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LOW-CARBON OPERATION AND MAINTENANCE TECHNOLOGIES AND APPLICATIONS FOR UNDERGROUND WASTEWATER TREATMENT PLANTS

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Abstract: As an important part of urban infrastructure, the stable operation and energy saving and emission reduction of underground wastewater treatment plants are of great significance to the sustainable development of cities. This paper discusses in depth the potential and practical path of underground wastewater treatment plants in terms of resilient, energy saving and low-carbon operation and maintenance. Through the investigation of the construction and development history and operation and maintenance of underground wastewater treatment plants at home and abroad, this paper analyzes and summarizes the problems such as operation and maintenance energy consumption, environmental pollution, comprehensive energy utilization, and intelligent monitoring of underground wastewater treatment plants, puts forward the resilience of underground wastewater treatment plants and low-carbon operation and maintenance ideas. Aiming at the problems of high energy consumption in operation and maintenance of underground wastewater treatment plants, difficulties in overhauling and odor treatment, etc., this paper carries out the research on the utilization of thermal energy of wastewater, refined intelligent control, and development and application of high-efficiency energy-saving equipment. Combined with different typical application cases, this paper explores the measures of low-carbon operation and maintenance management and intelligent monitoring system of underground wastewater treatment plants, explores the thermal energy, photovoltaic and reclaimed water utilization of wastewater, puts forward feasible and resilient operation and maintenance strategy and resource utilization scheme to realize cost reduction and efficiency which provide strong support for the sustainable development of the city. The research results of this paper provide an important reference value for guiding the resilient operation and maintenance of underground wastewater treatment plants and the application of low-carbon technologies.

Keywords: underground wastewater treatment plant, resilient operation and maintenance, energy saving and low-carbon, heat utilization, odor treatment

1. INTRODUCTION

With the acceleration of global urbanization, green ecological development needs and the continuous improvement of residents' environmental requirements, underground wastewater treatment plants with land intensification, high resource utilization and environmental friendliness have become the development trend and direction of urban wastewater treatment plants. Underground wastewater treatment plants in China have entered a stage of rapid development. Cities with a higher level of development and a larger population density have begun to explore the construction of underground wastewater treatment plants to address the contradiction between the shortage of land resources and the improvement of the ecological environment. As the main structure of underground wastewater treatment plant is limited space, the operation process of ventilation, deodorization, lighting, communication, inspection requirements are higher, facing a series of problems such as high energy consumption, maintenance difficulties, odor treatment, etc. These problems not only affect its own stable operation, but also pose a challenge to the sustainable development of the city.

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In recent years, the concept of resilience and low-carbon has received widespread attention globally, and in the face of increasingly severe environmental challenges and resource constraints, the traditional operation and maintenance mode of wastewater treatment plants has been difficult to meet the needs of cities to realize the coordinated development of economy, society and environment. Therefore, how to realize energy saving, emission reduction and low-carbon development on the basis of ensuring the stable operation of underground wastewater treatment plants has become an urgent problem to be solved.

This paper discusses the current situation, application cases and challenges of low-carbon operation and maintenance technology of underground wastewater treatment plants, and puts forward the development ideas of low-carbon operation and maintenance of underground wastewater treatment plants from the aspects of multi-energy complementary integrated energy utilization, energy saving and consumption reduction, resource recycling, low-carbon operation and maintenance technology research and application.

2. DEVELOPMENT HISTORY AND OPERATION AND MAINTENANCE STATUS OF UNDERGROUND WASTEWATER TREATMENT PLANTS

2.1. International development of underground wastewater treatment plants

Underground wastewater treatment plant development has been experienced for a long time. In the 1930s because of the cold climate,the Nordic countries built part of the wastewater treatment facilities underground. In 1932 in Helsinki, Finland, built the world's first underground wastewater treatment plant. In 1942, the world's first modern underground wastewater treatment plant was built in Stockholm, Sweden, in response to heavy winter snow and ice. Limited by the engineering technology at that time (such as ventilation, seepage control, construction machinery, etc.), the initial underground wastewater treatment plant is small in scale, the function of the plant focuses on the primary treatment (sedimentation, filtration), and the overall process is still mainly above ground.

Starting from the 1960s, with the acceleration of urbanization, the increasing scarcity of land resources, and the tightening of environmental regulations, coupled with the gradual maturity of underground wastewater treatment technologies (including key technologies such as ventilation, deodorization, and corrosion prevention), the technical support for the construction of underground wastewater treatment plants was established. Developed countries such as European countries, Japan, South Korea, and Canada have successively built multiple underground wastewater treatment plants. In 1994, the Viikinmäki Underground Wastewater Treatment Plant in Helsinki, Finland, was completed and put into operation near the city center, replacing approximately 10 small-scale above-ground wastewater treatment plants. As shown in Figure 1, the plant is primarily constructed within bedrock, making it one of the largest and technologically leading underground wastewater treatment plants in Europe at that time. Its model of deeply integrating underground space with urban functions provides a sustainable solution for wastewater treatment in high-density cities. In 1996, the Ariake Water Reclamation Center in Tokyo, Japan, was commissioned fully underground. The reclaimed water after treatment is used for urban non-potable purposes, landscape environments, and industrial water supply. The above-ground area is equipped with public facilities such as a gymnasium, heated swimming pool, and tennis courts, enhancing the overall regional environment and residents' quality of life, and providing important support for the city's sustainable development.

Since the 21st century, with the rise of concepts such as sustainable development, resource recycling, and ecological integration, underground wastewater treatment plants have entered a stage of diversified development. The Bekkelaget sewerage treatment plant in Oslo, Norway, put into operation in 2000, is constructed in a cave of the Oslo Fjord as shown in Figure 2. Using natural rock masses as structural support and centering on geological space innovation and resource circulation technology, it has achieved a low-carbon paradigm of "zero land expansion, negative energy growth, and complete resource recycling", providing a standardized path for the construction of wastewater plants in highly sensitive areas. The Changi Water Reclamation Plant in Singapore adopted the world's first multi-layer vertical stacking design to achieve maximum compactness and optimize land use, realizing the goals of "minimized land use, maximized production capacity, and near-zero emissions", and becoming a benchmark case for the sustainable development of environmental infrastructure in high-density cities. For underground wastewater treatment plants in selected international cities, please refer to Table 1.

