

Harnessing Marine Renewable Energy: The Future of Floating Photovoltaic Systems

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The Blue Economy encompasses the sustainable use of ocean resources for economic growth, improved livelihoods, and jobs while preserving the health of ocean ecosystems. It includes a wide range of activities, such as fisheries, aquaculture, maritime transport, coastal tourism, and increasingly, marine renewable energy (MRE).

As the world seeks sustainable energy solutions, MRE has become a cornerstone of the Blue Economy, offering significant potential for clean power generation from vast oceanic resources.

Among the technologies advancing this vision, Floating Photovoltaic (FPV) systems are emerging as a promising MRE solution. These systems are designed to float on bodies of water, providing a unique approach to addressing land scarcity challenges while generating renewable energy. Mature technologies such as offshore wind have already reached commercial viability, while tidal and wave energy are in earlier stages of development or still in the pilot or early commercialization stages.

FPV stands out for its potential to increase efficiency and reduce land use conflicts, making it a vital component of the renewable energy generation. Despite their promise, integrating FPV systems into existing power grids presents operational challenges, requires expert attention and significant studies unique to each development,

The global FPV market is expected to grow significantly, driven by technological advancements and increasing demand for clean energy. This article explores the role of FPV within the Blue Economy, highlights its challenges and opportunities, and establishes it as a promising MRE technology for the future.

The Promise of Floating Photovoltaic Systems

Floating Photovoltaic Systems represent a significant advancement in solar energy technology with key advantages over other renewable counterparts:

- By utilizing water surfaces, FPV systems alleviate the competition for limited land resources, a critical advantage in densely populated regions. Additionally, their placement on waterbodies reduces significant costs and simplifies ownership complexities, making them an efficient and practical choice for renewable energy projects.
- The cooling effect of water can enhance the efficiency of solar panels, allowing them to operate at optimal performance levels—often showing a performance increase of 5% to 10% (Source:1,2) compared to their land-based counterparts.

The global market for floating solar is witnessing rapid growth, projected to reach approximately \$54 billion by 2032, up from \$6.69 billion in 2024, reflecting a compound annual growth rate (CAGR) of around 30% (Source:3). This expansion is driven by increasing demand for renewable energy sources and advancements in technology that facilitate the deployment of FPV systems.

FLOATING SOLAR MARKET SIZE 2022 TO 2032 (USD BILLION]



Source1

Operational Challenges and Environmental Considerations

Deploying FPV systems comes with its own set of challenges. Environmental conditions such as wave action, currents, and water level fluctuations must be carefully considered during the design and installation phases. The structures must be robust enough to withstand dynamic environmental loads over extended lifespans, often requiring detailed site characterization and structural assessments, supported by hydrodynamic and soil condition analyses, as well as comprehensive risk evaluations.

Key considerations include:

- **Environmental Impacts:** Understanding local water quality is essential, as it can affect the material properties used in constructing floating structures. It is particularly important also to maintain water quality when FPV systems are deployed in drinking water reservoirs to ensure they do not compromise the safety and usability of these vital resources. Protecting marine ecosystems is another critical aspect of FPV projects.
- **Marine Activity Conflicts:** FPV systems must address potential conflicts with other water uses, such as navigation, fishing, and recreational activities. Effective stakeholder engagement is essential to mitigate these conflicts and the successful implementation of FPV projects into local environments.
- **Design Challenges:** Addressing these operational challenges requires a multidisciplinary approach to ensure minimal negative impact on marine and coastal environments.

Effectively addressing these operational challenges requires a multidisciplinary collaboration, bringing together marine engineers, environmental scientists, and local stakeholders. This cohesive approach ensures FPV systems are designed and implemented to minimize environmental impacts while maximizing sustainability and operational efficiency.

Strategic Considerations for Implementation

To successfully implement FPV systems, several strategic considerations must also be addressed:

Submarine cable connectivity and technological integration: Strategic planning for submarine cable routing and design is essential for efficient power transmission from FPV systems to onshore grids, minimizing environmental disruption. These cables must be designed to handle dynamic marine conditions while ensuring reliability and minimal energy losses. Integrating advanced technologies such as AI-driven monitoring systems further enhances operational efficiency by enabling real-time performance tracking and predictive maintenance, ensuring the long-term viability and optimization of FPV installations.

Submarine cable routing and design must consider seabed topography to minimise disruption, while selecting the correct type of cable—AC or DC, single-core or three-core—is crucial for efficient high-voltage transmission. Environmental impact assessments are essential, and installation requires precision with dynamically positioned vessels and cable protective strategies like burial to shield against physical threats.

