Research on the Implementation Path of Modular Design and Construction of Smart Environmental Protection Facilities in Waste Free Scenic Spots in Seaside Cities

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ABSTRACT Coastal scenic areas face significant challenges associated with marine debris accumulation, salt-spray corrosion, and seasonal fluctuations in waste generation. To address these issues, this study proposes a modular implementation framework for smart environmental protection facilities in waste-free coastal scenic areas. Multi-source environmental data are utilized to support adaptive facility deployment, while standardized modular units constructed from corrosion-resistant materials improve environmental durability. A wind–solar–storage microgrid architecture is introduced to enhance energy self-sufficiency, and a digital twin platform is employed for intelligent scheduling and operational management. Experimental results indicate that the proposed framework achieves an energy self-sufficiency rate of 88.2%, reduces overflow alarms by 73%, and significantly improves response efficiency. The study provides a replicable solution for sustainable coastal environmental governance and offers methodological references for wireless sensing, intelligent monitoring, and distributed environmental information systems.

INDEX TERMS modular design, waste-free scenic areas, digital twin, wireless sensing, intelligent environmental monitoring

I. INTRODUCTION

As a popular tourist destination, the ecological environment quality of coastal cities is directly related to the sustainable development image of the city, necessitating the implementation of high-performance technical materials for coastal protection and ecological restoration. These engineered material systems provide essential material erosion control and habitat support, ensuring that environmental management aligns with the city's long-term sustainability goals through advanced material science[1]. However, these areas face unique environmental governance dilemmas: on the one hand, marine debris is imported across borders with tides and ocean currents, increasing the uncontrollability of solid waste treatment in scenic areas; on the other hand, the high salt spray climate causes rapid corrosion of open-air environmental protection facilities, resulting in high equipment maintenance costs. More troublesome is that the surge in the number of tourists during the peak tourist season brings a pulse peak in garbage production, and traditional fixed and non-intelligent environmental protection facilities often suffer from insufficient capacity or untimely garbage collection, which seriously affects the construction process of "zero-waste scenic areas"[2,3]. Therefore, how to build an environmental protection facility system that can adapt to the special climate of coastal areas and achieve intelligent dynamic management under multiple environmental pressures has become a technical problem that urgently needs to be solved. In recent years, scholars at home and abroad have carried out a series of studies on the modular design and intelligent transformation of environmental protection facilities in scenic areas. Srpak et al. explored feasible solutions for implementing contemporary technological innovations such as the Internet of Things in existing tourist facilities at an affordable price to make up for the gap in the transformation of existing facilities[4]. Li et al. took Yezhai Middle School in Qianshan City as an example to explore wind environment optimization and facade energy-saving strategies for mountain campus buildings, providing practical experience for low-carbon transformation and promoting green and low-carbon development in smart cities [5]. Srpak et al. explored feasible solutions for implementing Internet of Things technology at affordable prices in existing tourist facilities through conceptual models and case studies, which are particularly suitable for small private renters [6]. Kamińska and Michalak discussed the trend of green and environmentally friendly exterior wall design in Poland and around the world, and analyzed the application of vertical "greening" in supporting sustainable urban development [7]. However, most existing studies treat modularization and intelligence separately, lack systematic solutions for special coastal environments (such as high salt spray corrosion and energy islands), and pay insufficient attention to the long-term service performance of modules under

extreme climates, resulting in a significant reduction in the application effect of research results in actual coastal scenarios. To address the above shortcomings, some scholars have attempted to introduce weather-resistant materials or independent energy systems to improve the environmental adaptability of facilities. For example, Santucci et al. evaluated the dry deposition flux of wet candle technology through interval testing, analyzed atmospheric corrosivity in conjunction with meteorological data, and quantified the contribution of chloride to deposition flux error [8]. Lin et al. proposed a power optimization configuration method based on the characteristics of wind and solar resources for independent microgrids of "wind/solar/storage" to meet the operation requirements of microgrids in island mode [9]. Wang et al. proposed a collaborative optimization method for energy storage capacity of wind-solar-storage complementary microgrid systems that considers reliability costs and the uncertainty of wind and solar resources at multiple time scales [10]. The above studies show that single-dimensional improvements are difficult to meet the comprehensive needs of environmental protection facilities in coastal scenic areas.To this end, this paper proposes a modular design path of "environmental adaptation-functional reconfiguration-intelligent integration," incorporating high-performance technical materials and independent microgrid technology into an organic system of weather-resistant material selection and digital twin scheduling. By utilizing smart fiber-reinforced structures as the physical substrate for intelligent integration, the framework resolves the balance between environmental adaptability, functional reconfigurability, and intelligent collaboration.

