust scrubbers) water supply, domestic (i.e., cleaning, sanitary flush), or landscaping. Directing reclaimed water to enter UPW production system for chip-making processes carries the highest risk of deteriorating production yield and contamination to UPW network, and requires advanced treatment process to ensure the water quality meets the criteria of at least those of the municipal water. Concerns over contamination by unintended, microscopic levels of contaminants in the likes of nano-scale particles, colloids and macromolecules (similar size to the wiring pitch width on a semiconductor device, which continues to shrink below the scales in the single-digit nm) (Ruth and Berndt, 2016; Nakata et al., 2017) and organic molecules (Liu et al., 2008) have driven more advanced UPW production technologies that require even more energy input. Other reuse purposes are far less sensitive to water quality for facility operations, though concerns over health-related risks are still a subject of discussion as regulations continue to evolve.

3.1. Water and energy consumption distributions in typical fab

Information about water and energy consumption patterns in many fabs worldwide is primarily considered confidential, because the data may implicate the productivity and process complexity. Consequently, details of water and energy consumption data specific to fabs, particularly those linking to manufacturing processes, are kept strictly confidential from public disclosure. Nevertheless, for benchmarking purpose, plants are willing to disclose non-process-related information for research purpose and for the greater benefit of the technology development. The Sankey diagrams presented in Fig. 3 outline the utility distributions in a typical fab. For energy use (Fig. 3a), manufacturing tools take up about 40% of the total energy consumption, whereas operating fab facility use about 56%. Noteworthy of the diagram is that water-related operations engross less than 10% of the total energy demand, although some crosscutting installations such as chillers, where water acts as a transport medium to remove the heat of the targeted premises, are categorized as a part of the air-handling system rather than water supply system. The energy consumption distribution also indicates that, despite engaging with more intense effort to reclaim spent water, the energy demand on water supply in a fab is still considered secondary.

Conversely, a dominant bulk of water eventually goes directly into process uses as UPW (Fig. 3b). About two-thirds of the spent process water flow can be regenerated for UPW production to replace the volume of tap water that otherwise would have been needed. These regeneration water streams mainly stem from the recyclable portion of the UPW production process (e.g., RO reject stream, filter media backwash streams) and the process effluents that are either lightly contaminated (e.g., rinsing water, tool's wetting water) or contain relatively simple components of pollutants. Regeneration of heavily contaminated process effluents for UPW production is usually considered cost intensive even in the presence of available treatment technology to achieve the level of purity necessary. Given the amount of money invested in microchip production, companies are often cautious of the risk of impairing the production yield by using reclaimed water until the feasibility has been sufficiently proven. About one-third of the spent water is regenerated for the use of cooling towers and air scrubbers. From the end-cycle perspective, about 67% of tap water flow entering a fab eventually discharges out of the fab boundary; the remaining fraction evaporates through cooling towers and other heat-related installations.

3.2. Water and energy consumption coefficient in fabs

The energy-water link is often overlooked when designing plant processes, though companies have begun to be more conscious of the economic benefit yielded by conserving energies through reducing water consumption. However, the correlation between water and energy for fabs has either not been extensively studied or has not been disclosed for confidentiality reason. Compartmentalized water and energy consumption has been even less examined. One such study does indicate that removing fabrication processes from consideration – because maintaining contamination-free production environment (i.e., cleanrooms) remains the single largest energy expenditure in fabs – there was a clear correlation between the water and energy consumption in the system compartments (Lin and Chang, 2016). For example, the UPW production ranks at the top among all non-process systems for the demand of both water and energy, with an annual-average energy intensity (per water volume) of 0.58 kWh/m^3. What follows are wastewater treatment (0.68 kWh/m^3 including collection, treatment, and discharge), water reclamation (0.24 kWh/m^3, including only purification process), and water distribution and transport (0.30 kWh/m^3). The overall non-process energy intensity per water volume in the fab was 0.46 kWh/m^3. Energy-saving opportunities thus exist if these water-related energy intensity benchmark can be established. For example, one can make a hypothetical calculation that, by improving the energy intensity of UPW production by 10%, a medium size fab with a UPW consumption of 8000 CMD could save more than 170 MWh of electricity a year, roughly 1–2% of the total energy of the fab or a day's worth of energy consumption.

