Scientific Research Publishing

Journal of Power and Energy Engineering, 2025, 13(7), 60-74
https://www.scirp.org/journal/jpee
ISSN Online: 2327-5901
ISSN Print: 2327-588X

Electrification of Offshore Oil and Gas Development: Progress, Challenges, and Outlook

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How to cite this paper: Yuan, S. and Zhang, Y.Y. (2025) Electrification of Offshore Oil and Gas Development: Progress, Challenges, and Outlook. *Journal of Power and Energy Engineering*, **13**, 60-74.
https://doi.org/10.4236/jpee.2025.137003

Received: June 27, 2025
Accepted: July 26, 2025
Published: July 29, 2025

Abstract

Driven by the "dual carbon" goals and energy transition, electrification of offshore oil and gas development has become an inevitable choice for sustainable development in the industry. This paper systematically analyzes the technological progress, challenges, and future directions of electrification transformation. Research shows that electrification technologies, through systemic restructuring, intelligent upgrades, and integration with renewable energy, can significantly reduce operational costs and environmental risks, promoting the industry's shift toward deeper waters, digitalization, and green low-carbon development. In recent years, key technologies such as all-electric subsea wells, shore power integration, and floating wind power supply have made breakthrough progress. The deep integration of digital twin and intelligent technologies—such as using digital twins for predictive maintenance of subsea equipment and real-time optimization of power flow in hybrid energy systems has further enhanced system efficiency. However, the electrification transformation still faces challenges such as high initial investment, technical reliability, and environmental regulation. Considering the current situation in China, it is recommended to strengthen R&D in core technologies, build an integrated "source-grid-load-storage" energy supply system, improve policies and standards, and promote deep integration of renewable energy to achieve coordinated development of energy exploitation and environmental protection. This study provides theoretical support and practical pathways for the low-carbon transition of the offshore oil and gas industry.

Keywords

Offshore Electrification, Low-Carbon Transition, Deepwater Oilfield Development, Hybrid Offshore Power Systems, Subsea Production Systems

1. Introduction

In the context of intensified global climate governance, the temperature control objectives outlined in the Paris Agreement are accelerating the transformation of the global energy structure. As onshore and shallow-water resources become increasingly depleted, the development of deepwater and ultra-deepwater oil and gas has emerged as a strategic focus for many countries [1] [2]. The offshore oil and gas industry faces four major challenges: controlling carbon emissions, reducing topside weight, protecting marine ecosystems, and optimizing operational costs. Electrification, as a means of replacing fossil fuel-driven systems, offers a crucial pathway for reducing carbon intensity per barrel and improving the integration of clean energy, thereby holding strategic significance in achieving "net-zero" targets [3].

Electrification technologies are reshaping the paradigm of offshore oil and gas development. At present, offshore operations largely rely on conventional hydraulic production systems, which, while reliable in shallow water applications, exhibit inherent limitations in terms of technical performance, environmental sustainability, and economic viability. For example, deepwater high-pressure environments necessitate ultra-high hydraulic pressures, significantly increasing the material and installation costs of umbilical cables. Near-zero temperatures can drastically increase the viscosity of hydraulic fluids, leading to pipeline blockages, ruptures, and pollution risks. In long tieback scenarios, the power of hydraulic actuation becomes inadequate, requiring costly system upgrades [4] [5]. In contrast, all-electric production systems, which offer lightweight and highly flexible low-carbon solutions, provide superior scalability, rapid responsiveness, and precise long-distance control, making them particularly well-suited for complex deepwater field development [3] [6]. By integrating shore power systems, offshore wind energy, energy storage, and digital twin platforms, electrification enables the construction of a low-carbon energy architecture that encompasses generation, grid, load, and storage, potentially reducing the carbon intensity per barrel by 15% to 40% [4] [7]. Digital twin technologies, in particular, play a vital role by enabling real-time simulation and monitoring of subsea production systems, facilitating predictive maintenance of critical equipment, and optimizing power flow and load balancing across hybrid energy systems. Concurrently, digital technologies enhance the efficiency of electrification systems and facilitate the emergence of new integrated "electric-digital" operational models.