II. ENVIRONMENTAL ADAPTABILITY ASSESSMENT AND MODULE DEPLOYMENT BASED ON MULTI-SOURCE DATA

The physical deployment of modules needs to comprehensively consider the unique environmental stress factors and dynamic cleaning requirements of coastal cities. Therefore, this study constructed a multi-source data-driven assessment framework. First, meteorological and marine environmental data for the target area over the past five years were collected, including hourly wind speed and direction, salt spray deposition (measured using the dry gauze method), tidal levels, and marine debris drift trajectories, to establish a spatial distribution map of environmental stress factors. Second, a spatiotemporal heat map of tourists in the scenic area was obtained, and combined with historical data on waste generation, kernel density analysis was used to identify hotspot areas and time periods for waste generation during peak seasons. Based on this, a multilayer overlay analysis was performed using a GIS platform: high-risk areas for salt spray corrosion, areas prone to marine debris landing (drift trajectory density areas), and high-density tourist areas were spatially weighted and overlaid to determine the corrosion protection level zones and dynamic cleaning requirement levels for facilities. Finally, based on the comprehensive scoring results of each zone, the physical layout coordinates and service radius of the modules were determined, and differentiated material protection standards (e.g., reinforced composite coatings for high-risk areas) and structural wind resistance design parameters were proposed for different zones. The categories, key indicators, and technical specifications of the above multisource data are summarized in Table 1.

III. STANDARDIZED DECOMPOSITION AND BIONIC DESIGN OF FUNCTIONAL MODULES

According to the environmental adaptability assessment completion and the spatial layout of the module, the abstract environmental protection functional requirements shall be converted to the concrete, prefabricated physical units. This paper initially breaks down the fundamental functions of the environmental protection facilities in the seaside scenic area with a system into five fundamental functional units, the waste compression unit, temporary storage and transfer unit, sewage treatment unit, environmental monitoring unit and human-computer interaction unit. In design every functional unit is an independent container, which meets the ISO standard container sizes and interface specifications which are made standard to guarantee plug and play as well as quick interchangeability between various functional units. For example, additional compression units can be temporarily added during peak tourist seasons to accommodate increased waste generation. Conversely, during off-peak periods, the modular interface allows for the integration of environmental monitoring units alongside existing compression units, enabling expanded ecological data collection without compromising core waste management functions.

The functional load-bearing capacity and environmental tolerance (both) have to be fulfilled simultaneously by the structural design of the modules. The primary frame is made of Q355NH weathering steel, which has a high density of oxide layer, which comes in handy in regards to the corrosion of salt sprays. The surface decorative coating makes use of Indonesian merbau wood which has been processed with anti-corrosion agents attached to the main structure through open-loop system. This facilitates maintenance and replacement, while the natural texture of the wood softens the visual appearance of the industrial structure, contributing to better integration with the coastal landscape. Regarding form design, a biomimetic design concept proposed in this

TABLE 1. Multi-Source Data Categories and Evaluation Parameters

Data Category	Key Indicators	Data Source and Technical Specifications	Spatial Resolution	Temporal Resolution
Meteorological data	Wind speed, wind direction, salt spray deposition	Measured by weather stations over the past five years; salt spray measured by dry gauze method	1 km grid	Hourly
Marine dynamics data	Tidal level, marine debris trajectory simulation	GNSS buoy tracking + FVCOM model	100 m grid	Daily
Tourist activity data	Instantaneous density, dwell time	Inversion of mobile signaling data	50 m grid	Hourly
Historical operation data	Waste generation, cleaning frequency	Records from scenic area sanitation management system	Module-level	Daily

study is the design of the seashell biomimetic wherein geometric structures and shape are taken out of the shells of the oyster, scallops as well as other marine creatures that are prevalent in the local intertidal zone. The technology of creating perforated patterns similar to skin texture is done by the use of parametric modeling technology. These designs have aesthetic and utilitarian value.

