POLITECNICO DI TORINO

Master's degree in Energy and Nuclear Engineering

A.a. 2024/2025

Graduation Session November 2025

Sustainability Assessment of Floating Solar-Wind Hybrids in China and Europe

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Abstract

Global decarbonization requires renewable energy systems with high capacity factors and economic competitiveness in offshore environments. Hybrid offshore installations combining photovoltaic and wind technologies offer time-based complementarity and shared infrastructure costs. This study develops a techno-economic methodology integrating ERA5 reanalysis data, wake-based turbine modeling, and bathymetry-dependent costs to optimize hybrid system configurations.

This methodology evaluates 200 MW installations in two contrasting locations: the South China Sea (Guangdong Province) and the Mediterranean Sea (Pantelleria). By varying the PV share (a) from 0.2 to 0.8, the study identifies economically optimal and balanced configurations using LCOE, NPV.

The results demonstrate significant geographic sensitivity. China achieves 1,000 GWh/year with an LCOE of 59.95€/MWh and an NPV of +155€ million, benefiting from its proximity to the grid. Pantelleria generates 6% more energy (1,059 GWh/year) thanks to its higher solar resources, but faces 2.9 times higher capital costs, the majority of which are attributed to the 71 km export cable. Despite the higher LCOE (168 €/MWh), high electricity prices provide a 5.5 times higher net present value (+852 €M) and a faster payback (16 years). Optimization shows that wind-dominated configurations (a = 0.2, 80% wind) minimize LCOE (46€–129€/MWh) and maximize NPV, reflecting the three-fold capacity advantage of wind power. Balanced designs (a = 0.5) reduce generation variance by 40% while maintaining commercial viability (IRR: 7–9%). An environmental assessment shows an annual reduction in CO_2 emissions of 0.55–0.74 million tonnes.

The study establishes design guidelines prioritizing sites within 30 km of shore and in water depths of 10–60 m, demonstrating that hybrid offshore systems achieve commercial viability while providing increased resilience through complementarity.

Acronyms

AEP	Annual Energy Production
CAPEX	Capital Expenditure
CF	Capacity Factor
CO_2	Carbon Dioxide
ECMWF	European Centre for Medium-Range Weather Forecasts
EF	Emission Factor
ERA5	ECMWF Reanalysis v5 (meteorological dataset)
GEBCO	General Bathymetric Chart of the Oceans
GWh	Gigawatt-hour
HVAC	High Voltage Alternating Current
HDPE	High-Density Polyethylene
HESS	Hybrid Energy Storage System
HLV	Heavy Lift Vessel
HOMER	Hybrid Optimization of Multiple Energy Resources
HOSWS	Hybrid Offshore Solar-Wind System
HRES	Hybrid Renewable Energy System
Hs	Significant Wave Height
HVDC	High Voltage Direct Current
IEA	International Energy Agency
IRR	Internal Rate of Return
LCOE	Levelized Cost of Energy
MW	Megawatt
MWh	Megawatt-hour
NPV	Net Present Value
O&M	Operations and Maintenance
OPEX	Operational Expenditure
PR	Performance Ratio
PV	Photovoltaic
SSRD	Surface Solar Radiation Downwards
STC	Standard Test Conditions
SWH	Significant Wave Height
Si	Silicon
SPIC	State Power Investment Corporation
STC	Standard Test Conditions
SV	Seasonal Variability
α	PV Capacity Fraction
η	Efficiency

Acknowledgements

I sincerely thank my supervisors from the MOREnergy Lab for the opportunity and the invaluable experience. Your guidance, expertise, and constructive feedback have greatly contributed to the development of this work.

To my family and friends, especially Nargiza, who believed in me unconditionally — thank you for your endless support, patience, and encouragement.

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Chapter 1

Introduction

The global energy sector is undergoing a profound transformation driven by the urgent need to reduce greenhouse gas emissions, increase energy security, and transition away from fossil-fuel-based power systems. At the COP28 Climate Change Conference, more than 130 national governments committed to tripling the world's installed renewable energy capacity by 2030, reflecting an unprecedented acceleration in the expansion of clean energy technologies. According to the latest IEA and IRENA reports, renewable installations reached 473 GW in 2023, representing 87% of all new power capacity, with solar photovoltaic (PV) alone accounting for nearly 73% of global additions. At the same time, the levelized cost of electricity (LCOE) of both solar PV and wind reached historic lows, outcompeting fossil-fuel-based electricity generation in most regions worldwide.

Within this rapidly evolving context, offshore renewable energy resources have gained heightened relevance. Offshore environments offer abundant and relatively untapped solar and wind resources, reduced land-use conflicts, and strategic proximity to densely populated coastal regions. As nations face increasing land scarcity, particularly in Asia and Europe, offshore renewable solutions—floating photovoltaics (FPV), offshore wind turbines (OWT), and their hybrid combinations—are increasingly considered a critical element of future energy systems.

A key insight emerging from recent research and industrial developments is the high complementarity between solar and wind resources in marine environments. Solar irradiation typically peaks around midday, while offshore wind speeds often intensify in the late afternoon and evening. This natural offset in production profiles enables hybrid floating systems to minimize variability, reduce curtailment, improve grid integration, and maximize the utilization of existing ocean space.

Industry interest in hybrid offshore solutions has intensified considerably. As reported by Offshore Magazine (Beaubouef, 2022), offshore wind developers are increasingly integrating floating solar technologies into their projects to enhance output stability and reduce LCOE. In 2022, China commissioned the world's first large-scale floating solar–wind hybrid system off the coast of Haiyang, developed by the State Power Investment Corporation (SPIC) [1]. The project, using Ocean Sun's patented floating solar technology, connects FPV floaters directly to the transformer of an offshore wind turbine, showcasing the technical feasibility and economic potential of hybrid offshore installations. Europe is following a similar trajectory: companies such as RWE and SolarDuck have initiated joint pilots in the Belgian North Sea, testing the robustness, survivability, and energy performance of offshore floating solar integrated within wind farms. These initiatives reflect a broader global shift toward co-located offshore hybrid energy plants, aiming to accelerate commercialization and reduce lifecycle costs through shared infrastructure.

Despite growing industrial attention, standalone offshore PV and wind installations still face significant challenges. Offshore wind, while mature, experiences intermittency, high capital intensity, and complex maintenance requirements. Floating PV systems, although increasingly studied, must withstand harsh ocean conditions, manage wave-induced loads, and address uncertainties in long-term degradation. Integrating the two technologies into a hybrid system presents a promising strategy to mitigate individual limitations, improve system reliability, optimize the use of foundations and electrical infrastructure, and achieve more balanced power generation profiles. However, comprehensive sustainability assessments—combining techno-economic, environmental, and operational dimensions—remain limited, especially for floating hybrid applications.

A significant research gap exists in the comparative performance of hybrid offshore solar–wind systems across different geographical and socio-economic contexts. Most existing studies analyze single sites or focus solely on resource complementarity without integrating full financial and environmental evaluations. Furthermore, hybrid systems in Asia—where offshore FPV is rapidly advancing—are not often compared with emerging European contexts, although such comparisons can provide critical insights into global deployment potential.

This thesis addresses this gap by conducting a sustainability assessment of floating offshore solar–wind hybrid systems in two contrasting yet highly relevant regions: Pantelleria (Italy) and Guangdong (China). Pantelleria represents a small, isolated island with high energy costs, deep waters, and strong policy incentives for decarbonization. Guangdong, by contrast, is one of the world's largest industrial and coastal provinces, with ambitious renewable energy expansion targets, rapid FPV deployment, and strong offshore wind development. The selection of these sites enables a comparative evaluation across different climatic conditions, regulatory frameworks, electricity markets, and resource profiles.

The main goal of this thesis is to evaluate the techno-economic and environmental feasibility of floating hybrid solar–wind systems in Europe and China, quantify the benefits of hybridization compared to standalone offshore PV and wind, and identify the key drivers that influence system performance, LCOE, and sustainability outcomes.

To achieve these objectives, this thesis develops a Python-based modeling framework that integrates two validated tools—one for floating PV performance and cost modeling, and one for offshore wind energy assessment—and extends them into a new hybridization module that generates combined hourly energy time series, annual energy production (AEP), capacity factors, cost breakdowns, and financial indicators. Using datasets from ERA5 and GEBCO, the methodology provides a reproducible workflow for hybrid offshore system assessment applicable to diverse locations.

The structure of this thesis is as follows. Chapter 2 presents a comprehensive literature review of offshore renewable technologies, hybrid solar–wind systems, and state-of-the-art projects. Chapter 3 describes the site selection criteria and provides detailed geographic, oceanographic, and regulatory contexts for Pantelleria and Guangdong. Chapter 4 outlines the methodological workflow, including data extraction, modeling tools, hybrid system formulation, and techno-economic calculations. Chapter 5 presents the results and comparative analysis of hybrid configurations in both sites. Finally, Chapter 6 summarizes the conclusions and discusses future research directions.

Chapter 2

State of the art of floating solar-wind hybrid systems

2.1 Global Expansion of Offshore Renewable Energy

The accelerating global transition toward carbon-neutral power systems has stimulated unprecedented growth in offshore renewable energy technologies. Offshore wind energy has already entered a phase of large-scale industrial deployment, with global capacity exceeding 65 GW in 2023 and further expansion projected to reach 240 GW by 2030, supported by substantial investments in Europe, China, and the United States. Offshore wind offers several advantages over its onshore counterpart, including higher and more stable wind speeds, reduced turbulence, and proximity to densely populated coastal load centers.

Meanwhile, floating photovoltaics (FPV) have emerged as one of the fastest-growing innovations in the solar power sector. Initially developed for inland reservoirs, FPV has expanded toward nearshore and offshore applications, driven by land scarcity, high irradiance potential at sea, and the increasing maturity of offshore engineering solutions. According to recent assessments, global FPV potential exceeds 4–5 TW, with particularly high suitability in Asia and Southern Europe.

Offshore renewable development is further motivated by:

- Land-use constraints in densely populated regions,
- Energy security concerns,
- Integrated marine spatial planning,

- Technological improvements lowering LCOE,
- National clean energy policies and subsidy schemes (e.g., China's offshore wind feed-in tariffs, EU Innovation Fund).

These drivers create the foundation for the emergence of hybrid offshore renewable systems, combining solar and wind technologies on a shared floating or bottom-fixed infrastructure.

2.2 Complementarity of Solar and Wind Resources

A key argument supporting hybrid offshore systems is the natural complementarity between solar and wind resources, which reduces power variability and improves grid integration.

- Solar radiation peaks during midday and exhibits high predictability.
- Offshore wind speeds tend to increase in the late afternoon, evening, and nighttime due to sea–land thermal gradients.
- Offshore environments exhibit lower diurnal temperature variability, increasing PV efficiency and reducing thermal losses.

Niccolai and Rabea et al.confirm that combining solar and wind profiles:

- Reduces ramp rates,
- Decreases curtailment,
- Improves battery-storage utilization,
- Smooths intermittency across seasons,
- Enhances system reliability and capacity value.

China's coastal regions and the Mediterranean Sea both demonstrate strong diurnal and seasonal complementarity, making them ideal testbeds for hybrid offshore deployments.

