


SUSTAINABLE SOLUTIONS AT TIMES OF TRANSITION ⋄ SUST.
NISYROS, 15-17.09.2025

BOOK OF PAPERS

S3. Sustainable Islands

CONTENTS

SIMULATION MODEL FOR SUSTAINABLE ENERGY PLANNING FOR DONOUSA ISLAND

Spiros Alexopoulos, Pedro Leandro

[1]Solar-Institut Jülich of the FH Aachen University of Applied Sciences, Jülich, Germany

[2]FH Aachen University of Applied Sciences, Jülich, Germany

e-mail: alexopoulos@sij.fh-aachen.de

ABSTRACT

A new energy project has been developed for Donousa, the northernmost island of the Cyclades in the Aegean Sea, which has fewer than 200 inhabitants. The project aims to generate electricity exclusively from renewable energy sources (RES) combined with energy storage systems.

This new energy plan aligns with the clean energy transition framework for islands and seeks to replace the island's current reliance on conventional fuels, primarily diesel generators, with a more sustainable and resilient energy system.

The authors selected an appropriate software able to deal with demand time series and weather data and used it for the optimization and creation of energy concepts for the island of Donousa including different energy systems.

The study aims to develop optimized energy concepts for the island of Donousa to support its shift toward a more sustainable and self-sufficient energy system. The main challenge addressed is the island's current dependence on conventional energy sources and limited infrastructure.

The authors applied integrated simulation models to compare the current energy supply with alternative scenarios, using a novel, data-driven approach suited to small island conditions. The simulation enables the calculation among others of the annual energy yield, of the contribution of different energy suppliers and the saving of carbon dioxide emissions.

Keywords: energy transition, remote island, renewable energy, clean energy, simulation model, self-sufficient energy island, storage system

1. INTRODUCTION

In Greece, there are a considerable number of remote islands, most of which are not interconnected with the mainland electricity grid of Greece. It is very common that such remote places with high potential for usage of renewable energy systems aren't being fully taken advantage of. On the contrary, the Public Power Corporation (PPC) uses autonomous thermal power plants to meet the needs of the Aegean islands [1]. These plants require large quantities of either light (diesel) or heavy (fuel oil) oil to operate, with correspondingly high carbon dioxide emissions.

A new energy project has been developed for Donousa, a small island in the Aegean Sea, which has fewer than 200 inhabitants. The island takes its name from the wild waves that rock it and is the easternmost tip of the Small Cyclades [2].

During the recent years, several small and medium scale PV parks have been installed in the majority of remote islands [3]. Due to their small size and distributed character, the local grid operator is obliged to absorb their production, thus limiting the corresponding wind power absorbance. Also for the Donousa island the new energy concept considers the installation of PV and additionally of wind systems.

The project aims to generate electricity exclusively from these two renewable energy sources (RES) combined with energy storage systems.

2. METHODOLOGY

The first step was to describe the current situation of the energy production at the island Donousa.

In the second step the renewable energy potential of the island was analysed in detail in order to find the most appropriate energy sources for the development of the new concepts.

In the next step two optimized energy concepts were developed for the island of Donousa to support its shift toward a more sustainable and self-sufficient energy system. The main challenge addressed is the island's current dependence on conventional energy sources and limited infrastructure.

The authors applied integrated simulation models to compare the current energy supply with alternative scenarios, using a novel, data-driven approach suited to small island conditions. The simulation enables the calculation among others of the annual energy yield, of the contribution of different energy suppliers and the saving of carbon dioxide emissions.

2.1. Description of current situation

The main source being used in the island of Donousa are the diesel generators which provide a consistent source of power, but they are costly to operate and maintain, and their emissions contribute to air pollution and climate change.

Table 1 shows a list of the available and running diesel generators on Donousa Island.

Table 1: List of diesel generators on Donousa Island as described in [4]

No.	Generator	Capacity [kW]
1	MAN D2566ME	80
2	MAN D2566ME	80
3	MAN D2566ME	80
4	VOLVO TAD 1345GE	250
5	VOLVO TAD 1345GE	250
6	VOLVO TAD 740GE	200

It is important to note that the six generators with a total capacity of 940 kW can produce more than the required demand of the island. These generators are switched on and off according to the real-time electricity demand.

Figure 1 shows the electricity demand on the island Donousa during the course of the year 2022.

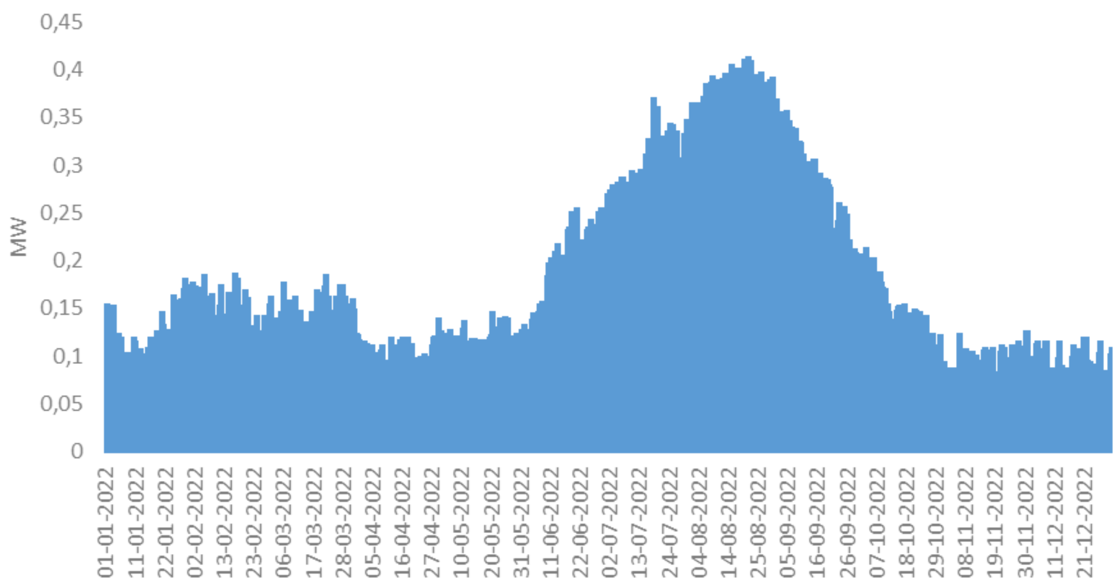


Figure 1: Electricity demand on the island Donousa

A strong seasonal trend in the load curve is clearly visible: while demand remains constant and low at around 0.1–0.2 MW during the winter months, it rises significantly in the summer months, reaching peak values of up to 0.411 MW. This increase in summer is probably due to high tourism activity and increased use of air conditioning. The highest load occurs between July and August, while the lowest electricity demand is recorded in January and December.