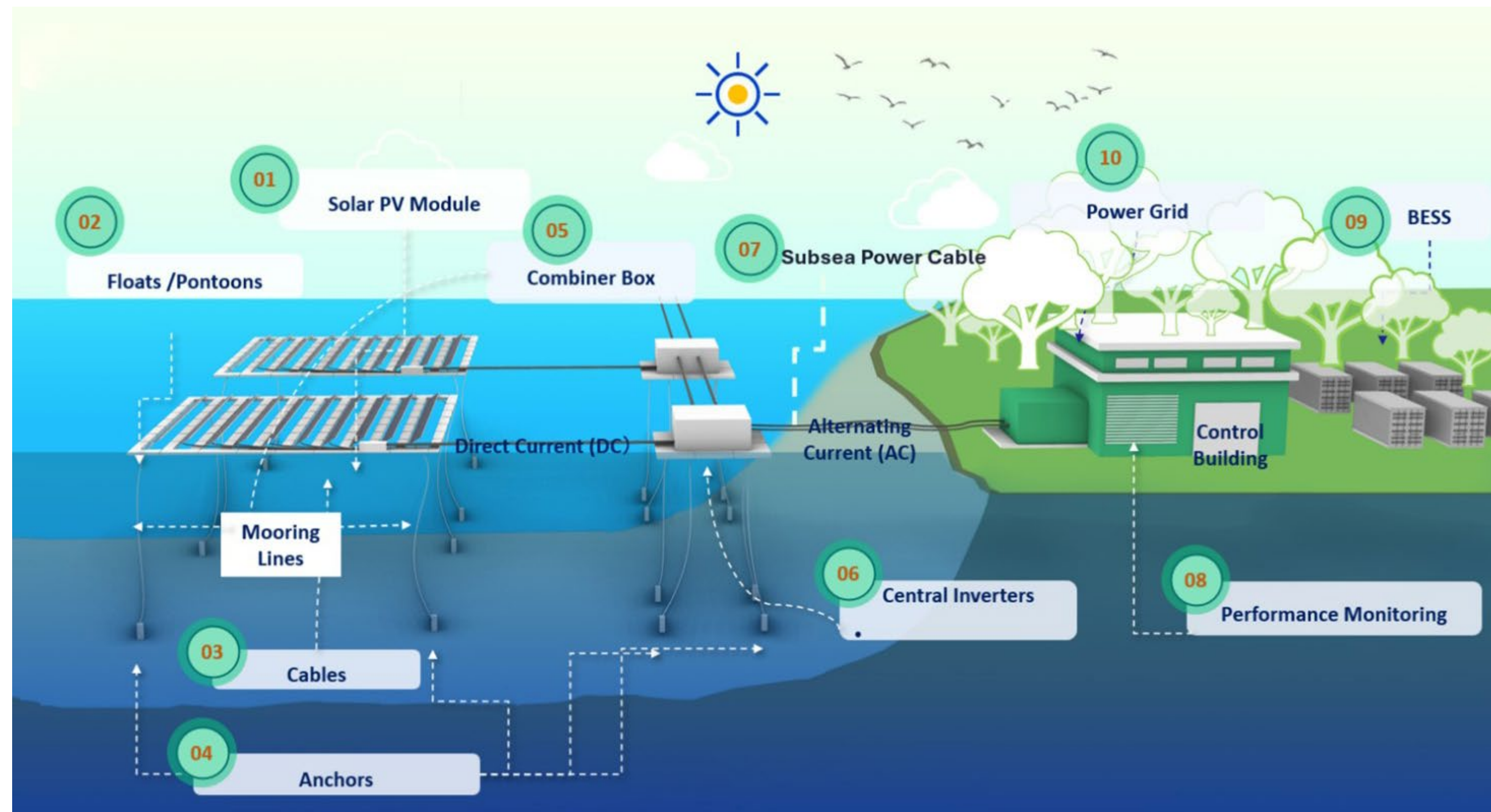
Collaboration with industry leaders: Effective collaboration with local authorities and regulatory bodies is vital to ensuring compliance with environmental standards and expediting project approvals. Partnering with experienced industry leaders and established players in the marine renewable energy sector brings invaluable technical expertise, practical insights, and access to cutting-edge resources. Such partnerships foster knowledge sharing and drive innovation, enabling the development of more efficient and sustainable

FPV solutions tailored to the unique challenges of marine environments. By leveraging the expertise of seasoned partners, stakeholders can streamline implementation processes and achieve higher operational efficiency in renewable energy projects.