Figure 1. *Viikinmäki underground wastewater treatment plant, Helsinki, Finland (https://esemag.com/wastewater/wastewater-treatment-plant-monitors-its-ghg-emissions/)*

Figure 2. *Bekkelaget sewerage treatment plant, Oslo, Norway (https://pstprojektai.lt/project/bekkelaget-water-treatment-plant/)*

Table 1. *Typical cases of underground wastewater treatment plant globally*

Year of construction	Name	Features	Remarks
Completed in 1942, multiple renovations	Henriksdal Underground Wastewater Treatment Plant, Stockholm, Sweden	Partial underground structure, with main facilities located in rock caverns	The world's first wastewater treatment plant built out of rock
Commissioned in 1987	Dokhaven Underground Wastewater Treatment Plant, the Netherlands	A 50.000 m² park is built above ground, with a total land area only 1/4 of that of a above-ground plant	The first underground wastewater treatment plant in the Netherlands
Commissioned in 1987, renovated in 2008	Geolide Underground Wastewater Treatment Plant, France	The famous Stade Vélodrome football stadium is built above the plant, achieving "no visual, no olfactory, no resounding nuisance"	The world's largest underground wastewater treatment plant in terms of land area

Year of construction	Name	Features	Remarks
Commissioned in 1998	Ariake Water Reclamation Center, Tokyo, Japan	Adopts a double-layer underground structure (upper layer for treatment facilities, lower layer for stormwater storage); the ground level is planned as a large sports stadium and commercial complex, creating a paradigm of "underground water management and surface-level empowerment" in high-density urban areas	The Paradigm of "Underground Water Management and Surface-level Empowerment" in High-density Urban Areas
Put into operation in 2001, upgraded and expanded in 2017	Bekkelaget Wastewater Treatment Plant, Oslo, Norway	Sewage collected via underground tunnel systems, gravity flow design reduces pumping energy consumption Ground transformed into coastal public spaces, including walkways, viewing platforms, and art installations	Provides a standardized path for constructing wastewater treatment plants in highly sensitive areas
Commissioned in 2009	Incheon Wastewater Treatment Plant, South Korea	Semi-underground construction type, with multiple light wells and green spaces set on the top	A representative facility in South Korea
Commissioned in 2008	Changi Water Reclamation Plant, Singapore	Operates in conjunction with the Deep Tunnel Sewerage System, using gravity flow for sewage transportation with significant energy savings Adopts NEWater technology to achieve circular reuse of sewage to drinking water Ground planned as a coastal barrage park	One of the largest underground wastewater treatment plants in Asia

2.2. Development of underground wastewater treatment plants in China

With the continuous acceleration of urbanization and the increasing improvement of environmental requirements in China, underground wastewater treatment plants have attracted the attention of the state and various provinces and cities due to their advantages such as green harmony and natural friendliness. Currently, there are more than 200 underground wastewater treatment plants either under construction or in operation, mainly concentrated in areas with relatively developed economies, high population density, and high requirements for land resources and environmental quality, with Guangdong and Zhejiang Province having the largest number [1]. The construction sites are mainly located in urban central areas and residential districts, and the construction forms include semi-underground, fully underground, tunnel-type, etc.

Hong Kong Stanley wastewater treatment plant is Asia's first underground wastewater treatment plant built in a cavern, built in 1995, as shown in Figure 3, mainly consists of three large cavernous chambers of about 120m long, 15m wide and 17m high, and is connected by more than 450m of roadway access and ventilation tunnels and shafts. It has a wastewater treatment capacity of 12.000 m^3/d and serves a population of about 27.000 people.

Figure 3. *Stanley wastewater treatment plant- tunnel type,Hong Kong,China (https://sc.news.gov.hk/TuniS/www.news.gov.hk/tc/record/html/2017/12/20171210_121806.lin.shtml)*

Shenzhen Buji Wastewater Treatment Plant has the top of its underground structures covered with 1.5m deep soil, planted with deep-rooted large tropical plants. The above-ground space is transformed into a municipal leisure park, equipped with sports facilities such as football fields, basketball courts, and badminton halls.

Figure 4. *Buji wastewater treatment plant,Shenzhen,China (https://www.163.com/dy/article/FKG6MQV50550AQSU.html)*

Neijiang Xiejiahe Underground Water Reclamation Plant, where the above-ground area is a sponge park featuring basketball courts, vehicle parking spaces, greenbelts, and pedestrian walkways, reclaimed water used as landscape water supplement for Xiejia River, municipal greening, and road flushing, effectively promoting water resource recycling. Photovoltaic power generation systems are installed above ground, enabling both sewage reclamation and photovoltaic power generation to achieve energy conservation and carbon reduction.

Figure 5. *Xiejiahe underground water reclamation plant,Neijiang,China (https://local.newssc.org/system/20231125/003465519.htm)*

Figure 6 shows the Guiyang hospital Water Reclamation Plant with dormitories and super high-rise office buildings built above, while Figure 7 depicts the landscape of Guangzhou Jingxi Underground Wastewater Treatment Plant. The undergrounding of municipal infrastructure has unleashed enormous ecological value, achieving a "win-win" situation for the composite development and utilization of urban green parks and underground spaces.Underground wastewater treatment plants in some Chinese cities are shown in Table 2 [2].

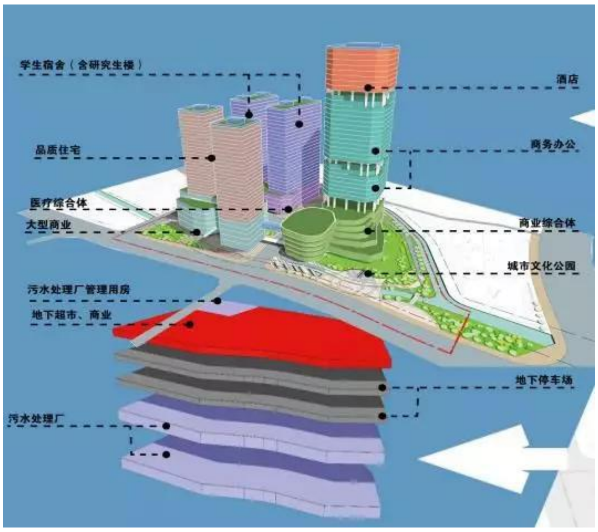

Figure 6. *Guiyang hospital water reclamation plant (https://www.sohu.com/a/365193326_120157162?scm=1002.44003c.fe0183.PC_ARTICLE_REC)*

Figure 7. *Jingxi underground wastewater treatment plant,Guangzhou,China (https://news.qq.com/rain/a/20231114A0A58C00)*