3.3. Energy intensity in water treatment and reclamation processes

Plappally and Lienhard V (2012) comprehensively reviewed the energy intensity throughout the life cycle of water, including extraction, transport, treatment, distribution, end use, collection and discharge, wastewater treatment, and reclamation. With water reclamation as a successive step of wastewater treatment, their review provides a snapshot of the energy needed to reclaim spent water from chip fabrication processes. For example, the NEWater

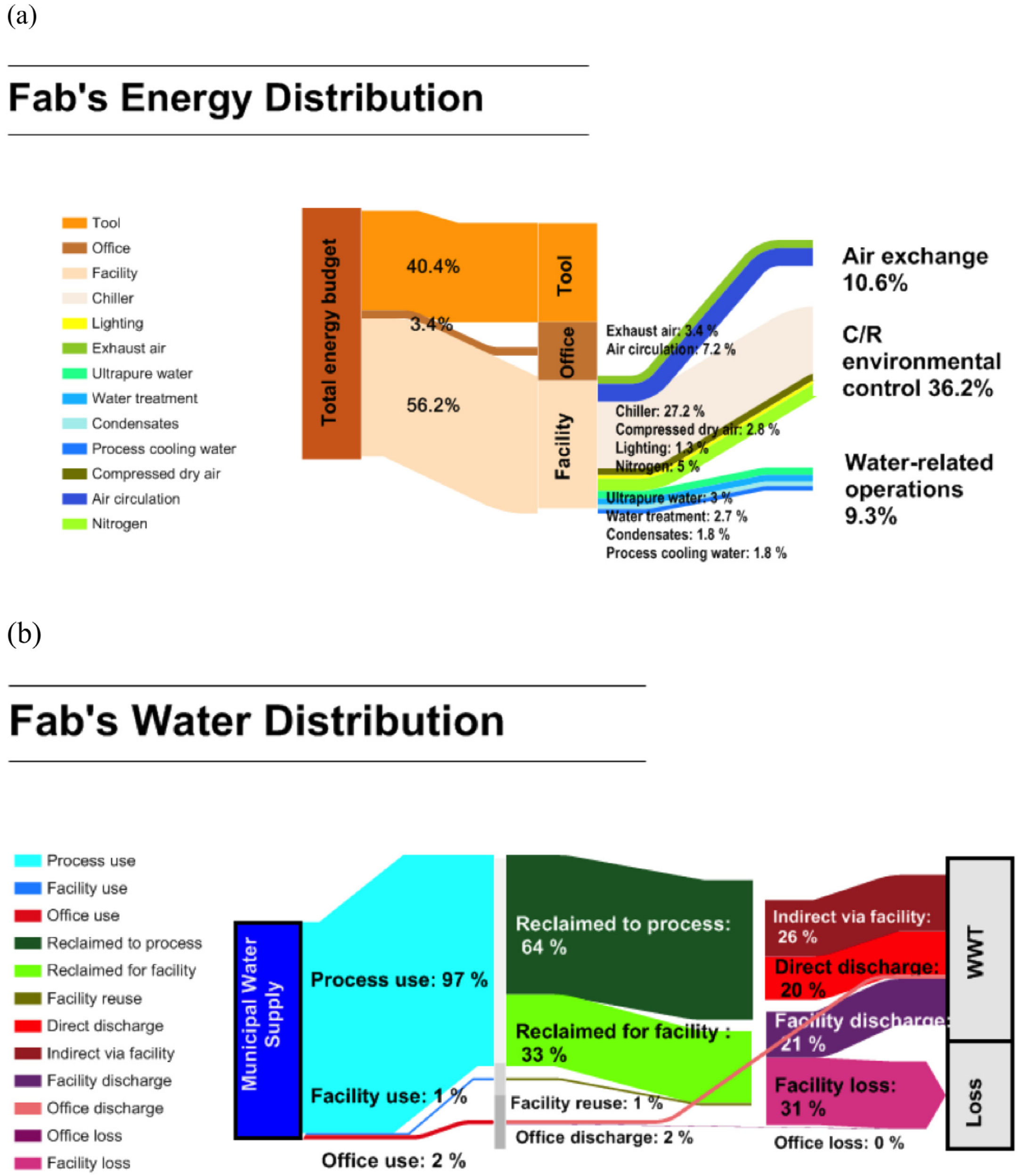

Fig. 3. Water (a) and energy (b) distributions of fabs. Data are compiled from plants (semiconductor, flat panel, solar panel fabs) with energy demands (electric load) greater than 10,000 kW or water demand more than 3000 cubic meter per day.