Economic viability: The financial feasibility of FPV projects including the submarine HV transmission system is a key consideration. Developers must assess the capital expenditure (CAPEX) and operational expenditure (OPEX) to determine the project's economic viability. Government incentives, subsidies, and favourable regulatory frameworks can significantly impact the financial attractiveness of FPV projects. Additionally, innovative financing models, such as public-private partnerships, can help mitigate financial risks and attract investment in large-scale FPV installations.

Environmental stewardship: Environmental stewardship is a critical aspect of FPV system deployment, emphasizing the need to protect aquatic ecosystems and preserve water quality. Projects must prioritize minimizing the impact on marine life by limiting shading effects, ensuring fish migration paths remain unobstructed, and using non-toxic construction materials. Continuous water quality monitoring is especially important when FPV systems are deployed in reservoirs or drinking water sources. By employing sustainable design approaches, such as recyclable or biodegradable materials for floats and mooring systems, FPV installations can significantly reduce their environmental footprint. Additionally, engaging with local communities and stakeholders in conservation efforts can enhance monitoring programs and strengthen environmental protection. Through these measures, FPV systems contribute not only to renewable energy generation but also to long-term ecological sustainability.





Source2

The diagram illustrates the major components of a Floating Solar Photovoltaic (FPV) system, detailing the flow of energy from generation to grid connection. Solar PV modules are mounted on floats or pontoons, which keep them afloat on the water's surface. These floats are anchored securely to maintain stability. The electricity generated by the solar panels is direct current (DC), which is transmitted via electrical cables.

Multiple outputs from the PV panels are combined in a combiner box and then converted into alternating current (AC) by central inverters. This AC power is carried to the control building through a subsea power cable. The system's performance is continuously monitored to ensure optimal functionality. Excess energy generated can be stored in a Battery Energy Storage System (BESS) for use during periods of low solar generation.

Finally, the electricity is fed into the power grid for distribution. This comprehensive layout highlights the essential elements that contribute to the successful operation of an FPV system, from floating solar modules and power conversion to monitoring, storage, and grid integration.

Case Studies: Successful FPV Projects

Singapore's Multi-Purpose Floating Structure

One of the most innovative projects undertaken by Surbana Jurong was the development of a multi-purpose floating solar PV system that integrated renewable energy generation with complementary applications such as aquaculture, water quality management, and marine biodiversity enhancement. The project's design incorporated elevated solar panel mounts supported by buoyant pipes, stabilized by an advanced elastic mooring system. This system was meticulously tailored to adapt to tidal variations while controlling horizontal movements under challenging marine conditions, demonstrating a forward-thinking approach to the technical and environmental complexities of marine-based renewable energy projects.

Surbana Jurong employed comprehensive site studies to ensure the project's success, including detailed assessments of tidal fluctuations, coastal currents, and wind forces. The chosen location, within a sheltered basin at Jurong Island, was selected to mitigate the risks of extreme weather while leveraging natural protection for the floating structures. The design can accommodate a floating solar plant with a capacity of 14MWp, although scalability was

limited due to the constrained sea surface availability. Strategies to minimize disruptions to the surrounding industrial marine zone included proactive stakeholder engagement and the preparation of deployment methodologies. Extensive collaboration with regulatory authorities, including JTC, MPA, and PUB, ensured alignment with safety and environmental standards, as well as minimal impact on marine traffic.

Environmental considerations played a pivotal role in the project's planning and execution. The design prioritized resilience against tropical weather conditions, and materials were selected for their durability, stability, and low maintenance requirements. Advanced simulations and analyses validated the suitability of the technology, including the elastic mooring system, which offered superior performance in maintaining stability and limiting the ecological footprint on the seabed. The project's innovative integration of technology, environmental stewardship, and multi-purpose utility set a benchmark for floating solar PV systems in coastal and industrial environments.

Integration with Hydroelectric Systems

One of the most ambitious and challenging projects involves the integration of GW-level Floating PV (FPV) systems with hydroelectric power generation at a large-scale dam. This mega-scale initiative, set in the Riau Islands of Indonesia, aims to combine renewable energy generation with critical water resource management, addressing both environmental and energy demands on an unprecedented scale. The project envisions deploying FPV systems across vast reservoir surfaces to optimize energy production during peak sunlight hours while complementing hydroelectric operations. To further ensure a continuous and reliable power supply, the initiative incorporates a GW-scale Battery Energy Storage System (BESS). This system is designed to mitigate the intermittency of solar energy and meet continuous load demand during non-sun hours. This dual-purpose approach seeks to enhance energy output and contribute significantly to water conservation efforts in arid and semi-arid regions, where reservoirs serve as essential sources for drinking water and irrigation.

