

Review

Offshore Integrated Energy Systems for Low-Carbon Transition: A Review of Offshore Renewables, Geothermal Integration, Multi-Energy Coupling, and Optimization Methods

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Abstract

Driven by the global low-carbon transition and the rapid expansion of marine energy development, offshore integrated energy systems are emerging as a critical configuration for coupling offshore renewable resources, geothermal and subsurface thermal resources, oil and gas infrastructure, hydrogen pathways, multi-carrier networks, and offshore loads. Unlike onshore integrated energy systems, offshore systems are constrained by resource intermittency, harsh marine environments, platform space and weight limits, long-distance transmission, operation and maintenance accessibility, safety risks, and cross-regional governance mechanisms. Recent studies have advanced offshore wind-to-hydrogen systems, oil and gas platform electrification, offshore energy hubs, platform repurposing, and offshore geothermal utilization. However, these studies remain fragmented in terms of system boundaries, multi-energy coupling mechanisms, engineering constraints, and optimization methods. This paper reviews offshore integrated energy systems from the perspectives of system configuration, key integration technologies, optimization and assessment methods, and future research needs. Offshore integrated energy systems are first classified into offshore renewable-energy-dominated systems, offshore wind–hydrogen systems, oil and gas platform integrated systems, offshore energy hubs and multi-carrier networks, decommissioned-platform repurposing systems, and offshore geothermal and repurposed-well systems. Resource-side, conversion-side, storage-side, network-side, and load-side integration technologies are then summarized. Capacity configuration, operational scheduling, stochastic and robust optimization, multi-objective optimization, energy, exergy, economic, and environmental (4E) assessment, advanced exergy analysis, and energy-hub modelling are further reviewed. Finally, key research gaps are identified, including resource uncertainty, offshore engineering constraints, multi-carrier network coupling, insufficient demonstration data, and policy and economic uncertainty. This review provides a structured reference for the modelling, integration, optimization, and demonstration of offshore integrated energy systems for low-carbon transition.

Keywords: offshore integrated energy system; offshore renewables; offshore geothermal energy; offshore hydrogen production; oil and gas platform repurposing; multi-energy coupling; optimization methods



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1. Introduction

Integrated energy systems couple electricity, heat, gas, hydrogen, storage, and demand-side resources to coordinate energy production, conversion, storage, transmission, and utilization. Geidl and Andersson developed an optimal power-flow formulation for multiple energy carriers, providing an early modelling basis for integrated energy systems [1]. Mancarella further emphasized that the value of multi-energy systems lies not only in efficiency improvement, but also in enhanced system flexibility and decarbonization capability [2].

In onshore applications, a relatively mature research base has been formed around wind–solar storage systems, combined cooling–heating power systems, and wind–solar–hydrogen storage systems. Su et al. designed a polygeneration system integrating solid oxide fuel cells, renewable energy, and waste heat recovery, demonstrating that multi-device coupling can improve overall system performance [3]. Chen et al. investigated a solar-driven polygeneration system and highlighted the importance of storage in improving renewable energy utilization [4]. Zheng et al. coupled photovoltaic thermal collectors, proton exchange membrane electrolyzer (PEME) units, solid oxide fuel cells, and thermal energy storage, providing a systematic design basis for later wind–solar–hydrogen systems [5]. Although these studies mainly focused on buildings or regional energy systems, their concepts of multi-source complementarity, storage regulation, and energy management are directly relevant to offshore applications.

With offshore wind development moving from nearshore to far-offshore areas, the research object of offshore energy systems has changed significantly. Wiegner et al. conducted a systematic review of offshore energy system integration in the North Sea and argued that offshore wind grid connection, offshore hydrogen production, storage, and institutional governance should be studied in an integrated framework [6]. The rapid growth of offshore wind development and the growing need for cross-area infrastructure coordination provide the resource and network basis for such systems [6].

Offshore integrated energy systems have greater engineering complexity than onshore systems. Neumann et al. showed that the role of hydrogen networks needs to be assessed together with existing gas infrastructure and electricity network expansion [7]. Hofmann et al. further demonstrated that the coordinated planning of hydrogen and carbon dioxide networks can affect the cost and infrastructure layout of deep decarbonization pathways [8]. Kazemi-Robati et al. showed that hybridizing existing offshore wind farms with wave energy and floating photovoltaics can improve sea-area utilization, although economic performance is strongly affected by resource complementarity and export capacity [9].

Geothermal and subsurface thermal resources provide an additional integration pathway for offshore systems because they can serve as relatively stable heat or power sources and can partly compensate for the intermittency of wind and solar generation. Santos et al. reviewed the repurposing of abandoned wells for geothermal energy and highlighted the potential of existing wellbores to reduce drilling-related barriers in geothermal projects [10]. Zhao et al. analyzed an offshore renewable-energy-powered integrated energy supply system and showed that multi-energy configurations can provide electricity, cooling, desalination, and storage services under offshore resource conditions [11]. In China, offshore geothermal potential has also been discussed for sedimentary basins such as the South China Sea. Yuan et al. reported geothermal gradients and heat-flow characteristics in the Qiongdongnan and Pearl River Mouth basins [12], while Chen et al. assessed geothermal resources in the Huangliu Formation of the Yinggehai Basin [13].

Existing studies on offshore integrated energy systems can be broadly grouped into six research streams. The first focuses on offshore renewable-energy-dominated systems. Ayyad et al. modelled water-cooling effects in floating offshore photovoltaics [14], while

Jin et al. evaluated the geographically constrained resource potential of integrating floating photovoltaics into existing offshore wind farms [15]. The second stream focuses on offshore wind-to-hydrogen systems. Wang et al. reviewed in situ green hydrogen production from offshore wind farms [16], and Pizzuti et al. examined energy storage and management for offshore wind-based green hydrogen production [17]. The third stream addresses oil and gas platform integrated energy systems. Romero-Filgueira et al. presented a renewable-energy- and green-hydrogen-based decarbonization methodology for the Oceanic Platform of the Canary Islands (PLOCAN) offshore platform [18]. The fourth stream studies offshore energy hubs and multi-carrier networks. Gea-Bermudez et al. assessed offshore market design in an integrated North Sea energy system [19]. The fifth stream explores repurposed offshore assets, including the reuse of existing natural gas infrastructure for offshore hydrogen production and transport [20]. The sixth stream focuses on offshore geothermal and repurposed-well systems, in which geothermal heat, wellbore heat exchangers, and organic Rankine cycle (ORC)-based conversion are combined with offshore platforms, hydrogen production, and thermal loads [10,11].

Despite these advances, a unified review framework for offshore integrated energy systems is still needed. Many studies focus on a single offshore wind-to-hydrogen chain, whereas others emphasize regional offshore network planning. The relationships among system types, physical integration design, optimization methods, and engineering constraints remain insufficiently synthesized. Therefore, this review adopts a literature-based classification and comparative approach. It contributes by classifying representative offshore integrated energy systems, summarizing integration technologies, reviewing optimization and assessment methods, and identifying future research directions for marine engineering constraints, multi-carrier network coupling, demonstration data, and policy uncertainty.

Review Scope, the Literature Selection Criteria, and Classification Logic

To improve the transparency and reproducibility of the review, the scope of this paper is defined as follows. The review focuses on offshore integrated energy systems that involve at least two energy carriers or functional subsystems, such as electricity, hydrogen, heat, gas, carbon dioxide, water, storage, or offshore loads. Purely single-device studies were included only when they provided direct implications for offshore multi-energy integration, such as wave-energy converters, offshore power-electronic interfaces, or repurposed-well geothermal conversion.

The literature was collected from Web of Science, Scopus, ScienceDirect, IEEE Xplore, SpringerLink, MDPI, and Google Scholar. The main search strings included “offshore integrated energy system”, “offshore wind hydrogen”, “offshore energy hub”, “multi-carrier offshore energy system”, “oil and gas platform electrification”, “decommissioned platform repurposing”, “offshore geothermal”, “repurposed well geothermal”, “offshore storage”, “energy hub optimization”, “4E assessment”, “advanced exergy analysis”, “digital twin”, and “offshore energy resilience”. The review primarily covers studies published from 2007 to 2026, with emphasis on recent studies from 2022 to 2026, and a small number of earlier foundational works on multi-energy modelling and offshore geothermal resource characterization.

The collection and screening process was conducted manually by the authors rather than through automated bibliometric software. Database searches were performed using the above search strings, and the bibliographic information was exported and organized in Microsoft Excel for duplicate removal, category coding, evidence-type coding, publication-year coding, and relevance checking. Citation snowballing from key review papers and recent original studies was also used to identify additional highly relevant sources. The

search window covered publications available online from January 2007 to May 2026. We used May 2026 as the end point because 2026 is not complete and because the this review considered after the first five months of the 2026 literature became available.

The phrase “with emphasis on recent studies from 2022 to 2026” means that recent publications were prioritized when discussing emerging offshore wind–hydrogen systems, offshore energy hubs, floating photovoltaic (PV)/wave hybridization, power–electronic interfaces, artificial intelligence forecasting, risk-aware optimization, and hydrogen-oriented multi-energy systems. In the final cited set of 50 references, 43 sources (86%) were published between 2022 and May 2026, while 7 sources (14%) were earlier foundational studies from 2007 to 2021. The older studies were retained mainly for foundational multi-energy modelling, early energy-hub concepts, and offshore geothermal resource characterization. This distribution shows a clear shift from general multi-energy modelling and resource assessment in earlier studies toward offshore-specific integration, hydrogen conversion, hybrid renewables, network planning, and digital operation in recent studies.

