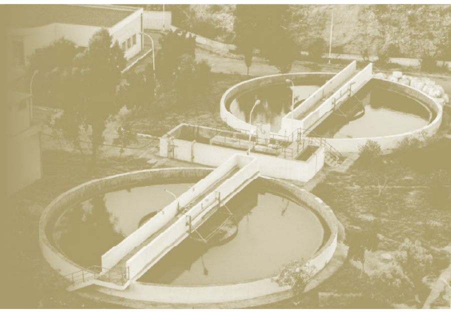
Integrated Sustainable Water Circulation



Background

In the context of global climate change and continued economic growth, the challenges associated with water resources have intensified. Water is no longer merely an issue of supply and demand; it is intrinsically linked to energy, food, environmental, resource, and economic security. The traditional linear model of water management, "withdrawal–use–discharge" is no longer adequate for addressing the diversified demands of industry, agriculture, and domestic sectors, nor the impacts of increasingly frequent extreme weather events.

In recent years, international developments in water management, exemplified by the International Water Association (IWA), have actively promoted a next-generation water cycle paradigm centered on Water Resource Recovery Facilities (WRRFs). This paradigm reconceptualizes wastewater from a "waste" to a "carrier of resources," treating it as a "water–energy resource reservoir" rich in water, energy, nutrients, and other critical resources. By leveraging innovative technologies to recover these assets, we can enhance the resilience of water supply while achieving the multi-faceted benefits of water recycling, energy creation, carbon reduction, and circular economy integration.

Global Outlook and Domestic Progress

In recent years, many advanced economies have elevated water resource circularity to a national strategic priority and have invested heavily in technology development and demonstration projects. Their core objectives extend beyond ensuring water security to include recovering energy, nutrients, and strategic materials from wastewater, thus constructing an integrated, sustainable water–energy–resource system.

United States: The U.S. Department of Energy (DOE) has strongly promoted energy efficiency and energy recovery in wastewater treatment. Initiatives include developing technologies such as anaerobic digestion for biogas production and hydrothermal liquefaction for biofuel production, alongside the RECOVER Program, which focuses on recovering high-value strategic materials, including ammonia, rare earth elements, cobalt, and magnesium, from wastewater to reinforce national supply-chain security. The Newtown Creek Facility in New York City is a representative water resource recovery center that co-digests sewage sludge and food waste to produce renewable natural gas, which is directly injected into the gas grid and supplied to more than 7,400 households.

Europe: Under the framework of the EU New Circular Economy Action Plan, instruments such as the Regulation on Minimum Requirements for Water Reuse have been adopted to systematically promote the use of reclaimed water in industrial and agricultural sectors. As a private sector leader, Veolia has commercialized energy-efficient and energy-generating wastewater treatment concepts, successfully transforming the Braunschweig Wastewater Treatment Plant in Germany into a 100% energy self-sufficiency facility and converting sewage sludge into green electricity in Urumqi, China, for grid connection. At the same time, Water UK's report Net Zero 2030 Routemap outlines strategies that include upgrading conventional anaerobic digestion to advanced anaerobic digestion (AAD), large-scale deployment of renewable energy, and the establishment of a carbon offset market for the water sector. Within the European innovation ecosystem, companies such as Firefly Green Fuels have developed cutting-edge technologies that convert sewage sludge into sustainable aviation fuel via hydrothermal liquefaction (HTL).

Asia: Japan's Ministry of Land, Infrastructure, Transport and Tourism (MLIT) has articulated a vision for a "Green Innovation Sewerage System" that goes beyond sludge utilization for fertilizers and fuels to include the development of nitrous oxide (N_2O) reduction technologies. Through collaborations such as that between Tokyo Gas and the City of Yokohama, Japan has successfully implemented projects in which hydrogen is generated by electrolysis using reclaimed water from sewerage centers, and the CO_2 contained in biogas is combined with this hydrogen to produce synthetic methane (e-Methane), thereby achieving carbon neutrality in urban gas systems. In addition, Japan has extensively adopted Internet of Things (IoT) and other smart-management tools to enhance the operational efficiency of wastewater treatment plants

Overall, global trends in water resource circularity are driven by a synergy of technological innovation, encompassing energy recovery and resource recovery, alongside smart management systems. These advancements are increasingly underpinned by robust policy frameworks, regulatory standards, and market-based mechanisms.

Taiwan: While Taiwan has established and expanded reclaimed water plants for industrial use, applications in agriculture and urban sectors remain limited. Regarding energy recovery, biogas-to-power systems are in place, they require optimization in methane leak detection and conversion efficiency. Nutrient recovery is currently confined to sludge composting, lacking high-value pathways for nitrogen, phosphorus, or mineral recovery. Furthermore, regulatory frameworks for agricultural risk management and green financial instruments for water infrastructure investment have yet to be fully integrated.

