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Marine Renewable Energy for Island Integrated Energy Systems Optimisation: a Review

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Combining marine renewable energy with traditional energy and rationally constructing an integrated island energy system is crucial to alleviating island energy supply problems and the clean transformation of coastal energy. This paper analyses the energy demand characteristics of different types of energy islands to introduce existing optimisation models and technologies for island integrated energy systems. The current solutions and their advantages and disadvantages from the perspectives of modelling methods and system simulation are discussed, with future research directions proposed to guide sustainable energy development in island regions. Integrated energy systems can enhance energy utilisation efficiency and promote the integration of renewable energy, this paper aims to inspire readers to develop new functionalities and modules based on existing technologies, providing valuable references and insights for sustainable energy development in island regions.

1. Introduction

Marine renewable energy (MRE) is a promising low-emission resource. MREs usually include energy from waves, tides, ocean currents, salinity, and temperature differences, collectively known as ocean energy. A broader definition also encompasses marine biomass, offshore wind, and offshore solar energy that utilize the ocean's surface (Taveira-Pinto et al., 2020). Global installed capacity in 2020 are shown in Figure 1. In recent years, global island development has surged, leading to increased utilization of these areas. Islands offer diverse resources like tourism, natural harbors, and minerals, expanding human activity and marine resource understanding (Khojasteh et al., 2023). Island power mainly depends on expensive and environmentally harmful methods like submarine cables or fuel generators, islands constitute only a small fraction of global greenhouse gas (GHG) emissions, their per capita emissions are notably high. For instance, Caribbean Islands contributed merely 0.4 % of worldwide GHG emissions in 2015, yet their per capita GHG production stood significantly elevated at 120 t compared to the global average of 5 t. These emissions primarily stem from fossil fuel usage (Meckling, 2018). Islands, particularly those within the Small Island Developing States group, face common challenges such as land limitations, isolated energy grids, and minimal natural resources. Many rely heavily on imported oil or diesel for energy generation, which not only incurs high costs but also contributes to pollution. Despite these challenges, islands and remote communities have the potential to embrace a "blue economy" model. This approach involves harnessing energy from oceans to support the decarbonization of crucial marine activities such as shipping, power generation, cooling, aquaculture, and water desalination (IRENA, 2020).

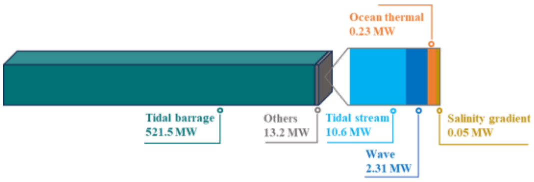

Figure 1: current ocean energy deployment (IRENA, 2020)

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Renewable energy faces challenges due to the variability and randomness of weather. Solutions like energy storage (ES), microgrid development, hybrid systems, demand management, distributed generation (DG), and smart grid construction are improving its utilization (Kuang et al., 2016). For island, it's critical to design clean, locally-adapted, low-cost energy systems. With varying technology levels and costs in energy supply equipment, storage, and demand-side loads for Integrated Energy Systems (IESs), and the complexity of their coupling, traditional IES strategies are becoming less effective. There's an urgent call for optimized scheduling in IESs that considers multiple energy sources with multi-objective and synergistic approaches (Ma et al., 2023).

Previous reviews have examined energy system research focuses on the optimization of system configuration and economical and efficient operation (He et al., 2023). The reviews on marine renewable energy optimization have primarily focused on isolated aspects without addressing the comprehensive integration of multiple energy sources and the specific needs of island regions. This paper fills these gaps by offering a holistic analysis of integrated energy systems tailored to islands, highlighting innovative approaches and technologies that have not been extensively covered in prior studies. This paper analyses the integration of marine energy with other clean energies in island energy systems， it also outlines the complex, multidimensional modelling and solution processes involved in island IES optimization. The key points of the current review include:

- Complementary use of MRE with renewable and traditional energy sources like natural gas. It analyses methods for designing and integrating efficient and reliable coupled marine energy systems to enhance overall efficiency and reliability.
- Existing optimization models and techniques for island IESs, including modelling methods, system simulation.