The inclusion criteria were: (i) peer-reviewed journal papers, conference papers, or authoritative technical reports with clear relevance to offshore multi-energy integration; (ii) studies that provide system configuration, optimization, techno-economic, reliability, or engineering information; and (iii) papers that contribute to identifying system boundaries, energy-carrier coupling, or offshore-specific constraints. Studies were excluded if they focused only on material-level device design without system relevance, lacked a clear offshore application context, or did not provide interpretable technical implications for offshore integrated energy systems.

In this review, “clear relevance to offshore multi-energy integration” was defined as meeting at least one of the following conditions: (a) the study explicitly considers an offshore or marine energy context and at least two coupled energy carriers or subsystems; (b) the study addresses offshore infrastructure that enables multi-energy coupling, such as subsea cables, hydrogen pipelines, offshore platforms, repurposed wells, or offshore power-electronic interfaces; or (c) the study investigates a single technology whose performance directly affects offshore multi-energy integration, such as wave-energy converters, ORC/binary-cycle conversion, offshore wind forecasting, or hydrogen storage. The review includes simulation and modelling studies, optimization studies, review papers, technical reports, and real or near-real project/case studies. Studies that only discuss material-level component design, purely onshore systems without offshore transferability, or general policy discussions without system-level implications were excluded.

The screening process started from 176 candidate records identified through database searches, citation tracing, and targeted searches for recent offshore energy studies. After removing duplicates and clearly irrelevant or inaccessible records, 139 records remained for title and abstract screening. Applying inclusion criterion (i) reduced the pool to 93 records. Applying criterion (ii), which required system configuration, optimization, techno-economic, reliability, or engineering information, reduced the pool to 67 records. Applying criterion (iii), which required clear implications for system boundaries, energy-carrier coupling, or offshore-specific constraints, resulted in 50 references finally cited and discussed in the manuscript. The final cited set includes 31 simulation/modelling or optimization studies (62%), 8 review papers (16%), 6 real-implementation, demonstration, project-oriented, or case-study sources (12%), and 5 technical reports or enabling-technology studies (10%).

For offshore-wind-related records in the final cited set, the reviewed literature was further coded by foundation or deployment context. Among 32 offshore-wind- or offshore-renewable-related sources, 11 records (34%) primarily concerned fixed-bottom or existing offshore wind farms and associated grid/export systems, 8 records (25%) concerned floating

foundations, floating photovoltaics, wave-energy converters, or floating hybrid platforms, and 13 records (41%) addressed general or network-level offshore wind integration without specifying a foundation type. In terms of multi-energy coupling, the most frequent combinations were wind–hydrogen, wind–floating PV/wave hybridization, wind–platform decarbonization, and power–hydrogen–CO₂ network coupling. These descriptive statistics are reported to characterize to clarify research trends rather than to represent a full bibliometric census of the entire field.

The six-category classification was derived from four objective dimensions: dominant energy input, conversion pathway, network connection, and load object. Overlaps among categories were resolved by assigning each study to the configuration that best represents its dominant system function. For example, a repurposed platform used mainly for hydrogen production was classified as a decommissioned-platform repurposing system, whereas a regional offshore network connecting wind power, hydrogen pipelines, and CO₂ transport was classified as an offshore energy hub and multi-carrier network.

Each cited source was assigned to one dominant category according to its primary research object. In the final cited set, offshore renewable-energy-dominated systems accounted for 8 references (16%), offshore wind–hydrogen systems for 12 references (24%), oil and gas platform integrated energy systems for 5 references (10%), offshore energy hubs and multi-carrier networks for 6 references (12%), decommissioned-platform repurposing systems for 4 references (8%), and offshore geothermal and repurposed-well systems for 5 references (10%). The remaining 10 references (20%) were cross-cutting foundational, methodological, or enabling-technology studies supporting more than one category. These shares indicate that recent research is concentrated in offshore wind–hydrogen coupling and hybrid offshore renewable systems, while geothermal integration and repurposed-well systems remain emerging but strategically important directions.

The scope and boundary of Figure 1 are defined as follows. The left-hand side represents major offshore energy inputs and reusable assets, including offshore wind, floating PV and marine energy, offshore geothermal/repurposed wells, and oil and gas platforms/reuse. The central offshore energy hub represents the multi-carrier coupling node. “Power transmission” refers to electricity export through offshore high-voltage alternating current/high-voltage direct current (HVAC/HVDC) and subsea cable networks to onshore grids or offshore loads. Battery/H₂/thermal storage is treated as a flexibility and balancing subsystem rather than as a final output. “H₂/electrofuels (e-fuels) pipeline/shipping” denotes hydrogen transport and the possible downstream transport of hydrogen-derived carriers such as ammonia and methanol; however, detailed fuel synthesis and international fuel trading are outside the core scope of this review. The thermal-output branch is defined as heat supply/cooling/desalination, which is enabled by geothermal heat, waste heat recovery, ORC/binary cycles, heat pumps, and thermal storage.

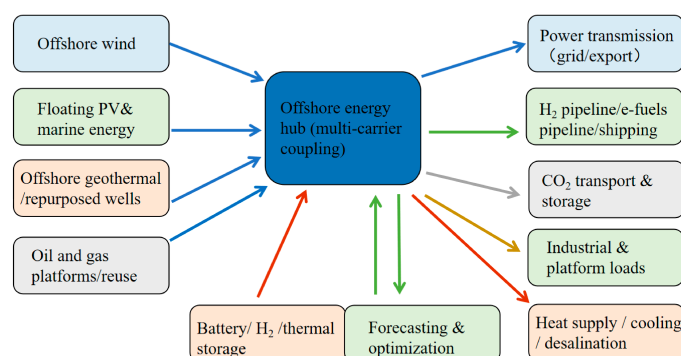


Figure 1. Conceptual framework and defined scope of offshore integrated energy systems with geothermal integration.

2. Classification of Offshore Integrated Energy Systems

After defining the research object, it is necessary to classify offshore integrated energy systems. Unlike onshore systems, which are often classified according to parks, buildings, or industrial loads, offshore systems should be classified according to energy inputs, conversion pathways, network connections, and load objects. Based on recent studies, this paper groups offshore integrated energy systems into six categories: offshore renewable-energy-dominated systems, offshore wind–hydrogen integrated systems, oil and gas platform integrated energy systems, offshore energy hubs and multi-carrier networks, decommissioned-platform repurposing systems, and offshore geothermal and repurposed-well systems.

This classification is not based merely on technology names, but on the dominant function of each system: resource aggregation, hydrogen conversion, platform decarbonization, regional network coordination, asset reuse, or subsurface thermal utilization. The purpose is to avoid mixing project-level configurations with network-level infrastructures and to make the comparison of maturity, constraints, and optimization requirements more transparent. The resulting classification framework, including the main energy carriers, system boundaries, representative research focus, and major limitations, is summarized in Table 1.

Table 1. Classification criteria, system boundaries, and limitations of offshore integrated energy systems.

Type	Main Energy Carriers	Typical System Boundary	Representative Research Focus	Main Limitation
Offshore renewable-energy-dominated systems Coded sources: 8 (16%)	Offshore wind, floating PV, wave/tidal energy, batteries	Offshore renewable energy farm or hybrid renewable station	Resource complementarity, farm hybridization, storage configuration, grid stability	Limited consideration of multi-carrier conversion and offshore engineering constraints
Offshore wind–hydrogen integrated systems Coded sources: 12 (24%)	Offshore wind, electrolysis, hydrogen storage, pipeline or shipping	Offshore wind farm, electrolyzer platform, hydrogen storage and transport, onshore demand	Hydrogen production route, storage and transport, economics, risk assessment	Insufficient coupling with platform loads, hydrogen networks, and market mechanisms
Oil and gas platform integrated energy systems Coded sources: 5 (10%)	Natural gas, electricity, hydrogen, heat, cooling, storage	Operating oil and gas platform or platform cluster	Platform electrification, gas-turbine substitution, waste heat recovery, low-carbon dispatch	Limited modelling of space, weight, safety distance, and maintenance windows
Offshore energy hubs and multi-carrier networks Coded sources: 6 (12%)	Electricity, hydrogen, natural gas, CO ₂ , heat, methane	Energy islands, offshore grids, hydrogen networks, CO ₂ networks	Regional planning, market design, cross-border transmission, multi-carrier coordination	Macro-level models dominate, while node-level engineering details are limited
Decommissioned-platform repurposing systems Coded sources: 4 (8%)	Existing platforms, subsea pipelines, hydrogen, storage, CCUS	Decommissioned platforms, existing pipelines, nearby offshore wind resources	Asset repurposing, pipeline reuse, life-cycle value	Structural recertification, hydrogen compatibility, and liability boundaries remain unclear

Table 1. *Cont.*

Type	Main Energy Carriers	Typical System Boundary	Representative Research Focus	Main Limitation
Offshore geothermal and repurposed-well systems Coded sources: 5 (10%)	Geothermal heat, abandoned wells, ORC, thermal storage, hydrogen, desalination	Offshore sedimentary basins, reused oil and gas wells, platforms and thermal loads	Resource assessment, wellbore heat exchange, ORC conversion, geothermal–wind–hydrogen coupling	Wellbore integrity, corrosion/scaling, thermal loss and regulatory liability

Note: The coded-source numbers indicate the dominant-category distribution within the final cited reference set. Because some references contribute to more than one theme, each source was assigned to the category that best represents its primary research object; cross-cutting foundational and methodological sources are discussed in the text rather than forced into a single category.