The color scheme of the module is also suitable to the coastal setting, the key colors used are sand white and light gray-blue, and the colors of the beach and seawater respectively. Touch of coral orange is applied as an indicator of the human computer interaction interface. The entire module design is such that it has an organic unity of functional unit reconfigurability, structural material weather resistance and harmony in terms of appearance with the landscape.

IV. INDEPENDENT MICROGRID-DRIVEN ENERGY SELF-SUSTAINING SYSTEM INTEGRATION

The scenic areas of the coast are frequently found in the end of the power supply in the city, and sometimes even in the outer islands or deserted coastal strips. The traditional municipal power supply has practical issues of being expensive to lay lines and being vulnerable to power cuts due to typhoons. To address the energy supply challenges in coastal areas, this study equips each module with an independent wind-solar-storage microgrid system. This configuration is designed to reduce reliance on the municipal power grid, with the storage unit serving as a short-term buffer to smooth intra-day power fluctuations. However, the current storage capacity is sized primarily for diurnal cycling; its ability to sustain operation through multi-day periods of low renewable generation remains a subject for future optimization.

At the system hardware level, every module is self-sufficient in terms of energy, with three energy units consisting of the following: first, a vertical axis wind turbine with a rated power of 1 kW, using an H-type Darrieus structure, capable of operating in wind speeds as low as 2.5 m/s. The turbine is designed to meet the structural requirements for a wind resistance rating of level 12 according to GB/T 31519-2015, though its actual performance under typhoon conditions remains to be validated through future structural testing, and its vertical axis architecture is not sensitive to changes in the wind direction making it the more useful to complex coastal wind environments; second, flexible thin-film photovoltaic modules with total installed capacity of 2 k An energy storage converter (PCS) is used to couple these three energy sources, and dispatched uniformly.

A hierarchical control approach that relies on the maximum power point tracking (MPPT) is taken at the system control level. The photovoltaic controller and wind turbine controller separately monitor the optimum power point in the prevailing weather conditions and direct electrical energy to the DC bus. Energy storage system will be considered as an energy buffer unit, which automatically switches between charging and discharging mode in regard to the variation of bus voltages: When power generation is much more than the load demand, the energy storage will charge to absorb the extra energy; when power generation is unsufficient the energy storage will discharge to counteract the power inadequacy. To prevent overcharging and over-discharging, the battery management system maintains the state of charge (SOC) within an operating window of 20% to 95%. When the SOC drops below 20%, the system executes a load-shedding sequence: non-essential loads (e.g., landscape lighting and multimedia screens) are automatically disconnected to prioritize power supply for core sensing and communication units. Conversely, when the SOC exceeds 95% and surplus generation persists, the system activates a dump load (e.g., an auxiliary seawater desalination module) or initiates active curtailment to prevent overcharging.

V. COLLABORATIVE SCHEDULING BASED ON EDGE COMPUTING AND DIGITAL TWINS

On the foundation of the features of the mentioned modules to independently supply power and collect data, the current research develops a three-layer model of the collaboration between the scheduling system utilizing the services of devices, the edge, and the cloud according to the device-edge-cloud structure. The perception layer is based on IoT sensor suites installed in each modules which measure three categories of core data in real-time: overflow rate (dual check with ultrasonic radar and vision), equipment operating conditions (count of compressor start/stop, motor current, bearing temperature), and environmental conditions (temperature, humidity, wind speed, irradiance). Data sampling and reporting follow differentiated strategies based on parameter type. Environmental parameters (temperature, humidity, wind speed, irradiance) are sampled by sensors at 1-minute intervals and logged locally. Overflow status is sampled continuously, with reported values transmitted every 15 minutes under normal conditions; when the measured fill level exceeds 80%, the reporting frequency automatically increases to once every 5 minutes. Equipment operational data (compressor start/stop counts, motor current, bearing temperature) are reported on an event-triggered basis, such as upon equipment failure or state change.