reclamation plants in Singapore consume energies in the range of 0.72–0.93 kWh/m^3 to produce potable-level water from the municipal effluent. In Australia, a plant reported that residential wastewater reuse had an energy intensity of 0.27–1.2 kWh/m^3. At Laguna Beach, California, wastewater reclaimed was for use as irrigation water at an energy expenditure of 2.9 kWh/m^3, and for use as potable water at the energy intensity of 3.1 kWh/m^3.

Considering that many of the water reclamation technologies are variants of municipal treatment systems, we select the treatment processes and energy intensity data that befit common spent water reclamation processes targeting various contaminants in fabs. Among those are activated sludge (0.33–0.60 kWh/m^3) and membrane bioreactor (0.8–0.9 kWh/m^3) for removal of the organic content of process effluents, ultraviolet (0.015–0.066 kWh/m^3) for disinfection, pressure-driving filtration for separation of colloids and macromolecules, and RO ($\sim$0.5 kWh/m^3) for the removal of total dissolved solids. The energy intensities of other advanced technologies for purification of a low level of TDS (less than 50,000 mg/l), including reverse electrodialysis, capacitive deionization, vibratory shear-enhanced process, fall within the similar range as that for RO. To treat highly concentrated waste streams, operations such as evaporation, crystallization, membrane filtration all demand a much higher level of energy (25–80 kWh/m^3). Emerging technology, such as adsorption desalination (Ng et al., 2013), developed for treating effluents with highly concentrated TDS, have claimed to be more energy efficient (2 kWh/m^3), though full-scale operation data are minimal.

Gabarrón et al. (2014) studied the energy intensity of several MBR units in plant operations, with design capacity ranging from 2160 to 35,000 CMD. Most of these are stand-alone units, and others are hybrid design retrofitted from existing oxidation ditch. The design flux of these units are related to the type of membranes installed and the aeration intensity provided to the membrane surface and the suspended biomass. They found that there was a clear dependence of the energy intensity to the operating hydraulic load (i.e., volume of wastewater treated), ranging from 0.51 kWh/m^3 at a high load (~70% of the design hydraulic load) to 2.1 kWh/m^3 at a low level (22%). Additionally, if a parallel biological treatment line (suspended or fixed-film activated sludge system) existed to form a dual-line system, then the range of energy intensity decreases substantially to 0.4–0.8 kWh/m^3, also corresponding to their hydraulic loads. The two most important factors on energy intensity are the operating treatment volume and operating flexibility of the MBR system. Majority of the treatment processes consistently demonstrated that the amount of the wastewater treated plays a vital role in the energy intensity for wastewater treatment processes; the higher the volume treated, the lesser the average energy intensity resulted (Plappally and Lienhard V, 2012). This result can be mainly attributed to the energy demand (0.18 and 0.8 kWh/m^3) by aeration systems that often account for the most significant fraction of plant energy expenditure (45–75%). Another comprehensive study by Longo et al. (2016) with data obtained from more than 600 wastewater treatment plants also showed that energy intensity correlated well with the load factor; plants receiving lower loads compared to design values present a significantly worse energy performance. Energy intensity decreases when approaching the optimal value of 100% and keeps decreasing for overloaded plants.

4. Case study – scenario analysis of "Inter-Plants and "Inter-Parks water reclamation

The overarching purpose of implementing water recycling and reuse goals is to reduce the source water demand, hence lowering the water footprint of the products and strengthening the corporate sustainability. From the perspective of liability management, the most straightforward approach is to mandate each plant in a SIP to meet both the discharge limit and the promulgated water use efficiency goals. The existing regulatory practice for Taiwan's SIPs follows this protocol – hereinafter referred as "in-plant water reclamation" scenario – by requiring plants to install water quantity and quality measuring devices, submitting monthly the water flow balance and complying with the periodical site auditing. The regulating authority imposes a fee-based approach based on the discharge flow quantity and quality (e.g., COD, SS, pH, NH_3-N), while fabs must also comply with the additional discharge limits applicable to other constituents (e.g., metals and organic compounds of health concerns).