2.3 Floating Photovoltaic Systems (FPV)

2.3.1 Technological Concept and Development

A standard floating photovoltaic (FPV) system is composed of several key elements: photovoltaic modules that convert sunlight into electricity, buoyant platforms that keep the system afloat, structural frames supporting the panels, a mooring setup to maintain the platform's position, and electrical balance-of-system components for grid connection. As illustrated in Figure 2.1, FPV systems function similarly to conventional ground-mounted PV arrays—the main difference lies in the fact that the solar modules are installed on floating structures instead of being anchored to the land surface. Its main advantage is the efficient use of space: instead of

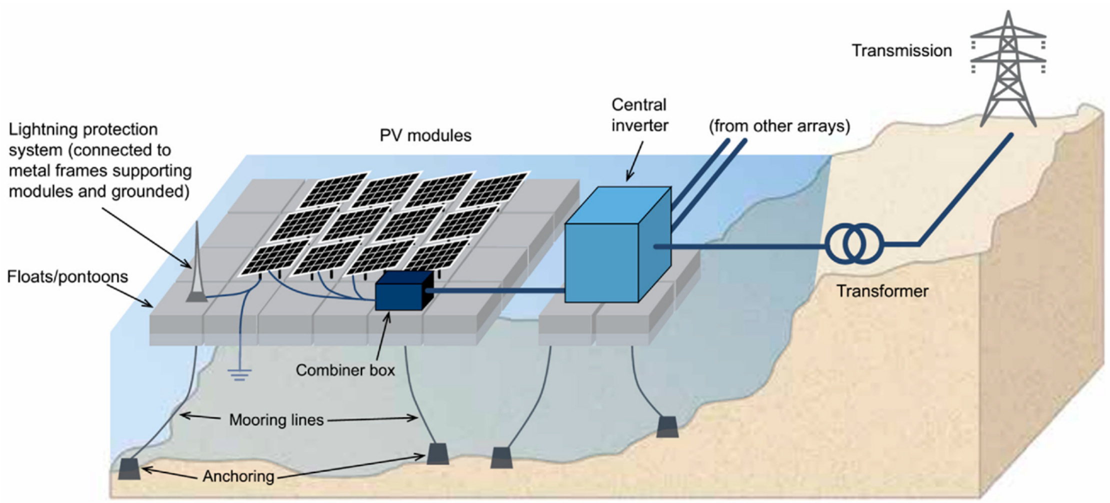

Figure 2.1: Chematic layout of a Floating Photovoltaic (FPV) system [2]

occupying fertile land or expensive sites, solar power plants are located on the surface of artificial and natural bodies of water, such as hydroelectric reservoirs, abandoned quarries, or irrigation canals. Placing panels on water offers a number of technical and environmental advantages. The aquatic environment provides natural cooling for the modules, reducing their operating temperature and increasing solar energy conversion efficiency compared to land-based systems. According to the, floating solar power plants can also reduce water evaporation, which is especially important for arid regions, and shading the surface limits the development of algae, thereby improving water quality.

2.3.2 Main Components of Floating Photovoltaic (FPV) Systems

PV modules

Photovoltaic (PV) modules form the core of any floating solar system, converting sunlight into electricity through semiconductor materials that exploit the photovoltaic effect. Most FPV installations employ crystalline-silicon (c-Si) technology—either monocrystalline or multicrystalline—because of its maturity, cost-efficiency, and reliability in large-scale production. Recent advancements, such as half-cell segmentation, have significantly reduced resistive losses and improved performance under partial shading, while double-glass designs enhance durability by minimizing moisture ingress and potential-induced degradation. Bifacial modules are gaining prominence for their ability to harvest reflected light from both sides, offering yield improvements of up to 10–15 %, although their performance over water depends strongly on surface albedo and float reflectivity. In marine environments, PV modules must also endure salt corrosion, humidity, and mechanical stresses from waves and wind, necessitating reinforced encapsulation materials and corrosion-resistant junction boxes. Thin-film technologies, including amorphous silicon and CIGS (Copper Indium Gallium Selenide), are being tested for FPV applications because of their flexibility, lightweight design, and superior cooling, though their lower efficiency limits large-scale deployment. [3]

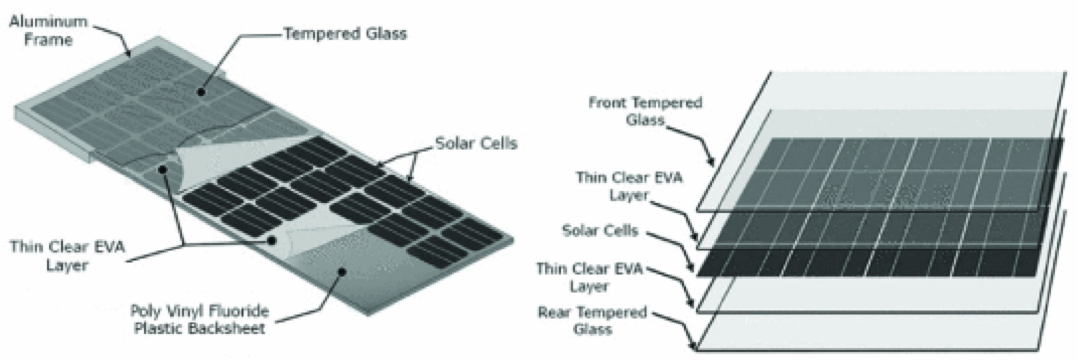

Figure 2.2: Conventional module and Double glass module structure [4]

Floating platform

According to [5], FPV platforms are broadly divided into three main configurations:

- Pure float systems, where each PV module is mounted directly on an individual buoyant float with integrated clamps or fixtures.
- Membrane-based systems, which support panels on a flexible, reinforced membrane surrounded by tubular rings that also house auxiliary components.
- Pontoon-type systems, which use interconnected rafts or decks to provide a stable base for larger arrays and allow better maintenance access.

Across studies, FPV design aims to achieve a balance between buoyancy, structural stability, and hydrodynamic resilience, using materials like HDPE, aluminum, and reinforced composites that resist corrosion and fatigue in marine environments. Modular, scalable architectures dominate current practice, enabling systems to adapt to varying wave heights, wind loads, and water depths, while maintaining cost efficiency and longevity.

Tracking systems

Tracking improves incident irradiance on the modules by aligning them more closely with the sun [6]. On water, two families are relevant:

- Horizontal-axis tilt systems, where the panel frame tilts relative to the float,
- Vertical-axis rotation, where larger sections—or an entire raft—yaw to follow the sun's azimuth.

Feasibility depends on platform stiffness, available freeboard, and allowable motions. While dual-axis solutions can deliver the largest energy increase, they introduce weight, complexity, and cost; many offshore designs therefore opt for fixed-tilt or single-axis arrangements that balance yield against simplicity and survivability.[7]

Electrical components

Power from strings is routed to combiner boxes, conditioned by DC–DC converters where needed, and processed by inverters before export. Cables—submerged or elevated—must be marine-rated for UV exposure, water ingress, and temperature cycles, with strain relief to accommodate platform motions [8]. Two siting options are typical:

1. Onshore power conversion: DC is exported to shore and converted in a land substation—simplifying maintenance and thermal management.
2. On-float conversion: inverters/transformers are mounted on dedicated floats; AC is then exported via subsea cable—reducing DC cable runs but raising offshore O&M demands.

Lightning protection and equipotential bonding of metallic frames are mandatory, with earthing integrated into moorings or dedicated electrodes..

Mooring and anchoring

The station-keeping system stabilizes the array and limits excursions. Choice depends on wave climate Hs (significant wave height) and Tp (wave peak period), wind loading, water depth, and seabed conditions [6]:

- Catenary lines (heavy chain) provide restoring force via line weight and are common in shallow–moderate depths
- Compliant layouts add floats or clump weights to tune dynamic stiffness
- Taut-leg systems keep lines under pre-tension using synthetic ropes and buoyancy modules, reducing footprint and motions
- Rigid or pile-guided systems mechanically constrain horizontal movement, allowing primarily heave

Anchors may be drag-embedment, suction piles, driven piles, or gravity types, selected to match soil properties and design loads.

2.4 Offshore Wind Energy (OWT)

2.4.1 Technology Overview

Offshore wind power is a renewable and infinite energy source, obtained from the generation of electricity through the harnessing of kinetic energy by clusters of wind turbines (so-called Wind Farms), placed on large bodies of water where strong winds allow for greater production. Unlike traditional offshore wind turbines

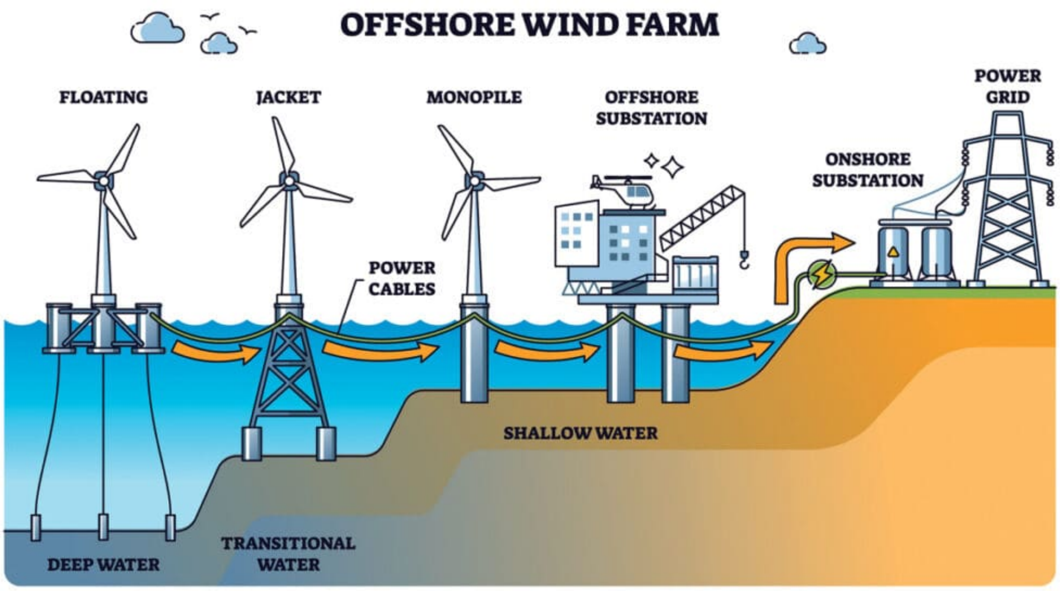

Figure 2.3: Offshore wind farm

installed on pile or gravity foundations, floating systems are mounted on pontoons or semi-submersible platforms secured with anchor systems. This allows for operation in water depths ranging from 50 to 1,000 meters, significantly expanding the geographic reach of wind energy projects. Since the launch of the first offshore wind farm in Vindeby, Denmark (Figure 2.4), in 1991, the offshore wind industry has evolved from a small experimental project into a leading force in renewable energy. The initial 0.45 MW installation served as a foundation for decades of progress, paving the way for larger, more efficient, and cost-effective wind farms. Continuous technological innovation, growing government support, and falling production costs have transformed offshore wind into a reliable and competitive energy source.

Figure 2.4: Vindeby offshore wind farm

By the end of 2024, the total installed offshore wind capacity worldwide had exceeded 80.9 GW (Figure 2.5), marking a 15% increase compared to the previous year. This expansion was driven primarily by China, which strengthened its global leadership by adding 6.9 GW within a single year, bringing its cumulative capacity to 39.1 GW. Europe remained the second major hub for offshore wind, with the United Kingdom continuing to lead the region at around 15 GW of installed capacity by 2023, while the Netherlands also experienced strong progress, expanding its capacity by an additional 1.7 GW in 2024.