Table 2. *Typical cases of underground municipal infrastructure in China*

City	Year of construction	Name	Features	Remarks
Hong Kong	1991	Stanley Wastewater Treatment Plant (Capacity 12.000 m^3/d)	The main body of the plant is hidden inside the mountain and blends in with the surrounding environment	Asia's first underground wastewater treatment plant built in a cavern

City	Year of construction	Name	Features	Remarks
	2012	Happy Valley Underground Stormwater Storage Scheme (Capacity 60.000 m^3/d)	• Collecting and storing rainwater and groundwater for urban water use to conserve water resources; • The roof of the cistern incorporates the design concept of "green trees and lawn on the roof of the cave", where the green elements not only cover the surrounding pump and fan rooms, but also enhance public connectivity by providing a recreational area for public enjoyment.	/
Beijing	2014	Huai Fang Underground Water Reclamation Plant (Capacity: 600.000 m^3/d)	• Utilizes reclaimed water to construct artificial wetlands, with 13 hectares of the 16-hectare wetland park built on the plant's roof. • China's first design attempt to integrate roof wetland landscaping with large-scale underground water reclamation infrastructure. • Sludge is used for biogas power generation, with the electricity produced applied to all stages of water reclamation, achieving circular energy use. • Enables land resource utilization and ecological environment improvement, providing a new green development concept for the construction, development, and intensive land use of gray infrastructure.	Asia's largest fully underground water reclamation plant and the largest rooftop wetland park in China
Shanghai	2015	Nanxiang Water Reclamation Plant (Capacity 150.000m^3/d)	Construct a water ecological park and water environment science museum above ground, saving land resources to half of that of traditional water plants.	The first underground water reclamation plant in Eastern China
Guangzhou	2010-2022	Underground wastewater treatment plants (Capacity 2,04 million m^3/d)	Adopting the concept of "building a plant underground and a park on the ground" , the rain garden, wetland park and other facilities are built on the top of the underground wastewater treatment plant to improve the surrounding environment, to further alleviate the "neighbor avoidance effect", and to effectively revitalize the land value.	China's largest wastewater treatment plants cluster
Guiyang	2016	Pengjiawan Wastewater Treatment Plant (Capacity 60.000 m^3/d)	The ground level is a landscape park, with the wastewater treatment plant located on underground floors 3-4 and the underground floors 1-2 serving as a complex.	China's first case of an underground wastewater treatment plant combined with urban renewal.

City	Year of construction	Name	Features	Remarks
Chengdu	2022	Qilong Water Purification Plant (Capacity 100.000 m³/d)	• the construction of ground landscape to enhance the surrounding environment and land development value; • compared with conventional above-ground wastewater treatment plant to save at least 30% of the land use; • to achieve organic unity of economic benefits and social benefits, ecological benefits.	/
Hangzhou	2022	Zhijiang Classification and Reduction Complex (Capacity 600 tons/day)	• A green ecological and environmentally friendly plant centered on people-oriented principles. • An "ecological-type" transfer station project that plays a demonstrative and leading role in the construction of underground transfer stations.	The first large-scale underground garbage transfer station in China

2.3. Status of operation and maintenance of underground wastewater treatment plants

The development of underground wastewater treatment plants has gone through an initial exploratory stage of small-scale construction, a development stage centered on capacity expansion, and entered a mature stage marked by the four-dimensional coordination of "water quality, resources, energy, and community". With their unique design and efficient treatment capabilities, underground wastewater treatment plants have effectively solved the problem of urban sewage discharge, improved the living environment of surrounding residents, reduced pollution to natural water bodies, and protected ecological balance. According to statistics, there are currently more than 200 underground wastewater treatment plants successfully constructed and stably operated in over 10 countries worldwide, all of which have achieved good economic, social, and ecological environmental benefits [3]. As the demand for intensive land use and environmental friendliness becomes increasingly urgent, and with the continuous maturity and improvement of wastewater treatment technologies, underground wastewater treatment plants will undoubtedly receive more attention from more countries and regions in the future due to their advantages of small land occupation, low environmental impact, and high treatment efficiency.

Based on the special working conditions of underground spaces, such as closure, high humidity, and lack of natural lighting, the configuration standards for lighting engineering, ventilation, and odor removal in underground wastewater treatment plants are significantly higher than those of above-ground counterparts, directly leading to increased operational energy consumption and carbon emissions. External factors such as process complexity and water quality fluctuations further exacerbate the pressure of energy consumption. According to relevant literature statistics, the total life-cycle carbon emissions of underground wastewater treatment plants are approximately 36,5% higher than those of above-ground plants [4]. Various countries and regions have already made certain explorations in energy self-sufficiency and carbon neutrality of wastewater treatment plants, but in specific practices, due to differences in water quality, water quantity, policy support, technical maturity, energy supply structure, etc., achieving carbon neutrality in wastewater treatment plants still has a long way to go.

3. TYPICAL CASES OF UNDERGROUND WASTEWATER TREATMENT PLANT CONSTRUCTION AND ANALYSIS OF LOW-CARBON OPERATION AND MAINTENANCE APPLICATIONS

3.1. Low-carbon operation and maintenance policy for underground wastewater treatment plants

Wastewater treatment plants, as an important part of urban infrastructure, consume large amounts of water, electricity and other energy, and their overall carbon emissions remain high. According to data from the United Nations Framework Convention on Climate Change (UNFCCC), carbon emissions from wastewater treatment in the EU reached 23 million tons in 2019, while the figure for the United States was 45 million tons. Although the greenhouse gas emissions from wastewater treatment plants have been reduced in recent years, wastewater treatment plants are still an important source of greenhouse gas emissions globally, and also one of the faster-growing sources of emissions. In the context of the global active response to climate change and the promotion of low-carbon development, the low-carbon operation and maintenance of underground wastewater treatment plants, as an important urban infrastructure, not only helps to reduce greenhouse gas emissions and alleviate environmental pressures, but also enhances the economic benefits and sustainable development of wastewater treatment plants themselves. The EU's European Climate Law legislatively defines the goal of achieving climate neutrality by 2050, requiring all types of infrastructure to consider low-carbonization during operation and maintenance, and to reduce carbon emissions through measures such as energy conservation and emission reduction, and improving energy efficiency. The Water Environment Federation (WEF) has proposed that wastewater treatment plants should no longer be waste treatment facilities, but rather water resource recovery plants, an idea that has been widely recognized.