The project has presented complex environmental challenges due to its scale and location. Managing water evaporation across an extensive reservoir is a primary concern, particularly in regions with high solar radiation. FPV panels are designed to provide broad shading,

aiming to reduce evaporation and stabilize reservoir temperatures, which can mitigate algal blooms and preserve water quality. However, the installation process must account for the reservoir's dynamic water levels and seasonal variations, requiring advanced environmental impact assessments and mitigation strategies to minimize ecological disruptions while ensuring long-term sustainability.

Strategically, the scale and integration demand of the project have necessitated innovative approaches in mooring, anchoring, and infrastructure design. Developing site-specific mooring systems capable of adapting to large-scale environmental forces, such as wind and fluctuating water levels, has been a key focus. The coordination of multiple stakeholders, including environmental agencies, hydropower operators, and local communities, has been critical to navigating regulatory requirements and addressing logistical challenges. This ongoing project represents a significant step forward in exploring the potential of large-scale FPV systems, aiming to maximize the efficiency of land and water use while advancing sustainable energy solutions.



Insight from Industry

Key drivers for FPV adoption include the global shift toward renewable energy and the increasing demand for innovative solutions to address land scarcity and energy diversification. Large-scale FPV installations are being planned for inland reservoirs and offshore sites, driven by the potential to integrate these systems with existing renewable energy infrastructures such as hydroelectric dams. According to recent market research, the Asia-Pacific FPV market is projected to grow from \$1.96 billion in 2022 to \$26.50 billion by 2032, (Source:1) reflecting an impressive compound annual growth rate (CAGR). This exponential growth highlights the untapped potential of FPV systems in addressing global energy demands.

Additionally, opportunities abound for deploying FPV systems in underutilized waterbodies, unlocking their potential for sustainable energy generation while addressing energy demand in densely populated regions. Emerging regions, particularly in Asia-Pacific and Africa, are poised to benefit from FPV technology as these markets expand their renewable energy portfolios.

Advancements in submarine high-voltage (HV) cables play a pivotal role in supporting FPV and offshore renewable energy projects. These cables enable the efficient export of power generated offshore and present opportunities for innovation in insulation materials, dynamic cable systems, and laying techniques to ensure minimal transmission losses and durability in harsh marine environments.

Investments in research and development will prioritize autonomous monitoring technologies that enable predictive maintenance and optimize the performance of FPV systems. These technologies ensure real-time data analysis and enhance operational reliability. Research institutes play a pivotal role by driving innovation through rigorous studies, prototyping, and the testing of advanced materials and technologies tailored to the unique challenges of marine environments. By combining these advancements with robust financial incentives and fostering public-private partnerships, the pathway is set for economically viable and environmentally sustainable marine renewable energy projects.

Key Drivers and Opportunities

The rapid growth of the FPV market, particularly in the Asia-Pacific region, highlights the scalability and versatility of these systems. In regions with limited land availability, large-scale FPV installations have become increasingly common, effectively meeting local energy demands. The success of FPV projects worldwide underscores the importance of innovative designs, engineering solutions, and the use of engineering materials, such as high-density polyethylene (HDPE) for solar PV floats, which offer enhanced durability and UV resistance. Advanced materials and elastic mooring systems have been crucial in ensuring the stability, efficiency, and long-term performance of FPV systems, even in challenging marine environments.

The development of subsea high-voltage (HV) cables has been instrumental in advancing marine renewable energy projects, enabling efficient power transmission from offshore installations to the grid. The reliability and efficiency of subsea HV cables are critical for the

success of marine energy systems like FPV and offshore wind. Advances in cable technology, including improved insulation materials and enhanced laying techniques, have significantly increased the durability and capacity of these cables, reduced transmission losses and improving overall system performance.

In addition, innovations such as dynamic cable systems, which are designed to accommodate movement from floating structures, have further contributed to the success of offshore energy projects. These cables are engineered to withstand harsh marine conditions, including strong currents, waves, and shifting seabed topography, ensuring the resilience of power transmission systems. The combination of robust subsea cable infrastructure and floating renewable energy installations paves the way for reliable, large-scale clean energy generation, addressing both energy demand and sustainability goals.

Path Forward

Floating photovoltaic (FPV) systems provide an innovative solution for harnessing renewable energy from oceans and waterbodies, addressing the challenges of energy transition. These systems offer significant opportunities for sustainable energy production and diversification. By integrating technical innovation, environmental stewardship, and partnerships with experienced stakeholders, FPV systems can advance global sustainability goals.

The successful deployment of FPV systems requires collaboration between governments, private sector players, and research institutions. Overcoming operational challenges and integrating FPV systems into existing infrastructure will unlock their potential for decarbonization and contribute to a cleaner, more resilient energy future. Expanding energy generation to marine landscapes is a transformative opportunity we must embrace.

Citations

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