The main point of scheduling is the edge computing layer. The built-in industrial-grade edge computing gateway (using an ARM quad-core processor and a lightweight Linux system) of each module has three functions: First, it cleans and compresses raw sensor data, filters outliers and packages and uploads it in a common format; Second, it implements a lightweight fault diagnosis algorithm on itself, instantly activating local alarms and performing protective shutdowns when anomalous changes in current flowing to a device or motor overheating are detected, without waiting to be told to do so by a node farther away; Thirdly, as a node in the regional network,

The layer of cloud platform creates a digital twin system, the Scenic Area Environmental Brain. According to the BIM and GIS technologies, all the physical modules in the scenic region are mapped in the three-dimensional visualized digital representations of the models and are associated with the real time streams of data of the physical modules. According to the twin model, two fundamental scheduling algorithms are implemented: a dynamic waste collection route optimization model which is constructed on the basis of enhanced ant colony algorithm. This model accepts real-time data on overflow and its goal is to minimize the overall mileage of the waste collection vehicles and the maximum response time. It also takes into account the effects of the tidal periods on traffic in the beaches and dynamically plans the optimal route of collecting wastes on the day and drives it to the waste collection vehicle terminal at dawn. The second is a peak and off-peak season adaptive operation strategy model. It forecasts the strength of the waste generation of every region the following day using past visitor heat maps and automatically sets the start and stop limits and hibernate and wake-up strategies of the compressors of the modules respectively. The off-peak season can also be used to put the ineffective modules on partial hibernation in order to conserve energy.

VI. MEASUREMENT OF THE SMART PERFORMANCE OF MODULAR FACILITIES

A. EXPERIMENTAL SETUP

To comprehensively verify the overall performance of modular smart environmental protection facilities in a real coastal environment, this study constructed a full-scale experimental platform in the demonstration area of Qinhuangdao Golden Coast Scenic Area.

The experimental period coincided with the local typhoon season, allowing for routine operational monitoring under natural wind conditions; however, no destructive structural tests were conducted to verify the modules' ultimate wind resistance capacity.

Experimental Site: Two cleaning areas, A and B, were designated within the park as control experimental areas. Both areas covered typical coastal functional areas such as the beach section, reef section, and entrance plaza section. Ten smart environmental protection modules were deployed in each area, for a total of 20 modules.Both areas were allocated identical operational resources, including one cleaning vehicle and two crew members per area, with a maximum cleaning frequency of three times per day for each. All modules integrated an independent "wind-solar-storage" microgrid, an edge computing gateway, and a full-scale sensor.

Sample Preparation: The module skin material (weathering steel + anticorrosive wood) was processed 1:1 according to the design drawings. Simultaneously, a traditional galvanized steel plate control sample (150mm × 70mm) was prepared for corrosion comparison experiments.

Equipment Configuration: Salt spray test chamber (model: YWX/Q-750), weather station (monitoring wind speed, irradiance, temperature, and humidity), power monitoring instruments (accuracy class 0.5), IoT data acquisition device (4G/5G dual-mode), and UAV aerial photography system (for waste distribution modeling).

Data Acquisition: Environmental data (salt spray deposition, light intensity, wind speed, and irradiance) are sampled at 1-minute intervals by the weather station and edge gateway. Energy data (power generation, power consumption, SOC) are sampled continuously and uploaded to the cloud platform at 1-minute intervals by the energy storage controller. Overflow status is reported every 15 minutes under normal conditions; when the fill level exceeds 80%, the reporting frequency automatically increases to once every 5 minutes. All data are synchronously stored in the "Environmental Brain" database for subsequent analysis.