To conform with these mandates, decision-makers in fabs often face dilemma prioritizing their objectives: Meeting discharge limits? Economizing plant's discharge fee? Or meeting water use efficiency goals? The principle of mass balance suggests that the more water reclaimed (i.e., improved water recycle and reuse performance), the more concentrated pollutants remain in the effluent to be discharged (i.e., higher risk to violate discharge limits) unless the installed reclaimed units are capable of substantially removing contaminants from the spent water. To meet both mandates of water reuse efficiencies and effluent discharge limits, the management of a fab may choose to reclaim spent water via a purification process, and simply use a portion of the reclaimed water for diluting another effluent stream to meet its discharge limit. This strategy, which also makes economic sense to fabs when the cost of water is markedly lower than paying for discharge fee, clearly distorts the purpose of conserving resources (i.e., water and energy) and may cause unintended consequences of wasting energy.

In view of meeting the objective of reducing water demand, reducing the energy exerted into reclaiming water to meet stringent mandates, and assessing the cost-benefit from water users' (plants) perspective, we present two scenarios, namely "inter-plant" and "inter-parks" water reclamation, that can help rectify the unintended consequences by practicing in-plant water reclamation policy. Fig. 4 shows the schematics of the three water reclamation scenarios. In doing so, the dynamics of the administrator-to-fabs relationship in the SIPs change from a strictly superintending role to a partnership. A cost-sharing mechanism must be structured if any of the proposed new water reclamation infrastructures is involved. Therefore, a preliminary survey needs to be conducted to examine the perception, from the perspectives of the fabs in the SIPs, for future implementation of the scenarios mentioned above.

The methodology adopted to conduct this survey-based study is as follows. Between June 2016 and September 2017, a total of 24 manufacturing plants were approached with interviews. The initial phase of the each interview was to obtain sufficient baseline data for benchmarking. In this phase, the water demand baseline data is collected from the standardized water balance chart completed by personnel of the participating plants in the Central Taiwan SIP campus. These fabs varied widely with the classification of products (e.g., semiconductors, displays, biotechnology, precision machinery), employee size, fab size, and degree of utility consumptions. The charts were reviewed, revised and verified. The water-related cost data was also provided in the questionnaires accompanying the water balance chart. Nineteen of the 24 plants responded with measurable results. While the number of plants represents only 13.3% of the total number of registered companies (including both manufacturing and non-manufacturing sectors), the total water consumption responsible exceeds 77% of recorded consumption over the entire Science Park. Among the 19 plants, six were in the sector of semiconductors, eleven were in optomicroelectronics, and one each in precision machinery and in biotechnology. With reference to the size of water demand, eight of the 19 plants used more than >5000 CMD at the time of the study, one consumed between 1501 and 5000 CMD, two used between 501 and 1500 CMD, and eight demanded less than 500 CMD.

Additionally, the water-related energy data was obtained through an onsite survey using the recorded electricity data matching the categories depicted in Fig. 4a. Next, from the verified water balance charts, our task team identified potential points of water recycle and reuse opportunities and consulted with personnel of the fabs, who also provided information on the water recycling, reclamation, and reuse strategies either in progress or planning stage. A revised water balance chart was generated accordingly, and the potential range of reuse water quantity and quality was estimated. The last phase involved a cost-benefit analysis under hypothetical cost structure of reclaimed water as compared to the cost of tap water (e.g., reclaimed water is to be sold and purchased at a price lower than tap water. Because of the hypothetical nature of the proposed scenarios, verbal communications with the respondents, all of whom were holding managerial positions at various levels at the time of the interview, were necessary to develop a sufficient understanding of the schemes. With the information provided by the surveyor concerning the baseline water and energy consumption, efficiency performance, and the potential points of water and energy saving other than the existing measures, the respondents were asked to provide a perceived level of water and energy reduction and the potential cost benefits, on an increment of 5% against the baseline level.