2. MRE-based island integrated energy system optimization

2.1 Types of energy for islands

Island power grids use renewable energy sources like hydropower, wind, and solar. Some islands also tap into biomass, geothermal, and marine energy. Energy facilities on the islands vary, integrated development is the core of building a new energy system, different energy combinations can yield additional economic benefits. By combining marine renewable energy with other offshore technologies and implementing innovative business models, there is a notable potential for decreasing the levelized energy costs. This can be achieved through the creation of economies of scale and the generation of more revenue streams. Such integration could pave the way for accessing new markets, exemplified by island regions as depicted in Table 1, and could represent a pivotal advancement for ocean energy. These collaborative approaches offer not only economic benefits but also contribute to enhancing the reliability of energy systems.

Table 1: Integrating marine renewable energy with other renewable sources in island regions

Islands	Energy type	Mode of operation and project scale	Refs
Ushant Island in the French Channel Islands	Solar, wind, energy storage, tidal	Solar energy (solar greenhouses, solar container, floating solar, solar tiles: 480 kW); wind turbine (1 x 900 kW); energy storage (2 MW / 2 MWh); tidal turbines (2 x D12-500)	Hussain and Thies, 2019
Orkney Island in the north of Scotland	Tidal, wind, solar, energy storage	Solar PV (0.5 MW); tidal (Sabella D12 x 21 MW); wind (0.9 MW); energy storage	Almoghayer et al., 2022
Estmanna Faroe islands in Sweden	Tidal Energy Kite delivers	Dragon12 (1.2 MW); main subsea cable (3.4 km)	Trondheim et al., 2021
Reunion Island, a French overseas region located in the Indian Ocean	Water, wind, solar, wave, ocean thermal energy	Hydroelectricity (133,6 MW); photovoltaic solar energy (186,6 MW); wind farms (14,8 MW); wave energy (2 MW); ocean thermal energy conversion (15 kW)	Selosse et al., 2018
Isola Piana, Italy, 0.21 km^2	Wave to energy and water	Wave energy utilizing an Attenuator (100- 150 kW); Reverse Osmosis desalination (capable of processing 1,500- 30,000 cubic meters); water storage	Henriksen et al., 2019

2.2 Island IES optimization

Island Integrated Energy System (IES) leverages energy cascade utilization and multi-energy coupling, coordinating various energy resources and integrating source-grid-load-storage. Figure 2 illustrates the basic framework of an Island IES based on existing research. It smooths out power load fluctuations, optimizes multiple energy uses, and achieves high energy efficiency. This system meets demands for cooling, heating, and electricity, while effectively absorbing surplus resources. Integrated energy system shares a common physical structure and equipment for generating, transmitting, storing, and using electrical, thermal, cooling, and gas energy. Typical equipment unit and its physical indexes are shown in Table 2. The energy hub is an essential part of IESs, which connects and manages different energy resources.