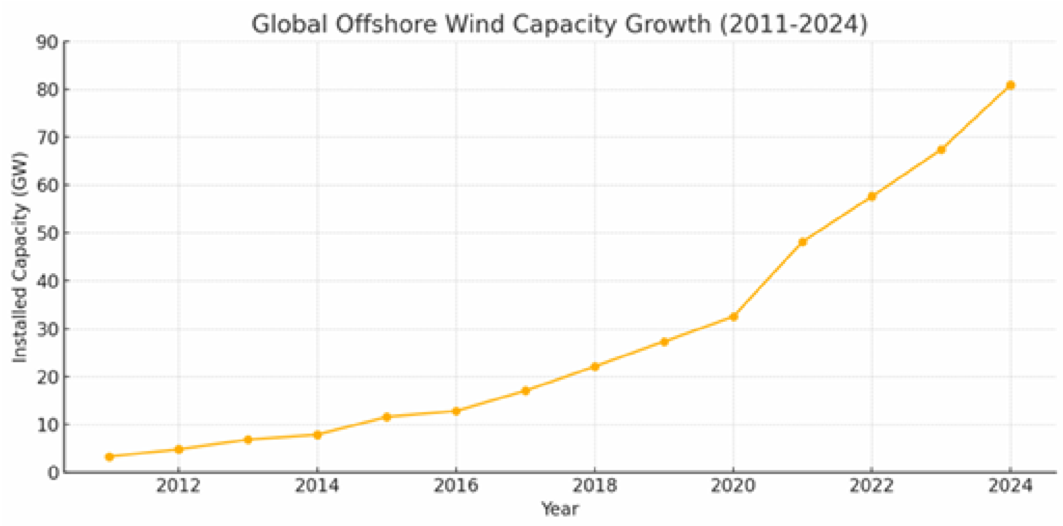

Figure 2.5: Global Offshore Wind Growth

2.4.2 Fixed vs Floating Offshore Wind Turbines

This section compares the well-established technology of Fixed-Bottom Wind Turbines (FBWTs) with the emerging and rapidly advancing Floating Offshore Wind Turbines (FOWTs). Fixed-bottom systems are installed directly onto the seabed through foundations such as monopiles, jackets, tripods, or gravity-based caissons, providing strong and stable support in shallow waters, typically up to 60 meters deep. Among these, monopiles are the most widely used due to their straightforward design and lower installation costs, while jacket structures, made of steel lattice frameworks, are preferred for moderate depths because of their high strength-to-weight ratio and robustness. A visual illustration of these foundation types is shown in Figure 2.6. The installation process typically includes transporting pre-assembled towers and foundations to the site using Heavy Lift Vessels (HLVs) or Jack-up Vessels. [**domingos2024full**] This is followed by seabed preparation,

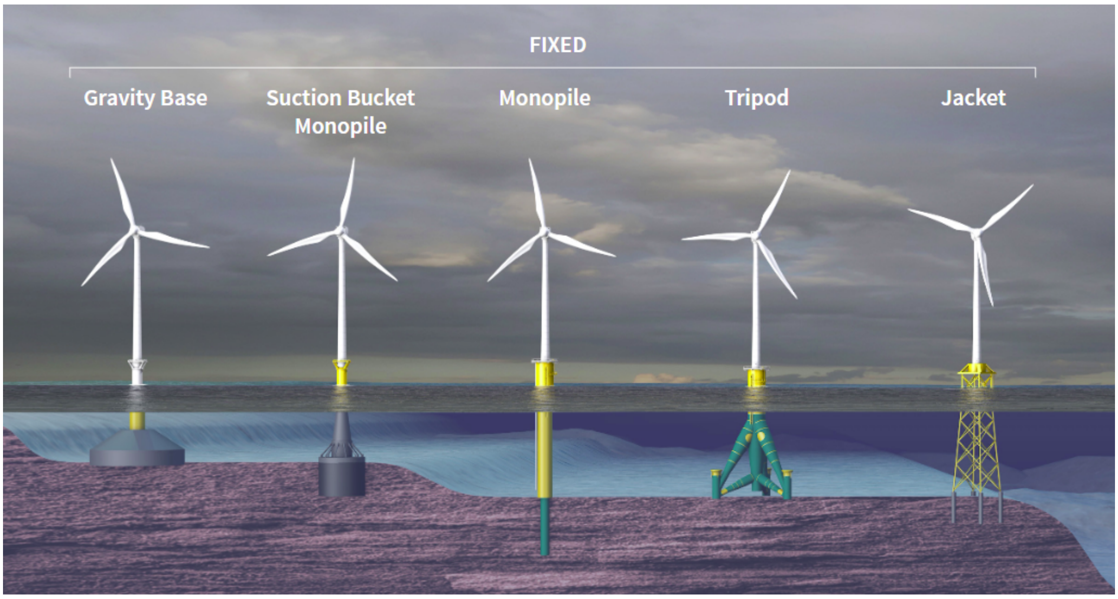

Figure 2.6: Types of foundation for FBWTs [9]

piling, and leveling operations, which must be carefully planned around favorable weather conditions. Routine inspections and maintenance activities are made easier by the stable, fixed foundations that allow safe and consistent access through jack-up vessels. The stationary structure provides secure working conditions and predictable scheduling, helping to maintain operation and maintenance (O&M) costs at relatively low levels.

Table 2.1: Comparative Technical and Economic Parameters of Fixed-Bottom and Floating Offshore Wind Turbines

Feature	**Fixed-Bottom**	**Floating**
Deployment Depth	0–60 m	60–1000+ m
Foundation Types	Monopile, Jacket, Gravity	Spar, Semi-sub, TLP
Installation Vessels	HLV, Jack-up	Tug, Tow, DP vessels
Tech Maturity	TRL 9 (commercial)	TRL 6–8 (pre-commercial)
CAPEX/OPEX	Lower	∼15–20% higher, decreasing with scale
O&M Complexity	Moderate (predictable)	High (platform motion, towing logistics)

2.4.3 Main Components of Floating Offshore Wind Turbine (FOWT) Systems

A Floating Offshore Wind Turbine (FOWT) consists of several main subsystems that work together to generate, stabilize, and transmit power from wind energy in deep-water environments. These components include the nacelle, rotor, tower, floating substructure, mooring systems, and dynamic electrical cables.

Nacelle

The nacelle serves as the central component of a wind turbine, containing the essential mechanical and electrical equipment responsible for transforming the rotor's rotational motion into usable electrical power. (Figure 2.7) Key internal components include:

- Main Shaft and Bearings: These transfer the mechanical torque generated by the rotor blades to the drivetrain, ensuring smooth and efficient energy transmission.
- Gearbox: This unit steps up the low rotational speed of the rotor to a higher speed suitable for the generator's input.
- Generator: Converts the mechanical power from the gearbox into electrical energy through electromagnetic induction.
- Yaw System: Rotates the nacelle to face the prevailing wind direction, maintaining optimal energy capture — particularly essential for floating platforms, which experience six degrees of freedom (heave, pitch, roll, surge, sway, yaw).
- Cooling System: Regulates the temperature of the generator, gearbox, and power electronics, preventing overheating and ensuring stable operation.
- Braking System: Provides emergency shutdown capability and prevents overspeed conditions or structural damage during high-wind events or system faults.

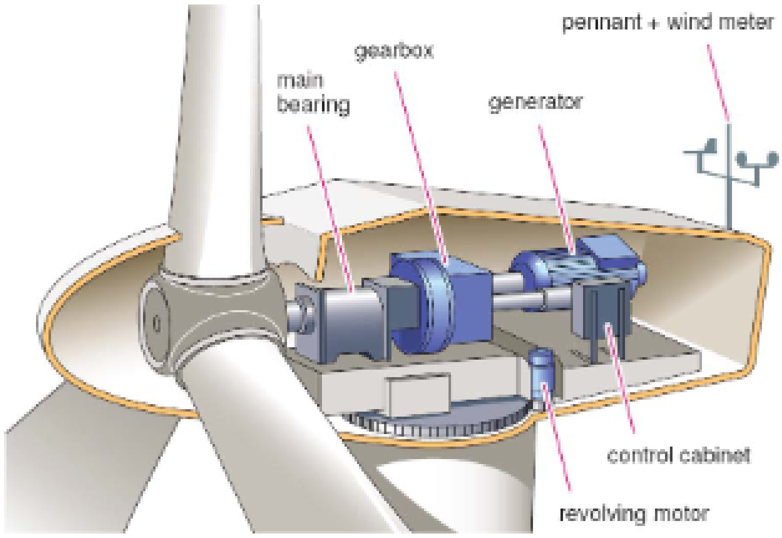

Figure 2.7: Wind turbine nacelle cross-section

Rotor

The rotor captures wind kinetic energy and converts it into shaft torque. It comprises the blades, hub casting, blade-root bearings, and the pitch actuation system. Rotor blades are usually made from fiber-reinforced composites (glass/epoxy and, in longer designs, carbon fiber laminates) to deliver high stiffness with low weight. Each blade is mounted on a pitch bearing that is bolted to the hub on the main shaft. The bearing enables the pitch system to rotate the blade about its root, allowing continuous adjustment of the blade angle. This pitch control regulates electrical output, mitigates structural loads, and manages operating states—for example, aiding smooth startup and providing safe, rapid shutdown during high winds or faults.

Tower

The tower provides the primary vertical support for the turbine, elevating the nacelle and rotor into higher, steadier wind regimes. It is typically a tapered tubular steel structure that also houses control and electrical systems and protects the internal access (ladders or service lifts). Recent studies investigate steel–concrete hybrid tower concepts to reduce overall mass, improve stiffness, and lower the center of gravity, enhancing structural performance and ease of installation.

Floating substructure

The floating substructure allows turbines to be installed in waters generally deeper than approximately 60 m, where fixed-bottom foundations are no longer practical or cost-effective. It carries the turbine and preserves stability by balancing buoyancy, ballast, and mooring restraint against wind, wave, and current loads. Core roles include providing primary structural support, managing the dynamic response of the system, and serving as the interface for both mooring lines and dynamic power cables.

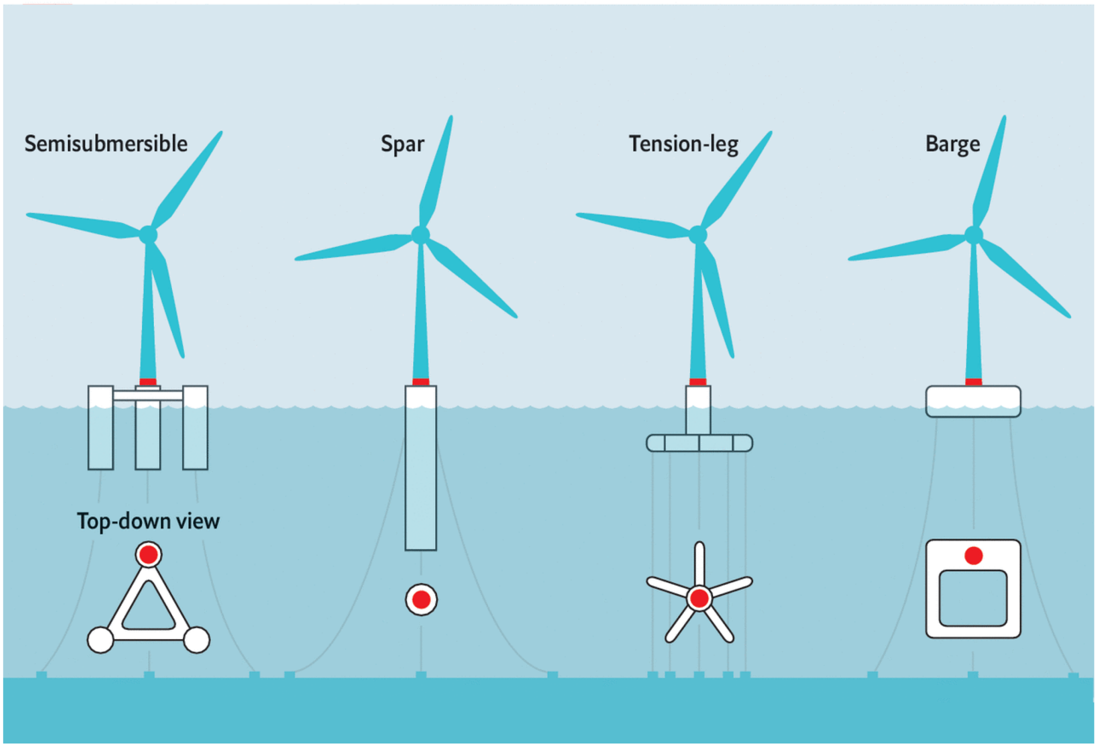

Figure 2.8: Different FOWT substructure design

Offshore and Onshore Substation

An offshore substation functions as the project's electrical hub: it gathers energy from the wind farm via inter-array cables, steps up the voltage, and routes the power to land through export cables. All turbine feeders converge at this node before transmission to the onshore grid. Depending on water depth and layout, the substation can be deployed on a fixed structure or a floating platform. They consist of a main electrical power system and auxiliary systems, housed on a topside structure. The onshore substation is where power from the offshore wind farm connects to the land grid. Electricity comes in through submarine export cables, is adjusted to the correct grid voltage, checked and metered, and then sent into the national network for use. It's the final handoff point from sea to shore.