This consumption dynamic is crucial for the design of a reliable, self-sufficient energy system, especially with regard to the dimensioning of storage and RES generation capacities.

2.2. Renewable energy potential analysis for Donousa

It is a fact that the vast majority of the remote Aegean and Ionian islands are characterised by a very high solar, but also a remarkable wind potential [5]. The choice of renewable energy technologies is illustrated by a potential analysis which focuses on the location of the island.

Figure 2 shows according to [6] the solar and wind energy potential for Greece.

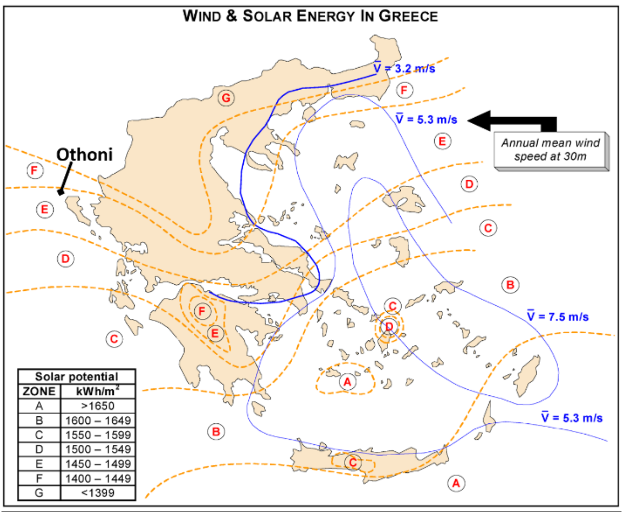


Figure 2: Solar and wind energy potential for Greece, according to [6].

As can be derived from this figure the solar potential for Donousa is very high in Greece with annual solar radiation values of over 1600 kWh/m² and annual mean wind speed at 30 m of 7.5 m/s which is the highest for the Aegean Archipelago [6].

2.3. New concepts for energy production in Donousa

As mentioned in [7] the main difficulty in drawing up an energy plan is that renewable energy production is always linked to storage, as it fluctuates throughout the day and the seasons.

Generating electricity through photovoltaic (solar) and various wind power systems offers a sustainable alternative to conventional energy sources. Over time, these renewable technologies can significantly reduce the island reliance on fossil fuels, helping to lower emissions and promote long-term energy security.

The two new concepts for the island of Donousa envisages a combination of these two types of energy production technologies, as they work well together. In winter, wind speeds are high, so more electricity is produced than wind power, and in summer, solar power is high while wind power is lower, so the two are balanced throughout the year.

As mentioned in [8], to address the issue of limited RES contribution, pilot projects that develop advanced and integrated solutions using energy storage could serve as a model for future efforts. Additionally for energy security, storage is also added to the new energy concepts to ensure that energy is available during the dark phase or in case of problems with the systems.

The aim of comparing two new energy concept variants is to show that there is no single “right” solution for a self-sufficient supply system based on renewable energies. Rather, there are numerous design options and variations, the suitability of which must always be assessed in the context of local conditions, technical feasibility, and economic conditions. A sound ecological and economic assessment is therefore crucial in order to identify the most suitable solution for a sustainable energy system on Donousa.

2.3.1. First concept

The first concept considers a 500 kW_p PV installation together with 3 kites and an electrical battery with a storage capacity of 9 MWh.

The distinctive feature of this concept is the use of Airborne Wind Energy Systems (AWES) instead of conventional wind turbines. Besides their operational advantages, such as altitude variability for adapting to changing wind conditions, kites are significantly easier to transport and install. This characteristic is of particular value in island contexts, where infrastructure and space for erecting large wind turbines are limited, unlike a conventional wind turbine of similar capacity, which would require large-scale infrastructure.

In combination with photovoltaic systems and a battery storage unit (500 kW maximum charge and discharge power), the AWES technology enables continuous electricity supply over diurnal cycles and extended low-generation periods. Photovoltaic modules operate with maximum power point tracking (MPPT), while all generation units are coordinated by an intelligent energy management system that prioritizes sources in real time.

2.3.2. Second concept

The second energy concept envisaged the installation of a single wind turbine with a rated output of 500 kW. The corresponding performance curve of the wind turbine used was determined according to [9] in order to enable a realistic calculation of the wind energy generation. This system is supplemented by a photovoltaic system with 2,000 modules, each with an output of 370 W, corresponding to a total peak output of 740 kW_p. A power storage unit with a capacity of 5,000 kWh is used for the temporary storage of surplus energy. This has a maximum charging and discharging capacity of 500 kW and a minimum state of charge of 10% to extend the battery's service life.

2.4. Simulation model development

Appropriate software was selected and used for the optimisation and creation of energy systems. For the energy study of the island, integrated simulation models were created both for the current total energy supply and for different scenarios of the newly developed energy planning.

The authors used the TOP Energy software, as it has a number of advanced features, which are mentioned in [10]:

- the possibility of carrying out economic and ecological evaluation
- the freedom to design and test new ideas

- the integration of solvers that help to find the right economic, ecological and energy optimum

The authors selected this appropriate software able to deal with demand time series and weather data and used it for the optimization and creation of energy concepts for the island of Donousa including different energy systems.

Figure 3 shows the first concept with new PV arrays, kites and a battery for Donousa island on the left part and the second concept with PV installation and one wind turbine on the right.