2.1. Offshore Renewable-Energy-Dominated Systems

Offshore renewable-energy-dominated systems normally take offshore wind as the primary energy input and couple it with floating photovoltaics, wave-energy, tidal current energy, and storage. Their purpose is to increase the energy yield per unit sea area and reduce the impact of single-resource variability. Kazemi-Robati et al. [9] proposed a stochastic optimization framework for hybridizing existing offshore wind farms with wave energy converters and floating photovoltaic systems. Their model considered existing turbines, export cable capacity, renewable generation uncertainty, and market price uncertainty, showing that hybrid expansion can improve the utilization of existing sea areas and transmission assets [9].

Ayyad et al. studied the water-cooling effect of floating offshore photovoltaics and showed that seawater cooling can improve PV performance under specific geographic conditions [14]. Jin et al. evaluated the geographically constrained resource potential of integrating floating PV into global existing offshore wind farms and found that such integration can improve the energy density of offshore areas [15]. Liu et al. reviewed recent offshore floating photovoltaic systems and identified wave loading, salt–mist corrosion, mooring stability, cable connections, and maintenance accessibility as key engineering barriers [21].

Wind–wave hybrid systems represent another important research direction. Faragiana et al. proposed and optimized a hybrid device for capturing offshore wind and wave energy, focusing on structural design and energy capture [22]. Overall, research on offshore renewable-energy-dominated systems has progressed from single offshore wind development to multi-source offshore complementarity, but studies on multi-carrier conversion, storage regulation, and cross-carrier scheduling remain limited.

Recent wave-energy studies also demonstrate that the hydrodynamic behaviour and geometric design of wave-energy converters strongly influence their applicability in offshore hybrid systems. Xia et al. analyzed a submerged cylindrical wave-energy converter under combined wave-current conditions and provided nonlinear hydrodynamic evidence for wave-energy converter (WEC) integration [23]. Zhang et al. further investigated a system integrating a WEC array and a very large floating structure (VLFS), showing that converter geometry affects array performance and the feasibility of integrated offshore renewable platforms [24]. These studies strengthen the physical basis for coupling wave energy with offshore wind and floating photovoltaic systems.

2.2. Offshore Wind–Hydrogen Integrated Systems

Offshore wind–hydrogen integrated systems are among the most active research topics in offshore integrated energy systems. As offshore wind farms move farther from shore,

conventional electricity export faces increasing cable costs, grid-connection pressure, and curtailment risks. Converting offshore wind power into hydrogen offers an alternative route for long-distance transport, large-scale storage, and industrial decarbonization.

Wang et al. [16] conducted a prospective review of in situ green hydrogen production from offshore wind farms. They found that offshore wind power, water electrolysis, hydrogen storage, and hydrogen transport technologies are generally mature, but their adaptation to variable ocean environments remains under optimization [16]. Pizzuti et al. focused on energy storage and management in offshore wind-based green hydrogen production, emphasizing that complex energy-flow dynamics exist between offshore wind generation and electrolyzers [17].

From an operational perspective, a recent study proposed a nonlinear convex energy management strategy for a dual-storage offshore wind system, considering electrolyzer operating states and battery degradation [25]. Yang et al. developed an optimal control method for a hybrid wind storage–hydrogen system based on wind power prediction, showing that electrolyzer-array control can reduce frequent start–stop operations [26]. Jin et al. studied the joint planning of collection and transmission systems for offshore wind farms integrated with hydrogen production platforms, showing that platform capacity, location, and cable routing are strongly coupled [27]. Liu et al. further considered offshore wind power, underwater compressed air energy storage, and hydrogen production in a power–hydrogen microgrid [28]. These studies indicate a clear shift from technical feasibility assessment to capacity planning, energy management, and multi-market value evaluation.

2.3. Oil and Gas Platform Integrated Energy Systems

Oil and gas platform integrated energy systems are designed to reduce the dependence of offshore platforms on gas-turbine self-generation by introducing offshore wind, hydrogen, energy storage, waste heat recovery, and intelligent dispatch. Unlike general offshore wind–hydrogen systems, platform energy systems have explicit load objects, including drilling and production equipment, compressors, pumps, heating, cooling, and auxiliary services.

Romero-Filgueira et al. [18] proposed a renewable-energy- and offshore green-hydrogen-based decarbonization methodology for the PLOCAN ocean platform. Their case study integrated photovoltaic panels, vertical-axis wind turbines, lithium-ion batteries, PEME units, and proton exchange membrane fuel cell (PEMFC) units, demonstrating that full decarbonization is technically feasible under real offshore constraints. This platform-oriented research indicates that renewable generation, hydrogen storage, and backup generation must be coordinated to ensure continuous offshore operation.

Studies on wind-powered hydrogen production for offshore oil and gas platforms have also proposed two low-carbon modes: integrating wind and hydrogen systems into operating platforms, and converting decommissioned platforms into offshore wind-to-hydrogen hubs [29]. Existing studies show strong engineering potential, but platform space, equipment weight, safety distance, operation and maintenance windows, and production continuity need to be modelled more explicitly.

2.4. Offshore Energy Hubs and Multi-Carrier Networks

Offshore energy hubs and multi-carrier networks represent the transition from single-site integration to regional offshore energy network coordination. Their core function is to connect offshore wind, hydrogen production, natural gas production, carbon capture and storage, and onshore demand through offshore grids, hydrogen pipelines, natural gas pipelines, and CO₂ transport and storage networks.

Gea-Bermudez et al. analyzed offshore market design in integrated North Sea energy systems towards 2050, showing that market structures can significantly influence operating costs, congestion management, price formation, and emissions [19]. Hofmann et al. examined H₂ and CO₂ network strategies for the European energy system and demonstrated that coordinated planning of hydrogen and carbon networks can affect deep decarbonization costs and infrastructure layouts [8]. Neumann et al. further examined the potential role of a hydrogen network in Europe and found that repurposing existing gas infrastructure can reduce system cost under certain conditions, although hydrogen networks cannot fully substitute electricity network expansion [7]. These findings suggest that offshore integrated energy systems should be planned as multi-carrier infrastructure systems rather than as single-purpose offshore wind export systems.

2.5. Decommissioned-Platform Repurposing Systems

Decommissioned offshore platform repurposing is a distinctive research direction for offshore integrated energy systems. As many offshore oil and gas assets approach the end of their production life, existing jackets, topsides, subsea pipelines, cables, berthing facilities, and maintenance systems may be converted into offshore wind operation bases, hydrogen production platforms, energy storage nodes, marine energy platforms, or carbon capture, utilization, and storage (CCUS) nodes.

Vreeburg and Garcia-Navarro evaluated the potential of repurposing offshore natural gas infrastructure on the Dutch Continental Shelf for hydrogen production and transport. Their geographical information system analysis identified a group of existing platforms that could potentially support offshore electrolysis capacity and benefit from nearby wind resources and pipeline connections [20]. Zhang et al. proposed a conceptual design for an offshore hydrogen platform, providing an early engineering reference for offshore hydrogen infrastructure [30].

Repurposed platforms may also support wave-energy conversion and offshore carbon management. However, important questions remain regarding residual structural life, recertification standards, hydrogen compatibility of pipelines, CO₂ transport suitability, ownership responsibility, and the coupling of repurposed assets with offshore wind, hydrogen, storage, and CCUS systems.

2.6. Offshore Geothermal and Repurposed-Well Systems

Offshore geothermal and repurposed-well systems extend the system boundary from above-sea renewable generation to subsurface thermal resources. Compared with wind and solar resources, offshore geothermal energy has a higher stability and lower climatic dependence, and therefore can function as a baseload heat or power source in offshore integrated energy systems. Repurposed oil and gas wells can also reduce drilling demand and shorten project development cycles, although their feasibility depends on wellbore integrity, casing corrosion, thermal losses, and reservoir conditions [10].

Zhao et al. examined an offshore renewable-energy-powered integrated energy supply system, showing that offshore multi-energy configurations can provide integrated electricity, heat, water, and storage services under different resource and load conditions [11]. When combined with the abandoned-well geothermal reuse perspective discussed by Santos et al. [10], this evidence suggests that geothermal integration should be treated as a stabilizing subsystem rather than as an isolated geothermal development route. However, the practical deployment of this category still depends on wellbore integrity assessment, corrosion and scaling control, compact ORC or binary-cycle modules, and regulatory responsibility for repurposed assets. Representative studies on the major categories of offshore integrated energy systems are summarized in Table 2.

Table 2. Representative studies on major categories of offshore integrated energy systems.

Section	Representative Study	Research Object	Method	Main Implication
Section 2.1	Kazemi-Robati et al. [9]	Existing offshore wind farms coupled with wave energy and floating PV	Stochastic optimization and Copula-based uncertainty modelling	Multi-source complementarity can improve sea-area and cable utilization
Section 2.2	Wang et al. [16]	In situ offshore wind-to-hydrogen production	Review of technical, economic, environmental and risk aspects	The hydrogen chain is technically promising, but ocean adaptation remains critical
Section 2.3	Romero-Filgueira et al. [18]	PLOCAN offshore platform decarbonization	Resource assessment, simulation and techno-economic analysis	Renewable energy plus hydrogen storage can support isolated offshore platforms
Section 2.4	Hofmann et al. [8]	North Sea power and hydrogen networks	Energy-system optimization	Electricity and hydrogen network coordination can increase offshore wind integration
Section 2.5	Vreeburg and Garcia-Navarro [20]	Reuse of Dutch offshore gas infrastructure	Geographic information system (GIS) screening and capacity assessment	Existing platforms and pipelines may support offshore hydrogen production and transport
Section 2.6	Santos et al. [10]; Zhao et al. [11]	Abandoned-well geothermal reuse; offshore integrated energy supply	Review, thermodynamic and techno-economic analysis, multi-objective optimization	Geothermal resources can provide stable heat/power input, but wellbore integrity, corrosion, scaling and regulatory boundaries remain key constraints

The comparative maturity and quantitative indicators of these system categories are further presented in Table 3.