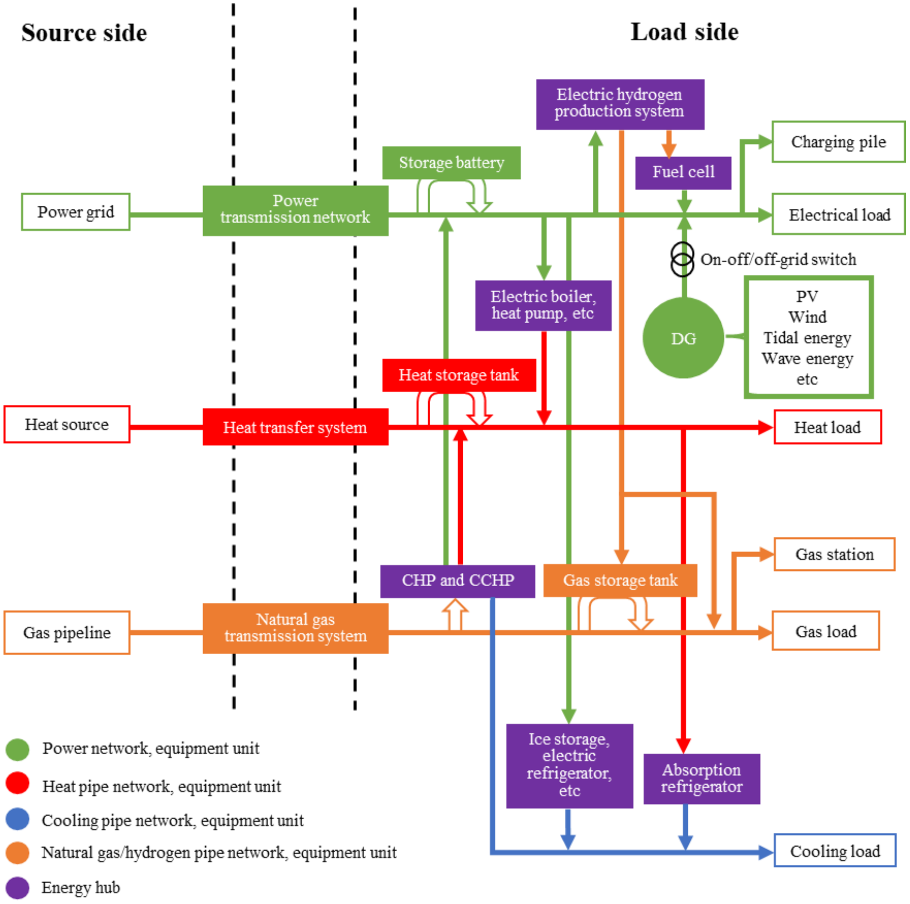

Figure 2: Framework schematic diagram of Island Integrated Energy System

The optimisation models can be categorised into basic models and models that consider energy flow variations, system flexibility, and system randomness. Basic models consist of general models and unified models, where the former individually models each energy system and coupling component, while the latter employs theoretical equations such as energy hubs or circuits to express multiple energy relationships uniformly (Dai et al., 2020). Models considering energy flow variations address time-scale differences in system optimisation, ensuring the matching and balancing of energy transmission speeds (Osiadacz and Chaczykowski, 2020). Models considering system flexibility enhance economic viability and renewable energy integration capacity through conversion, coordination, and the addition of coupling components and energy storage devices, leveraging pipeline storage characteristics and building thermal properties (Pombo et al., 2023). Models addressing system randomness focus on uncertainties arising from renewable energy integration and electricity price-induced load fluctuations, employing stochastic optimisation and robust optimisation methods for decision-making (Yang and Su, 2021). The energy management system aims to maximise the utilisation of renewable energy resources, minimise operation costs, and improve grid reliability and resilience (Zhong et al., 2020), and reduce environmental costs, selecting and sizing facilities for minimal carbon emissions (Li et al., 2020). These goals can be met by managing renewable resources, traditional DGs, ES units (Nkwambe et al., 2024), and adjustable loads in reaction to possible issues, changes in utility grid status, and intermittent renewable energy (Sahoo et al., 2020).

Table 2: Typical equipment unit and its physical indexes of integrated energy system

Category	Main physical index
Electric power equipment: Distributed generation (DG), Transmission and distribution network Grid (Lines & Subs), Energy Storage (Battery), Charging pile	Voltage, current, phase Angle difference (AC), power (active power, reactive power (AC)), transmission and storage losses, charge and discharge power and efficiency
Thermal equipment: Heat network (pipeline, pump), thermal storage tank, heat pump	Temperature, pressure, transmission and storage efficiency
Natural gas equipment: Gas network (pipeline, station), gas storage tank, gas station	Pressure, flow, transmission and storage efficiency
Gas-Electricity coupling device: Micro-combustion power generator, hydrogen fuel cell	Electrical output power, gas consumption, gas-electric conversion efficiency
Gas-Thermal- Electricity coupling device: Combined heating and power units (CHP)	Gas consumption, electrical output power, thermal output power, gas-electric conversion efficiency, gas-thermal conversion efficiency, etc
Gas-Cold-Thermal- Electricity coupling device: Combined cooling heating and power units (CCHP)	Gas consumption, electrical output power, thermal output power, cold output power, gas-electric conversion efficiency, gas-thermal conversion efficiency, etc
Gas-Thermal coupling device: Gas-fired heating boiler	Gas consumption, thermal output power, gas-thermal conversion efficiency
Electricity-Gas coupling device: Electric hydrogen production system	Hydrogen production, electrolytic voltage, electrolytic current, hydrogen storage capacity
Electricity-Thermal coupling device: Electric boiler, electric heating, heat pump	Power consumption, thermal output power, electric-thermal conversion power
Heat-Cold coupling device: Absorption refrigerator	Input thermal power, output cold power, thermodynamic coefficient
Electricity-Cold coupling device: Absorption refrigerants, ice storage, etc	Temperature, cooling efficiency, cold storage efficiency