In December 2023, the National Development and Reform Commission (NDRC), the Ministry of Housing and Urban-Rural Development (MOHURD), and the Ministry of Ecology and Environment (MEE) of China jointly issued the Implementation Opinions on Promoting Synergistic Efficiency Improvement in Pollution Reduction and Carbon Emission Control for Sewage Treatment. The document states that sewage treatment is an energy-intensive industry, accounting for over 1% of the total energy consumption in society. Meanwhile, wastewater contains substantial energy resources, presenting enormous potential for energy utilization. The guidelines propose multiple energy-saving and carbon-reducing measures, including promoting high-efficiency energy-saving equipment, optimizing load matching, establishing smart water management systems, and popularizing sewage-source heat pump technology. These measures aim to enhance resource recycling, energy conservation, and carbon reduction in sewage treatment, thereby reducing greenhouse gas emissions.

3.2. Typical cases of low-carbon operation and maintenance technologies for underground wastewater treatment plants

The Kakolanmäki underground wastewater treatment plant in Turku, Finland, was converted from an abandoned underground rock quarry. It has a designed maximum treatment capacity of 144.000 m³/day and an average flow rate of 120.000 m³/day, commissioned on January 1, 2009. As a typical case integrating energy utilization and thermal energy recovery, the secondary effluent of the plant has an average temperature of 14 °C, serving as a heat source to recover waste thermal energy for heating and cooling the plant and surrounding areas.By 2020, the comprehensive energy consumption of the Kakolanmäki plant was 35 GWh/a, while its self-generated energy reached 225 GWh/a. The total recovered energy (electricity and thermal energy) was 6,4 times higher than its own energy consumption, with nearly 90% recovery efficiency of waste thermal energy for heating/cooling. Achieving a 333% carbon neutrality rate, it has become an underground energy plant[5]. The practice of this plant demonstrates that the key to carbon-neutral operation of wastewater treatment lies in emphasizing the recovery of substantial waste thermal energy from effluents.

Figure 8. *Kakolanmäki wastewater treatment plant,Turku, Finland (https://www.filtralite.com/en/case_studies/filtraliter-clean-kakolanmaki-wastewater-treatment-plant-finland)*

The PANTAI Wastewater Treatment Plant, Malaysia's first underground wastewater treatment facility, is located in the Pantai District of Kuala Lumpur. Originally designed with a capacity of 320.000 tons per day, the plant became an "urban eyesore" due to urban expansion, negatively impacting the cityscape and residents' quality of life while restricting the development potential of surrounding areas. In 2014, the facility was transformed into an underground treatment plant, with its former site converted into a sports park spanning nearly 100.000 m² of green space.The project integrates multiple green and low-carbon technologies, including intelligent control systems, water-source heat pumps, fiber-optic daylighting, biogas power generation, rainwater recycling, and photovoltaic power generation. The heat recovered by water-source heat pumps is used for heating and cooling the administrative complex and equipment buildings. Landscape water bodies serve as underground lighting channels, while fiber-optic systems combined with lighting windows in the green space maximize natural light for illumination in enclosed areas. High-efficiency energy-saving measures include precision aeration systems and intelligent lighting controls.This initiative has successfully created an environmentally friendly model that revitalizes ecosystems and emphasizes green energy conservation. The low-carbon technologies reduce carbon emissions by 21.659,3 to 22.432,0 tons of CO_2 equivalent annually and save operational costs by CNY 9,312 to 9,612 million per year[6].

Figure 9. *PANTAI Wastewater Treatment Plant ,Kuala Lumpur,Malaysia (https://penetronmalaysia.com/portfolio/pantai-treatment-plant/)*

The Hongqiao Wastewater Treatment Plant in Shanghai adopts an intensive underground layout, with all sewage treatment structures sunken underground. Its design integrates the construction concept of "sponge city", establishing two major systems: an underground reclaimed water system and an above-ground reclaimed water system. During rainy days or when exceeding the design flow, sewage first enters a storage tank for temporary retention, then undergoes treatment on sunny days. With a green coverage rate of over 90%, the plant has created an innovative "garden-on-top, plant-below" environmental model, effectively resolving the contradiction between sewage treatment and surrounding environment.While researching the reuse of urban sewage as a water resource, the Hongqiao Underground Wastewater Treatment Plant has developed its energy attributes by using high-temperature water-source heat pumps to absorb sensible heat from sewage, replacing gas boilers to produce high-temperature hot water (85°C–90°C) for sludge drying. Compared with natural gas boilers, high-temperature water-source heat pumps are more economical, ensuring the thermal demand and efficiency for sludge dewatering and drying while significantly reducing energy consumption in sludge treatment, achieving synergistic effects of pollution reduction and carbon emission mitigation.As of the first half of 2023, the project reduced natural gas consumption by 530.000 m³ year-on-year, saving CNY 2,37 million in natural gas costs. After deducting electricity consumption, the energy cost for sludge drying decreased by 22%. Under design conditions, the system can recover 51.103 GJ of heat annually, saving 341 tons of standard coal and reducing carbon emissions by 745 tons. In September 2023, the technical transformation project of "low-temperature vacuum sludge drying with high-temperature water-source heat pumps" was awarded the "Top 10 Excellent Cases of Waste Heat Utilization in Shanghai".

Figure 10. *Hongqiao Wastewater Treatment Plant,Shanghai,China (https://www.shanghaiwater.com/Events/3236.html)*

The Huai Fang Water Reclamation Plant in Beijing is Asia's largest fully underground reclaimed water plant and China's first benchmark project to achieve the integration of "above-ground wetland + underground wastewater treatment" functions. With a designed daily treatment capacity of 600.000 m³ , all structures are built underground, while the above-ground area features a wetland park nourished by reclaimed water, covering approximately 18 hectares. This urban ecological green lung absorbs about 1.200 tons of carbon dioxide annually. Treated sewage is purified through surface artificial wetlands and replenishes downstream rivers via dedicated pipelines, achieving 100% reuse of reclaimed water and aquatic ecosystem restoration. The plant demonstrates the possibility of symbiosis between wastewater treatment facilities and urban ecology, providing a Chinese solution for high-density cities to address the“neighbor avoidance effect”and achieve green transformation. The plant applies sewage source heat pump technology to extract waste heat from the wastewater treatment process, supplying heating and cooling for the plant's office area and surrounding buildings. Biogas generated from sludge anaerobic digestion powers about 30% of the plant's electricity demand. Dried sludge is converted into nutrient soil or incinerated for power generation, achieving 100% resource utilization. The ground wetland park is equipped with distributed photovoltaic panels with a capacity of 1,2 megawatts, generating approximately 1,5 million kWh of electricity annually to further reduce carbon emissions. Through a series of green and low-carbon measures, the plant has achieved efficient, resource-oriented, and ecological wastewater treatment. Compared with traditional plants, this plant reduces carbon emissions per unit of water treatment by over 40%, being awarded the "Beijing Green Ecological Demonstration Zone" and becoming a model for underground reclaimed water plants in China.