In recent years, China has actively promoted electricity substitution, with the "dual carbon" goals injecting strong momentum into the electrification of the oil and gas industry. The 2016 Guidelines on Promoting Electricity Substitution incorporated industrial electrification into national strategy; the 2022 14th Five-Year Plan for a Modern Energy System set a binding target of 30% terminal electrification by 2025; and the 2024 Guidelines on Vigorously Advancing Renewable Energy Substitution emphasized the green and low-carbon transformation of industrial energy use [8]-[10]. Offshore electrification plays a strategic role in ensuring energy security and fulfilling China's carbon commitments. Against this backdrop, advancing research on offshore oil and gas electrification is of paramount importance for establishing a self-reliant and controllable deep-sea energy development system. This paper systematically analyzes the current technological landscape and associated challenges, outlines future development trends, and proposes strategic recommendations, aiming to provide theoretical support for China's transition to green offshore oil and gas development.

2. Electrification: Driving the Upgrade of Offshore Oil and Gas Development

Traditional offshore oil and gas development has established a comprehensive technological system covering operations from shallow to ultra-deep waters. Platform construction technologies are mainly divided into fixed platforms and floating platforms. Fixed platforms, supported by jacket structures and pile foundations, are suitable for water depths up to 1500 feet. Floating platforms include compliant towers (suitable for 1000 - 2000 feet), tension leg platforms (up to 4000 feet), SPAR platforms (around 3000 feet), and Floating Production Storage and Offloading systems (FPSOs), which serve as core infrastructure for marginal ultra-deepwater fields [11]-[13].

Subsea production systems are primarily composed of wellheads, Christmas trees, and umbilicals [1]. These systems have long relied on electro-hydraulic control systems, which exhibit notable shortcomings: high-pressure deepwater environments demand extremely high hydraulic pressures, significantly raising umbilical material and installation costs; near-zero temperatures drastically increase fluid viscosity, raising the risk of blockages, ruptures, and leakage; and in long-distance tiebacks, hydraulic power often proves insufficient, necessitating costly system expansions [4] [5].

Offshore platforms generally utilize star-configured power grids radiating from a single central platform or interconnected chain- and ring-type grids. Most platforms rely on self-contained power stations, which suffer from low efficiency, high maintenance costs and poor environmental performance. These power stations also occupy valuable topside space [14] [15].

Traditional generation methods, such as diesel generators and gas turbines, are under mounting economic and environmental pressures. A single 1100 kVA diesel unit—requiring corrosion-resistant design—can cost approximately USD 2.5 million annually in fuel and maintenance, emit 318 tons of CO_2, and release significant volumes of sulfur and nitrogen oxides. Platforms equipped with multiple such units may face annual operating costs in the tens of millions [3]. While gas turbines may utilize associated gas to reduce fuel expenses, they require pre-treatment of impure natural gas and cannot eliminate carbon emissions. Furthermore, both systems present fuel storage safety concerns and are vulnerable to oil price volatility.

Electrification offers a systemic solution to these challenges. By eliminating hydraulic units, pipelines, and subsea distribution components, all-electric technologies significantly simplify production architecture [16] [17]. Electrically controlled trees eliminate hydraulic fluid leakage risks and enhance environmental compatibility. Electric power transmission extends beyond the range limits of hydraulic systems, allowing access to marginal reserves and reducing the need for subsea infrastructure. Smart control architectures integrating multi-node systems via single cables—supported by real-time data and digital twins—enable predictive maintenance and production optimization.

Advancements in renewable energy integration have enhanced the economic feasibility of electrification. Offshore wind, floating photovoltaics, and advanced energy storage systems can bring power supply costs down to USD 0.30/kW [3]. Compared to gas turbines, subsea power cables can cut lifecycle costs by USD 1.19 million, while wind-powered systems may save up to USD 63 million annually [16].

3. Key Technologies and Project Developments

The electrification of offshore oil and gas development is evolving through multiple technological pathways (as shown in **Figure 1**), including the electrification of subsea production systems, shore power integration, renewable energy integration, innovations in subsea power distribution, and optimization of subsea cable transmission. Regionally, Norway and the United Kingdom are leading electrification efforts in the North Sea, thanks to their rich offshore wind resources and mature shore power infrastructure. On the Norwegian Continental Shelf, multiple offshore fields have undergone partial or full electrification, with several additional projects approved and under development [18]. The UK, guided by the North Sea Transition Deal, has set a target of reducing offshore production carbon intensity by 50% by 2030, accelerating the pace of platform electrification. In the Asia-Pacific, Australia has launched subsea equipment electrification initiatives, while China's Bohai Bay has implemented shore power systems covering seven oilfield clusters and more than 150 offshore platforms, demonstrating regional-scale application [19]. Operators in other major producing regions are also exploring various technical schemes to reduce energy consumption and emissions.