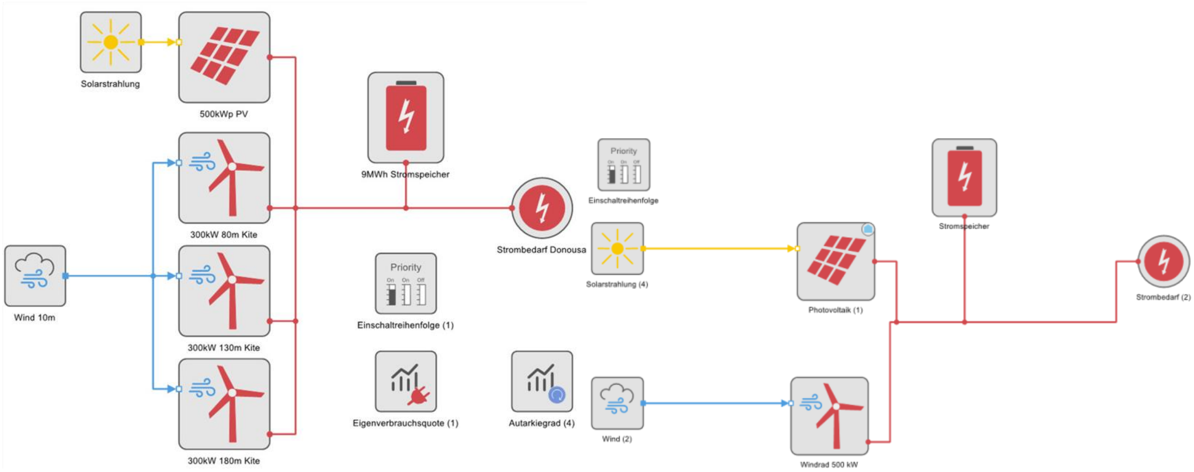


Figure 3: Diagram of the new concepts (left: concept 1, right: concept 2) for Donousa island

Key input variables such as wind speed and solar radiation are represented by corresponding components. The wind data component is linked to the kite components, while the solar radiation component is connected to the photovoltaic system. Both generators feed into the consumer components together – consisting of the electricity storage system and the electricity demand. In addition, the components for calculating key parameters (including self-sufficiency level and self-consumption rate) are also included here.

3. RESULTS

Table 2 shows an overview of the results: the electrical power output for both new energy concepts from RES (solar PV and wind) and the electricity demand for the island of Donousa.

Table 2: Yearly electrical power output from RES and electricity demand of Donousa

Variable	**Concept 1**	**Concept 2**
Electrical power output of the PV system	0.54 GWh	0.30 GWh
Electrical power output of the wind system	0.84 GWh	1.00 GWh
Total power output of RES	1.38 GWh	1.30 GWh
Electricity demand	1.21 GWh	1.21 GWh

As the two new concepts are based entirely on renewable energies, they can save over 800 tonnes of CO_2 per year. However, it should be noted that energy must be used to construct the renewable energy plants, which will most likely also emit CO_2. This fact must therefore ultimately be taken into account when considering the CO_2 savings potential.

The results for concept 1 show that the proposed project achieves full energy autonomy, a self-consumption rate of about 87.9%, and an almost complete reduction of CO_2 emissions during operation (remaining only manufacturing-related emissions). These findings underline the technical feasibility and ecological benefits of the concept.

Figure 4 shows the course of generation and consumption on 15 August.

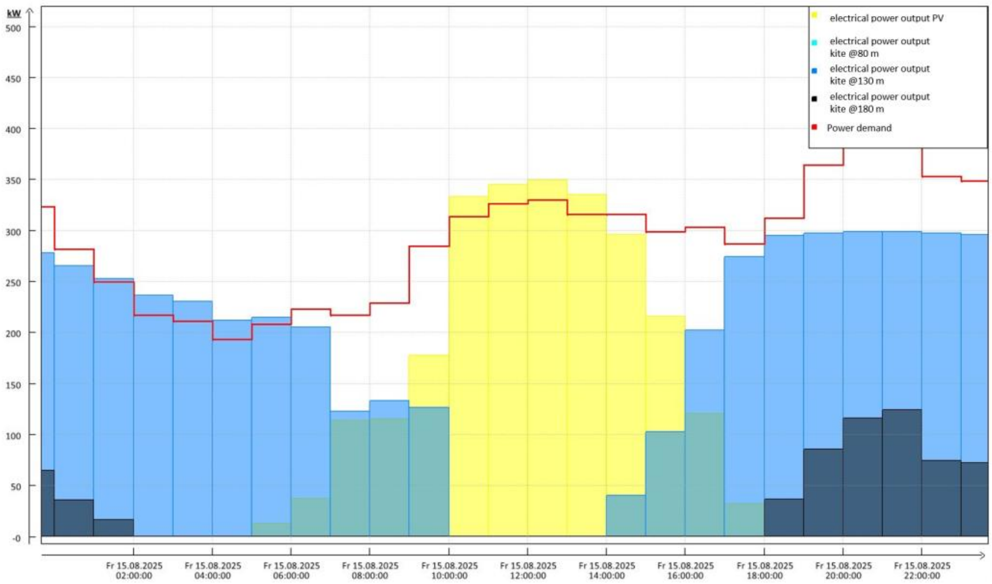


Figure 4: Characteristic summer day for Donousa (results for concept 1)

The red curve represents Donousa's electricity demand, the yellow bars represent PV generation, and the different shades of blue represent the three kites with different working heights.

Consumption rises noticeably in the evening hours. The individual bars for the generators cannot always exceed this. However, when added together, they show the total generation. If this exceeds consumption, the storage unit is charged. If it is below consumption, it is discharged. At midday, it is clear that PV generation dominates. During this phase, the kites are partially regulated, as PV and storage can cover demand independently.

Figure 5 shows the corresponding daily curve for 12 January. Electricity demand here is significantly lower than in summer. In many hours, it is only a third of the summer value.