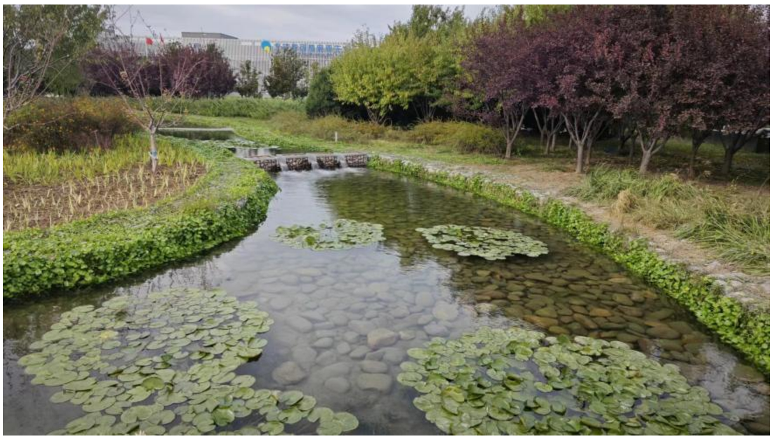

Figure 11. *Huai Fang Water Reclamation Plant,Beijing,China (https://sainteco.com/newsinfo/6472923.html)*

3.3. Underground wastewater treatment plant low-carbon operation and maintenance technology application analysis

By analyzing the typical cases of operation and maintenance of underground wastewater treatment plants at home and abroad, it can be seen that the application of toughness and low-carbon operation and maintenance technology is mainly reflected in the following four aspects.

1) Diversified renewable energy application to achieve efficient utilization of energy and comprehensive benefit enhancement. Recycling of wastewater waste heat, wastewater contains a large amount of waste heat resources, through the wastewater source heat pump to implement the transfer and utilization of energy, used in the plant or the surrounding buildings for heating, cooling or sludge drying link. Utilizing the biogas generated in the process of anaerobic digestion of sludge to generate electricity, and at the same time installing solar photovoltaic panels on the roof of the plant, open space and other areas to realize “self-generation and self-consumption + surplus electricity on the Internet”. According to the International Water Association (IWA), Denmark's Marselisborg Wastewater Treatment Plant recovered biogas from sludge anaerobic digestion for power generation, achieving 100% energy self-sufficiency in 2016 and a 50% power surplus.

2) Reuse of water and sludge resources to implement resource recycling and sustainable development. The deeply treated reclaimed water is used for urban greening irrigation, road spraying, river and landscape replenishment, etc. The utilization rate of reclaimed water in some of the plants reaches 100%, which saves water resources and at the same time improves the water ecological environment of the city. Through anaerobic digestion, aerobic fermentation and other technologies, sludge is transformed into biogas, organic fertilizer and other resources.

3) Application of intelligent operation and maintenance management technologies.Sensors are used to real-time monitor operation parameters of underground wastewater treatment plants, including water quality, quantity, and equipment status. Real-time data automatically adjusts equipment operation parameters to avoid long-term high-load or low-efficiency operation, achieving optimized control of the wastewater treatment process. This

improves energy consumption management efficiency and precision, enhancing energy efficiency while ensuring the safe and stable operation of underground plants.

4) Construction mode innovation and enhancement of urban resilience. Comprehensive integration of single-function wastewater treatment plant with urban landscape, implementation of wastewater recycling and water ecological restoration, through the addition of storage ponds to cope with extreme weather or sudden loads, to ensure the stability of the system.

4. CHALLENGES OF RESILIENCE AND LOW-CARBON OPERATION AND MAINTENANCE TECHNOLOGIES FOR UNDERGROUND WASTEWATER TREATMENT PLANTS

4.1. High construction and operation and maintenance costs

The construction of underground wastewater treatment plants requires deep foundation pit excavation, support, waterproofing, high-strength building materials, and complex construction technologies. Meanwhile, underground equipment must have characteristics such as corrosion resistance, moisture-proofing, and explosion-proofing, with procurement costs significantly higher than ordinary equipment. During construction, supporting facilities like fire protection, ventilation, and lighting must also be considered, further increasing construction costs. The unit construction investment of underground wastewater treatment plants is 1,5 to 2 times higher than that of traditional above-ground plants.

In terms of energy consumption, the daily operation of underground wastewater treatment plants requires 24-hour artificial lighting and comprehensive mechanical supply-exhaust ventilation systems to meet environmental requirements. Odor collection and treatment cover areas such as tanks, pretreatment sections, and sludge zones, leading to increased odor treatment volume. The enclosed underground environment and discharge outlets located in populated areas raise gas emission standards, while the upgraded process configuration and additional equipment for deodorization systems also contribute to higher energy consumption. Although low-carbon operation and maintenance technologies like renewable energy utilization and energy recovery help reduce energy consumption, the high upfront costs of technical transformation and equipment investment make it difficult to fully offset energy expenses in the short term.

In terms of equipment maintenance, the humid underground environment and limited ventilation make equipment prone to corrosion and damage, resulting in frequent repairs and replacements, which increases maintenance costs. Safety requirements for fire protection, flood control, etc., in underground spaces also add to construction and operation costs. According to relevant literature, the lighting energy consumption of fully underground wastewater treatment plants with the same scale and treatment standards is approximately 4 to 6 times higher than that of above-ground plants, ventilation energy consumption is 4 to 6 times higher, and deodorization energy consumption is 2 to 3 times higher. The unit energy consumption indicators and composition of some underground wastewater treatment plants in China are shown in Table 3[7].