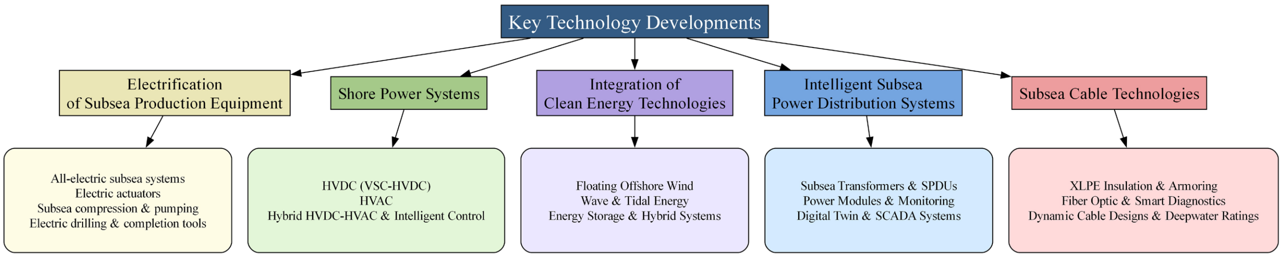

Figure 1. Framework of key technology developments.

3.1. Electrification of Subsea Production Equipment

Key technologies include all-electric subsea production systems, subsea compressors, subsea pumps, and electric drilling and completion tools. In these systems, electric Christmas trees, electric subsurface safety valves, and electric control modules constitute the core components for wellhead electrification. In 2008, Total E&P Netherlands BV piloted the world's first all-electric subsea system at the K5F gas field in the Dutch North Sea, initially achieving partial electrification while retaining some hydraulic controls. In 2016, the K5F-3 well was fully equipped with an electric tree, Halliburton's DepthStar electric subsurface safety valve, and TechnipFMC's electric subsea control module—marking the world's first truly all-electric subsea well [18] [20]. Electric actuator technology is now maturing [21]. Aker Solutions offers modular, standardized electric actuators with advanced condition monitoring and multiple load configurations [22]. TechnipFMC's actuators integrate rechargeable lithium batteries and battery management systems, enabling precise monitoring of valve position and vibration [23] [24]. Bosch Rexroth's compact electric actuators match the dimensions of hydraulic versions, allowing seamless integration and providing full drive and fail-safe functions [25] [26]. OneSubsea has simplified its actuator designs to enhance shaft control accuracy [27] [28].

For subsea compression, electric drives are widely adopted for gas boosting. Since 2015, the Åsgard Field in Norway has deployed MAN HOFIM™ electric compressors, which have accumulated over 100,000 hours of nearly fault-free operation [29]. SLB's Ormen Lange multiphase compression system raised recovery efficiency from 75% to 85% while halving energy consumption [30]. Subsea pumping systems, including multiphase and water injection pumps, are also being electrified. Compared to traditional gas-lift methods, electric submersible pumps offer higher efficiency and output under similar conditions [31]. Meanwhile, electric drilling and completion technologies are progressing, with key components under development and validation.

3.2. Shore Power Systems: Technologies and Applications

As a crucial pathway for decarbonizing offshore platforms, shore power systems are seeing increasing global deployment. These systems transmit electricity from onshore grids to offshore platforms via subsea cables, thereby substantially reducing carbon emissions from traditional fuel-based generation. Currently, two main transmission technologies are used: high-voltage direct current (HVDC) and high-voltage alternating current (HVAC). Each is suitable for specific scenarios [4] [32]. For long-distance and high-capacity transmission, voltage source converter-based HVDC (VSC-HVDC) systems offer superior performance. For instance, Norway's Johan Sverdrup Phase I project successfully achieved 200 km stable transmission using a ±80 kV VSC-HVDC system, demonstrating its feasibility and reliability [33].

However, HVDC entails higher initial investment, with converter stations and specialized cables costing 1.5 - 2 times more than HVAC systems [34]. In contrast, HVAC offers advantages in nearshore applications due to simpler structure, faster deployment, and lower capital expenditure. Norway's Martin Linge platform employs a 162 km HVAC cable with static VAR compensators (SVCs) to address reactive power issues [35]. In China, extensive HVAC deployments in the Bohai Bay have provided substantial engineering experience. HVAC systems face limitations over long distances due to capacitive losses. Improving efficiency and stability requires breakthroughs in power control, fault ride-through capability, and corrosion-resistant high-voltage cables.