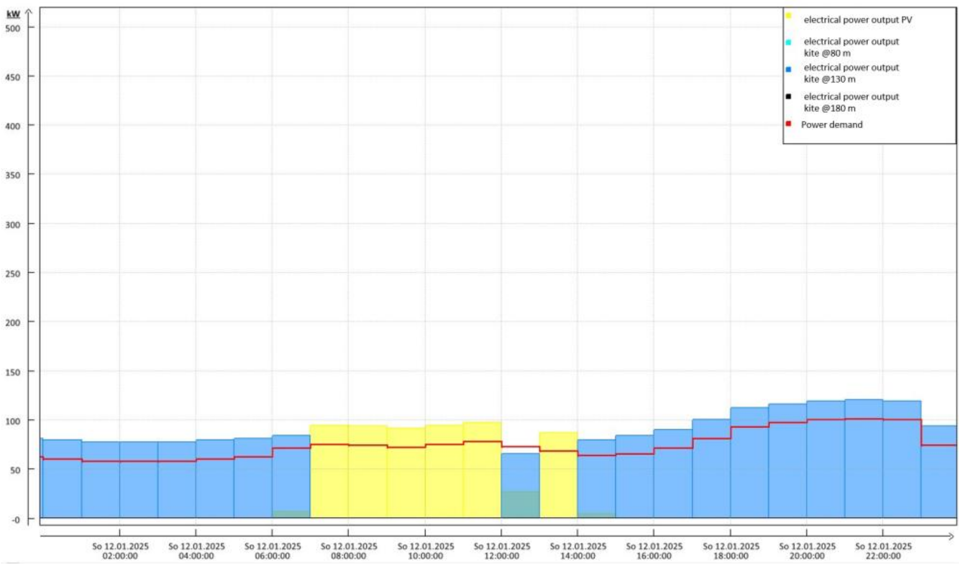


Figure 5: Characteristic winter day for Donousa (results for concept 1)

Generation output is also reduced. On this day, the combination of the PV system and the kite at a height of 130 metres is completely sufficient to cover the electricity demand. In this case, the storage system is charged continuously.

In the second concept, the PV and wind power systems generate a total of 1.3 GWh over the course of the year. The wind power system generates more than three times as much energy as the PV system, and the storage system delivers a total of 120.09 MWh of energy over the course of the year.

The second concept achieves like the first concept an autarky rate of 100% and an own consumption share of 100%.

Figure 6 shows three typical days in summer, which differ greatly from the pattern in winter.

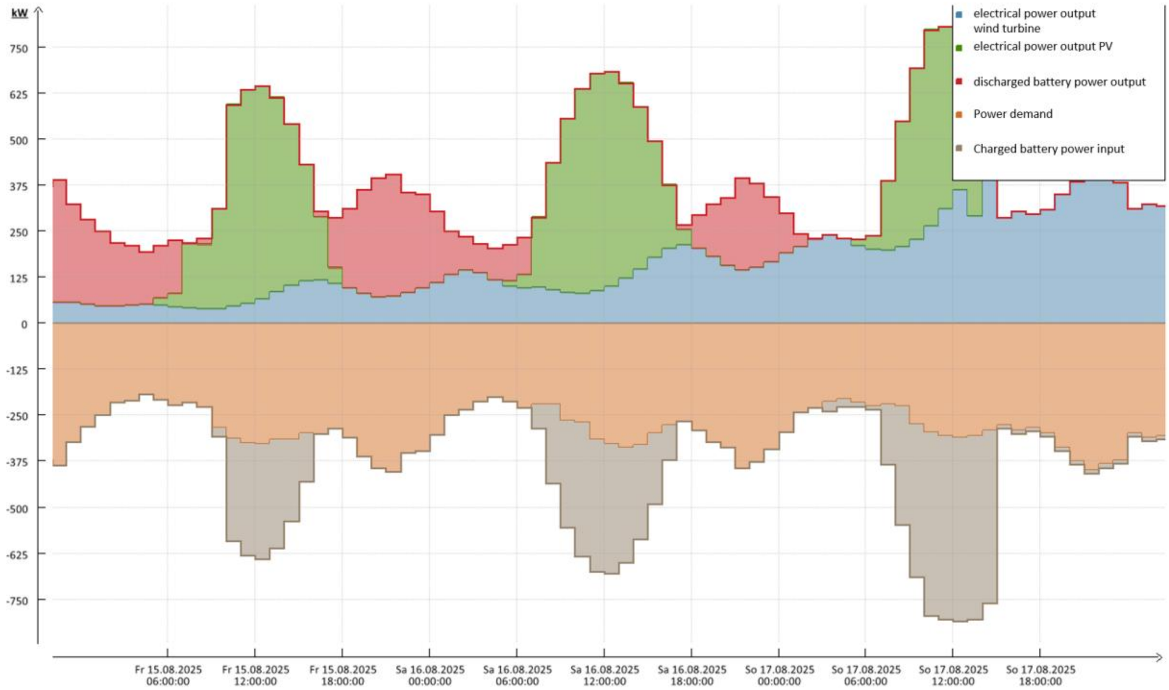


Figure 6: Three characteristic summer days of August for Donousa (results for concept 2)

Although the wind turbine covers a large part of consumption, the PV system generates high amounts of energy at midday with a noticeable parabolic curve. During daytime both on Friday and in the weekend the battery can be charged as both the PV and the wind turbine produce more electricity than needed.

At night, when there is no solar radiation, the storage system takes over a large part of the demand if the wind turbine is unable to cover the entire energy requirement due to calm winds.

4. CONCLUSIONS

Two new energy concepts for the production of electricity on a selected remote Greek island with a population of less than 200 inhabitants has been developed for Donousa in the Aegean Archipelago, using only renewable energy sources (RES).

The electricity demand coverage needs on Donousa are so far covered by the use of conventional fuels with the operation of diesel engines. Taking into account the pressing need to meet the energy needs of Donousa without further use of polluting fuels, the prospects of developing new energy systems on the island, based mainly on the exploitation of the available solar and wind potential and the use of energy storage systems, were explored.

The new energy plan aligns with the clean energy transition framework for islands and seeks to replace the island’s current reliance on conventional fuels, primarily diesel generators, with a more sustainable and resilient energy system.