Table 3. *Unit energy consumption index and composition of an underground wastewater treatment plant*

Item	Unit energy consumption kw-h/m³	Percentage%
Secondary Sewage Treatment	0,221	43,30
Advanced Sewage Treatment	0,072	14,04
Sludge handling	0,044	8,55
Lighting	0,008	1,58
Ventilation and air conditioning	0,061	11,97
Deodorization	0,079	15,37
Transformer damage	0,027	5,19
Total	0,511	100

4.2. Difficulty in operation and maintenance management

Underground wastewater treatment plants adopt clustered, integrated, and modular layouts for some structures to save land area and make full use of vertical space. This intensive spatial design poses multiple challenges for plant operation and maintenance, including limited operational space, difficult fault diagnosis and repair, complex system coordination, insufficient digital adaptation, and superimposed cost risks. With the increasing demand for urban wastewater treatment, existing facilities may fail to meet processing requirements. However, expansion requires more underground space, involving complex engineering design and construction, which is costly and difficult to implement, making capacity expansion arduous.

The relatively enclosed underground space of these plants features a complex and changeable environment. Equipment failures, pipeline leaks, or poor ventilation can all lead to the accumulation of hazardous gases. These hidden dangers not only damage the facilities but also threaten the safety of maintenance personnel. Although digital and intelligent technologies have been widely applied in underground wastewater treatment plants, deficiencies remain in data management, such as incomplete data collection and poor data sharing, affecting the scientificity and timeliness of operation and maintenance decisions.

4.3. Lack of synergy between a variety of low-carbon technologies

Underground wastewater treatment plants have actively introduced renewable energy technologies such as solar and wind power, while also exploring energy reuse methods like wastewater residual heat recovery. However, there is often a lack of effective coordination between these energy supply technologies and in-plant energy consumption technologies—such as the configuration of solar/wind energy and energy cascade utilization—making it difficult to form an organic whole and leading to low energy utilization efficiency.

Resource recovery technologies help improve the resource utilization efficiency and resilience of wastewater treatment plants. However, some wastewater treatment processes fail to fully consider the needs of subsequent resource recovery during design and optimization, making it difficult to effectively extract and utilize resources from treated sewage or sludge.

4.4. Lack of technical standards for low-carbon operation

The technical standards for low-carbon operation and maintenance of underground wastewater treatment plants are still incomplete. Most existing standards related to wastewater treatment plants are formulated based on above-ground facilities, failing to fully consider the particularities and complexities of underground plants. This includes insufficient technical specifications and operation guidelines for underground plants in aspects such as energy optimization of process schemes, selection of high-efficiency energy-saving equipment, utilization of renewable energy, resource circular use, and operation management. As a result, different regions and enterprises may adopt varying standards and practices during actual construction and operation, prone to issues like inappropriate technology selection and poor operation effects, which hinder the promotion and development of green and low-carbon underground wastewater treatment plants.

5. THOUGHTS ON LOW-CARBON OPERATION AND MAINTENANCE TECHNOLOGIES FOR UNDERGROUND WASTEWATER TREATMENT PLANTS

With the promotion of the "carbon peaking and carbon neutrality" goals of China, the requirements for low-carbon development in the wastewater treatment industry will become increasingly stringent. Carrying out research and application of low-carbon operation and maintenance technologies for underground wastewater treatment plants is an inevitable choice to achieve the sustainable development of the wastewater treatment industry.

5.1. Multi-energy complementary integrated energy application model

The low-carbon operation and maintenance of underground wastewater treatment plants involve multiple technical fields, including renewable energy, high-efficiency energy-saving equipment, energy recovery, and intelligent control utilization. Effectively integrating these technologies to achieve optimized system operation presents a complex technical challenge. The research on multi-energy complementary integrated energy systems for underground wastewater treatment plants aims to fully leverage various energy forms, realizing efficient energy utilization and diversified supply.

Specifically, it is necessary to explore low-carbon pathways such as sewage thermal energy utilization and sludge energy utilization: converting waste heat into heating and cooling energy through waste heat recovery technology, and transforming organic matter in sewage into biogas for heating and power generation via biogasification technology. Meanwhile, study the application pathways of photovoltaic (PV), energy storage, direct current (DC), and flexible technologies in underground wastewater treatment plants—install PV modules in the overhead areas of above-ground structures, achieve energy storage through energy storage electrical equipment and energy storage devices, and carry out application research on low-voltage DC power supply for existing power distribution system equipment such as lighting, fans, and air conditioners.

Actively explore and promote the construction of "four-in-one" wastewater treatment plants that integrate wastewater treatment, wetland parks, photovoltaic power generation, and integrated energy applications to reduce reliance on traditional energy, lower energy costs, and cut carbon emissions. Establish an energy collaborative management mechanism by building an intelligent integrated energy management platform in accordance with the principles of digital, intelligent, refined, and integrated energy control. Through real-time monitoring and analysis of supply-demand dynamics for various energy sources, this platform enables intelligent monitoring and optimized management of the entire energy system, enhancing energy efficiency and ensuring stable, reliable energy supply. Such measures promote energy conservation and carbon reduction to achieve a win-win situation for economic and environmental benefits, demonstrating the feasibility of integrating ecological protection with industrial development.

Table 4. *Multi-energy complementary pathway table*

Input Energy	Conversion Technology	Output Form	Main Applications	Complementary Logic
Sludge biogas	Biogas combined heat and power (CHP)	Electricity and waste heat	Equipment power supply, digester heating	Substitutes for photovoltaic power during cloudy days/nights; waste heat assists in heating
Solar energy	Photovoltaic power generation	Electricity	Lighting, water pumps, deodorization equipment	Prioritizes power supply on sunny days; surplus power stored or fed into the grid
Sewage thermal energy	Sewage source heat pump	Thermal/cooling energy	Plant heating/cooling	Collaborates with biogas waste heat to meet seasonal demands
Solar thermal energy	Solar water heating system	Thermal energy	Process hot water, domestic hot water	Supplements biogas waste heat to reduce gas consumption
Grid electricity	Intelligent power distribution system	Electricity	Peak regulation or emergency backup	Automatically switches on when renewable energy is insufficient

5.2. Development and research of energy efficient equipment

Underground wastewater treatment plants, as major energy consumers, are facing unprecedented pressure for energy conservation and emission reduction. By exploring and applying new technologies, materials, and processes, researching and developing high-efficiency energy-saving equipment, and promoting the industrial application of new technologies, the technical level and competitiveness of the wastewater treatment industry can be improved. This provides strong support for energy conservation, emission reduction, cost reduction, efficiency improvement, and sustainable development of wastewater treatment plants, driving the industry towards intelligence, greening, and low-carbonization.