From a techno-economic perspective, HVAC is generally more cost-effective for transmission distances below 100 - 150 km, while HVDC becomes preferable for longer distances or higher power loads, where its reduced line losses and superior control outweigh the higher capital costs [36] [37]. Lifecycle cost comparisons—including maintenance and energy losses—further reinforce the importance of context-specific evaluation.

Emerging technologies, such as hybrid HVDC-HVAC schemes, intelligent dispatch, and adaptive control, remain under development but are expected to enhance system flexibility and economic performance in the future [4] [6]. Ultimately, a scenario-based selection framework—factoring in distance, load, platform size, regulatory context, and upgrade potential—will be critical to optimizing shore power deployments across diverse offshore fields.

3.3. Integration of Clean Energy Technologies

To reduce emissions and ensure sustainability, the offshore oil and gas sector is actively integrating clean energy into platform power systems. Floating offshore wind—particularly suitable for deep waters—offers zero-emission, low-operating-cost solutions. However, intermittency and variability require energy storage or intelligent control. High installation and maintenance costs in deepwater remain a significant barrier to large-scale adoption [17] [18].

A landmark example is Norway's Hywind Tampen project, the world's first floating wind farm powering offshore platforms. It comprises 11 × 8 MW turbines (totaling 88 MW), supplying about 35% of the electricity needs for the Gullfaks and Snorre fields and reducing CO_2 emissions by ~200,000 tons annually [18] [37]. In China, the "Haiyou Guanlan" platform (commissioned in 2023) marks the country's first deep-sea floating wind platform, with a capacity of 7.25 MW, supplying power to the Wenchang oilfield cluster via dynamic cables—signifying a major breakthrough in wind-oil-gas integration [38].

Other marine renewables, such as wave and tidal energy, show potential due to predictability and abundance, but current device efficiency, durability, and costs hinder commercial deployment. Storage systems (e.g., lithium-ion batteries) are essential for stabilizing intermittent output, yet challenges remain regarding safety and lifecycle under harsh marine conditions. Hybrid systems (e.g., wind + gas turbines) can enhance power reliability while reducing emissions by 15% - 50%. However, they introduce complexity in architecture, load switching, and control algorithms, which must be addressed for broader adoption [16] [17].

3.4. Intelligent Subsea Power Distribution Systems

Subsea power distribution is vital for delivering, transforming, distributing, and controlling electrical power in offshore fields. With all-electric systems advancing rapidly, subsea power infrastructure is trending toward greater intelligence and modularity [14] [39]. Key components include subsea transformers, distribution units (SPDUs), power modules, and intelligent monitoring/communication systems. Hitachi Energy's OceaniQ™ 24 MVA subsea transformer, deployed in OneSubsea's Ormen Lange compression project, supports 850 m depths and exemplifies leading-edge design [40]. ABB has achieved engineering deployment of switchgear in water depths up to 3000 m. Subsea 7's SEPDU system enables precise power allocation for heated pipelines, improving energy efficiency and project flexibility [41]. TechnipFMC's integrated power modules, combining transformers and variable speed drives (VSDs), have cut retrofit costs by up to 60% in mature fields [42]. Siemens Energy's Subsea PowerGRID features digital control, remote monitoring, and self-diagnostics [43]. Proserv's One Cable Housing (OCH) system allows simultaneous power and data transmission, streamlining layout and improving reliability [44]. Siemens is also applying digital twin technology to real-time monitoring and predictive diagnostics via SCADA systems [43]. Overall, subsea power systems are evolving toward deeper water, longer distances, higher capacity, and stronger intelligence—laying the foundation for fully electric offshore production.