Table 3. Comparative maturity and quantitative indicators of the six offshore integrated energy-system categories.

Category	Indicative Quantitative Focus	Maturity/TRL Tendency	Main Advantage	Main Limitation
Offshore renewable-energy-dominated systems Coded sources: 8 (16%)	Electric efficiency depends on wind/floating PV/WEC mix; WEC hydrodynamic efficiency remains device-specific	Medium to high for offshore wind; low to medium for floating PV and WECs	Higher sea-area utilization and resource complementarity	Mooring, cable routing, extreme-wave loads, and hybrid platform dynamics
Offshore wind-hydrogen systems Coded sources: 12 (24%)	Electrolyzer utilization and LCOH are highly sensitive to wind profile, storage size, and transport route	Pilot to early commercial	Long-duration storage and industrial decarbonization potential	High CAPEX, low electrolyzer load factor, offshore safety and hydrogen logistics

Table 3. *Cont.*

Category	Indicative Quantitative Focus	Maturity/TRL Tendency	Main Advantage	Main Limitation
Oil and gas platform integrated systems Coded sources: 5 (10%)	Carbon reduction depends on renewable penetration and gas-turbine backup strategy	Pilot to demonstration	Direct decarbonization of high-value offshore loads	Deck area, weight, critical-load protection, explosion-proof design, operation and maintenance (O&M) windows
Offshore energy hubs and multi-carrier networks Coded sources: 6 (12%)	System value mainly measured by annual system cost, congestion reduction, and CO ₂ network value	Conceptual to early infrastructure planning	Regional coordination of power, hydrogen, gas, and CO ₂ networks	Cross-border regulation, market design, large-scale investment and spatial planning
Decommissioned-platform repurposing systems Coded sources: 4 (8%)	Economic benefit depends on avoided decommissioning cost and reuse of pipelines/platforms	Conceptual to pilot	Life-cycle asset value and reduced offshore construction cost	Structural recertification, hydrogen embrittlement, ownership and liability
Offshore geothermal and repurposed-well systems Coded sources: 5 (10%)	ORC/binary-cycle efficiency is typically lower than high-temperature geothermal but can provide stable heat/power	Conceptual to early pilot	Baseload complement to intermittent renewables and hydrogen/desalination support	Wellbore integrity, corrosion/scaling, thermal loss, and limited demonstration data

Note: Quantitative indicators are reported as literature-coded trends rather than unified engineering benchmarks because system boundaries, site conditions, capacity scales, and cost assumptions differ substantially across the reviewed studies. Where project-level cost, levelized cost of energy (LCOE), levelized cost of hydrogen (LCOH), capital expenditure/operating expenditure (CAPEX/OPEX), or CO₂-mitigation data were not publicly available or were commercially sensitive, the review avoids unsupported numerical extrapolation and instead reports maturity tendencies, main indicators, and key constraints.

3. System Design and Key Integration Technologies

After classification, the next question is how different offshore systems can be designed and integrated. An offshore integrated energy system is not a simple aggregation of offshore wind turbines, electrolyzers, storage devices, and platform loads. It requires the identification of conversion relationships among energy carriers, differences in time scale, and offshore engineering constraints. Liu et al. proposed a wind–solar–hydrogen multi-energy supply system that couples wind power, photovoltaic generation, concentrated solar power, proton exchange membrane electrolysis, hydrogen storage, and proton exchange membrane fuel cells [31]. Although the system was not designed specifically for offshore applications, its electricity–heat–hydrogen structure and energy management logic provide useful references for offshore integrated energy-system design (Figure 2).

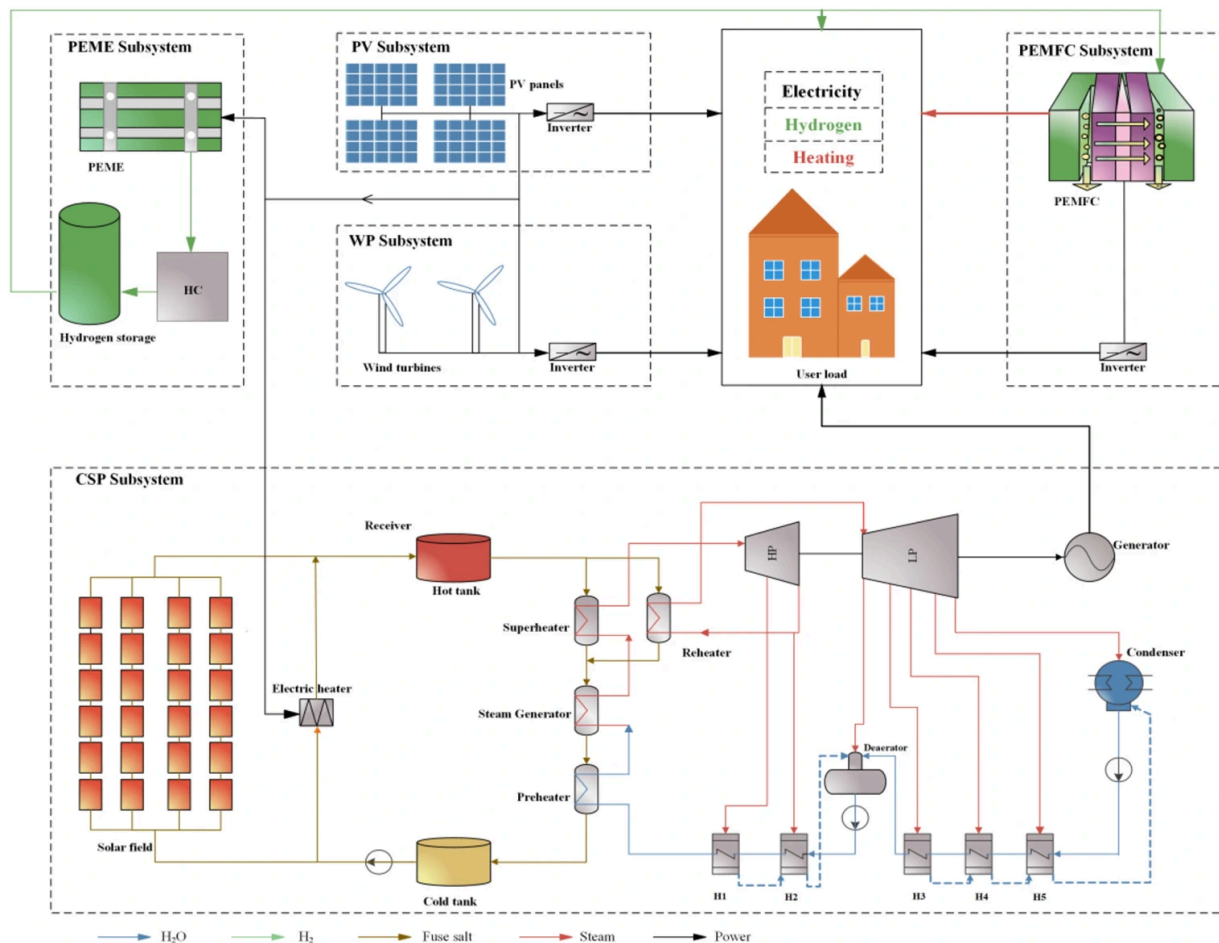


Figure 2. Schematic diagram of a wind-solar-hydrogen multi-energy supply system, adapted from Liu et al. [31].

3.1. Resource-Side Integration

Resource-side integration concerns the complementary use of offshore wind, floating photovoltaics, wave energy, tidal current energy, waste heat from oil and gas operations, and seawater resources. Kazemi-Robati et al. incorporated wind, wave, and solar resources into the expansion optimization of an existing offshore wind farm, illustrating the transition from single-resource development to multi-resource coordination [9].

Geothermal and repurposed-well resources add a relatively stable thermal layer to this resource-side framework. In petroleum-bearing sedimentary basins, geothermal gradients and existing wellbore infrastructure can spatially overlap with offshore oil and gas assets, making geothermal reuse particularly relevant for offshore platforms and energy islands [12,13]. Unlike wind, wave, and solar resources, geothermal heat can support baseload heat supply, ORC-based power generation, or thermal assistance for hydrogen production and desalination, thereby improving the temporal complementarity of offshore resource portfolios [11].

For future far-offshore systems, resource-side integration should also consider seawater desalination and electrolysis. Seawater is not only a feedstock for offshore hydrogen production but also a material-flow link connecting water treatment, hydrogen production, and platform or island energy demand.

3.2. Conversion-Side Integration

Conversion-side integration includes wind-to-electricity, wind-to-hydrogen, hydrogen-to-electricity, gas-to-power/heat/cooling, waste heat recovery, and carbon capture and storage. Tian et al. incorporated electrolyzer operating states into the energy management of a dual-storage offshore wind system, showing that converter dynamics directly affect dispatch results [25].