Improving equipment energy efficiency is crucial for low-carbon operation and maintenance. It is necessary to intensify research and development of water treatment technologies and equipment featuring high efficiency, energy conservation, land saving, integration, and intelligence to achieve compact and efficient equipment. For example, the application of precision aeration systems and intelligent dosing systems can reduce operation costs. The development of high-efficiency energy-saving odor treatment equipment adopts advanced nanosecond pulse plasma technology and intelligent control systems, with the technical core of generating short-pulse plasma through a stable high-voltage power supply. A specially configured reaction chamber enhances removal efficiency, while intelligent control technology real-time monitors the equipment's operation status and automatically adjusts working parameters. This achieves functions such as improving deodorization efficiency, enhancing emission gas quality, increasing automation, and boosting operational stability. According to current research results, this odor treatment process equipment consumes 30% to 60% less energy than conventional chemical deodorization equipment, saves 40% to 60% of operation and maintenance costs overall, and reduces equipment floor space by over 30% compared with biological treatment processes under the same treatment scale. It effectively addresses the pain points of traditional deodorization equipment, such as large footprint, low efficiency, high energy consumption, and difficult maintenance.

5.3. Application of multi-functional integrated robot inspection

Underground wastewater treatment plants feature narrow spaces, crisscross pipes, dense equipment, and hazardous gases. Inspection personnel need to navigate through narrow passages and equipment intervals, which not only restricts mobility but also poses high safety risks. Meanwhile, manual inspection is inefficient, making it difficult to comprehensively and timely cover all corners and equipment of the plant. Aiming at the environmental characteristics of underground wastewater treatment plants, multi-functional integrated inspection robots are developed to real-time monitor environmental parameters such as gas composition, temperature, humidity, and pressure, and conduct condition detection on various equipment. These robots integrate with the intelligent management system of underground wastewater treatment plants to achieve real-time data sharing and interaction.

Based on equipment operation status and historical inspection data, the inspection frequency and key areas are dynamically adjusted, and inspection routes are optimized to improve the pertinence and effectiveness of inspections, providing a basis for process regulation and equipment maintenance. This enhances the overall intelligent management level, operation efficiency, and safety stability of underground wastewater treatment plants, driving the wastewater industry towards intelligence and automation.

5.4. Research on fine-grained intelligent control system technology

Conduct research on fine-grained intelligent control system technologies for underground wastewater treatment plants, adopting a multi-parameter control strategy of "feed forward + model + feedback". Utilize deep learning algorithms to model and predict the wastewater treatment process, develop an intelligent process regulation system to achieve full-process intelligent control of underground plants, and explore potential energy-saving, consumption-reduction, and operation optimization strategies through big data analysis. Based on feed forward information such as influent water quality and quantity, combined with wastewater treatment models, predict process operation parameters in advance and automatically adjust control parameters like aeration volume and chemical dosage. Real-time evaluate and adjust the regulation effects through feedback information to ensure the process operates at optimal conditions, reducing energy consumption and carbon emissions while maintaining stable effluent compliance.

Install preventive maintenance devices to real-time monitor the equipment of underground wastewater treatment plants. Establish a full-life cycle management system for equipment to manage the entire process from procurement, installation, operation, maintenance to decommissioning, improving equipment operational safety and reliability while reducing maintenance costs.

5.5. Low-carbon operation and maintenance technology application case and carbon reduction analysis

For low-carbon operation and maintenance technology, take a new underground wastewater treatment plant with a design capacity of 100.000 m^3/d in Jiangsu Province ,China, as an example, the project covers an area of about 30.000m^2 and the ground is a park. Through the application of low-carbon technologies such as biogas power generation, photovoltaic power generation, solar thermal collector, wastewater heat source, reclaimed water reuse, energy-efficient equipment, green space, etc., the carbon emission reduction of each technology is estimated to provide a reference for the green and low-carbon operation and maintenance of underground wastewater treatment plants.

1) Biogas power generation

The sludge output of the plant is relatively stable throughout the year, with an average monthly sludge production of about 2.400 tons. The daily biogas production after thermal anaerobic digestion is about 704m^3/d, and the biogas generator set with combined heat and power supply is used to realize biogas combustion for power generation.

Calculation formula for carbon reduction of electric energy recovery (1)

$$C_d = L_d \cdot EF_d / M_n \quad (1)$$

Where, C_d is the carbon reduction of electric energy recovery, kg CO_2 /m^3 ; L_d is the total electric energy produced in the evaluation year, kWh/a; EF_d is the electric power emission factor of the area, kg CO_2 /kWh; M_n is the total amount of domestic wastewater treatment in the evaluation year, m^3 /a.

The annual biogas power generation is calculated to be about 514.000kwh, and according to the carbon dioxide emission index of 0,7035kg/kWh for the East China Power Grid, the annual carbon emission reduction is about 361,6t.

2) Photovoltaic (PV) power generation system

The case plant is located in an area with moderate solar resources, where the annual total horizontal irradiance is 1.400–1.500 kWh/m². To fully utilize solar energy, PV modules are installed overhead in the covered areas and green belts of the underground wastewater treatment plant. Fixed or tracking PV systems are selected based on installation positions—tracking systems can increase power generation by approximately 15%–25% compared to fixed systems at the same installed capacity. PV walkways are also set up in some pedestrian passages.

Meanwhile, the PV-storage-direct current-flexible (PVSDCF) technology prioritizes PV power for DC motor systems. For example, DC motors replace some asynchronous motors in lighting and ventilation equipment to reduce voltage conversion losses and improve equipment energy efficiency. The case plant's PV system can generate about 181.000 kWh of electricity annually, reducing carbon dioxide emissions by approximately 127,34 tons per year.

3) Wastewater source heat pump system application

Utilizing heat pump technology to recycle the heat energy contained in wastewater is one of the important means for wastewater treatment plants to realize the synergistic effect of pollution reduction and carbon reduction. In the effective reduction of fuel, electricity and other energy consumption, saving operating costs while significantly reducing greenhouse gas emissions. The normal water temperature of the recycled water source is 16℃~17℃, in winter, the heat pump device extracts the heat energy resources contained in the water and transfers them together with the consumed energy to the buildings to achieve the purpose of heating; in summer, the wastewater source heat pump unit can also absorb heat from the high temperature environment and release the heat into the water to achieve the effect of refrigeration; and it can provide a cooling and heating source for the equipment rooms in the plant and the nearby buildings.