Fig. 5 shows the range of the perceived benefits of adopting "inter-plants" and "inter-parks" scenarios, in reference to the existing "in-plant" water reclamation. While none of the respondents expressed any negative "benefits," those from fabs with the largest water consumption (>5000 CMD) collectively perceived a greater benefit by giving a greater degree of change in both water and energy reduction than those from smaller ones. For the "inter-plant" water reclamation scenario (Fig. 4b), an in-park water reclamation center (WRC) is to be constructed to which excess

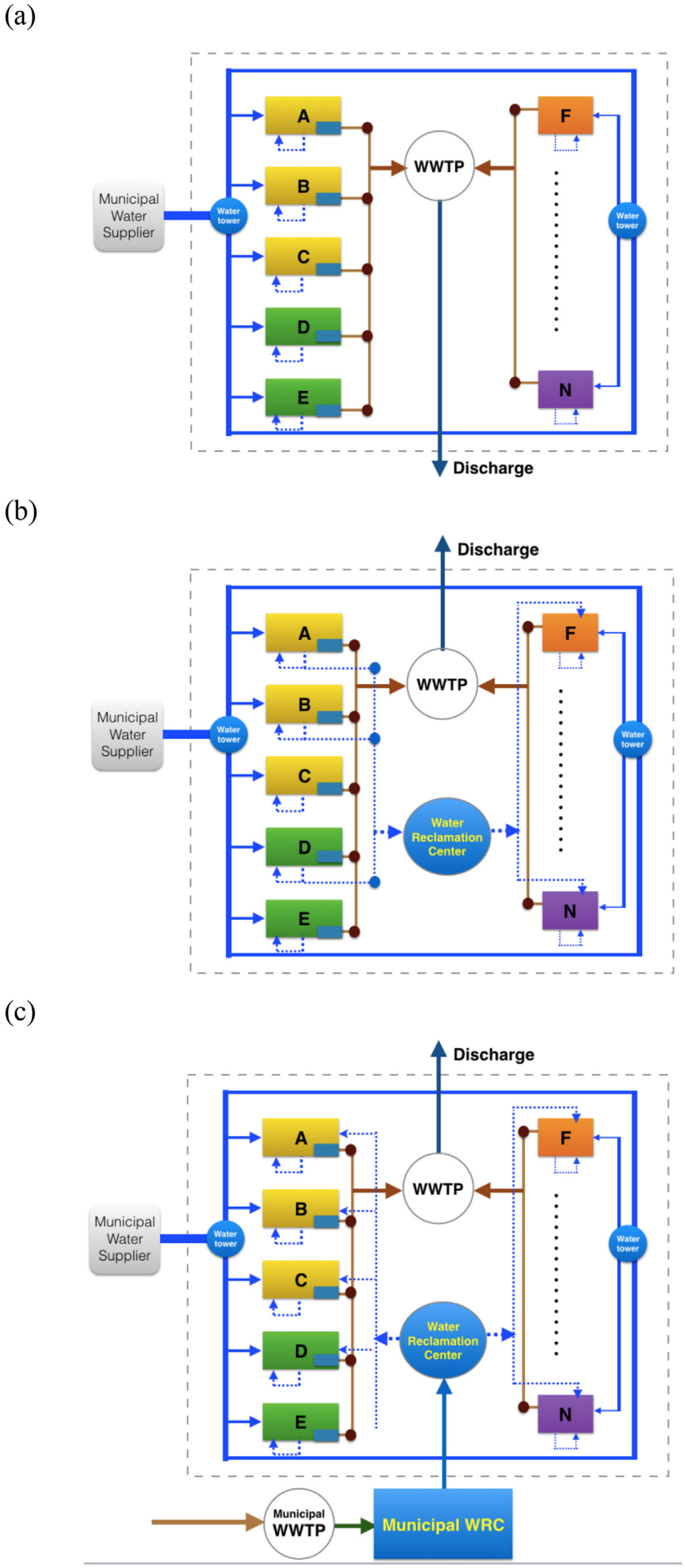

Fig. 4. Schematics of (a) in-plant, (b) inter-plant, and (c) inter-parks water reclamation. The boxed letters indicate separate entities (fab) from the first (designated as A) to the last (designated as N) to express the presence of n plants in an industrial park. Boxes A through E are aligned on one side and F through N on the other side to conceptually express that the water supply lines may be different for a plant depending on its location. Note that, while the presence of two rows has no discernable difference for Part (a) and Part (c), there is a significant implication for Part (b). In this scenario, Plants A through E (left column) are reclaimed water sellers, whereas Plants F through N are buyers.