For geothermal integration, conversion-side design is mainly associated with medium- and low-temperature heat utilization. ORC systems, binary cycles, and heat-pump-assisted configurations can convert geothermal or waste heat into electricity, heating, cooling, or desalination services. In offshore systems, these conversion technologies must be modular, compact, corrosion-resistant, and compatible with platform space and weight constraints. When combined with offshore wind–hydrogen pathways, geothermal conversion can also reduce the low-load operation of electrolyzers and improve the utilization of hydrogen production equipment [11].

Fuel cells, especially PEMFC units, are valuable for integrated energy systems because of their high efficiency, low operating temperature, and fast response. Soyuturk et al. designed and analyzed a photovoltaic/thermal (PV/T) and PEMFC-based hybrid energy system for an off-grid house [32]. Ghenai et al. investigated a hybrid solar PV, PEMFC, and diesel-generator power system for a cruise ship [33]. Chen et al. assessed a PEMFC-based micro combined cooling, heating, and power (micro-CCHP) system integrated with geothermal-assisted methanol reforming [34]. These studies show that PEMFC units can enhance system regulation, although fully renewable-driven offshore conversion systems require further study.

3.3. Storage-Side Integration

Storage-side integration is essential for stable offshore system operation. Short-term fluctuations can be mitigated by batteries, supercapacitors, or flywheels, while medium- and long-term energy transfer can rely on hydrogen, liquid hydrogen, ammonia, methanol, underwater compressed air energy storage, or thermal storage. Pizzuti et al. argued that energy storage in offshore wind-to-hydrogen systems affects not only power smoothing but also electrolyzer efficiency and operation [17]. Liu et al. introduced underwater compressed air energy storage into an offshore wind–hydrogen microgrid, showing the potential of marine-space-based storage solutions [28].

Liquid hydrogen and liquefied natural gas (LNG) storage studies provide additional insights for offshore hydrogen systems. Ratnakar et al. reviewed hydrogen supply-chain challenges in large-scale liquid hydrogen storage and transportation, emphasizing that insulation, low-temperature handling, and materials compatibility are critical for large-scale hydrogen logistics [35].

3.4. Network-Side Integration

Network-side integration includes subsea cables, high-voltage direct current transmission, hydrogen pipelines, natural gas pipelines, CO₂ networks, and shipping systems. Wiegner et al. emphasized that offshore energy system integration should be assessed across power, hydrogen, storage, and governance dimensions rather than through a single infrastructure option [6]. Hofmann et al. further suggested that future offshore integrated energy systems may serve both as clean-fuel supply nodes and as carbon-management network nodes [8].

Recent offshore power-electronics studies provide additional technical support for network-side integration. Su et al. proposed an energy-coordinated control strategy for centralized direct current (DC) choppers in offshore wind modular multilevel converter-

based high-voltage direct current (MMC-HVDC) systems, highlighting the importance of stable DC-link operation and energy dissipation control in offshore transmission [36]. Li et al. proposed an active-soft-switching DC transformer for DC offshore wind turbines, indicating that advanced DC conversion interfaces can improve the feasibility of offshore power transmission and energy-hub infrastructure [37].

3.5. Load-Side Integration

Load-side integration determines the operational target of an offshore integrated energy system. Typical loads include production loads on oil and gas platforms, offshore electrolysis loads, desalination loads, onshore industrial hydrogen demand, island energy demand, marine aquaculture, and port fuel supply. Fayek et al. studied a wave-energy-based microgrid for integrated water, hydrogen, and electricity supply and trade, showing that desalinated water can be an important material link between marine energy conversion and hydrogen production [38]. The key integration dimensions and offshore-specific constraints of offshore integrated energy systems are summarized in Table 4.

Table 4. Key integration dimensions and offshore-specific constraints of offshore integrated energy systems.

Integration Dimension	Main Devices or Carriers	Representative Study	Design Problem	Offshore-Specific Constraint
Resource side	Offshore wind, floating PV, wave/tidal energy, seawater	Kazemi-Robati et al. [9]	Resource complementarity and spatial layout	Ocean conditions, boundary-layer effects, mooring and flow interactions
Conversion side	Electrolyzers, fuel cells, waste heat recovery, carbon capture	Tian et al. [25]; Chen et al. [34]	Conversion efficiency and dynamic response	Frequent start–stop operation, explosion protection, offshore maintenance
Storage side	Batteries, hydrogen, liquid hydrogen, underwater compressed air energy storage (CAES)	Pizzuti et al. [17]; Zhang et al. [28]	Short-, medium-, and long-term storage coordination	Volume, weight, insulation, corrosion, and safety distance
Network side	Subsea cables, hydrogen pipelines, CO ₂ networks	Hofmann et al. [8]; Su et al. [36]; Li et al. [37]	Transmission routes and network expansion	Route planning, seabed installation, cross-border coordination, infrastructure reuse
Load side	Platform production, desalination, industrial hydrogen demand	Fayek et al. [38]	Load characteristics and demand response	Critical-load protection and isolated-platform reliability
Geothermal/subsurface thermal integration	Repurposed wells, wellbore heat exchanger (WBHX), ORC, binary cycles, thermal storage	Santos et al. [10]; Zhao et al. [11]	Baseload heat/power supply and thermal support for hydrogen/desalination	Well integrity, corrosion, scaling, thermal loss and compact modular design

The representation of offshore engineering constraints in planning and operation models is further summarized in Table 5.

Table 5. Representation of offshore engineering constraints in planning and operation models.

Constraint	Possible Modelling Representation	Main Modelling Gap
Platform space and weight	Area and load-bearing capacity constraints; module layout variables	Often simplified as capacity upper bounds; ignores dynamic load and fatigue
Corrosion and scaling	Reliability penalty, degradation rate, maintenance interval, material selection cost	Long-term marine corrosion data and geothermal brine data are scarce
Safety distance and explosion protection	Minimum spacing, hazardous-zone constraints, hydrogen storage limits	Difficult to combine with continuous capacity optimization
Maintenance accessibility	Weather-window constraints, vessel availability, downtime probability	Rarely coupled with stochastic dispatch and O&M cost models
Subsea pipeline flow assurance	Pressure-drop, leakage, impurity, and inspection constraints	Hydrogen/CO ₂ pipeline models rarely include internal inspection/capsule-induced effects
Extreme marine events	N-1 or scenario-based resilience constraints; typhoon/wave-load scenarios	Computational burden increases when coupled with multi-carrier networks

4. Optimization and Assessment Methods

The physical structure of an offshore integrated energy system defines the system boundary, whereas optimization and assessment methods determine whether a design can balance economy, decarbonization, reliability, and engineering feasibility. Existing methods can be grouped into capacity configuration optimization, operational scheduling, stochastic and robust optimization, multi-objective optimization, 4E assessment and advanced exergy analysis, and energy-hub or multi-carrier network modelling.

4.1. Capacity Configuration Optimization

Capacity configuration optimization determines how to size offshore wind farms, floating PV systems, wave energy converters, electrolyzers, hydrogen tanks, fuel cells, batteries, underwater compressed air storage, and backup generators. Kazemi-Robati et al. optimized the capacities of wave and floating photovoltaic additions to existing offshore wind farms [9]. Jin et al. jointly optimized offshore hydrogen platform capacity, siting, and array-cable routing, revealing the strong coupling between capacity configuration, spatial planning, and network routing [27]. Liu et al. proposed a capacity-operation co-optimization model for a wind–solar–hydrogen multi-energy supply system and included energy efficiency, net present value, and advanced exergy indicators as optimization objectives [31].

4.2. Operational Scheduling Optimization

Operational scheduling focuses on day-ahead, intra-day, and real-time decisions under given capacities, including wind power consumption, electrolyzer start–stop decisions, charging and discharging of storage, fuel cell generation, gas-turbine backup, and platform load protection. Tian et al. optimized power allocation and electrolyzer states in a dual-storage offshore wind system by combining dynamic programming and convex optimization [25]. Yang et al. used rolling optimization to control electrolyzer arrays and reduce frequent start–stop operation under wind power fluctuations [26]. For offshore platforms, future scheduling models should further include vessel accessibility, harsh-weather maintenance windows, and critical-load priority.

4.3. Stochastic and Robust Optimization

Offshore wind speed, wave height, solar radiation, electricity price, hydrogen price, platform load, and component failure are all uncertain. Stochastic and robust optimization are therefore critical. Kazemi-Robati et al. used Copula theory to model the dependence among wind, wave, solar resources, and market prices [9]. Liu et al. used Latin hypercube sampling and K-means clustering to generate wind-speed scenarios for capacity optimization of offshore power–hydrogen microgrids [28]. Gao et al. studied low-carbon energy scheduling for integrated energy systems considering offshore wind power–hydrogen production and dynamic hydrogen blending strategy, showing the sensitivity of low-carbon dispatch to carbon trading, hydrogen blending, and energy prices [39].

Deep-learning-based marine forecasting can further improve uncertainty representation. He et al. used long-term marine LiDAR measurements to compare long short-term memory (LSTM), convolutional long short-term memory (ConvLSTM), Transformer, and Informer models for short-term multi-height wind-vector prediction, showing that ConvLSTM achieved stable multi-height speed prediction while errors increased under weak or non-stationary wind conditions [40]. Such data-driven forecasting methods can be embedded into stochastic scheduling and model-predictive control for offshore integrated energy systems.