Further investigations are required to provide a holistic evaluation. Future work should address economic assessments including investment and operational costs, potential downtimes and maintenance requirements, and the integration of local heating and cooling demands since here only the electricity demand was taken into account.. In addition, systematic evaluation of the limitations and possible drawbacks of AWES technology will be necessary to realistically determine its role in future energy systems.

ACKNOWLEDGEMENTS

The authors would like to thank at this point the TOP Energy team for their assistance and software support. The authors would like to thank Dardan Ahmeti and Fouad Ghazzaoui for their contribution to the preparation of the second concept for the island of Donousa.

The main author would like to thank Prof. J. K. Kaldellis for his scientific contributions through his publications on energy planning for remote Greek islands. His work provided valuable foundational information on renewable energy potential and energy concept ideas, which significantly supported the development of this paper.

REFERENCES

[1] Annual production plan of autonomous power stations. Technical Report prepared by Island Production Department of Greek Public Power Corporation, Athens, Greece.

[2] ΕΘΝΟΣ, 2025, Δονούσα: Το «σμαράγδι» των Μικρών Κυκλάδων , newsroom Travel, 24.07.2025.

[3] Kaldellis J. K., Tzanes G. T., Papapostolou C., Kavadias K., Zafirakis D., 2027, Analyzing the Limitations of Vast Wind Energy Contribution in Remote Island Networks of the Aegean Sea Archipelagos, Energy Procedia 142 (2017) 787–792

[4] Publication of NII Daily Energy Planning Data. [online] Available: https://deddie.gr/en/ [Accessed 22 Apr. 2023].

[5] Alexopoulos S., Alpesjkumar P., Slyamov D., and Suthar D., 2024, Simulation model for autonomous energy planning for Othoni island, 1st Belgian Symposium of Thermodynamics, 16-18 December 2024, Liège, Belgium.

[6] Kaldelis J.K., 2021. Supporting the Clean Electrification for Remote Islands: The Case of the Greek Tilos Island, Energies 2021, 14, 1336

[7] Alexopoulos, S. and Mathew G. 2024, Simulation model for autonomous energy planning for Milos island, Eurosun 2024, ISES Conference Proceedings (2024)

[8] Tzanes G., Zafeiraki E., Papapostolou C., Zafirakis D., Moustris K., Kavadias K., Chalvatzis K., Kaldellis J.K., 2019, Assessing the Status of Electricity Generation in the Non-Interconnected Islands of the Aegean Sea Region, Energy Procedia 159 (2019) 424–429

[9] Quaschning V. (o. J.)., 2024 *Windpark-Ertragsanalyse*. Accessed on 18.07.2025, from https://www.volker-quaschning.de/software/windertrag/index.php

[10] Schwarzkopf I., 2022, Autarke Energie- und Klimaschutzkonzepte für ausgewählte kleine deutsche und griechische Inseln, Bachelorarbeit FH Aachen University of Applied Sciences.

CLEAN WATER SUPPLY WITH RO DESALINATION FOR REMOTE ISLANDS VIA PV AND BATTERY SOLUTIONS. THE CASE OF KARPATHOS ISLAND

Michalis Bratitsis[1], Zografia Andreosatou[1], Emilia M. Kondili[2], John K. Kaldellis[1*]

[1]Soft Energy Applications and Environmental Protection Lab.
[2]Optimisation of Production Systems Lab.
Dep. of Mechanical Engineering, University of West Attica
e-mail: jkald@uniwa.gr

ABSTRACT

The increased touristic activity and the remarkable decrease of precipitation in the SE Mediterranean area, worsen the already difficult situation concerning the water resources availability especially for the small and medium size islands of the area. Traditionally, the water demand in all these islands has been covered by water drillings and in some specific cases by water dams and water ground reservoirs. Recently, the imperative water demand problem is being faced in many islands with the development and operation of Reverse Osmosis (RO) desalination plants, that they are significantly increasing, however at high operational and environmental cost. One of the most serious RO desalination unit's problems is their high energy demand. On the other hand, this water demand normally coincides with the electricity demand, both peaked during the summer period imposing the existing local electrical power systems to operate near their upper limit. Moreover, emergency situation appears in case of electrical black out.

For the radical solution of all these critical problems, on top of improving the water resources management, the water demand profile should systematically be measured or estimated along with the existing local water supply (water drillings, water reservoirs, etc.) potential. Accordingly, the corresponding water production related electricity consumption is estimated/measured. Subsequently, using the above-described parameters along with the available solar irradiance and ambient temperature the opportunity to support the necessary desalination plants with appropriate photovoltaic installations is examined. In this context, the current work investigates the sizing and the operation of appropriate PV plants used to provide the necessary electricity demand of existing or new RO desalination plants replacing the operation of diesel-based thermal power stations. For the safe and undisturbed operation of the desalination plants the introduction of small batteries is also examined along with the necessary power electronics, stabilizing the power input of the entire installation. The proposed parametric analysis, using several combinations of PV park peak power and battery capacity values, attempts to maximize the clean energy autonomy of a representative desalination plant, minimizing the fossil fuels consumption, at a rational investment cost. The developed numerical algorithm is applied for the Island of Karpathos using real world data and providing very interesting results.

Keywords: Water-energy nexus, Water Potential, Solar Potential, Energy balance

1. INTRODUCTION

Small and medium-sized islands of the South-East Mediterranean face increasing challenges regarding the sustainable management of water and energy resources. Climate change has intensified the hydrological imbalance, with precipitation showing a remarkable long-term decrease, while at the same time population growth and intensive touristic development significantly increase seasonal water demand. As a result, the traditional solutions of water supply —mainly groundwater drilling, small dams, and reservoirs— are often insufficient and environmentally unsustainable. Overexploitation of aquifers has already led to seawater intrusion and deterioration of water quality in many islands, rendering the reliance on wells a short-term solution rather than a viable long-term strategy.