Modelling methods include dispatch (or operational) optimisation, single-objective (or multi-objective) investment (or expansion capacity) optimisation (Prina et al., 2021). Dispatch optimisation follows merit-order logic. A production simulation model for a renewable energy-based power system is developed, encompassing costs from thermal plant operations, energy storage systems, and positive and negative reserve costs, the optimisation goal is to minimise the total operational expenses, realistic system parameters and cost data are collected, reflecting various wind power fluctuations and grid-connected scenarios (Yan et al., 2024). Investment optimisation focuses on expanding capacity. Island electricity systems have heightened vulnerability to power quality, reliability, and resilience issues compared to continental systems; addressing these challenges requires capacity-planning models specifically tailored for island systems. An optimization model for long-term planning in island electricity systems was developed by Barrera-Santana and Sioshansi (2023). Considering the technical constraints specific to island systems, the best mix of generation and transmission capacity to meet energy demand at minimum cost is found by this model. Bi-level frameworks are often used to effectively resolve multi-objective problems to convert multiple objectives into single objectives or use different stages. Ma et al. (2023) developed a two-layer optimisation strategy for islanded energy systems, focusing on resilience and economic efficiency. A Pareto-based multi-objective optimisation model is applied; it treats water production and treatment systems as flexible loads and examines various water supply infrastructures and combinations of PV/wind power to find the best energy-water setup (Cabrera et al., 2021). A stochastic optimization framework considering uncertainties, AC and HVDC transmission, renewable generators, and energy storage was suggested by Boffino et al. (2019). It focuses on two main decisions: investments (like generation, transmission, and storage infrastructure) and operations (how assets are used to meet energy needs and operational requirements).

2.3 System simulation

Energy system simulation refers to the actual simulation and analysis of these models using computer software. Simulation software is specifically designed to execute these models and generate simulation results. They typically include functionalities such as model input, parameter setting, running simulations, analysing results, and visualization, offering advantages like explicitness, logical consequences, and comprehensiveness (Liu et al., 2018). In the simulation of island integrated energy systems combining renewable energy, the mostly used bottom-up energy system models are EnergyPLAN, HOMER, Unit Commitment models, MATLAB/Simulink, and TRNSYS (Prina et al., 2021). These tools offer the capability to establish models of IESs and evaluate the impact of different energy combinations on system performance and economic viability. EnergyPLAN applies the Smart Energy System concept and can simulate the entire energy system, connecting different sectors. The details about its algorithm are in manuals, reports, and documents on the website www.energyplan.eu (van Beuzekom et al., 2015). Although EnergyPLAN is user-friendly, it limits subsequent executions. To vary decision variables in a specific energy system model, the MATLAB Toolbox for EnergyPLAN was created. This toolbox includes functions to call and manage EnergyPLAN from MATLAB (Cabrera et al., 2020). Ye et al. (2017) used the HOMER hybrid optimization model to assess meeting energy demand feasibility and applied the model to a 2.8 km^2 isolated island in the South China Sea to confirm technological and economic feasibility. The simulation also includes many specialized ocean energy simulation software, such as WEC-Sim for wave energy simulation and TELEMAC- 3D for tidal energy simulation; they can assist in the integration of marine energy into the island-integrated energy system. Using TELEMAC- 3D to simulate tidal hydrodynamics, Almoghayer et al. (2022) explored the most economical approach to incorporate tidal energy into the Orkney energy system.