B. ACCELERATED CORROSION TEST OF MODULE WEATHER RESISTANCE

A neutral salt spray accelerated corrosion test was conducted according to GB/T 10125-2021 standard. Two groups of samples were set up: the experimental group consisted of weather-resistant steel-anticorrosion wood composite material, and the control group consisted of traditional galvanized steel sheet, with 10 parallel samples in each group. A 5% NaCl solution was continuously sprayed into the test chamber, and the temperature was kept constant at 35±2°C. The test lasted for 720 hours, with spraying interrupted every 72 hours. Samples were then removed, cleaned, and dried. The corrosion level was evaluated according to GB/T 6461-2002, and the mass was measured using an electronic balance to calculate the cumulative weight loss rate. Specific data are shown in Figure 1:

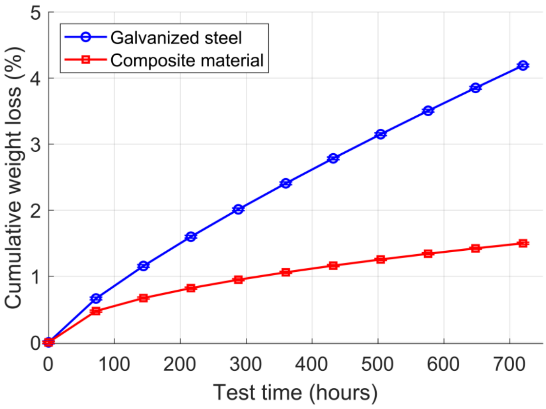

FIGURE 1. Accelerated Corrosion Assessment of Module Weather Resistance

After 720 hours of neutral salt spray accelerated corrosion test, the weather-resistant steel-anticorrosion wood composite material used in the module exhibited superior weather resistance compared to the traditional galvanized steel sheet. Experimental data showed that the cumulative weight loss rate of the composite material was 1.5%, while the weight loss rate of the control group (galvanized steel sheet) reached 4.2%, indicating that the corrosion rate of the composite material was reduced by approximately 64% compared to the control group. From the corrosion kinetic curves, the corrosion rate of the composite material tended to level off in the later stages of the experiment, exhibiting good passivation characteristics. This result preliminarily verifies the effectiveness of the material selection and composite coating designed for high salt spray environments, providing a material basis for the long-term service of the module in a coastal environment. It should be noted that this experiment is an accelerated simulation test for corrosion resistance; the structural performance of the modules under extreme wind loads (e.g., typhoons) has not been experimentally validated in this study and requires separate investigation in future work.

C. EXPERIMENTAL TEST ON ENERGY SELF-SUFFICIENCY OF INDEPENDENT MICROGRIDS

As a test object, a standard smart environmental protection module in the scenic area was chosen. It was made up of 1 kW vertical axis wind turbine, 2 kWp flexible photovoltaic modules and 5 kWh/48V lithium iron phosphate energy storage system making it a microgrid. The duration of the experiment was 7 consecutive days, which encompassed the normal of meteorological conditions like sunny days, rainy days and typhoon passage. Parameters of measurement were: real-time generation of power of the photovoltaic and wind turbines, load power consumption, state of charge of the energy storage system, ambient wind speed and irradiance. All data were noted after every 1 minutes and posted to the cloud platform.