In this context, seawater desalination through Reverse Osmosis (RO) has emerged as the most reliable technology to ensure water availability and supply security. RO units have already been installed and operated in several Aegean and Mediterranean islands, increasingly replacing conventional water supply methods. Nevertheless, desalination presents a serious drawback: it is an energy-intensive process, with electricity consumption typically ranging between 3-7 kWh per cubic meter of potable water produced. For non-interconnected islands the energy imports depend mainly on local diesel-fired thermal power stations, implying very high operational cost and considerable environmental footprint mainly due to greenhouse gas emissions. In addition, this water demand normally coincides with the electricity demand, both peaked during the summer period imposing the existing local electrical power systems to operate near their upper limit. Moreover, emergency situation appears in case of electrical black out [1,2].

The interdependence between water security and energy supply in small islands underscores the critical importance of the so-called water–energy nexus. Addressing water scarcity without simultaneously tackling the cost and availability of electricity leads to partial solutions that may increase dependency on imported fossil fuels and undermine long-term sustainability. Conversely, improving energy autonomy through renewable energy integration directly supports water security, as desalination and groundwater pumping —two of the most critical loads— can be powered by clean, locally available resources [3].

Among renewable technologies, photovoltaics (PV) is particularly suitable for island environments due to their modularity, decreasing installation cost and the high solar irradiance availability in the entire Mediterranean region. Moreover, when combined with modern lithium-ion battery storage, PV systems can provide reliable and stable electricity for desalination units, ensuring continuous operation even under variable solar conditions. Such hybrid systems contribute not only to improved energy efficiency but also to system resilience, reducing dependence on diesel generators and protecting the local economy from fuel price volatility [4].

This study focuses on the island of Karpathos, where desalination has become a critical component of the local water supply system. By systematically analyzing the water demand profile and its translation into an electrical load curve, this work investigates the technical feasibility of covering desalination loads with PV generation supported by limited battery storage. A parametric analysis of different PV capacities and storage sizes is performed to evaluate the degree of clean energy autonomy achievable, while maintaining realistic cost-effectiveness. Beyond the case of Karpathos, the study provides insights that are directly applicable to numerous Mediterranean islands facing similar constraints, offering a pathway towards sustainable water resource management and energy transition in insular regions [5].

2. THE PROBLEM TO BE SOLVED

One of the most representative medium-sized island cases that face increased energy and water demand is the island of Karpathos. Karpathos, the second largest island of the Dodecanese, belongs to the South Aegean Region and is home to 6,567 permanent residents according to the 2021 census (ELSTAT), distributed across 10 villages. The capital, Pigadia (Karpathos), is the administrative and economic center of the island with 3,047 inhabitants, followed by Arkasa with 540 residents. The central and northern part of Karpathos is designated as a Natura 2000 protected area, hosting rare species of flora and fauna as well as significant marine habitats that enhance the island’s environmental value [6] The climate of Karpathos is typically Mediterranean, with mild winters and hot, dry summers. Rainfall is particularly scarce, not exceeding 270 mm per year during the period 2022–2024 (Hellenic National Meteorological Service, HNMS). Sunshine is abundant, reaching an average of 13 hours per day during the summer months and around 9 hours per day in winter (HNMS 2022–2024). Due to its southeastern Aegean location, Karpathos also receives high levels of solar radiation, which increases its potential for renewable energy exploitation, particularly solar power.

Figure 1: Map of Karpathos (Greek Map Net, 2017)

Despite these natural advantages, water scarcity is one of the most pressing challenges the island faces. Limited rainfall and over-extraction of groundwater have resulted in aquifer depletion and seawater intrusion, especially in areas with high population density and tourism activity. Water consumption is highest in Pigadia and Menetes, followed by Arkasa, reflecting the concentration of both residents and visitors. However, the coastal position of Pigadia and Arkasa makes them more suitable for the installation of seawater desalination units, offering a potential solution to the growing water demand.

Water consumption is monitored on a semi-annual basis. Data show that 60% of the total consumption occurs between February and the end of July, coinciding with the peak tourist season and increased temperatures, while the remaining 40% is recorded between August and January. Annual water consumption figures indicate a clear upward trend: in 2022 the island consumed approximately 440,000 m³ of water, whereas in 2023 this rose to almost 500,000 m³ (Municipal Water Supply Service of Karpathos) as shown in Figure (2). Seasonal analysis further reveals that consumption does not remain evenly distributed throughout the year but peaks from April to August, when the combination of high temperatures and tourism activity places additional stress on water resources.

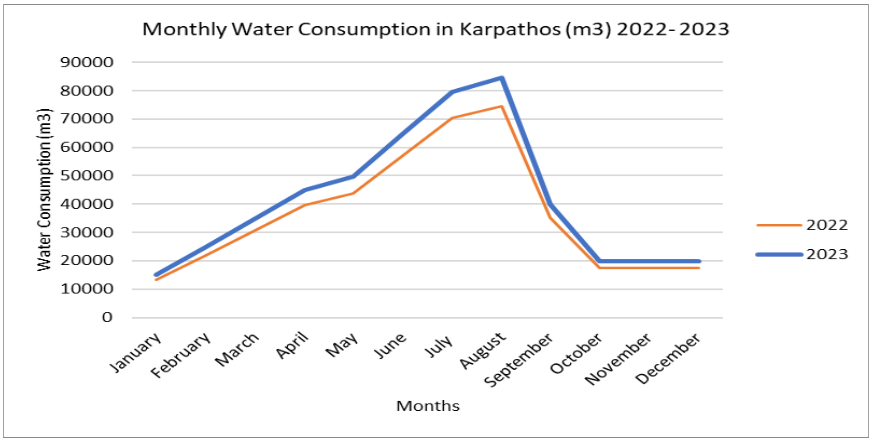


Figure 2: Monthly water consumption in Karpathos for 2022-2023

Currently, Pigadia is supplied by four groundwater wells with a total production capacity of 8 m³/h, supported by five storage tanks with a combined capacity of 1,390 m³. In Arkasa, water supply comes from a single well and a storage tank of 480 m³. Nevertheless, despite this infrastructure, groundwater production cannot meet the high seasonal demand. In Pigadia, shortages are particularly severe from April through August, while in Arkasa they become acute in July and August, resulting in frequent interruptions to water supply.