2.4 Technical challenges

Island integrated energy system's operational stability is impacted by load fluctuations, energy/communication issues, and inter-network interactions, while uncertainties like distributed energy output and load variations persist, renewable energy relies on distributed microgrids, facing challenges in stability due to variable output and consumption (Qu et al., 2021). The integration of variable renewable energy sources, balancing technologies, storage, and demand-side management requires higher temporal resolution for accurate behaviour capture (hourly time steps in energy system modelling represent the highest resolution) (Ye et al., 2017). Major technical challenges include the following: coordinating control among devices for overall optimisation across periods, accurately modelling diverse circuit topologies in energy optimisation, managing different operational requirements in grid-connected and island modes, and addressing device limits and operation constraints such as generator capacity, start-up time, costs, energy efficiency, and line voltage/current limits (Yang et al., 2019).

3. Conclusions and future directions

Integrated energy systems can enhance energy utilisation efficiency and promote the integration of renewable energy. This paper analyses the research trends in the optimisation of integrated energy systems, summarises and organizes the research status of integrated energy system optimisation from the perspectives of models and methods, inspires readers to develop new functionalities and modules based on existing technologies, aims to provide references and insights for sustainable energy development in island regions. With the continuous development and application of new technologies and equipment, the basic architecture of integrated energy systems is also evolving. The power models of distributed energy rely on environmental parameters, and prediction methods based on parameters such as wind speed and sunlight can be employed to schedule systems in advance to achieve economic efficiency and stability. The technologies of wave energy, tidal energy, and biomass energy generators are continuously improving, and corresponding models should be updated accordingly. Further research could focus on coordinating electricity with other forms of energy (such as LNG cold energy) on islands.

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References

Almoghayer M.A., Woolf D.K., Kerr S., Davies G., 2022, Integration of tidal energy into an island energy system – A case study of Orkney islands, Energy, 242, 122547.

Barrera-Santana J., Sioshansi R., 2023, An optimization framework for capacity planning of island electricity systems, Renewable & sustainable energy reviews, 171, 112955.

Boffino L., Conejo A.J., Sioshansi R., Oggioni G., 2019, A two-stage stochastic optimization planning framework to decarbonize deeply electric power systems, Energy economics, 84, 104457.

Cabrera P., Carta J.A., Lund H., Thellufsen J.Z., 2021, Large-scale optimal integration of wind and solar photovoltaic power in water-energy systems on islands, Energy conversion and management, 235, 113982.

Cabrera P., Lund H., Thellufsen J.Z., Sorknæs P., 2020, The MATLAB Toolbox for EnergyPLAN: A tool to extend energy planning studies, Science of computer programming, 191, 102405.

Dai W. et al., 2020, A Static Equivalent Model of Natural Gas Network for Electricity-Gas Co-Optimization, IEEE transactions on sustainable energy, 11(3), 1473-1482.

Henriksen M., Simon D.L.P., Lai M., 2019, New Combined Solution to Harness Wave Energy—Full Renewable Potential for Sustainable Electricity and Fresh Water Production, Proceedings, 20(1), 10.

Hussain E.K., Thies P.R., 2019, Assessing Energy Transition Scenarios for Islands through Network Reliability and Power Flow Analysis, IEEE, pp 1-5.

IRENA, 2020, ocean energy database, International Renewable Energy Agency, <irena.org/publications/2020/Dec/Innovation-Outlook-Ocean-Energy-Technologies>, accessed 26.03.2024.

Khojasteh D., Shamsipour A., Huang L., Tavakoli S., Haghani M., Flocard F., Farzadkhoo M., Iglesias G., Hemer M., Lewis M., Neill S., Bernitsas M.M., Glamore W., 2023, A large-scale review of wave and tidal energy research over the last 20 years, OCEAN ENGINEERING, 282, 114995.

Kuang Y., Zhang Y., Zhou B., Li C., Cao Y., Li L., Zeng L., 2016, A review of renewable energy utilization in islands, Renewable and Sustainable Energy Reviews, 59, 504-513.