4.4. Multi-Objective Optimization

Multi-objective optimization is appropriate when offshore systems must simultaneously minimize total cost, carbon emissions, wind curtailment, and equipment degradation while maximizing hydrogen output, renewable-energy utilization, and reliability. Recent studies have also explored energy management and multi-objective optimization for wind/PV/hydrogen/battery and hydrogen-based integrated energy systems [41,42]. Tian et al. developed a mixed-integer second-order cone programming approach for storage sizing and energy management in grid-connected wind/PV/hydrogen/battery systems [41]. Rong et al. evaluated and optimized renewable-energy-driven hydrogen-based integrated energy systems using artificial neural network (ANN) models and non-dominated sorting genetic algorithm II (NSGA-II) [42]. For offshore applications, such optimization should be expanded to include platform weight, deck area, safety distance, corrosion risk, maintainability, and resilience to extreme weather.

Risk-aware optimization is also becoming important for hydrogen-oriented integrated energy systems. Xu and Yang developed a risk-aware low-carbon optimization framework for hydrogen-oriented multi-energy systems with a linear approximation of a bi-product fuel cell [43]. Although their model was not offshore-specific, it provides a useful basis for incorporating market risk, operational risk, and hydrogen-system flexibility into offshore wind–hydrogen scheduling.

4.5. 4E Assessment and Advanced Exergy Analysis

4E assessment, namely energy, exergy, economic, and environmental assessment, is widely used to evaluate integrated energy systems. Liu et al. assessed a wind–solar–hydrogen system from energy, exergy, economic, and enviro-economic perspectives, showing the potential of multi-renewable coupling and hydrogen storage for sustainable energy production [44]. Liu et al. later developed a comprehensive sustainability assessment and multi-objective optimization method for a renewable-energy-driven multi-energy supply system, incorporating life-cycle energy, economic, environmental, and social dimensions [45]. The corresponding energy-management structure is shown in Figure 3, illustrating how renewable energy inputs, storage devices, hydrogen conversion units,

and system management signals are coordinated in a wind-solar-hydrogen multi-energy supply system.

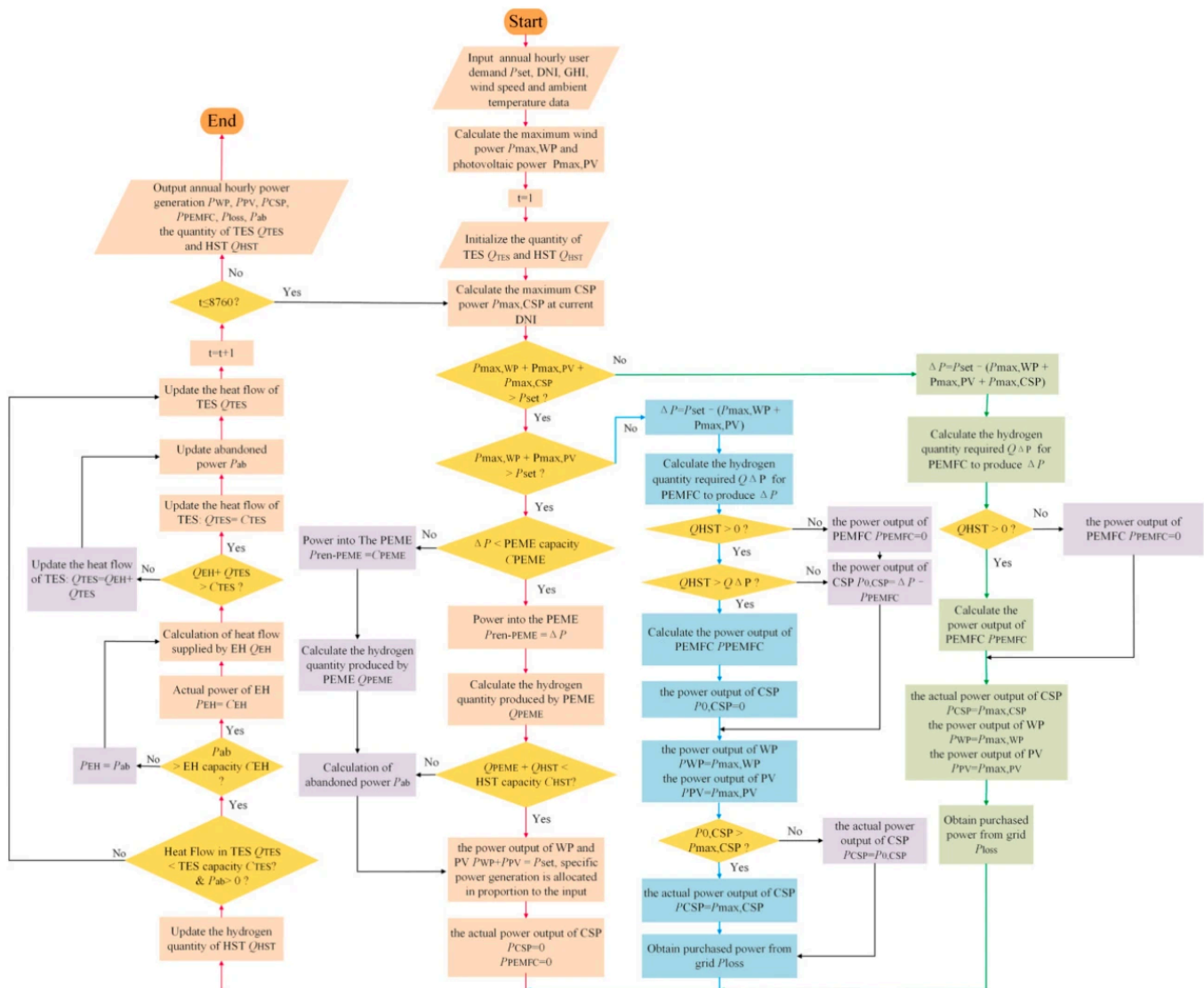


Figure 3. Energy management strategy for a wind-solar-hydrogen multi-energy supply system, adapted from Liu et al. [45].

Conventional exergy analysis can locate the magnitude of exergy destruction but cannot fully identify its source, component interaction, or real improvement potential. Advanced exergy analysis divides exergy destruction into avoidable/unavoidable and endogenous/exogenous parts. Liu et al. developed a bi-level capacity-operation co-optimization model with advanced exergy analysis for a wind-solar-hydrogen multi-energy supply system. Their results showed that the optimization priority derived from advanced exergy analysis differs from that obtained through conventional exergy analysis [31]. The solution process of this bi-level capacity-operation co-optimization model is illustrated in Figure 4.

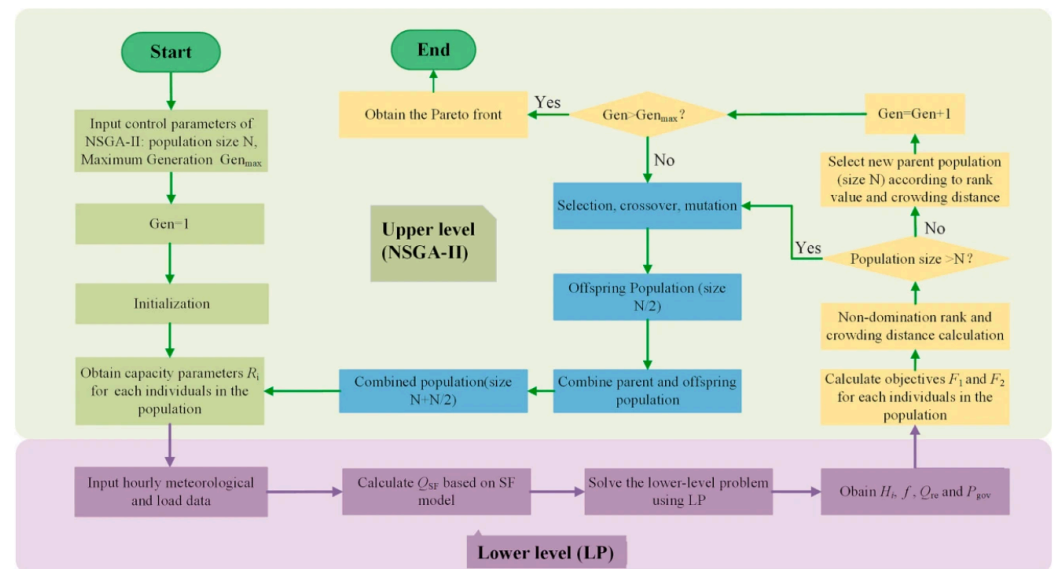


Figure 4. Flowchart for solving a bi-level capacity-operation co-optimization model, adapted from Liu et al. [45].

Chen et al. applied conventional and advanced exergy analysis to an integrated energy system with a parabolic trough collector, absorption heat pump, and absorption chiller [46]. Atalay et al. applied advanced exergy analysis to a solar-and-wind-energy-driven hybrid dryer and identified the wind turbine as a key component for improvement [47]. Moham-madi et al. compared six supercritical CO₂ Brayton-cycle layouts using advanced exergy analysis, highlighting the role of configuration in exogenous exergy destruction [48]. Tian et al. showed that conventional and advanced exergy analyses may identify different optimization priorities in an organic Rankine cycle [49]. These studies confirm the diagnostic value of advanced exergy analysis, but its application to offshore wind–hydrogen-platform systems remains limited.

4.6. Energy-Hub and Multi-Carrier Network Modelling

Energy-hub models describe the relationships among inputs, converters, storage devices, and outputs of different energy carriers. They are suitable for modelling electricity, hydrogen, gas, heat, CO₂, and water within offshore energy hubs. Gea-Bermudez et al. showed that market design can significantly affect the operation of integrated North Sea systems [19]. Hofmann et al. further demonstrated that regional offshore energy system modelling must jointly consider offshore wind, power networks, hydrogen networks, carbon networks, and industrial demand [8]. Compared with single-site optimization, multi-carrier network modelling better captures cross-regional infrastructure value, but it also requires high-quality spatial data, cost assumptions, and policy scenarios.