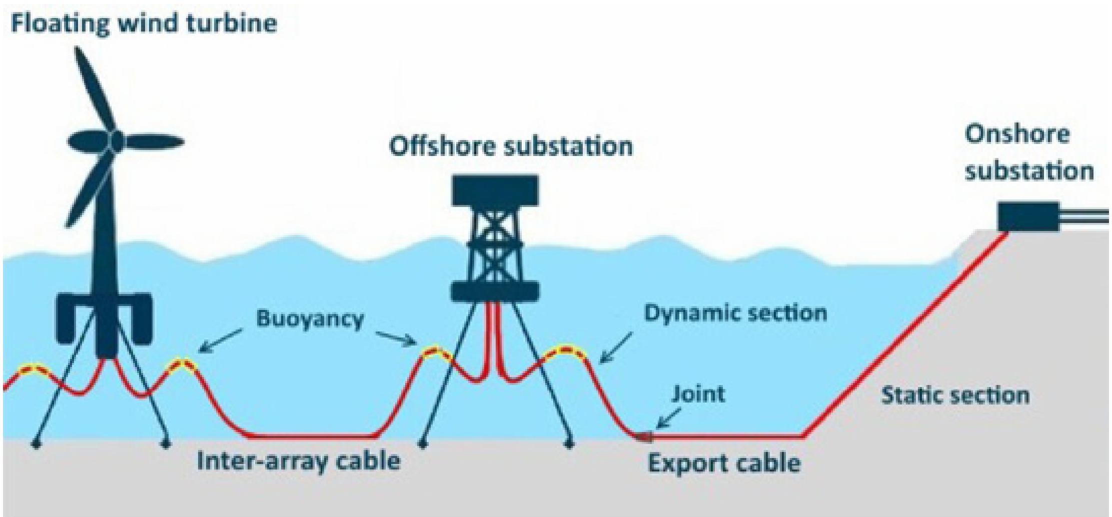

Figure 2.9: Offshore and Onshore substation layout

Electrical System, Cables and Mooring System

The electrical system handles producing power in the turbine, stepping up its voltage, transmitting it to shore, and managing protection and control along the way. Although its overall role mirrors that of fixed-bottom turbines, a FOWT's electrical design must also cope with platform motion, flexible/dynamic cable layouts, and variable offshore conditions that introduce extra mechanical and fatigue loads. Cables are essential to the operation of FOWTs, serving as the primary infrastructure for the electrical system, data communication, and control signaling. The mooring system serves as an anchoring of the floating substructure to the seabed, maintaining its position within specified tolerances under varying environmental conditions. The main types of mooring systems:

- Catenary (chain/wire with seabed touchdown): robust and simple; larger seabed footprint and higher seabed interaction.
- Taut-leg (polyester or hybrid chain–rope): reduced footprint, higher vertical stiffness; common for semi-subs in 80–200 m.
- Tension-leg (TLP): minimal heave/pitch but higher complexity and strict installation tolerances.

2.4.4 Cost Structure

OWT costs are dominated by:

- Turbine manufacturing (30–40%),
- Foundation/substructure (20–30%),
- Electrical infrastructure (20–25%),
- Installation (10–15%),
- O& M costs (fixed + distance-dependent).

LCOE trends indicate strong cost reduction from 150–180 €/MWh (2015) to 65–90 €/MWh (2023), with floating wind approaching commercial competitiveness.

2.5 Hybrid Offshore Solar–Wind Systems

2.5.1 Definition and Classification of Hybrid Energy Systems

Hybrid energy systems broadly refer to power-generating facilities that combine more than one energy conversion technology at a single point of connection to the grid or a stand-alone load. According to the commonly used definition, a hybrid system integrates multiple generation modules — sometimes alongside storage — to convert primary energy into electricity in a coordinated manner. These combinations may involve conventional fossil technologies, renewable sources, or storage technologies such as batteries and hydrogen. Given the wide variety of existing hybrid configurations, it is important to clearly define the conceptual boundaries relevant to this thesis. A frequently cited taxonomy by the International Energy Agency(IEA) and later refined in academic literature distinguishes hybrid systems into three categories:

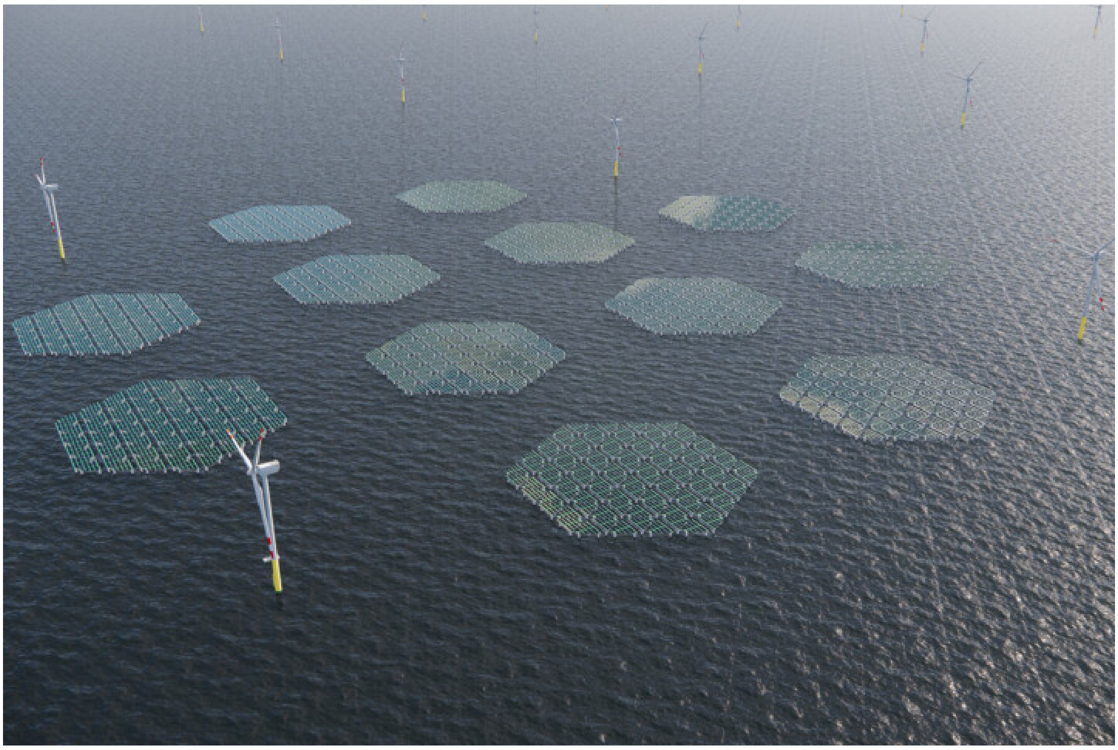

Figure 2.10: Solarduck floating hybrid system

- Co-located resources — Different technologies are physically located at the same site but operate independently. There is no operational coordination, and they typically have separate electrical interfaces.

- Virtual power plants (VPPs) — Different technologies are geographically dispersed but are operated under a unified control system. Their hybrid nature lies in coordinated dispatch rather than physical colocation.

- Full hybrid systems — Technologies are both colocated and operationally integrated. This means that energy conversion units share physical infrastructure (such as a substation, export cable, or mooring field), and their power output is optimized jointly.

In the context of this thesis, the focus is placed exclusively on full hybrid systems, specifically those integrating floating photovoltaic (FPV) platforms and offshore wind turbines. This choice is justified by several reasons:

- These technologies exhibit complementary temporal generation profiles, enhancing output stability.

- They allow efficient use of marine space and shared infrastructure. Their development aligns with emerging offshore energy strategies in both Europe and China.
- Full hybridization best represents the “next generation” of offshore renewable plants, where cost reductions are obtained through shared CAPEX and optimized power output.

These technologies exhibit complementary temporal generation profiles, enhancing output stability. They allow efficient use of marine space and shared infrastructure. Their development aligns with emerging offshore energy strategies in both Europe and China. Full hybridization best represents the “next generation” of offshore renewable plants, where cost reductions are obtained through shared CAPEX and optimized power output.

2.5.2 Technical Aspects of Offshore Hybrid Systems

Mooring and Structural Stability

Mooring systems are critical for hybrid installations due to the interaction between wind turbine foundations and FPV platforms. The literature identifies common mooring approaches:

- Single-point mooring for FPV, allowing rotational freedom.
- Multi-line spread mooring, improving stiffness and reducing drift.
- Shared anchor systems, leveraging existing wind turbine foundations to reduce cost.

Key structural challenges include:

- hydrodynamic coupling between wind turbines and FPV platforms
- extreme storm loads ($Hs > 8$ m in many offshore areas)
- fatigue accumulation from combined wave–wind forces
- platform deformation and water ingress

Studies (e.g., SolarDuck, Ocean Sun) emphasize the importance of maintaining platform elevation above wave peaks.

Electrical Infrastructure

Hybrid electrical design requires:

- shared offshore substation (HVAC or HVDC, depending on distance)
- unified export cable sized for peak hybrid output
- optimized intra-array cable routing
- protection schemes for combined solar + wind circuits
- offshore-rated inverters and transformers

Chapter 3

Case study selection

3.1 Rationale for Selecting the Case Study Regions

The assessment of hybrid offshore renewable systems strongly depends on local environmental, technical, and economic conditions. For this reason, the selection of representative and contrasting sites is crucial to demonstrate how geographical, climatic, and market factors affect the feasibility of hybrid floating solar–wind systems.

In this thesis, two significantly different locations are chosen:

- Pantelleria Island, Italy – a small, isolated Mediterranean island with high solar radiation and low wave activity, typical of southern Europe's coastal energy profile.
- Guangdong, China – a large subtropical coastal region along the South China Sea, characterized by high solar irradiance, strong monsoon-driven offshore winds.

These two locations represent two extreme but meaningful scenarios:

- a constrained, high-cost, energy-dependent island (Pantelleria)
- a densely populated, industrial, large-scale renewable hub (Guangdong)

By contrasting these sites, the analysis reveals how HOSWS (Hybrid Offshore Solar-Wind System) performance and costs scale under varied marine forcing, guiding location-specific technology choice and financial planning.

3.2 Pantelleria Island (Italy)

The island of Pantelleria, with the following coordinates [36.780, 11.953], is situated in the Strait of Sicily between Italy and Tunisia, and serves as a strategic point approximately 100 km southwest of Sicily. The island relies heavily on a diesel power plant for its energy needs, generating 39.0 GWh annually, supplemented by 0.5 GWh from distributed PV systems on rooftops. This dependence on diesel generators results in high import costs, as fossil fuels are transported from the mainland.

The island's water supply relies on energy-intensive desalination processes, Consuming about 3.7 GWh of electricity per year. This interdependence between water and energy systems underscores the potential benefits of integrating FPV systems. By exploiting more solar energy, the island could reduce its reliance on costly diesel imports, optimize the desalination process, and improve overall sustainability. It has also been proven that there is an alignment between the peak water production/electricity demand and high solar irradiance, further supporting the feasibility of this renewable energy solution.