Li Z., Zhang H., Meng J., Long Y., Yan Y., Li M., Huang Z., Liang Y., 2020, Reducing carbon footprint of deep-sea oil and gas field exploitation by optimization for Floating Production Storage and Offloading, Applied Energy, 261, 114398.

Liu Y., Yu S., Zhu Y., Wang D., Liu J., 2018, Modeling, planning, application and management of energy systems for isolated areas: A review, Renewable and Sustainable Energy Reviews, 82, 460-470.

Ma H., Wang Y., He M., 2023, Collaborative Optimization Scheduling of Resilience and Economic Oriented Islanded Integrated Energy System under Low Carbon Transition, Sustainability, 15(21), 15663.

Meckling J., 2018, The developmental state in global regulation: Economic change and climate policy, European journal of international relations, 24 (1), 58-81.

Nkwambe M.S., Sutherland T., Seodigeng T., Musamba B., 2024, Energy Storage Through a Regenerative Hydrogen Fuel Cell in a Hybrid System of Renewable Energy for Power Generation, Chemical Engineering Transactions, 108, 73-78.

Osiadacz A.J., Chaczykowski M., 2020, Modeling and Simulation of Gas Distribution Networks in a Multienergy System Environment, Proceedings of the IEEE, 108(9), 1580-1595.

Pombo D.V., Martinez-Rico J., Spataru S.V., Bindner H.W., Sørensen P.E., 2023, Decarbonizing energy islands with flexibility-enabling planning: The case of Santiago, Cape Verde, Renewable & sustainable energy reviews, 176, 113151.

Prina M.G., Groppi D., Nastasi B., Garcia D.A., 2021, Bottom-up energy system models applied to sustainable islands, Renewable & sustainable energy reviews, 152, 111625.

Qu M., Ding T., Jia W., Zhu S., Yang Y., Blaabjerg F., 2021, Distributed Optimal Control of Energy Hubs for Micro-Integrated Energy Systems, IEEE transactions on systems, man, and cybernetics, Systems, 51, 2145-2158.

Sahoo S., Mishra S., Jha S., Singh B., 2020, A Cooperative Adaptive Droop Based Energy Management and Optimal Voltage Regulation Scheme for DC Microgrids, IEEE transactions on industrial electronics, 67(4), 2894-2904.

Selosse S., Garabedian S., Ricci O., Maïzi N., 2018, The renewable energy revolution of reunion island, Renewable & sustainable energy reviews, 89, 99-105.

Taveira-Pinto F., Rosa-Santos P., Fazeres-Ferradosa T., 2020, Marine renewable energy, Renewable Energy 150, 1160-1164.

Trondheim H.M., Niclasen B.A., Nielsen T., Silva F.F.D., Bak C.L., 2021, 100 % Sustainable Electricity in the Faroe Islands: Expansion Planning Through Economic Optimization, IEEE open access journal of power and energy, 8, 23-34.

van Beuzekom I., Gibescu M., Slootweg J.G., 2015, A review of multi-energy system planning and optimization tools for sustainable urban development, IEEE, pp 1-7.

Yan J., Liu S., Yan Y., Zhang H., Liang C., Wang B., Liu Y., Han S., 2024, A data-driven model for power system operating costs based on different types of wind power fluctuations, Journal of Environmental Management, 351, 119878.

Yang F., Feng X., Li Z., 2019, Advanced Microgrid Energy Management System for Future Sustainable and Resilient Power Grid, IEEE transactions on industry applications, 55(6), 7251-7260.

Yang J., Su C., 2021, Robust optimization of microgrid based on renewable distributed power generation and load demand uncertainty, Energy, 223, 120043.

Ye B., Zhang K., Jiang J., Miao L., Li J., 2017, Towards a 90 % renewable energy future: A case study of an island in the South China Sea, Energy Conservation and Management, 142, 28-41.

Zhong W., Wang L., Liu Z., Hou S., 2020, Reliability Evaluation and Improvement of Islanded Microgrid Considering Operation Failures of Power Electronic Equipment, Journal of Modern Power Systems and Clean Energy, 8(1), 111-123.