3. PROPOSED METHODOLOGY

To ensure the reliable coverage of energy demand for critical loads in small islands such us the desalination plants, an autonomous photovoltaic (PV) generator coupled with appropriately sized lithium-ion storage is proposed [4,7]. Desalination is a critical infrastructure load, exhibiting both base-level consumption and significant peaks during the summer tourist season. A dedicated renewable-based system can effectively meet this demand, while reducing dependence on the local thermal power station (TPS). Figure (3).

In this framework, a grid-compatible system is designed, consisting of a PV generator, lithium-ion battery modules, maximum power point tracking (MPPT), charge controllers and high-efficiency inverters. The proposed system is designed so that desalination units operate exclusively during daytime hours, directly utilizing the photovoltaic (PV) output. In this way, the electrical demand of the reverse osmosis process is primarily covered by solar energy in real time, maximizing renewable penetration and minimizing conversion losses. In periods of excess PV production, the surplus electricity is stored in the battery system to ensure optimal resource utilization. Conversely, when PV generation is insufficient to fully cover the desalination load, the storage unit provides the necessary balancing power, maintaining uninterrupted operation of the plant. This strategy enables the desalination facility to operate independently of fossil-fuel-based generation under normal conditions, while ensuring that system flexibility and reliability are preserved even under variable solar irradiance [5,7].

To simulate the system's performance, it is necessary to define the desalination plant's electric load profile based on the island's water demand over an extended period. Accurate modeling requires hourly data to capture the operational dynamics of the RO units and associated pumping equipment.

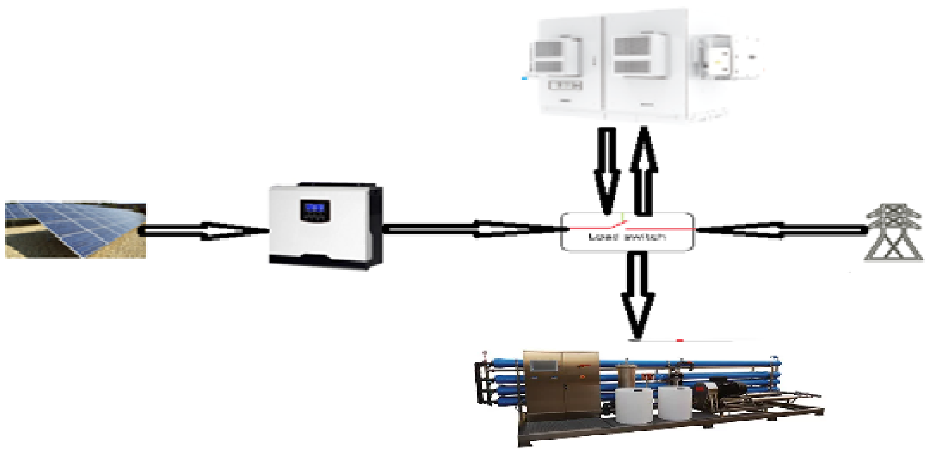


Figure 3: Desalination Plant Energy Coverage from PV-Battery System

In parallel, long-term solar irradiance data and ambient temperature measurements are essential to calculate the expected energy yield of the PV installation. Additional inputs such as wind potential and local environmental factors (e.g., dust and salt deposition) further improve the accuracy of the energy production estimates. Moreover, the operational parameters of the battery —round-trip efficiency, maximum depth of discharge (DOD_{max}), and voltage response under varying state-of-charge and temperature conditions— are necessary to capture storage dynamics. Inverter efficiency curves and input voltage windows must also be considered, as they significantly influence the overall system performance [8].

The water supply system of Karpathos exhibits seasonal variability, which directly shapes the desalination load profile. The proposed solution suggests that from January to April and from October to December, the island's water demand will be met exclusively by desalination plants, protecting the island underground water reserves, making electricity consumption for reverse osmosis a critical year-round baseline. In May, the first half of the month should rely solely on desalination, whereas during the second half groundwater wells partially contribute to supply, reducing the desalination share. The summer period, from June to August, the water demand will be covered by a combination of groundwater extraction and the desalination units. In September, the first half of the month will follow a mixed scheme with both wells and desalination units contributing to the total demand, while in the second half desalination once again becomes the exclusive source of potable water.

In Figure (4) the load demand of the desalination system of Pigadia is presented. In this diagram the horizontal axis represents the hourly analysis for every month (24 hours) and the vertical axis describes the hourly electricity consumption of the desalination unit. The energy demand varies between 50 and 450 kWh/h with maximum energy demand during spring period, based on the above system design. In a future work one may optimize the operation mix between groundwater extraction and desalination units' operation in order to protect the island water reserves minimizing also the size of the proposed PV-battery installation.

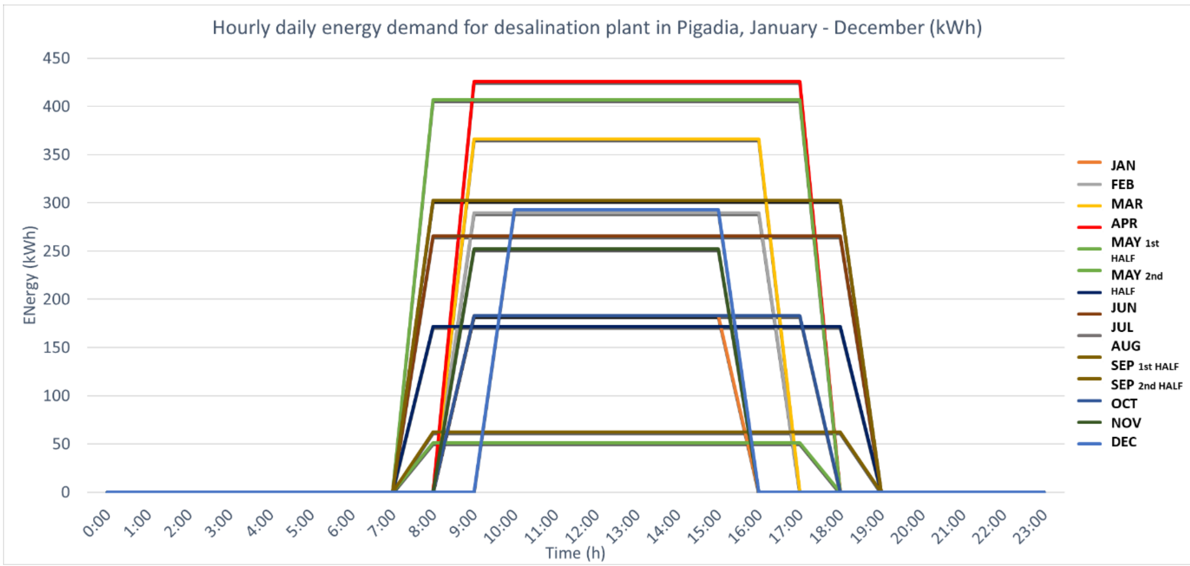


Figure 4: Hourly daily energy demand for desalination plant in Pigadia – Karpathos.