4.7. Artificial Intelligence, Digital Twins, and Predictive Maintenance

In addition to mathematical programming, artificial intelligence (AI) and machine-learning approaches are increasingly relevant to offshore integrated energy systems. Their main applications include offshore wind and wave forecasting, electrolyzer load prediction, anomaly detection, predictive maintenance, corrosion monitoring, and digital-twin-based operation. Compared with deterministic scheduling models, data-driven methods can better capture nonlinear marine dynamics and component degradation, but they require reliable long-term operational datasets.

For offshore systems, the most promising digital-twin subsystems are electrolyzer arrays, hydrogen storage and pipelines, subsea cables, platform structural components,

and corrosion-prone geothermal or seawater-contact equipment. Digital twins can link measured data with physics-based models to update failure probability, maintenance windows, and operational constraints in real time. However, cybersecurity, data governance, and model validation must be incorporated before digital twins can support safety-critical offshore dispatch.

4.8. Comparative Suitability of Optimization Approaches

Different optimization approaches have distinct applicability. Stochastic optimization is suitable when probabilistic scenarios for wind, wave, price, and load uncertainty are available, but its computational burden increases rapidly with scenario number. Robust optimization is more conservative and useful for harsh marine conditions, but may lead to oversized systems. Multi-objective optimization is suitable for balancing cost, emissions, reliability, and hydrogen output, but decision-making requires post-processing of Pareto solutions. Energy-hub modelling is powerful for regional power–hydrogen–gas–CO₂ networks, but it depends strongly on spatial infrastructure assumptions and policy scenarios. The comparative suitability of these optimization approaches is summarized in Table 6.

Table 6. Comparative suitability of optimization approaches for offshore integrated energy systems.

Approach	Main Advantage	Main Limitation	Most Suitable Offshore Application
Stochastic optimization	Explicitly represents uncertainty using scenarios	Scenario explosion and dependence on probability distributions	Wind/wave/PV uncertainty, market price uncertainty, O&M weather windows
Robust optimization	Provides conservative protection under worst-case uncertainty	May overestimate capacity and cost	Critical platform loads, extreme marine events, safety-constrained operation
Multi-objective optimization	Balances cost, emissions, reliability, hydrogen output and exergy	Requires decision-making after Pareto-front generation	Capacity sizing and trade-off analysis for offshore wind–hydrogen systems
Energy-hub modelling	Captures multi-carrier conversion and network flows	Requires detailed spatial, infrastructure, and policy data	Regional offshore energy islands and electricity–hydrogen–gas–CO ₂ networks
AI/digital-twin methods	Useful for forecasting, fault diagnosis and predictive maintenance	Needs high-quality data and cybersecurity protection	Operational forecasting, corrosion monitoring, equipment health management

Representative optimization and assessment methods reviewed in Sections 4.1–4.6 are further summarized in Table 7.

Table 7. Optimization and assessment methods for offshore integrated energy systems.

Method Type	Representative Study	Research Object	Typical Method	Main Conclusion
Capacity configuration	Kazemi-Robati et al. [9]	Offshore wind farm with wave energy and floating PV	Stochastic optimization	Hybrid expansion improves sea-area and cable utilization
Capacity configuration	Jin et al. [27]	Offshore wind-to-hydrogen platform	Joint planning model	Capacity, siting, and cable routing are strongly coupled

Table 7. *Cont.*

Method Type	Representative Study	Research Object	Typical Method	Main Conclusion
Operational scheduling	Tian et al. [25]	Dual-storage offshore wind system	Dynamic programming and convex optimization	Electrolyzer states affect dispatch and degradation
Stochastic optimization	Gao et al. [39]; He et al. [40]	Integrated energy system with offshore wind–hydrogen production	Low-carbon scheduling	Hydrogen blending and carbon trading affect system economics
Multi-objective optimization	Rong et al. [42]; Xu and Yang [43]	Renewable hydrogen-based integrated energy system	ANN and NSGA-II	Cost, performance, and environmental objectives require joint trade-off
4E and advanced exergy	Liu et al. [31]	Wind–solar–hydrogen multi-energy supply system	Bi-level optimization and advanced exergy analysis	Advanced exergy analysis identifies different improvement priorities
Energy-hub modelling	Hofmann et al. [8]	European H ₂ -CO ₂ networks	Network strategy modelling	Hydrogen and CO ₂ networks affect deep decarbonization costs

Because advanced exergy analysis is particularly useful for identifying component-level improvement priorities, representative advanced-exergy studies and their implications for offshore integrated energy systems are summarized in Table 8.

Table 8. Advanced exergy analysis studies and implications for offshore integrated energy systems.

Advanced Exergy Study	Research Object	Main Finding	Implication for Offshore Integrated Energy Systems
Atalay and Aslan [47]	Solar and wind energy driven hybrid dryer	The wind turbine is a key improvement component	Advanced exergy analysis can identify weak components in offshore multi-energy systems
Mohammadi et al. [48]	Supercritical CO ₂ Brayton cycles	Configuration affects exogenous exergy destruction	Useful for comparing offshore power-cycle and waste heat recovery layouts
Tian et al. [49]	Organic Rankine cycle with three-fluid condenser	Conventional and advanced analyses provide different priorities	Traditional exergy analysis may misjudge improvement priorities
Liu et al. [31]	Wind–solar–hydrogen multi-energy supply system	Optimization priority differs from conventional exergy analysis	Applicable to wind-electrolysis-storage-fuel cell system diagnosis

4.9. Economic Viability and Market Uncertainty

Economic viability remains one of the main barriers to large-scale deployment. Key indicators include LCOE for offshore renewable generation, LCOH for offshore hydrogen production, CAPEX for offshore platforms, electrolyzers, subsea cables and pipelines, OPEX for marine maintenance, payback period, net present value, and sensitivity to electricity price, hydrogen price, carbon price, and capacity factor. For coordinated wind-solar-hydrogen-battery systems, Wang et al. further showed that operational scheduling can simultaneously affect hydrogen-production economics, carbon-emission reduction,

and renewable-energy utilization, confirming the need to integrate techno-economic and environmental objectives in hydrogen-oriented integrated energy-system optimization [50].

From the perspective of data availability, this review distinguishes between quantitative values that are publicly reported and those that are not consistently available. Across the reviewed studies, the most comparable indicators are electrolyzer utilization, LCOH or LCOE, annual system cost, renewable curtailment, CO₂-emission reduction, and capacity factors. However, many offshore project data, especially platform-retrofitting CAPEX, offshore O&M cost, hydrogen-pipeline compatibility cost, and avoided decommissioning cost, are project-specific and often commercially confidential. Therefore, this review reports public quantitative indicators where available and uses technology readiness level (TRL)/maturity, evidence type, and dominant constraints to avoid misleading comparisons across incompatible system boundaries.

Current evidence suggests that offshore wind–hydrogen systems are highly sensitive to electrolyzer utilization hours and hydrogen transport mode, whereas repurposed platforms can be attractive only when avoided decommissioning cost, residual structural life, and pipeline compatibility are favourable. Therefore, future techno-economic models should standardize system boundaries and explicitly report CAPEX, OPEX, capacity factors, replacement cost, carbon benefits, and uncertainty ranges rather than relying on single-point LCOE or LCOH values.

5. Representative Applications and Regional Prospects

The purpose of this section is to connect the typological review in Section 2 and the methodological discussion in Section 4 with real or near-real application contexts. It distinguishes commercially demonstrated technologies, pilot-scale applications, and conceptual future pathways, thereby avoiding the impression that all offshore integrated energy-system configurations have reached the same maturity level. The demonstration status and commercialization challenges of representative offshore integrated energy pathways are summarized in Table 9.

Table 9. Demonstration status and commercialization challenges of representative offshore integrated energy pathways.

Pathway	Current Maturity	Evidence Base	Main Commercialization Challenge
Offshore wind power export	Commercial	Large-scale offshore wind farms and HVDC/HVAC export	Grid congestion, transmission cost, extreme weather resilience
Offshore wind-to-hydrogen	Pilot to early demonstration	PosHYdon and North Sea hydrogen concepts	Electrolyzer utilization, safety, offshore O&M, LCOH
Oil and gas platform electrification	Commercial/pilot depending on region	North Sea electrification and platform renewable integration	Power reliability, gas-turbine backup, cable cost, regulatory approval
Energy islands and multi-carrier hubs	Conceptual to early infrastructure planning	Bornholm and North Sea energy-hub concepts	Cross-border market design, financing, spatial planning
Repurposed platforms and pipelines	Conceptual to pilot	Dutch Continental Shelf screening and offshore hydrogen platform concepts	Recertification, hydrogen embrittlement, liability allocation
Offshore geothermal/repurposed wells	Early pilot/conceptual	Abandoned-well geothermal reuse and offshore renewable-powered supply systems	Well integrity, corrosion/scaling, thermal loss, lack of long-term data

5.1. North Sea Offshore Integrated Energy Systems

The North Sea is one of the most active regions for offshore integrated energy-system research. It combines large offshore wind resources, mature oil and gas infrastructure, cross-border grid interconnections, and CO₂ storage potential. Wiegner et al. showed that North Sea integration involves offshore wind connection, storage, power-to-hydrogen, and spatial governance [6]. Hofmann et al. further showed that the value of offshore hydrogen production and CO₂ networks depends on regional demand, industrial decarbonization pathways, and infrastructure reuse [8].