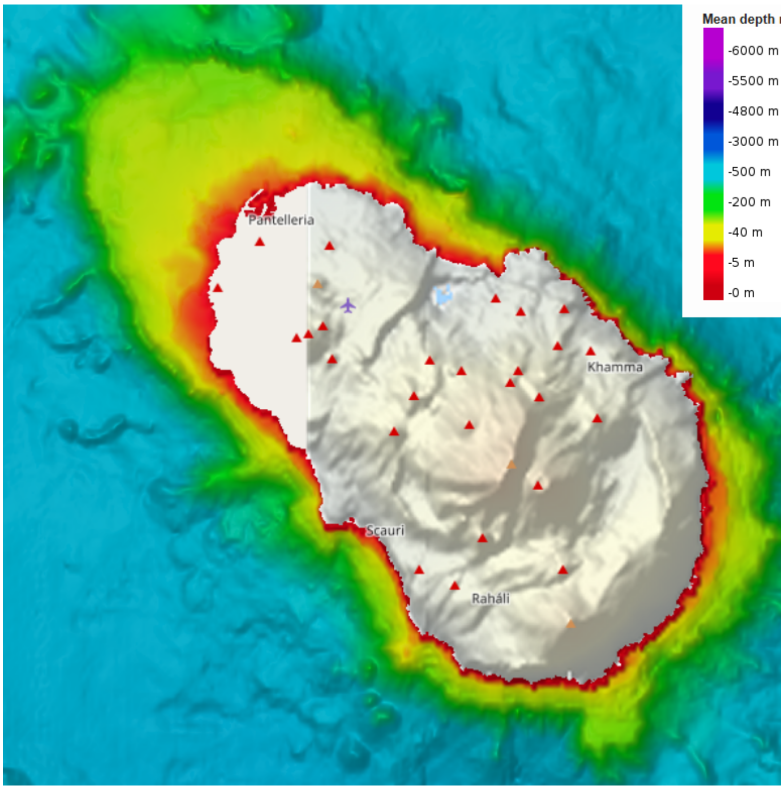

Figure 3.1: Bathymetric map of the Pantelleria island

3.3 Guangdong Province (China)

The Guangdong province in southern China, located along the South China Sea between [21.0–23.5°N, 112.0–116.5°E], is one of the country's most populated and industrialized coastal regions, with over 126 million inhabitants. The province relies primarily on a coal-dominated power system, producing more than 800 TWh of electricity annually, supplemented by rapidly expanding offshore wind farms and large onshore solar installations. Guangdong is also home to China's earliest large-scale offshore wind developments, with several multi-GW projects concentrated near Yangjiang and Shantou.

Guangdong's coastal climate is characterized by high solar irradiance, strong monsoon-driven winds, and seasonal typhoons, making it a representative case of subtropical Asian offshore conditions. The region's renewable capacity has grown rapidly: by 2024, Guangdong installed over 5 GW of offshore wind power and more than 30 GW of solar PV, driven by national decarbonization targets and provincial renewable energy policies. However, the variability of monsoon winds and the intermittency of solar resources present challenges for grid stability, particularly in coastal industrial zones with peak daytime demand.

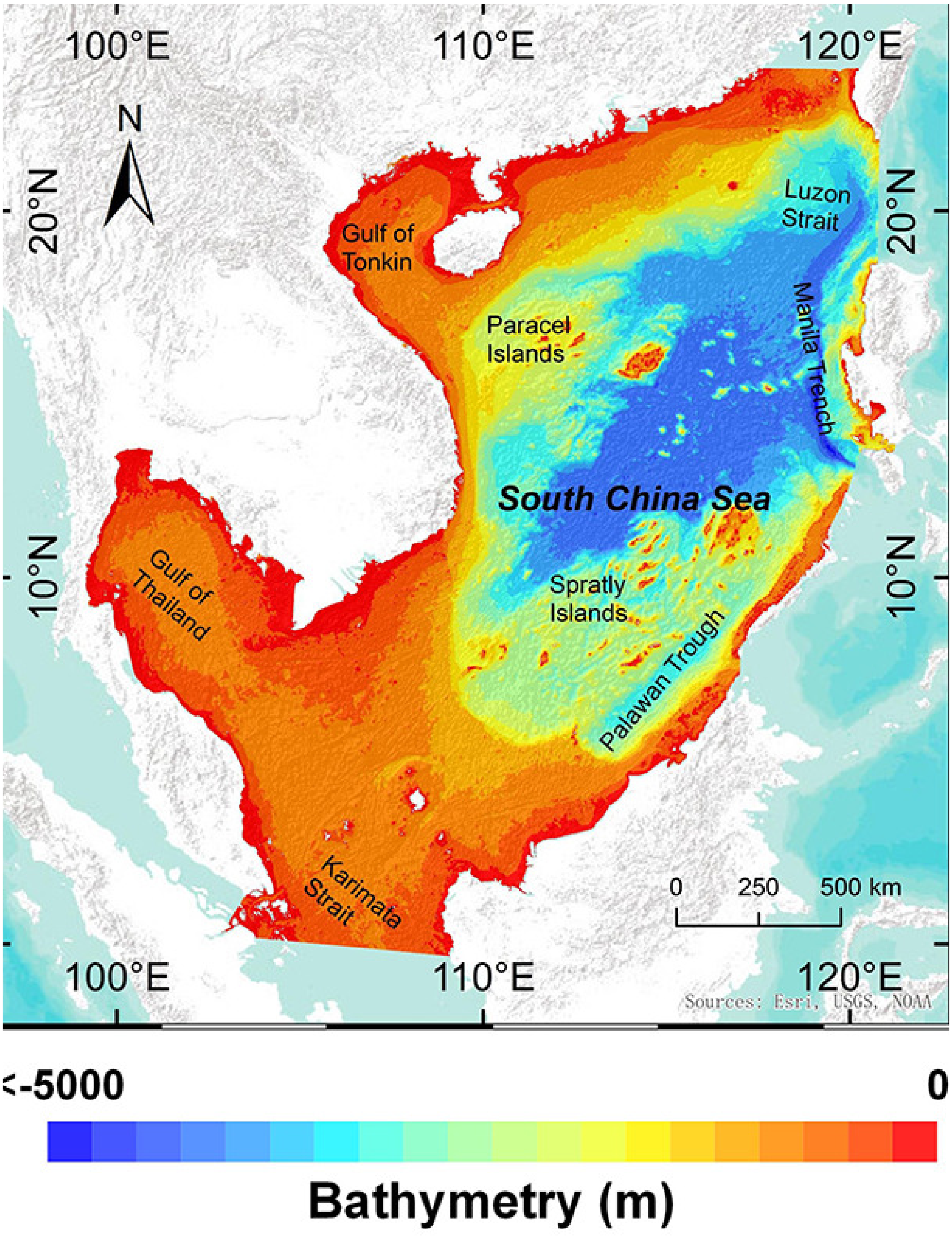

Figure 3.2: Bathymetric map of the Guangdong province

3.4 Political and Regulatory Support for Offshore Renewable Deployment

Table 3.1: Policy and Regulatory Comparison Between Pantelleria (EU/Italy) and Guangdong (China)

Category	Pantelleria (EU / Italy)	Guangdong (China)
Main Policy Drivers	EU Green Deal (2050 neutrality); REPowerEU (RES acceleration); EU Offshore Renewable Strategy (300 GW wind by 2050); Clean Energy for EU Islands Initiative	"Dual Carbon Targets": peak by 2030, neutrality by 2060; 14th Five-Year Plan for offshore wind; National Renewable Energy Law; Offshore Wind Development Roadmap
Regional Objectives	Decarbonize isolated islands; Replace diesel generation; Increase energy autonomy	Build multi-GW offshore wind clusters; Expand floating solar offshore; Strengthen industrial energy supply
Financial Incentives	High feed-in tariffs; Island decarbonization subsidies (ARERA); EU funding for innovation and storage	VAT reductions for renewables; Subsidized financing; Provincial offshore-wind and FPV support funds
Grid Integration Rules	Priority dispatch for RES; Dedicated programs for island microgrids; Support for storage and hybrid systems	Mandatory grid priority for RES; Fast-track connection for offshore wind; Integration of hybrid FPV–wind pilot projects
Market Characteristics	Small isolated grid; High electricity prices (~0.28 €/kWh); High dependence on diesel imports	Large industrial grid; Moderate electricity prices (~0.07 €/kWh); Rapidly increasing offshore capacity

Chapter 4

Methods and materials

4.1 Research workflow

This thesis applies a systematic research method to assess the technical and economic feasibility of floating solar-wind systems. This method consists of several interconnected modules.

1. Module 1 – Data Input: Specification of analysis parameters, including year, desired system capacity, and geographic coordinates
2. Module 2 – Resource Assessment: Extraction of resource data, including solar radiation (srrd), wind speeds at 10 m and 100 m heights, significant wave height (Hs), and wave period (Tp).
3. Module 3 – Technical Modeling: Calculation of Annual Energy Production (AEP) and Capacity Factor (CF) for each technology.
4. Module 4 – Hybrid Configuration: Designing various hybrid system configurations by varying the PV fraction parameter (a) from 0.2 to 0.8, determining the installed capacities of solar (Ppv) and wind (Pwind) components, and calculating the resulting hybrid capacity factor (CFhyb).
5. Module 5 – Economic Analysis: Calculation of key financial indicators, including Net Present Value (NPV), payback time, and Levelized Cost of Energy (LCOE).
6. Module 6 – Optimization & Sensitivity: Identification of optimal configurations that minimize LCOE and maximize NPV
7. Module 7 – Results Output: Final results including optimal configurations, techno-economic metrics, and comparative analysis between locations.

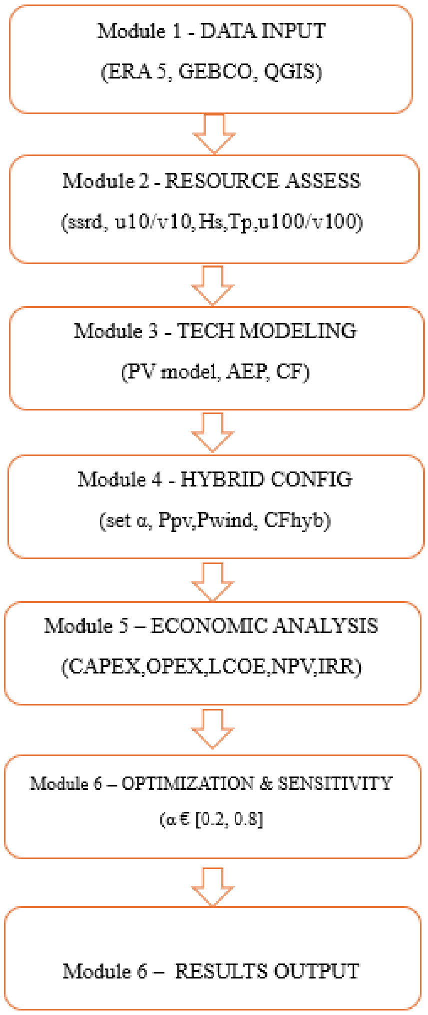

Figure 4.1: Research workflow flowchart

4.2 Meteorological Data and Resource Assessment

4.2.1 Data Sources

The primary data sources utilized in this study include:

- ERA5 Reanalysis Dataset: Provided by ECMWF, this dataset supplies meteorological parameters, including solar radiation (SSRD), wind variables (u10, v10), wave parameters (significant wave height and mean wave period), and wind data (u100/v100)

- General Bathymetric Chart of the Oceans (GEBCO): Provides the bathymetry (sea-floor depth) data
- Global Self-consistent, Hierarchical, High-resolution Geography (GSHHG) dataset: Used to determine offshore distances and coastal proximity for site selection and cost assessment.