According to the theoretical calculation of energy and resource recovery of wastewater treatment plant, the theoretical cold/heat in wastewater can be calculated in equation (2):

$$Q=M\times\Delta T\times C \tag{2}$$

Where:Q indicates the cold/heat, kJ; M indicates the mass of wastewater, kg; ΔT indicates the temperature difference between the wastewater in and out of the extraction, according to the project to take 8 ℃; C indicates the specific heat capacity of the wastewater, take 4,18kJ-/(kg- ℃);

According to the definition of the cooling coefficient COP, the actual heat supply/cooling capacity of the heat pump can be calculated in equation (3):

$$Qh/c =Q\pm W= Q\pm Q/COP\pm 1 \tag{3}$$

Where, Qh/c indicates the total heating/cooling capacity of the heat pump (subscript h/c represents the heating/cooling conditions respectively), kJ; W indicates the contribution of the electrical energy consumed by the heat pump to the output thermal energy; COP is calculated as 3,7.

Carbon reduction can be calculated in equation (4):

$$C_h= Q_{h/c}\times EF_h /M_n \tag{4}$$

Where, C_h is the amount of carbon reduction by heat energy recovery, kg CO_2 /m^3; $Q_{h/c}$ is the heat energy that can be exported to the outside of the wastewater treatment system in the evaluation year, GJ/a; EF_h is the emission factor of fossil fuels, kg CO_2/GJ; M_n is the total amount of domestic wastewater treatment in the evaluation year, m^3 /a.

In this case, the water source heat pump calculates the heat energy recovery by 75% of the average treated water volume in daily operation, and the amount of wastewater extracted by the water source heat pump is calculated by 2737,5*104m^3 for the whole year, and the actual carbon emission can be reduced by about 1.080t per year.

4) Reclaimed water reuse system

The project site is equipped with a large number of green roofs, which effectively reduce the total roof runoff and runoff pollution load. Meanwhile, decentralized intelligent carbon fiber rainwater collection modules are set in the green belts to carry out source treatment of rainwater runoff. The tail water enters the ecological wetland for further purification, and the reclaimed water is used for landscape and road watering, reducing the consumption of tap water and realizing the circular utilization of reclaimed water. The reclaimed water reuse volume of this project is 10,22 million tons, and the annual carbon emission reduction is about 3.004,7 tons.

5) Application of energy-efficient equipment and refined intelligent control system

The project adopts a precise aeration control system, which collects corresponding instrument signals to real-time track and evaluate the dissolved oxygen and aeration demand of each aeration control zone according to the changes of pollution load and process operation status in the sewage plant. It automatically controls the blower and air regulating valve, adjusts and distributes the aeration volume on demand, stably and accurately controls the dissolved oxygen in the aerobic zone, and ensures the efficient and stable operation of the sewage treatment process. At the same time, low-carbon strategies are adopted to minimize the aeration volume, reduce the energy consumption and chemical consumption of the sewage treatment plant, and achieve refined operation and management of the sewage treatment plant. The precise aeration system can save about 5,0694 million kWh of electricity annually, reducing carbon dioxide emissions by about 3.566,3 tons.

6) Application of landscape green space carbon sink

The project adopts fully underground construction, and the ground greening ecosystem forms a carbon sink space, which also alleviates the heat island effect and achieves the purpose of regulating microclimate.

The estimation method for carbon sequestration of plants in green spaces follows the Technical Guide for Carbon Accounting and Emission Reduction Pathways in Urban Water Affairs Systems, and the calculation formula is as shown in (5):

$$C_{zb}=EF_{zb}\cdot S_{zb} \tag{5}$$

Where, C_{zb} is the amount of carbon sequestered by vegetation, kg CO_2-eq;EF_{zb} is the carbon sequestration factor of vegetation, kg CO_2-eq /m² ; S_{zb} is the area covered by plants, m² .

The greening area of this project is nearly 20.000m², and the annual carbon sequestration is about 2,9t.

The low-carbon technical scheme of the case underground sewage treatment plant makes full use of multiple energy recycling technologies such as biogas power generation, photovoltaic power generation, sewage thermal energy, and reclaimed water reuse, with obvious carbon reduction effects. It saves 3.331,42 tons of standard coal and reduces carbon dioxide emissions by 8.664,54 tons annually. See Table 5 for details, with remarkable economic and environmental benefits.

Table 5. *Statistics on the amount of standard coal saved and carbon dioxide emission reduction by the application of low-carbon technologies*

Low-carbon technology	Standard coal consumption (tons)	CO_2 emissions (tons)	note
biogas	139,08	361,6	The CO_2 emission index is taken as 0,7035 kg/kWh (with reference to the East China Power Grid)
photovoltaic power generation	48,98	127,34	
wastewater source heat pump	415,38	1.080	
reclaimed water reuse	1.155,65	3.004,7	
energy efficient equipment and fine intelligent control	1.572,71	4.088	
landscape green space carbon sink	/	2,9	
total	3.331,42	8.664,54	

6. CONCLUSION

As an important part of urban infrastructure, the resilience and low-carbon operation and maintenance of underground wastewater treatment plant is of great significance for the sustainable development of the city.

1) Sustained technological innovation to achieve the green transformation of underground wastewater treatment plants. With the innovation of underground wastewater treatment process technologies and the application of advanced resource recovery technologies, multi-faceted measures such as process optimization, equipment upgrading, resource recycling, energy consumption optimization, and clean energy utilization can further improve the energy efficiency and resource recovery rate of underground wastewater treatment plants. This promotes their transformation from purely wastewater treatment facilities to "resource factories," achieving a win-win situation for environmental and economic benefits, and providing strong support for urban sustainable development.

2) Deepening integrated development models to promote ecological harmony. Further deepen the integrated development of underground wastewater treatment plants with urban ecological construction, urban planning, and technological innovation. Achieve harmonious coexistence between underground wastewater treatment plants and urban functional areas as well as the urban ecosystem, accelerate the carbon neutrality process of underground wastewater treatment plants, and enhance the overall ecological environment quality of cities and the living standards of residents.

3) Policy guarantee for low-carbon operation and maintenance. Strengthen policy guidance, introduce policy mechanisms and targeted policies to encourage the resilient and low-carbon operation and maintenance of underground wastewater treatment plants, stimulate the enthusiasm and innovation of enterprises, and provide strong support for the implementation of low-carbon operation and maintenance projects. Meanwhile, formulate and improve technical standards for low-carbon operation of underground wastewater treatment, provide a basis for the standardized and healthy development of underground wastewater treatment plants, and promote the development of underground wastewater treatment plants towards a green and low-carbon direction.

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