Moving forward, Taiwan can strategically draw upon international best practices by focusing on high-efficiency anaerobic co-digestion, renewable energy and fuel production, the recovery of strategic materials, cross-sectoral collaboration, and smart management systems. These initiatives must be underpinned by regulatory reforms and supportive mechanisms to build a resilient, efficient, and internationally competitive water–energy- resource circularity system.

Strategic Planning Frameworks

The "Water-Energy Resource Circulation" strategy is anchored in four dimensions, R&D, Society, Industry, and Governance, comprising six core strategies (Figure 1). Through cross-sectoral integration and public–private collaboration, these strategies seek to systematically establish an innovation ecosystem for water–energy-resource circularity in Taiwan.

The six strategies are mutually reinforcing: they begin with the development and large-scale deployment of advanced low-carbon smart water purification technologies; proceed through integrated regional demonstration zones for water circularity and the formation of circular-economy clusters; and culminate in the establishment of regulatory frameworks and standards for water-sector carbon offset markets. Collectively, these strategies are intended to drive the green transformation of wastewater treatment.

The long-term vision is to build a resilient, net-zero water circularity system that transforms wastewater treatment plants into carbon-neutral recovery hubs, maximizes the circular use of water, energy, nutrients, and other high-value materials, thereby catalyzing sustainable regional resource circulation.

Strategy 1: Research, Development, and Deployment of Key Technologies for Energy and Resource Recovery from Wastewater

This strategy aims to broaden the deployment of integrated technologies for low-carbon, high-efficiency water treatment; sludge-to-energy conversion; and the recovery of key resources (e.g., phosphorus and nitrogen). It emphasizes research, development, and scale-up of frontier technologies, such as novel anaerobic biological treatment systems that greatly reduce reactor volume while enhancing treatment efficiency; high-performance biofilm technologies; electro-separation processes capable of selectively recovering specific ions; and advanced treatment technologies for trace micropollutants, including per- and polyfluoroalkyl substances (PFAS).

These technologies are to be integrated with smart-management tools such as artificial intelligence (AI) and the Internet of Things(IoT), and embedded in digital twin systems to enable simulation-based optimization and predictive maintenance. Through these efforts,

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1. Integrate smart technologies with advanced low-carbon water purification technologies through research, development, and scalable deployment to enhance wastewater treatment efficiency and energy recovery.
2. Validate integrated water resource recovery and circular transformation demonstration zones, and accelerate the development of regional circular economy industrial value chains.
3. Develop carbon offset market regulations and standards for the water sector to support and promote the green transformation of wastewater treatment.

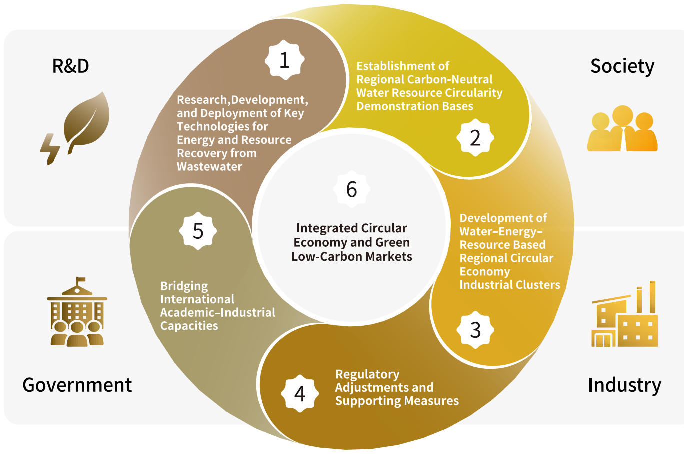

Figure 1 Strategic Framework for Water-Energy-Resource Circularity
Source: Taiwan Science and Technology Office for Net-zero Emission (T-STONE) (2025)

the strategy supports the digital transformation of water resource management, enhancing both treatment performance and energy efficiency.

Strategy 2: Establishment of Regional Carbon-Neutral Water Resource Circularity Demonstration Bases

To accelerate technology deployment and validate new operational models, this strategy proposes the establishment of emblematic carbon-neutral water–energy resource circularity demonstration bases in northern, central, and southern Taiwan, designed in accordance with regional characteristics (e.g., metropolitan, industrial, or agricultural).