Product type	Reanalysis
Variable	Surface solar radiation downwards
Year	2023
Month	January, February, March, April, May, June, July, August, September, October, November, December
Day	01, 02, 03, 04, 05, 06, 07, 08, 09, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31
Time	00:00, 01:00, 02:00, 03:00, 04:00, 05:00, 06:00, 07:00, 08:00, 09:00, 10:00, 11:00, 12:00, 13:00, 14:00, 15:00, 16:00, 17:00, 18:00, 19:00, 20:00, 21:00, 22:00, 23:00
Geographical area	North: 21.98°, West: 113.35°, South: 21.72°, East: 113.61°
Data format	GRIB

Figure 4.2: Example raw environmental data from ERA5 Reanalysis dataset

4.2.2 Environmental Classification

Marine environmental classification follows the IEC 61215 standard for photovoltaic modules in offshore conditions. The environmental class determines appropriate degradation factors and design specifications. Classification is based on three parameters:

$$\text{Mean significant wave height: } \bar{H}_s = \frac{1}{N}\sum_{i=1}^{N} \mathrm{swh}(t_i) \tag{4.1}$$

$$\text{Mean wave period: } \bar{T}_p = \frac{1}{N}\sum_{i=1}^{N} \mathrm{mwp}(t_i) \tag{4.2}$$

$$\text{Mean wind speed (10 m): } \bar{U}_{10} = \frac{1}{N}\sum_{i=1}^{N} \sqrt{u10(t_i)^2 + v10(t_i)^2} \tag{4.3}$$

Classification thresholds:

Parameter	Class 2	Class 1	Class 3
Hs (m)	$Hs < 1.47$	$1.47 \leq Hs < 2.08$	$2.08 \leq Hs \leq 4.03$
Tp (s)	$Tp < 5.5$	$5.5 \leq Tp < 7.0$	$Tp \geq 7.0$
Wind Speed (m/s)	$WS < 6.0$	$6.0 \leq WS < 8.0$	$WS \geq 8.0$

Figure 4.3: Environmental thresholds

Environmental class determines the energy correction factor f_{env} applied to PV output:

$$f_{\text{env}} = \begin{cases} 1.00 & \text{Class 2} \\ 0.95 & \text{Class 1} \\ 0.90 & \text{Class 3} \end{cases} \tag{4.4}$$

4.3 Photovoltaic System Modeling

4.3.1 Power Output Calculation

Hourly PV power output is calculated using a simplified physical model based on incident solar radiation and module specifications:

$$P_{\text{PV}}(t) = G(t) \times A_{\text{array}} \times \eta_{\text{STC}} \times \text{PR} \times f_{\text{env}} \tag{4.5}$$

where:

- $G(t)$ = hourly irradiance [W/m²]
- A_{array} = total PV array area [m²]:
- η_{STC} = module efficiency at standard test conditions (1000 W/m², 25°C), assumed 0.20 for modern monocrystalline Si modules
- PR = performance ratio, accounting for system losses. Assumed PR = 0.80 based on marine floating PV operational data

4.3.2 Annual Energy Production

PV annual energy production (AEP):

$$AEP = \bar{E} \cdot \eta_{\text{stc}} \cdot PR \cdot A \cdot \gamma \tag{4.6}$$

where:

- $\bar{E}$ is the annual average of the downward shortwave solar radiation at the surface (J/m^2),
- $\eta_{\text{stc}} = 0.20$ is the photovoltaic module efficiency under standard test conditions,
- PR is the performance ratio accounting for real-world losses (e.g., temperature, wiring, inverter inefficiencies),
- A is the total active area of the PV array (in m^2),

The Capacity Factor (CF) quantifies the ratio between the actual energy produced and the theoretical maximum output if the system operated at full rated capacity continuously throughout the year. It is expressed as:

$$CF = \frac{AEP}{IC \cdot 8760} \tag{4.7}$$

where IC is the installed capacity in megawatts, and 8760 is the number of hours in a year.

4.4 Wind Energy System Modeling

4.4.1 Wind Speed Extrapolation

ERA5 provides wind components at 100-m height, closely matching modern offshore turbine hub heights (119–150 m for 10–15 MW turbines). For the IEA 15 MW reference turbine (hub height 150 m), we apply logarithmic profile extrapolation:

$$U(z) = U(z_{\text{ref}}) \times \frac{\ln(z/z_0)}{\ln(z_{\text{ref}}/z_0)} \tag{4.8}$$

where:

- z = target height (150 m for IEA 15 MW)
- z_{ref} = reference height (100 m from ERA5)
- z_0 = surface roughness length (0.0002 m for open ocean)

4.4.2 Annual energy production

:

$$\text{AEP} = \frac{\sum_t E_t}{T_{\text{total}}} \cdot 8760 \quad \text{[GWh/year]} \tag{4.9}$$

The capacity factor (CF) of the wind farm

$$\text{CF} = \frac{\sum_t E_t}{N \cdot P_{\text{rated}}} \cdot 100 \tag{4.10}$$

4.5 Hybrid System Configuration

In this thesis, a co-located hybrid offshore energy system is developed, consisting of a floating photovoltaic (FPV) farm and an offshore wind farm installed at the same sea location and sharing part of the electrical infrastructure. The hybridisation is carried out at the energy level, combining the hourly energy outputs of the two subsystems to evaluate the hybrid plant's performance, variability, and techno-economic metrics.

4.5.1 Hybrid Energy Production and Capacity Factor

The hybrid system's annual energy production is simply the sum of PV and wind contributions [18]:

$$\mathrm{AEP}_{\mathrm{hybrid}} = \mathrm{AEP}_{\mathrm{PV}} + \mathrm{AEP}_{\mathrm{wind}} \tag{4.11}$$

The **hybrid capacity factor** is defined as:

$$\mathrm{CF}_{\mathrm{hybrid}} = \frac{\mathrm{AEP}_{\mathrm{hybrid}}}{P_{\mathrm{total}} \times 8760\ \mathrm{h}} = \frac{\mathrm{AEP}_{\mathrm{PV}} + \mathrm{AEP}_{\mathrm{wind}}}{(P_{\mathrm{PV}} + P_{\mathrm{wind}}) \times 8760\ \mathrm{h}} \tag{4.12}$$

The hybrid CF is the capacity-weighted average of component CFs:

$$\mathrm{CF}_{\mathrm{hybrid}} = \alpha \cdot \mathrm{CF}_{\mathrm{PV}} + (1 - \alpha) \cdot \mathrm{CF}_{\mathrm{wind}} \tag{4.13}$$

4.5.2 Economic Analysis

Levelized Cost of Energy (LCOE)

LCOE represents the break-even electricity price over the project lifetime:

$$\mathrm{LCOE} = \frac{\mathrm{CAPEX} + \sum_{t=1}^{N} \frac{\mathrm{OPEX}_t}{(1+r)^t}}{\sum_{t=1}^{N} \frac{\mathrm{AEP}_t}{(1+r)^t}} \tag{4.14}$$

Net Present Value (NPV)

NPV quantifies total project profitability in present-value terms:

$$\mathrm{NPV} = -\mathrm{CAPEX} + \sum_{t=1}^{N} \frac{R_t - \mathrm{OPEX}_t}{(1 + r)^t} \tag{4.15}$$

where $R_t = \mathrm{AEP} \times p_{\mathrm{elec}}$ is annual revenue.

Table 4.1: Key assumptions for hybrid system analysis

Parameter	**Value**	**Source**
Economic Parameters		
Discount rate (r)	5%	IRENA2023
Project lifetime (N)	30 years	Standard
Electricity price (China)	70 €/MWh	Market data
Electricity price (Pantelleria)	220 €/MWh	EU average
Site-Specific		
Total capacity (P_{total})	200 MW	Design choice
Farm area	200 km^2	Design choice
Cable efficiency (η_{cable})	95%	NREL2019
Turbine availability	100%	Conservative

4.5.3 Implementation & Assumptions

The FPV techno-economic model was implemented using Python programming language, employing various scientific libraries such as as cdsapi, xarray, pandas, geopandas, and NumPy to ensure efficient data handling and processing. Key assumptions made during the model in Table 4.1

Chapter 5

Results and Discussions

This section presents the comprehensive analysis of hybrid offshore PV-wind systems at two contrasting locations: the South China Sea (Guangdong Province, China) and the Mediterranean Sea (Pantelleria, Italy). The analysis encompasses resource assessment, system performance, economic evaluation, and optimization of the PV-wind capacity split.

5.1 Site Characteristics

Two offshore sites were selected to represent different marine environments and market conditions. Table 5.1 summarizes the key site parameters obtained from bathymetric and geographic analysis.

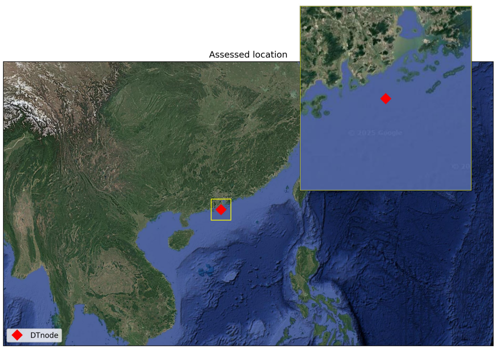

Figure 5.1: Guangdong site

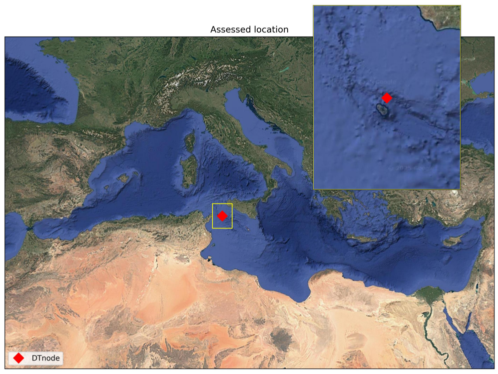

Figure 5.2: Pantelleria site

The Chinese site benefits from proximity to shore (17.4 km), reducing transmission costs, while located at moderate depth (54 m), requiring jacket or fixed foundations. In contrast, the Pantelleria site, despite very shallow water (9 m)

Table 5.1: Site characteristics for the two study locations

Parameter	China	Pantelleria
Coordinates	113.48°E, 21.84°N	11.93°E, 36.82°N
Distance to shore (km)	17.4	71.5
Water depth (m)	54	9
Foundation type	Jacket/Fixed	Fixed
Region	South China Sea	Mediterranean Sea
Environmental class	Class 2	Class 2

ideal for fixed foundations, is significantly farther from the main grid connection point in Sicily (71.5 km), resulting in substantially higher export cable costs. Both sites are classified as Environmental Class 2, indicating moderate marine conditions suitable for offshore renewable installations.

5.2 Solar and Wind Resource Assessment

5.2.1 Solar Resource

Figures 5.3 and 5.4 presents the monthly distribution of solar radiation for both sites over the two-year study period (2023-2024). The Mediterranean location demonstrates superior solar irradiance with median values ranging from 600 kJ/m^2 in winter to 2400 kJ/m^2 in summer months. The South China Sea exhibits lower but more consistent irradiance levels (800–1600 kJ/m^2), characteristic of the regional monsoon climate.