3.5. Subsea Cable Technologies

Subsea cables are fundamental to electrified offshore energy systems [45]. Advances in materials, structure, and engineering are enabling higher voltages, greater capacity, and improved environmental resilience. Cross-linked polyethylene (XLPE) is the mainstream insulation material due to its pressure tolerance, thermal stability, and corrosion resistance [46]. Non-magnetic armoring reduces electromagnetic loss in AC systems, while DC systems use steel armor with asphalt impregnation for durability and corrosion protection. Integrated fiber-optic units support smart diagnostics and monitoring. Dynamic cable designs now feature annular umbilical structures and thermoplastic liners, enhancing resistance to deepwater mechanical loads [47]. Pressure ratings exceed 15,000 psi, and upgraded terminal connections improve reliability under extreme conditions [48]. Chevron's deepwater project in Australia used a 145 kV dynamic cable with a metal-foil/polymer composite insulation, delivering stable power at 1400 m depth—setting a benchmark for deepwater electrification [49]. A cross-sectoral trend is emerging: deepwater cable engineering experience from oil and gas is being adopted in offshore wind, while HVDC innovations (±500 kV) from wind projects are feeding back into centralized power solutions for future oil and gas platforms [50] [51].

4. Challenges and Emerging Trends

4.1. Major Challenges Facing Electrification Transition

Although electrification presents new opportunities for decarbonization and efficiency improvement in offshore oil and gas development—driving the industry toward low-carbon, high-efficiency, and sustainable operations—its implementation remains constrained by a range of technical, economic, environmental, and policy challenges. These challenges are reflected in the following aspects:

1) High upfront investment and cost feasibility: Key components such as HVDC converter stations and cables, subsea substations, electric trees, and compression equipment require substantial capital expenditures. While operational savings can be realized over the long term, the high initial investment remains a significant barrier—particularly for small- and medium-sized projects that are highly sensitive to oil price fluctuations [4] [5] [39].

2) Technical reliability in extreme environments: Deepwater systems face high pressure, humidity, and salinity [21] [35]. Subsea batteries must withstand pressures at 3000 m. Energy Management Systems (EMS) must ensure dynamic stability across multiple renewable sources, demanding complex control strategies [33] [34]. Maintenance depends on ROVs and specialized vessels, increasing complexity and cost.

3) Uneven maturity of technologies: While HVDC/HVAC and subsea pumps are commercially deployed, wave/tidal energy and electric pulse drilling remain experimental [18] [33]. Ultra-high-voltage dynamic cables require further long-term reliability validation.

4) Industry conservatism and lack of standards: Operators often prefer mature, lower-risk hydraulic systems. Divergent international standards complicate design and compliance, adding costs—especially for smaller firms with limited R&D budgets.

5) Environmental impacts and policy gaps: Cable/pump/substation installation can disrupt seabed ecosystems, triggering regulatory scrutiny under EU Marine Strategy Framework and similar rules. Inconsistent standards, insufficient incentives, and lengthy permitting processes further hinder adoption [47] [51].

6) Decommissioning complexity and lifecycle footprint: Electrified offshore infrastructure—such as subsea cables, substations, and embedded control systems—poses new challenges during decommissioning [36] [37]. The retrieval and disposal of high-voltage assets require specialized procedures, potentially increasing environmental risk and end-of-life costs. Moreover, current regulations on electrified asset removal and recycling are often fragmented or lacking, complicating planning and liability management in long-term asset lifecycle assessments [52] [53].

4.2. Development Trends

Key trends driving the future of offshore electrification include:

1) Multi-energy integration and intelligent systems: Electrification will evolve toward “multi-source coordination + intelligent control”, integrating shore power, offshore wind, wave/tidal energy, and storage into smart microgrids. Coordination across generation, grid, load, and storage will be enabled by HVDC, dynamic cables, and EMS [14] [18]. AI, digital twins, and SCADA will optimize load pre-

diction and remote O&M. Electric trees, compressors, and pumps will simplify platform architecture and reduce operational costs.

2) Modularization for deployment scalability: Modular design divides complex systems into standardized, functionally independent units for flexible combination and rapid replacement. It enhances maintainability, reduces downtime, and enables factory prefabrication. Already used in PLCs and VSDs, modularization is expanding to power distribution and microgrid systems [25].

3) Commercialization through maturity and cost reduction: With maturing technologies, electrification is entering large-scale commercialization. Ocean energy (wave, tidal), electric drilling, and advanced cables are nearing readiness. EU programs and the Hywind Tampen project offer critical testbeds [3] [37]. Standardization and supply chain scaling will reduce costs. Modular microgrids and prefabricated substations will boost economic feasibility [41] [48].