These bases will integrate regional biomass feedstocks such as food waste and agricultural residues and will serve as platforms to test modular combinations of advanced anaerobic co-digestion, novel value-added resource extraction technologies, innovative biological sludge-to-energy processes, hydrothermal treatment or gasification, and smart/low-carbon irrigation systems. Through such modular demonstration, each base will become a flagship site showcasing wastewater-to-resource circularity.

Strategy 3: Development of Water–Energy–Resource Based Regional Circular Economy Industrial Clusters

This strategy promotes cross-sectoral collaboration among water utilities, energy providers, agriculture, and industry in order to build a diversified industrial ecosystem for water–energy –resource circularity. Using the demonstration bases as nuclei, the aim is to cultivate local based regional circular economy clusters, linking surrounding communities, industrial parks, and agricultural zones to form symbiotic networks of energy and resource sharing. Examples include tailored recovery and stable supply of reclaimed water, green energy (e.g., biogas power), fertilizers, and critical materials to meet local demand. In this way, the economic and environmental benefits of regional resource circularity can be maximized.

Strategy 4: Regulatory Adjustments and Supporting Measures

This strategy calls for a comprehensive review and revision of environmental, water, agricultural, and energy-related legislation to open legitimate application pathways and market channels for value-added recovered products such as reclaimed water, digestate, bioliquids, and biofuels.

It further emphasizes the establishment of risk-management systems for the use of reclaimed water in agricultural irrigation, and the development of a green-finance support framework for the water-resource circularity sector—such as green bonds and green-growth funds. In addition, it proposes to explore emerging business models that combine energy-efficiency improvements in municipal wastewater treatment with Energy Service Company (ESCO) approaches, and to develop methodologies for quantifying the carbon-reduction benefits of advanced water treatment technologies, thereby enabling alignment with international carbon-credit mechanisms.

Strategy 5: Bridging International Academic–Industrial Capacities

This strategy advocates the active establishment of international cooperation platforms or academic–industrial alliances on water–energy–resource circularity with leading countries such as the United States, European Union member states, and Japan. Through joint research, technology transfer, and patent licensing, Taiwan can introduce and localize next-generation technologies, including novel biological treatment processes and sludge-to-low-carbon-fuel pathways (e.g., sustainable aviation fuel and e-Methane).

At the same time, Taiwan can draw on the operational experience of overseas demonstration sites to develop domestic testing and verification schemes tailored to water–energy–resource circularity technologies.

Strategy 6: Integrated Circular Economy and Green Low-Carbon Markets

This strategy seeks to implement full life-cycle management within water–energy–resource circularity sites and to build transparent and trustworthy markets for water-related economic activities. It calls for proactive development of high-value products derived from recovered resources—such as sustainable aviation fuel for the aviation sector, struvite for use as slow-release fertilizer, and critical metals required by industry—thus opening up new blue-ocean opportunities in the circular economy.

In parallel, it aims to link the carbon-reduction benefits of water resource circularity with carbon markets by integrating them into greenhouse gas emissions trading and carbon offsetting schemes. This would create diversified economic incentives for the green transformation of wastewater treatment.

Potential Benefits

The initiative is expected to generate several core benefits, including expanding reclaimed water supply, reducing dependence on natural water resources, and enhancing industrial and agricultural resilience. In parallel, energy-saving and energy-generating measures in wastewater treatment are expected to deliver tangible carbon reduction benefits. Recovering valuable resources, such as of nitrogen, phosphorus, and metals, can significantly minimize virgin material extraction and process-related emissions, This approach not only drives the transition toward circular economy development but also creates an emerging green industrial value chain dedicated to integrated water-energy-resource recovery. The expected quantified benefits are detailed below:

(1) Establishment of a carbon-neutral demonstration site: A flagship model carbon-neutral water-energy-resource recovery plant with an annual treatment capacity exceeding 10,000 metric tons will be established. The facility aims to cut site-level carbon emissions by more than 50% as a critical step toward carbon neutrality.

(2) Promotion of energy recovery and low-carbon processes: The integration of co-digestion power generation systems with low-carbon biological treatment processes is projected to slash electricity consumption by 50%. By expanding the deployment of these energy recovery and low-carbon facilities to process 15% of the national wastewater volume, the system can achieve an estimated annual carbon reduction of 12,000 tCO_2e.

(3) Waste(water) resource recovery: The strategic recovery of ammonia-nitrogen recovery from wastewater will be accelerated to produce high-value commodities, such as ammonium hydroxide or liquid ammonia, as they can directly replace conventional industrial feedstocks. By scaling this technology to process 10% of Taiwan's total ammonia-nitrogen wastewater volume, this initiative is expected to drive an annual carbon reduction of approximately 16,000 tCO_2eq.

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