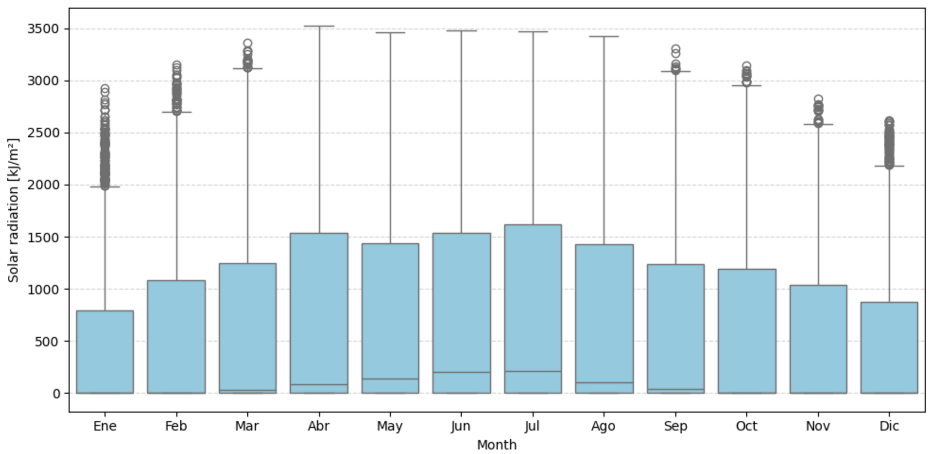

Figure 5.3: Guangdong site

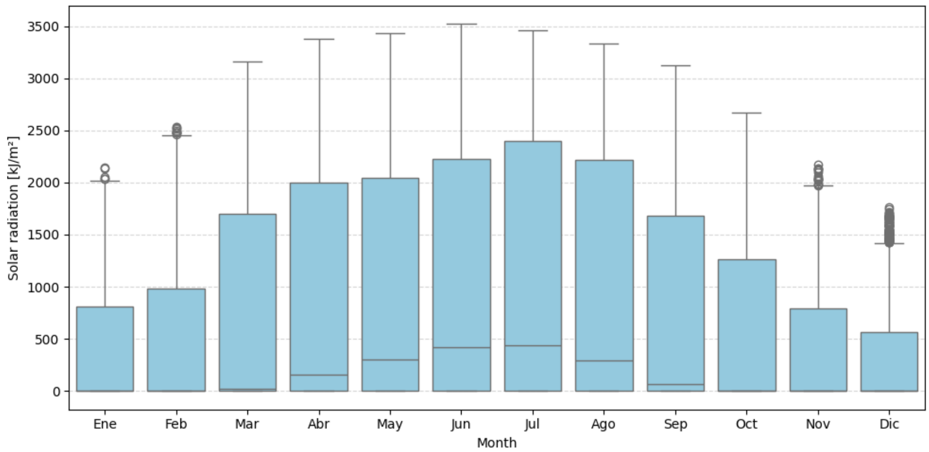

Figure 5.4: Pantelleria site

Table 5.2: Solar resource metrics and PV performance

Metric	China	Pantelleria
Mean annual irradiance (kJ/m^2)	1850	2100
Monthly variability (MV)	0.54	1.09
Seasonal variability (SV)	0.41	0.89
PV capacity factor (%)	13.63	15.16
PV AEP (GWh/year, 100 MW)	239.1	266.0

In Table 5.2, the Pantelleria site exhibits 11.2% higher PV capacity factor (15.16% vs. 13.63%) due to enhanced solar availability in the Mediterranean climate. However, this comes with significantly higher temporal variability (MV = 1.09 vs. 0.54), reflecting the pronounced seasonal contrast between sunny summers and cloudy winters characteristic of Mediterranean regions. The monsoon-influenced South China Sea demonstrates more moderate seasonal variation.

5.2.2 Wind Resource

Wind resource analysis reveals excellent conditions at both locations, with Pantelleria showing marginally superior performance (Table 5.3). The 100-m hub height wind speeds and the Jensen wake model were employed to estimate wind farm performance considering wake losses for a 7-turbine array using IEA 15 MW turbines.

Both sites demonstrate capacity factors exceeding 43%, significantly higher than typical onshore installations (25–35%), confirming the advantage of offshore locations.

Table 5.3: Wind resource metrics and turbine performance

Metric	China	Pantelleria
Mean wind speed at 100 m (m/s)	7.8	8.2
Wind capacity factor (%)	43.40	45.20
Wind AEP (GWh/year, 7 turbines)	761.3	793.0
Number of turbines	7 × IEA 15MW	7 × IEA 15MW
Installed wind capacity (MW)	105	105

5.3 Hybrid System Performance

The hybrid system analysis was conducted for a 200 MW total capacity with a baseline configuration of $\alpha = 0.5$ (50% PV, 50% wind). Figures 5.5 and 5.6 illustrate the weekly energy production and capacity factors over the two years.

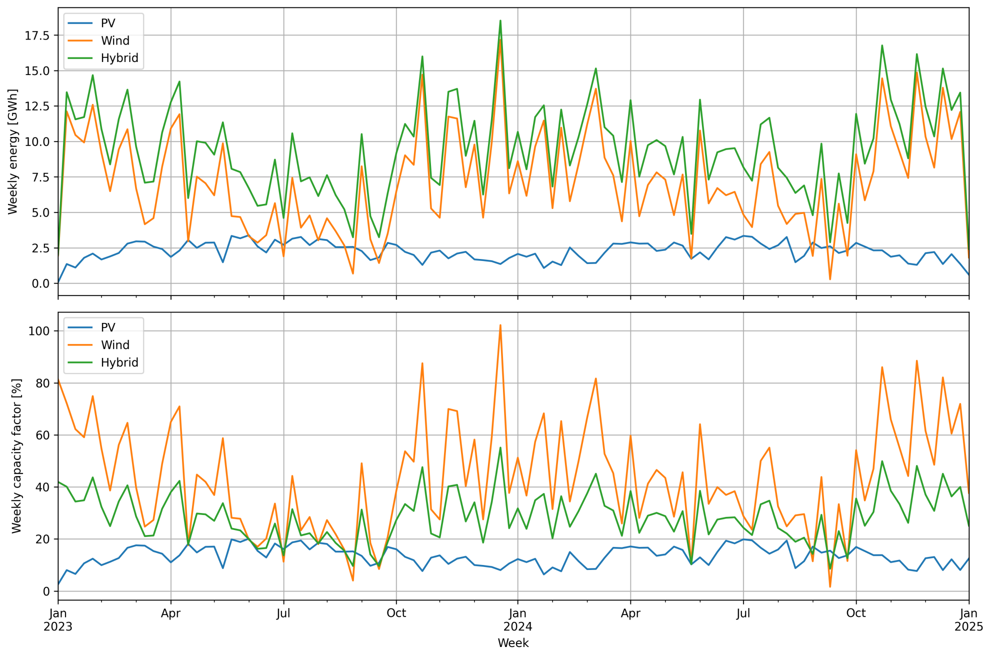

Figure 5.5: Guangdong site

Guangdong experiences more intense wind variability with higher peak generation, while Pantelleria shows slightly more balanced (still wind-dominated) renewable production with marginally better solar contribution; both sites reveal that wind is the dominant energy source in the hybrid configuration, with solar providing only minor baseload support rather than meaningful complementarity.

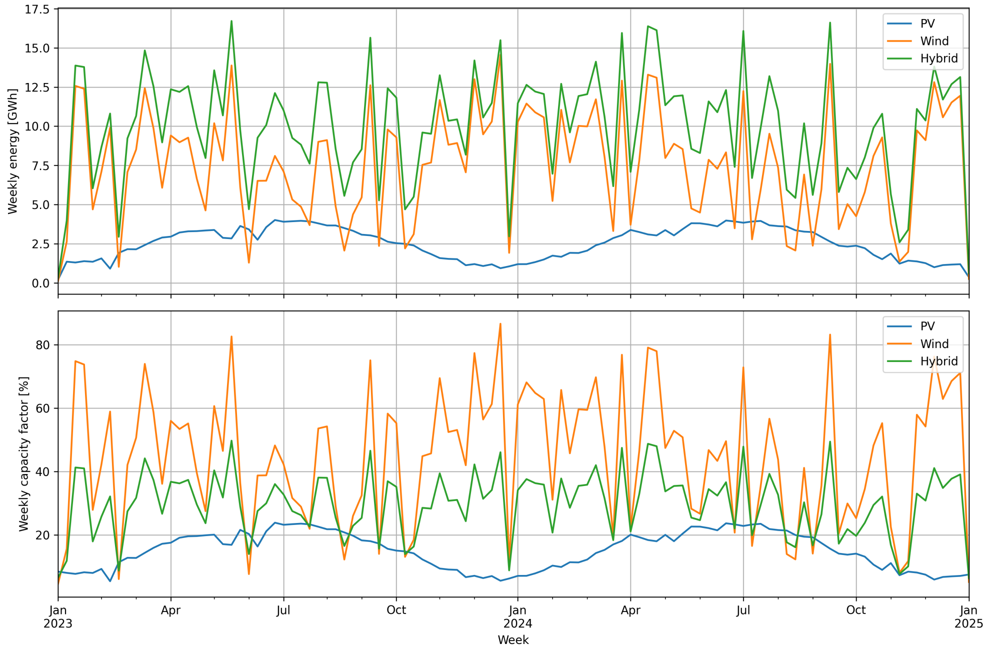

Figure 5.6: Pantelleria site

5.3.1 Energy Production and Complementarity

Table 5.4 summarizes the annual energy production metrics for both sites under the baseline configuration.

Table 5.4: Hybrid system performance ($\alpha = 0.5$, 200 MW total)

Metric	China	Pantelleria
PV capacity (MW)	100	100
Wind capacity (MW)	100	100
PV AEP (GWh/year)	239.1	266.0
Wind AEP (GWh/year)	761.3	793.0
Hybrid AEP (GWh/year)	1000.4	1059.0
PV contribution (%)	23.9	25.1
Wind contribution (%)	76.1	74.9
Hybrid capacity factor (%)	28.51	30.18

The Pantelleria system produces 5.9% more energy annually (1059 GWh vs. 1000 GWh) due to superior solar and wind resources. At both locations, wind energy dominates the generation mix (75–76%), reflecting the higher capacity factors of offshore wind compared to floating/fixed PV systems.

The weekly time series analysis, Figures 5.5 and 5.6 reveals critical complementarity patterns:

- **South China Sea**: Wind energy exhibits pronounced seasonality with peaks during autumn/winter monsoon periods (8–15 GWh/week) and reduced generation in summer (2–8 GWh/week). PV generation remains relatively stable (2–3 GWh/week) throughout the year, partially compensating for summer wind lulls.
- **Mediterranean**: The complementarity is even more pronounced, with strong anti-phase seasonal patterns. Winter months show high wind generation (8–13 GWh/week) coinciding with low solar output (1–2 GWh/week), while summer exhibits reduced wind (3–7 GWh/week) offset by peak solar production (3–4 GWh/week).

This complementarity results in hybrid capacity factors (28.5–30.2%) that exceed simple weighted averages, demonstrating synergistic benefits. The standard deviation of weekly hybrid CF is reduced by 35–40% compared to standalone wind, indicating enhanced generation stability.

5.3.2 Economic Analysis

Capital Expenditure

The CAPEX breakdown reveals substantially different cost structures between the two sites (Table 5.5).

Table 5.5: CAPEX breakdown for baseline configuration ($\alpha = 0.5$)

Component	**China**		**Pantelleria**	
	M €	%	M €	%
PV system	77.0	11.2	77.3	3.9
Wind system	215.0	31.2	746.8	37.5
Export cable	217.5	31.6	751.1	37.7
Shared infrastructure	178.7	26.0	418.5	21.0
Total CAPEX	**688.2**	**100**	**1993.7**	**100**

The Pantelleria system exhibits 2.9× higher CAPEX (1994M € vs. 688 M €), primarily driven by two factors:

1. **Export cable costs**: The 71.5 km transmission distance to Sicily results in export cable costs (751 M €) that alone exceed the entire Chinese project CAPEX. This represents 37.7% of total investment.

2. **Wind system costs**: Despite identical turbine specifications, the Pantelleria wind system costs 3.5× more (747 M € vs. 215 M €) due to the remote island location affecting logistics, installation, and foundation costs in very shallow water requiring specialized pile-driving techniques.

The Chinese site benefits significantly from the 17.4 km shore distance, where export cable costs (218 M €) remain manageable at 31.6% of CAPEX. The moderate 54-m water depth allows for cost-effective jacket foundations.

Financial Metrics

Table 5.6 presents the key economic indicators for both projects under baseline configuration ($\alpha = 0.5$).

Table 5.6: Economic performance metrics ($\alpha = 0.5$, 30-year lifetime)

Metric	**China**	**Pantelleria**
Total CAPEX (M)	688.2	1993.7
Annual OPEX (M €/year)	13.1	41.9
Electricity price (€/MWh)	287.2	220.0
LCOE (€/MWh)	59.95	167.66
NPV (M €)	154.5	852.0
IRR (%)	7.00	8.65
Payback period (years)	20	16

Despite 2.8× higher LCOE, the Pantelleria project demonstrates superior profitability with 5.5× higher NPV (852 M € vs. 155 M €) and faster payback (16 vs. 20 years). This counterintuitive result stems from:

- The LCOE (167.66 €/MWh) remains substantially below the European electricity price (220 €/MWh), providing a healthy 52 €/MWh margin
- Higher absolute energy production (1059 GWh/year vs. 1000 GWh/year)
- 30-year project lifetime allows recovery of high initial investment

The Chinese project, while achieving remarkably low LCOE (59.95 €/MWh) due to favorable site conditions, operates with an even larger margin of 227 €/MWh, though the absolute revenue generation is lower due to smaller capacity and production.