4) Policy support and global cooperation: Carbon pricing, green finance, and market reforms are enhancing electrification's economic appeal. Norway's carbon policies have spurred adoption of shore/wind power; China's "dual carbon" strategy is accelerating wind-oil integration [8] [10]. International standardization is reducing regulatory friction. Organizations like the UN and IEA are supporting global deployment via knowledge-sharing and funding.

5. Insights and Recommendations

Offshore oil and gas electrification is transitioning from pilot demonstrations to large-scale deployment. Amid global decarbonization and green development, electrification offers a practical path to building cleaner and more efficient energy systems while supporting deep-sea resource development. Although challenges remain—such as reliance on foreign technologies, cost pressures, and limited institutional support—advancing technologies, falling costs, and supportive policies are accelerating progress. For China, seizing this opportunity can drive green transformation and enhance strategic competitiveness. Based on this, the following phased recommendations are proposed (**Figure 2**).

1) Short-term (2025-2026): Building foundational capacity and policy readiness.

In the immediate term, China's offshore electrification efforts should concentrate on alleviating key bottlenecks in core technologies, industrial support, and institutional mechanisms. Priority should be given to strengthening indigenous innovation by advancing R&D in smart microgrids that integrate "generation-grid-load-storage", utilizing AI and digital twin technologies to enhance platform-level energy management [14] [39]. To reduce dependence on foreign technologies, a target of 30% domestic production of critical components—such as IGBT modules, subsea storage systems, and HVDC cables—should be set for 2026. Concurrently, two national-level testing and certification centers for subsea electrical systems should be established to support equipment validation. Policy and regulatory tools also need refinement, including the implementation of carbon pricing mechanisms, green investment subsidies, and streamlined permitting tailored for offshore electrification retrofits [4] [18]. Regulatory sandboxes in key coastal regions (e.g., Bohai Bay, South China Sea) should be introduced to encourage controlled experimentation with emerging technologies like wave energy and hybrid grid control. Lastly, harmonization with international technical standards (e.g., IEC, ISO) must begin to facilitate long-term global integration and technology export.

2) Medium-term (2027-2030): Scaling deployment and industrializing core technologies.

Once the foundational capabilities are established, the next stage should focus on scaling deployment and consolidating the industrial base. Modular and standardized solutions—such as prefabricated microgrids, substations, and subsea cable modules—should be developed to streamline construction, enhance flexibility, and reduce costs. At least three coastal regional service hubs (e.g., Tianjin, Yantai, Zhuhai) should be built to provide localized manufacturing, logistics, and maintenance support [37] [39]. The domestic production rate of electrification equipment should be increased to 60% - 70%, ensuring basic supply chain autonomy. To validate the commercial viability of standard solutions, five electrified pilot clusters should be established across China's major offshore basins. These clusters will serve as critical reference models for subsequent replication. Additionally, national technical standards must be formalized by 2030, covering all essential aspects such as system safety, grid integration, fault resilience, and environmental performance, thereby ensuring regulatory consistency and technical interoperability across projects.

3) Long-term (2031-2035): Achieving deep integration and systemic transformation.

In the final stage, offshore electrification should evolve into a fully integrated and decarbonized energy system, supporting China's leadership in global offshore clean energy. This entails advancing hybrid "wind-oil-gas" clusters connected through multi-terminal DC grids, as well as piloting wave and tidal energy systems in synergy with existing oil and gas infrastructure. Intelligent and adaptive energy management systems (EMS), enhanced by AI, must be deployed to manage the increasingly complex task of dispatching renewable, storage, and load resources across large-scale systems [16] [20]. Technological self-reliance should be further consolidated, with the domestic content of core technologies reaching 80% by 2035, particularly in critical areas such as ultra-deep subsea storage, HVDC cable production, and insulation materials. China should aim to build at least three national-level integrated "green offshore energy zones", where platform emissions are reduced by over 70% through the deployment of combined electrification and renewable solutions. Finally, environmental and social governance (ESG) should be strengthened through lifecycle impact assessments, the use of low-disturbance installation techniques, community engagement initiatives, and the pursuit of international green certifications (e.g., DNV GreenPower) to enhance global market acceptance and investor confidence.