5.2. Offshore Wind-to-Hydrogen and Energy Island Projects

Offshore wind-to-hydrogen and energy island projects are important transitions from research concepts to engineering demonstration. Projects such as PosHYdon, NorthH₂, AquaDuctus, and Bornholm Energy Island indicate a trend towards coupling offshore wind, electrolysis, hydrogen transport, cross-border grids, and energy markets. Wang et al. showed that in situ offshore hydrogen production can reduce the need for long-distance electricity transmission [16]. Pizzuti et al. emphasized that storage and energy management are crucial for stable offshore green hydrogen production [17].

5.3. Oil and Gas Platform Decarbonization Cases

Oil and gas platform decarbonization is one of the most practical application scenarios for offshore integrated energy systems. Romero-Filgueira et al. showed that a hybrid renewable and hydrogen system can support the full decarbonization of an isolated ocean platform under real offshore constraints [18]. Existing platform-oriented studies demonstrate that optimized low-carbon operation requires coordination among renewable generation, storage, hydrogen conversion, and backup generation [18]. These studies indicate that platform decarbonization should not be viewed merely as grid electrification, but rather as a multi-energy integration problem involving renewable generation, hydrogen storage, fuel cells, waste heat, and load management.

5.4. Development Potential in China

China has both offshore resource potential and engineering foundations for offshore integrated energy systems. The Bohai Sea, Yellow Sea, East China Sea, and South China Sea differ in oil and gas resources, offshore wind potential, marine energy resources, and infrastructure conditions. The Bohai Sea has concentrated oil and gas platforms and is suitable for pilot projects on platform electrification, offshore wind supply, and hydrogen storage. The Yellow Sea and East China Sea have favourable wind resources and may support offshore wind-to-hydrogen and offshore storage projects. The South China Sea has rich oil and gas and marine resources but more challenging environmental conditions.

Geothermal integration can further enrich this regional pathway. In the northern South China Sea, the Qiongdongnan and Pearl River Mouth basins have been reported to exhibit geothermal-gradient and heat-flow characteristics that may support medium- and low-temperature geothermal utilization [12]. The Yinggehai Basin has also been discussed as a potential target for geothermal resource assessment and development planning [13]. Therefore, in regions with dense offshore platforms and suitable geothermal conditions, repurposed-well geothermal systems, ORC modules, and wind-hydrogen systems may be jointly considered as part of China's future offshore integrated energy demonstrations.

China should not simply copy the North Sea model. Instead, offshore integrated energy systems should be developed in stages according to domestic offshore platforms, nearshore and far-offshore wind layouts, offshore CCUS potential, and coastal industrial energy demand. Short-term efforts may focus on platform electrification and offshore

wind-to-hydrogen demonstration. Medium-term development may couple offshore wind, hydrogen production, storage, transport, and coastal industrial hydrogen demand. Long-term development may form integrated electricity–hydrogen–carbon networks connecting offshore wind bases, oil and gas platforms, CO₂ storage sites, and coastal industrial clusters.

5.5. Global Strength-Weakness-Opportunity-Threat (SWOT) and Political, Economic, Sociological, Technological, Legal, and Environmental (PESTLE) Analyses

A global perspective requires not only technical comparison but also assessment of policy, market, legal, social and environmental conditions. Therefore, SWOT and PESTLE analyses were added to summarize how offshore integrated energy systems may be supported or constrained in different regions. The SWOT analysis of offshore integrated energy systems is presented in Table 10.

Table 10. SWOT analysis of offshore integrated energy systems.

Dimension	Key Points
Strengths	High offshore renewable potential; possibility of coupling electricity, hydrogen, heat, water and CO ₂ ; reuse of oil and gas assets; reduced land-use conflict
Weaknesses	High CAPEX and marine O&M cost; limited demonstration data; engineering constraints related to corrosion, safety distance, platform weight and maintenance windows
Opportunities	Industrial hydrogen demand, offshore CCUS, energy islands, platform electrification, digital twins, and decommissioned-asset reuse
Threats	Policy uncertainty, hydrogen price volatility, supply-chain bottlenecks, extreme marine events, cybersecurity risks, and unclear liability for repurposed assets

To further complement the internal and external strategic assessment, the PESTLE analysis of offshore integrated energy systems is summarized in Table 11.

Table 11. PESTLE factors affecting global deployment of offshore integrated energy systems.

Factor	Main Issue
Political	Offshore spatial planning, energy-security strategy, cross-border cooperation, and support for hydrogen and CCUS infrastructure
Economic	CAPEX/OPEX, LCOE/LCOH, carbon price, electricity and hydrogen market design, financing cost, and avoided decommissioning cost
Sociological	Public acceptance of offshore infrastructure, employment transition from oil and gas, and community perception of hydrogen and CO ₂ transport
Technological	Electrolyzers, offshore storage, HVDC, DC transformers, ORC, corrosion-resistant materials, digital twins, and subsea inspection technologies
Legal	Asset ownership, platform recertification, hydrogen-pipeline codes, CO ₂ storage liability, decommissioning funds and environmental permitting
Environmental	Marine ecological disturbance, greenhouse gas (GHG) reduction, brine or chemical leakage, seabed impact, and resilience to typhoons and extreme waves

6. Challenges and Future Research Directions

6.1. Unclear Complementarity Among Offshore Resources

The complementarity among offshore wind, solar, wave, and tidal resources is affected by seasonality, sea state, spatial scale, and device layout. Existing studies often rely on historical meteorological data and statistical correlations, while interactions among floating PV, atmospheric boundary layers, wave-energy converters, and floating wind platforms require more coupled physical and energy-system modelling.

6.2. Insufficient Consideration of Marine and Platform Engineering Constraints

Many models still borrow assumptions from onshore integrated energy systems. Offshore systems, however, must account for salt–mist corrosion, typhoons, wave loads, lifting constraints, vessel-access windows, platform space and weight limits, and explosion-proof safety distances. These constraints should be converted into explicit design variables and operating constraints.

6.3. Immature Coupling Models for Electricity–Hydrogen–Gas–Heat–Carbon Networks

Offshore energy hubs may involve electricity, hydrogen, natural gas, heat, CO₂, and water. Current models focus mainly on electricity–hydrogen coupling, whereas the substitution and coordination relationships among hydrogen pipelines, natural gas pipelines, CO₂ networks, and shipping remain insufficiently studied.

6.4. Lack of Demonstration Data and Long-Term Operational Data

Offshore integrated energy systems remain at an early stage of demonstration and commercialization. Many studies rely on simulation parameters and idealized assumptions. Long-term data on corrosion degradation, maintenance cost, failure rates, safety incidents, and hydrogen leakage are still limited.

6.5. Economic and Policy Uncertainty

The economics of offshore integrated energy systems are sensitive to offshore wind costs, electrolyzer costs, hydrogen prices, electricity prices, carbon prices, certificate mechanisms, sea-area policies, and cross-border transmission rules. Future studies should strengthen policy sensitivity analysis and market-mechanism modelling.

6.6. Future Research Directions

Future research should focus on five directions. First, multi-carrier network models should be developed for electricity, hydrogen, gas, heat, and carbon in far-offshore regions. Second, capacity configuration and operation scheduling should incorporate marine environmental constraints, platform layout, and maintenance windows. Third, offshore wind-to-hydrogen should be demonstrated together with platform electrification, asset repurposing, and offshore CO₂ storage. Fourth, digital twins, predictive maintenance, and intelligent dispatch platforms should be developed for offshore multi-energy systems. Fifth, evaluation should shift from single-project economics to life-cycle carbon reduction, infrastructure reuse, and energy security.

In addition, future work should explicitly address cybersecurity, resilience under extreme marine events, and reliability under component failures. Large-scale offshore integrated energy systems will rely on digital communication, remote control, and automated dispatch; therefore, cyber-physical security and contingency-aware operation should be treated as core design requirements. Resilience metrics should consider typhoon and extreme-wave impacts, subsea cable or pipeline failures, hydrogen leakage, electrolyzer outages, and delayed maintenance caused by poor weather windows.

7. Conclusions

Offshore integrated energy systems represent an important extension of integrated energy systems from land to ocean. Their core value is not the development of a single offshore energy technology, but the coordinated integration of multiple resources, devices, networks, and time scales. This review classified offshore integrated energy systems into six types: offshore renewable-energy-dominated systems, offshore wind–hydrogen integrated systems, oil and gas platform integrated energy systems, offshore energy hubs and multi-carrier networks, decommissioned-platform repurposing systems, and offshore geothermal and repurposed-well systems.

The review further summarized system design logic from the resource, conversion, storage, network, and load sides, and discussed capacity configuration, operational scheduling, stochastic and robust optimization, multi-objective optimization, 4E assessment, advanced exergy analysis, and energy-hub modelling. Existing studies have made progress in offshore wind-to-hydrogen systems, platform decarbonization, North Sea energy hubs, and offshore asset repurposing. However, system boundaries remain inconsistent, offshore engineering constraints are insufficiently modelled, demonstration data are limited, and multi-carrier network coupling methods require further development.

Future studies should pay more attention to engineering feasibility and system-level value under marine conditions. For China, development pathways should be designed according to offshore wind bases, oil and gas platform clusters, coastal industrial demand, and offshore carbon storage potential. Coordinated progress in technology integration, optimization modelling, demonstration projects, and policy mechanisms will be essential for realizing offshore integrated energy systems.

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