reclaimed water can be sold and stored. The in-park WRC is responsible for managing inbound reclaimed water quantity and quality and outbound distribution. In this scenario, the total water demand for processing for each plant remains unchanged. The conceptualization is based on the assumption that fabs with high water demand already possessed the capability to meet the water reuse efficiency mandates, and thus potentially excess reclaimed water to supply a part of the water demand by plants with smaller water consumption (referred to as "smaller plants"). The proposed concept is supported by the fact that the largest 10% water users (fabs) are responsible for approximately 90% of the total water demand in the science park. Additionally, our previous studies (Lin et al., 2015) showed plants with water consumption less than 500 CMD did not perform well in water reuse efficiency, primarily attributable to the lack of economic incentive to invest in equipment to recycle or reclaim water. These smaller plants can choose to purchase the excess reclaimed water generated from the large fabs via the in-park WRC rather than reclaiming water in their plants. Plants selling and using (purchasing) excess reclaimed water still get credit toward the mandated water recycling efficiency. The WRC is then held accountable to ensure the reclaimed water quality sold needs to be meet at least that for facility use.

The difference between "in-plant" and "inter-plants" water reclamation scenarios is the more efficient use of the excess reclaimed water which would not be wasted but rather converted into a byproduct of values for both suppliers and users. Therefore, water recycling efficiency would be viewed as a mandate for a SIP campus as the responsible entity, as opposed to plants as the individually responsible entities. Economically, for major water-consuming plants, water-related costs are reduced by converting excess reclaimed water into revenue to partially offset the high facility and energy costs needed to meet stringent mandates. For smaller water-consuming plants with no economic incentives and less pressure to recycle water, they would be incentivized to spend less on using reclaimed water in replacement of tap water, and are credited with using reclaimed water to boost the plant's water recycling performance. Also benefiting from the "inter-plants" scenario is that the energy on water reclamation would reduce because not all plants are mandated to meet the common water recycling requirements, but would remain about the same for the major plants because of their existing ability to reclaim water and to meet the mandates.

There would inevitably be a considerable cost incurred from the installment of the in-park WRC and the water redistribution network system. Cost transferring from plants to publicly-owned infrastructure must be legitimized to sustain the WRC operation. While the purchasing price of reclaimed water by users should not be higher than tap water cost to generate an incentive for demand, the selling price of reclaimed water by plants must be lower than that of the purchasing price to leave a marginal profit for the WRC.

Fig. 4c conceptualizes the next scenario, namely the "inter-parks" water reclamation which involves external reclaimed water supplier of a public or private entity outside of the administrative boundary of a SIP campus. In this scenario, the quality of reclaimed water meets only the facility-level, and plants can choose to purchase reclaimed water and directly use for facility operation, or to further polish into the process-level water in place of tap water. The major difference between the "inter-plants" and "inter-parks" water reclamation approaches are i) SIP administrators take no responsibility of managing in-park WRC, which serves only as an interim reservoir for external reclaimed water. In-park infrastructure would still be needed to transport reclaimed water to users, but the park administrator takes responsibility for neither identifying supply and demand parties nor the pricing issues.

With the assumption that plants purchasing and using external reclaimed water would still get credit toward water efficiency performance, medium or major water users in the Park will consider buying reclaimed water to boost their water efficiency performance, which only slightly helps to replace tap water source. They will not invest in an additional process to polish the reclaimed water to replace more tap water. Major water users with excess in-plant reclaimed water capacity, however, are less inclined to purchase external reclaimed water because doing so provides neither economic incentive if the price of reclaimed water is not substantially lower than that of tap water, nor any other value to replace tap water supply. Smaller water users in the Park with limited reclamation ability are also uninterested in using reclaimed water to replace tap water because of similar pricing between the water supply sources.