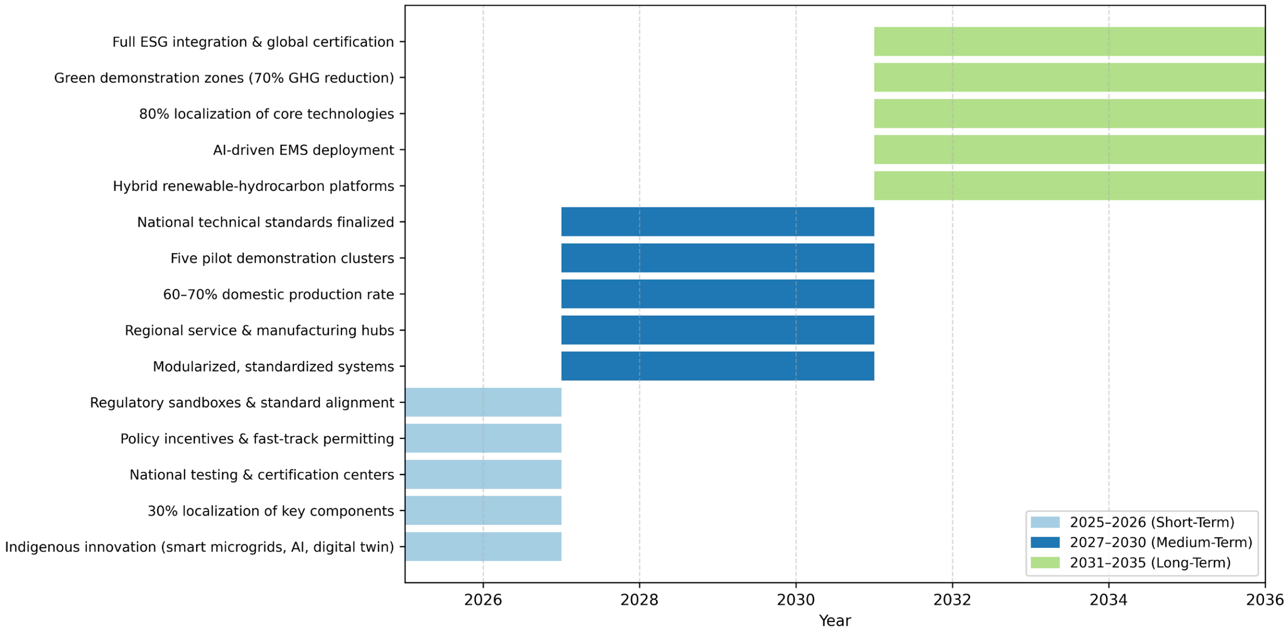

Figure 2. Phased strategic roadmap for offshore electrification.

6. Conclusions

Electrification has become a key pathway for the transformation and upgrading of offshore oil and gas development, directly addressing the industry's major challenges. Firstly, by integrating renewable energy and shore power systems, electrification significantly reduces carbon emissions, contributing to global decarbonization efforts. Secondly, the adoption of all-electric subsea equipment and optimized power distribution lowers topside weight by replacing heavy hydraulic systems with compact electrical alternatives, facilitating safer and more efficient deepwater operations. Thirdly, electrification supports ecosystem protection by minimizing fuel combustion offshore, reducing pollution, and enabling smarter environmental monitoring through digital technologies. Lastly, it effectively reduces operational costs through improved energy efficiency, intelligent control systems, and streamlined maintenance enabled by digital twin and AI-driven solutions.

Recent technological breakthroughs include reliable all-electric subsea wells, successful shore power integration in regions such as Norway, the UK, and China, and the commissioning of the world's first floating offshore wind farm supplying platform power. Advances in subsea substations, AI and digital twin technologies, and smart fiber-optic power cables have further enhanced system intelligence and operational efficiency.

Despite these advances, challenges remain. High upfront costs, technological complexity, environmental constraints, decommissioning difficulties, and regulatory gaps continue to limit widespread adoption. To effectively promote offshore electrification, a phased development approach is recommended. In the near term, efforts should focus on partial electrification of subsea production equipment and shore power integration, which can deliver immediate carbon emission reductions and operational improvements with relatively mature technologies. Moving into the mid term, the focus shifts to integrating renewable energy sources such as floating offshore wind farms and energy storage systems, enhancing sustainability and system resilience while addressing intermittency challenges. Finally, in the long term, the goal is to achieve fully intelligent subsea power distribution and digitalized operations through the deployment of advanced AI, digital twin technologies, and smart monitoring systems. This comprehensive approach optimizes performance, reduces downtime, and supports scalable, sustainable offshore energy development.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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