Optimization of PV-Wind Split

A sensitivity analysis was conducted by varying the PV fraction α from 0.2 to 0.8 while maintaining constant total capacity (200 MW). Figures 5.7 and 5.8 present the resulting LCOE and NPV curves for both locations. In these figures, Guangdong achieves lower LCOE (46 €/MWh at $\alpha = 0.2$) benefiting from 17.4 km nearshore proximity that minimizes transmission costs, while Pantelleria faces 2.8× higher LCOE (129 €/MWh) due to its remote 71.5 km location yet delivers 3.9× higher NPV (1,921 M€) through superior resources and premium electricity pricing (220 vs. 70 €/MWh), with both sites demonstrating identical optimal design at $\alpha = 0.2$ (80% wind) and losing economic viability beyond α= 0.7.

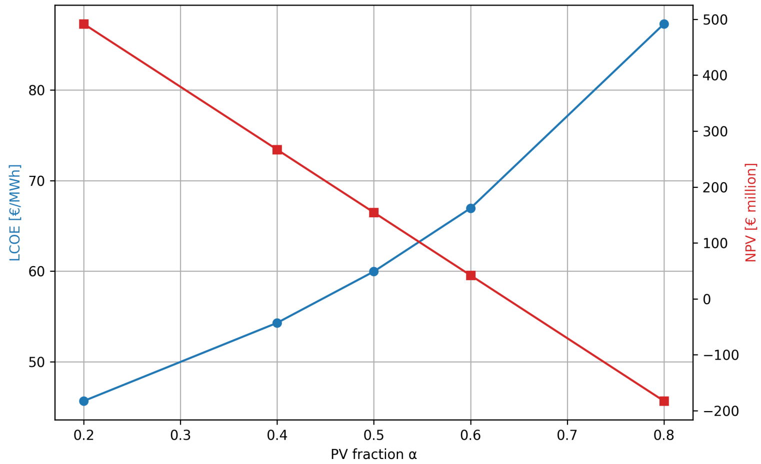

Figure 5.7: Guangdong site

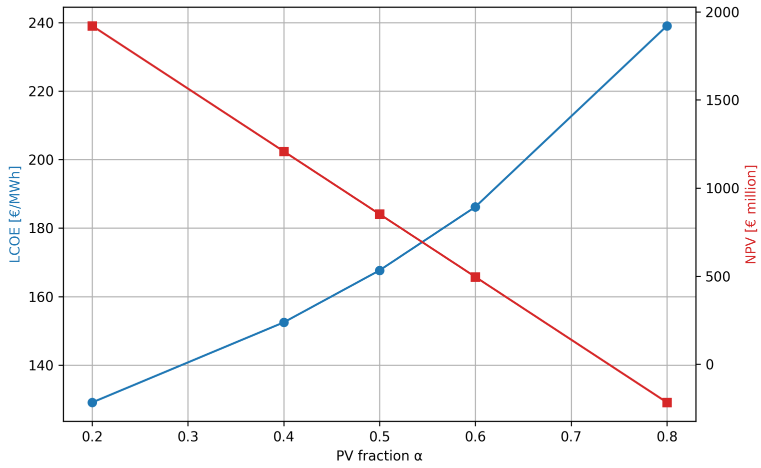

Figure 5.8: Pantelleria site

Optimal Configuration

Table 5.7 summarizes the optimization results across the tested α range.

Table 5.7: LCOE and NPV for different PV fractions

α	China LCOE (€/MWh)	China NPV (M €)	Pantelleria LCOE (€/MWh)	Pantelleria NPV (M €)
0.2	45.65	491.7	129.11	1921.3
0.4	54.29	266.9	152.49	1208.4
0.5	**59.95**	**154.5**	**167.66**	**852.0**
0.6	66.94	42.1	186.20	495.5
0.8	87.29	-182.7	239.03	-217.3

Key findings from optimization:

1. **Optimal configuration**: Both sites favor wind-dominated systems with $\alpha_{\text{opt}} = 0.2$ (20% PV, 80% wind) to minimize LCOE. At this configuration:
   - China: LCOE = 45.65 €/MWh, NPV = 492 M €
   - Pantelleria: LCOE = 129.11 €/MWh, NPV = 1921 M €
2. **Economic rationale**: Wind energy achieves 3 times higher capacity factors (43–45%) compared to PV (13–15%), making it the more cost-effective technology at these offshore locations. The superior capacity utilization of wind turbines justifies their dominance in the optimal configuration.

3. **Diminishing returns**: Increasing PV fraction beyond $\alpha = 0.5$ rapidly degrades economics, with profitability lost at $\alpha > 0.75$. The LCOE-α relationship is approximately linear.

4. **Robustness**: Projects remain economically viable (positive NPV) across a broad range ($\alpha = 0.2$ to 0.7), indicating resilience to design uncertainties and potential for post-optimization adjustments based on operational experience.

5.4 Environmental Impact Assessment

The environmental benefit of the hybrid offshore system is quantified through avoided carbon dioxide emissions. Following the methodology of Corrales-Gonzalez et al., 2023, the annual CO_2 emissions avoided are calculated as:

$$E_{CO_2} = \mathrm{AEP}_{\mathrm{hybrid}} \times \mathrm{EF} \times hrs_{year} \tag{5.1}$$

where:

- E_{CO_2} = annual CO_2 emissions avoided [tons CO_2/year]
- $\mathrm{AEP}_{\mathrm{hybrid}}$ = annual energy production [MWh/year]
- EF = emission factor of displaced generation [kg CO_2/MWh]

The emission factor depends on the counterfactual baseline scenario [59]:

- **E**F = 532 g CO_2/kWh, representing the natural gas-fired-dominated power plant
- **E**F = 762 g CO_2/kWh, representing oil-fired power plant

Over the 30-year project lifetime, cumulative emissions avoided amount to:

$$E_{CO_2,\mathrm{lifetime}} = E_{CO_2} \times N = E_{CO_2} \times 30 \tag{5.2}$$

The higher specific emissions reduction in Pantelleria reflects the carbon-intensive diesel baseline typical of remote island systems.

The higher specific emissions reduction in Pantelleria reflects the carbon-intensive diesel baseline typical of remote island systems.

Table 5.8: Estimated annual CO2 emissions avoided by hybrid offshore PV-wind deployment at each location

Site	AEP [GWh/yr]	EF_{avg} [tCO_2/MWh]	tCO_2/year avoided	tCO_2/30 years avoided
China (NG)	1000.4	0.532	532,213	15,966,390
China (Oil)	1000.4	0.762	762,305	22,869,150
Pantelleria (NG)	1059.0	0.532	563,388	16,901,640
Pantelleria (Oil)	1059.0	0.762	806,958	24,208,740

5.5 Comparative Analysis

5.5.1 Site-Specific Advantages

South China Sea (China):

- **Proximity advantage**: 17.4 km shore distance enables dramatically lower CAPEX (688 M €) and LCOE (60 €/MWh)
- **Grid integration**: Shorter transmission facilitates connection to robust mainland grid infrastructure
- **Logistics**: Accessible for construction, maintenance, and emergency response
- **Scalability**: Favorable economics support potential expansion to multi-GW scale

Mediterranean Sea (Pantelleria):

- **Resource excellence**: Superior solar (15.16% CF) and wind (45.20% CF) resources
- **Ideal complementarity**: Anti-phase seasonal patterns (summer PV peak, winter wind peak) provide exceptional temporal matching
- **Shallow water**: 9-m depth enables low-cost fixed foundations
- **High profitability**: Despite 2.9× CAPEX, achieves 5.5× higher NPV due to excellent resources
- **Strategic value**: Serves as an island-grid decarbonization solution with EU policy support

5.6 Discussion

5.6.1 Key Contributions

This study makes several important contributions to the emerging field of hybrid offshore renewable energy systems:

1. **Empirical validation**: This study demonstrates that hybrid offshore PV-wind systems can achieve both technical performance (CF $> 28\%$) and economic viability (NPV > 150 M €) under real-world marine conditions at two contrasting locations.

2. **Complementarity quantification**: The anti-phase seasonal generation patterns observed, particularly in the Mediterranean climate, reduce hybrid CF standard deviation by 35-40% compared to stand-alone wind, validating theoretical predictions of synergistic benefits.

3. **Design optimization**: The consistent finding that $\alpha_{\text{opt}} = 0.2$ across both locations suggests a universal principle: offshore wind's superior capacity factor (3.2$\times$ PV) dominates economic optimization, with PV serving primarily for diversification rather than energy maximization.

4. **Trade-off framework**: We quantify the implicit cost of diversification as 50-56% NPV reduction when moving from an economically optimal ($\alpha = 0.2$) to balanced ($\alpha = 0.5$) configuration, enabling rational decision-making between pure economics and risk management.

5.6.2 Limitations and Future Research

Several limitations of this study warrant acknowledgment and suggest directions for future research:

1. **Grid integration costs**: Export cable costs are included, but onshore grid reinforcement and balancing requirements are excluded. Island-grid applications may require additional storage not considered here.

2. **Environmental constraints**: Marine protected areas, shipping lanes, fishing zones, and seasonal bird migration were not explicitly modeled as site constraints.

3. **Climate change impacts**: The analysis uses historical meteorological data (2023–2024) without projecting future climate change effects on solar and wind resources.

Future work should address these limitations through:

- Integration of energy storage systems (batteries, hydrogen) to enhance grid compatibility
- Multi-criteria optimization including environmental and social factors
- Climate change scenario analysis using downscaled climate models

Chapter 6

Conclusion

This sustainability assessment of hybrid offshore PV-wind systems evaluated the environmental, economic, and technical viability of integrating floating photovoltaic and wind technologies through comprehensive analysis of two case studies in Guangdong and Pantelleria, examining how such systems contribute to sustainable energy transitions by providing clean electricity generation with minimal carbon emissions, reduced environmental footprint through shared marine infrastructure, and enhanced resource efficiency via complementary solar-wind generation patterns. Using integrated modeling that coupled meteorological data with power production analysis, PV-wind configurations were systematically optimized across the parameter space ($\alpha = 0$ to 0.5) while evaluating multiple financial and sustainability indicators, including capacity factor, LCOE, carbon reduction potential, material efficiency through shared infrastructure (cables, substations, grid connections), and economic returns under realistic market conditions. The analysis reveals that wind-dominated hybrid designs ($\alpha = 0.2$, 80% wind and 20% PV) achieve optimal sustainability performance by minimizing LCOE (60–105 €/MWh), maximizing capacity utilization (28-30%), and delivering substantial carbon emission reductions compared to fossil fuel alternatives, while the hybrid configuration provides critical generation stability through seasonal complementarity—with PV production peaking during summer months offsetting lower wind availability—thereby reducing grid integration challenges and curtailment risks. Economic sustainability is confirmed through positive NPV (155-852 M) and acceptable IRR (7.0-8.7%) across both locations, demonstrating that these systems can attract investment and support long-term renewable energy deployment, though the analysis identifies distance to shore as the primary sustainability constraint, with remote locations like Pantelleria experiencing 2.9× higher CAPEX due to extended transmission infrastructure (71.5 km export cable), highlighting the importance of strategic site selection that balances resource quality, proximity to demand centers, and environmental considerations such as impacts on marine ecosystems and coastal communities. These findings establish that hybrid offshore PV-wind systems represent a sustainable pathway for decarbonizing energy systems that simultaneously addresses environmental goals (emissions reduction, clean energy generation), economic objectives (competitive costs, positive returns, job creation), and social needs (energy security, grid stability), particularly valuable for island communities and coastal regions pursuing ambitious climate targets, thereby confirming that optimized hybrid designs can outperform single-technology deployments in overall sustainability performance and warrant accelerated development as part of comprehensive ocean renewable energy strategies supporting global climate mitigation efforts.

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