Whether the city operates the WWTP and WRC or transfers operation to a private entity, generating revenue is a dominant driving force. Therefore, reclaimed water pricing will be a more important factor and is likely to be substantially higher than that in the "inter-plants" scenario. Therefore, if tap water price increases markedly (+20%), the WRC managing company will find more wiggling room for pricing reclaimed water to create cost incentive for all plants in the science park. Energy reduction can

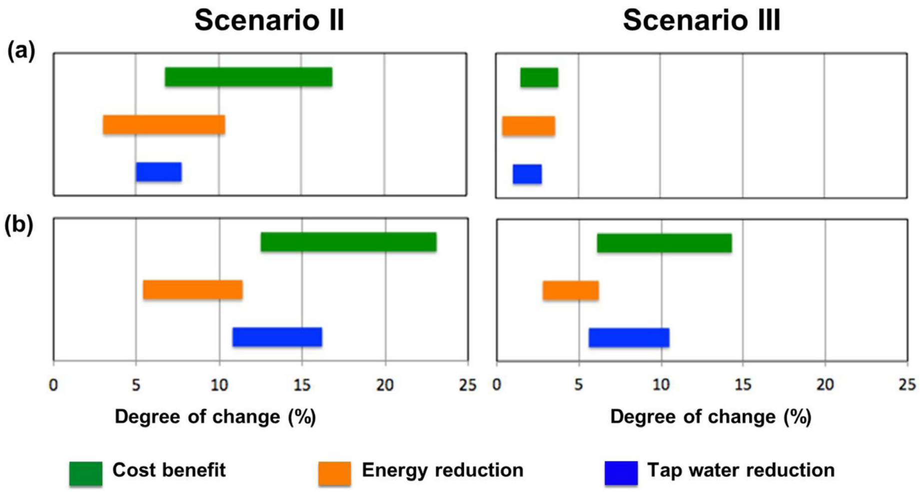

Fig. 5. Perceived benefits of water, energy, and cost by adopting "inter-plants" (Scenario II) and "inter-parks" (Scenario III) approaches with (a) tap water price as is, and (b) tap water price increase by 20%.

be significant if the major plants choose to use reclaimed water to replace part of the facility-level water to maintain the same water efficiency performance.

The three scenarios discussed above involve an increasingly larger number of stakeholders, and the successful design and implementation of either “inter-plants” or “inter-parks” scenario would require a prolonged stakeholders engagement process. Through the jurisdictional EIA, the general public relies on the effective EIA auditing and transparent reporting of the SIP administrative office to ensure the water use efficiency of the fabs in the SIPs. Any change in the method of auditing and reporting as a result of the revamped water reclamation system would have to gain full public support. Our survey indicates that corporates are willing to engage with different water reclamation scenarios under the conditions of increased water security and consistent water quality at a reasonable cost range. The lack of a priori knowledge on the consistency of water quality to meet the stringent requirement of the high-tech fabs is among the most challenging obstacles to be overcome.

5. Conclusions

Many water-intensive industries such as semiconductors and related high-tech industries are increasingly more conscious about the risks of water shortage to the corporate sustainability and thus have been proactively pursuing options to secure water resources. Regenerating spent water from processes has become an important option to achieve this goal. Using Taiwan’s SIP – an agglomerate of companies forming either vertical or horizontal integration in the supply chain of a wide array of microelectronic devices – as an example, we revisited the progress made in water consumption efficiency of the industries in the most recent years. Regulatory mandates aside, companies are also careful with the overall cost-benefit of the investment into gaining in-plant regenerated water as an alternative water resource. One of the major cost components is the energy involved in the purification system of spent water for reuses. While this water-energy linkage for the industry-specific perspective is still in its early stage of the investigation, companies are willing to explore options that venture beyond individual fabs, which in itself is an important milestone because sharing information between competing fabs had never been in the culture of the industry. Fabs mostly viewed these options, including an inter-plants scenario and an inter-park scenario, with positive responses regarding gaining overall cost and energy benefit. The risks of reclaimed water quality, especially those involving reuses as source water for UPW, and the relative costs of tap water and reclaimed water are the two primary considerations for these fabs in their decision-making.

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