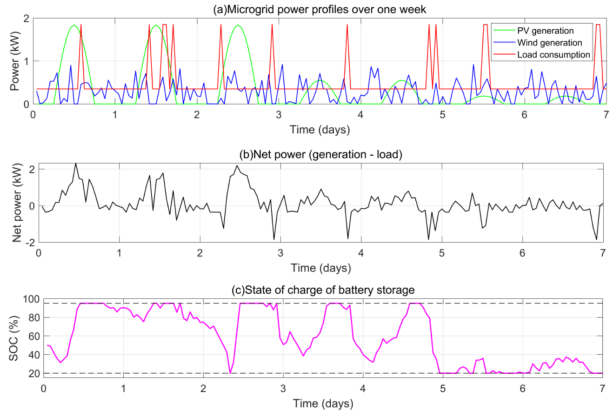

FIGURE 2. Assessment of Energy Self-Sufficiency of Independent Microgrids

Figures 2 (a-c) show the power generation and consumption curves, net power curve, and changes in the state of charge of the energy storage system over one week. The results demonstrate that wind-solar generation significantly exceeds the module's average load, validating resource adequacy in coastal environments. However, the 5 kWh storage capacity is insufficient to capture excess generation, resulting in 29.6 kWh of curtailed energy over the one-week test. This limited storage also constrains the system's ability to bridge consecutive days of low renewable generation. The measured self-sufficiency rate of 88.2% reflects performance under the specific meteorological conditions during the test week; a more conservative estimate would be expected under prolonged adverse weather. Notably, this self-sufficiency rate was achieved alongside 29.6 kWh of curtailed energy, indicating that while generation capacity is abundant, storage capacity remains the limiting factor for achieving higher self-sufficiency. Future work will focus on optimizing the storage-to-generation ratio based on site-specific meteorological profiles.

D. COMPARATIVE EXPERIMENT OF SMART DISPATCH PLATFORM FOR WASTE COLLECTION EFFICIENCY

Qinhuangdao Golden Coast Scenic Area was divided into 2 cleaning areas (A and B) with 10 smart environmental protection modules in each of them. Area A operated on the standard mode of scheduled waste collection (3 times a day), and area B was linked to the platform of the "Environmental Brain" digital twin , in which the waste route was planned dynamically, with the help of the optimized ant colony algorithm. All other operational parameters, including the number of cleaning vehicles and crew, remained identical between the two areas to ensure that the observed differences were attributable solely to the dispatching algorithm. The overflow alarms, average time taken to collect waste, and total mileage of the waste collection vehicles were equated during 7 successive days to compare the efficiency of the two modes in terms of waste collection.

TABLE 2. Comparison of Waste Collection Efficiency of Smart Dispatch Platform

Zone	Cleaning Mode	Overflow Alarm Frequency (times/week)	Average Response Time (minutes)	Cleaning Vehicle Mileage (km/week)
A	Fixed schedule	41	45	187
B	Smart dispatching	11	12	129

Table 2 shows that the smart dispatch platform exhibits a significant advantage in waste collection efficiency. After adopting the improved ant colony algorithm for dynamic path planning in Area B, the number of weekly overflow alarms decreased to 11, a 73% reduction compared to 41 in Area A; the average response time decreased from 45 minutes to 12 minutes, also a 73% reduction; and the mileage of garbage trucks decreased from 187 kilometers to 129 kilometers, a 31% reduction. The results indicate that the intelligent dispatch platform effectively prevented garbage overflow, significantly improved emergency response efficiency, and reduced carbon emissions and operating costs during the garbage collection process.

VII. CONCLUSION

The modular design framework presented in this paper integrates corrosion-resistant materials, a wind-solar-storage microgrid, and digital twin technology, offering a potential solution to the environmental durability and operational efficiency challenges of facilities in seaside scenic areas. While the modules are theoretically designed to withstand typhoon-level winds based on structural design codes, this study experimentally validated only their corrosion resistance and energy self-sufficiency; their structural integrity under extreme wind loads remains to be verified through dedicated mechanical testing. Systematic experiments confirm the

technical feasibility of the proposed approach, with the microgrid achieving a self-sufficiency rate of 88.2% under the tested meteorological conditions. This rate was achieved despite 29.6 kWh of curtailed energy, highlighting that the current 5 kWh storage capacity is undersized relative to generation capacity—a limitation that will be addressed in future optimization. Future work will focus on optimizing the storage-to-generation ratio based on site-specific meteorological profiles, enhancing the generalization capability of the intelligent scheduling algorithm across diverse operational scenarios, and conducting long-term durability assessments of the modules under natural exposure conditions.

AUTHOR CONTRIBUTIONS

Conceptualization –Qihao Lv, Chuxin Wang and Ni Du; methodology – Qihao Lv, Chuxin Wang and Ni Du; investigation – Qihao Lv, Chuxin Wang and Ni Du; writing-original draft preparation – Qihao Lv, Chuxin Wang and Ni Du. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

FUNDING

This research was supported by,

Research on the Construction Path of "Zero-Waste Scenic Areas" in Qinhuangdao City under the Context of Smart Tourism(QN2025736)

ACKNOWLEDGEMENTS

Not applicable.

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