This integrated simulation approach enables the accurate assessment of how a PV–battery system can reliably support a desalination plant in a remote not interconnected island. It ensures optimal dimensioning of the renewable energy system, minimizing both oversizing and reliance on diesel generation, while safeguarding energy security and water availability for the local population and seasonal visitors.

This alternating operation pattern leads to a highly dynamic electrical load profile, with peak desalination demand occurring in the winter and spring months, while reduced but non-negligible operation is maintained during the summer tourist season. Such variability must be incorporated into the energy system design, ensuring that the proposed PV–battery installation is adequately sized to cover the desalination load in periods of maximum reliance, while maintaining flexibility during lower-demand months.

Consequently, Figure (5) demonstrates representative solar-potential data, obtained from 15-minute averaged measurements and aggregated on monthly basis, for photovoltaic modules tilted at 30°. The initial raw observations were recorded on the horizontal plane. The monthly in-plane irradiation varies from 75 to 290 kWh/m^2, increasing from winter to summer.

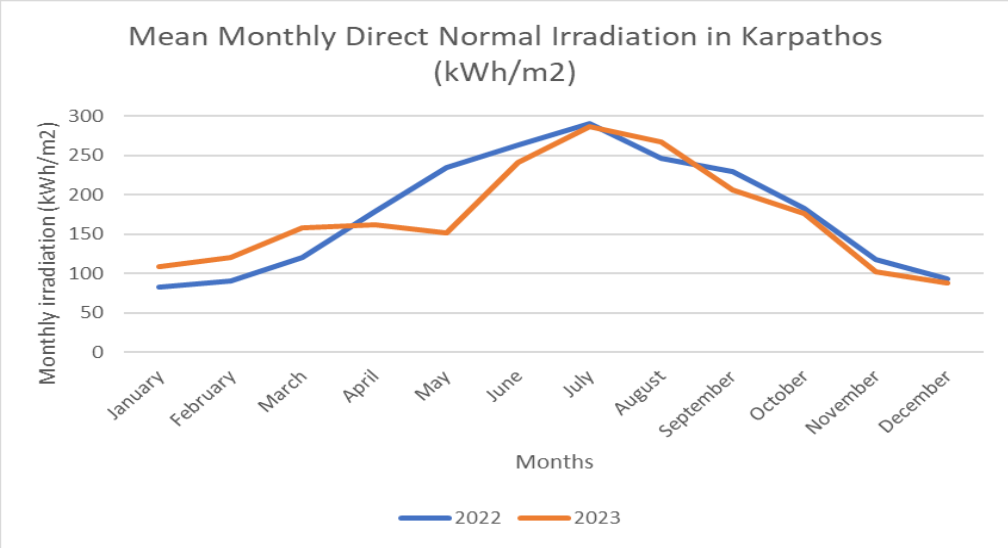


Figure 5: Mean monthly direct normal irradiation in Karpathos for 2022-2023.

For the simulation of the proposed system a time step of one hour is selected, where the PV production ''P'' is being compared with the load energy demand ''P_L'' of the desalination plant. The maximum Depth of Discharge (DOD_{max}) of the energy storage system is a crucial parameter in order the system controller to decide the energy flow through the different parts of the proposed installation. More specifically the system energy/power balance ΔP(t) at every time point (t) is estimated as:

$$\Delta P(t) = P(G,\theta_a) - P_L(t) \quad (1)$$

where the PV generator power output $P(G,\theta_a)$ depends [8] on the solar irradiance and the ambient temperature, while "G(t)" is the solar irradiance at the desired tilt and azimuth angle and "θ_a" is the corresponding ambient temperature [9].

If ΔP(t) > 0 then the PV production is covering the whole energy demand of the desalination plant and the energy excess is used to charge the energy storage system.

In case DOD = 0 (i.e. the energy storage system is full) the energy excess can be forwarded to other low non-critical loads, with the corresponding energy surplus recorded.

If ΔP(t) < 0 then the PV production is covering part of the electricity consumption and the rest is covered by the energy storage system.

If DOD is near the DOD_{max} (i.e. the batteries are almost empty) then the energy deficit is covered by the local TPS and the corresponding energy deficit ''E_d'' is calculated.

In Figure (6) the energy management algorithm used for the entire system simulation is depicted being a modified version of the original algorithm PV-Diesel v.12 [4,10].

Applying the above analysis, for a given load profile and for every pair of installed PV generator peak power "P_o" and battery capacity "E_{ss}", the algorithm provides, for a desired period of one or more years, the time-series of:

PV system power production "P(t)"

Power and Energy balance "ΔP(t)"

Energy storage system Depth of Discharge "DOD(t)"

or equivalently State of Charge "SOC(t)" (i.e. SOC(t)=100-DOD(t))

and the local TPS power contribution "$P_d(t)$"

For a given evaluation window "Δt" (e.g. one month, one year, etc.), the model calculates the total PV generator output "E_{tot}" and its demarcation in a "direct" provided component "E_{pv}" and to a via "battery-based" component "E_{bat}". The residual demand is met by the local diesel plant "E_d", thus the corresponding fuel consumption "M_f" and CO_2. emissions "M_{CO2}" may be estimated. Finally, the overall system loss "E_{loss}" and the corresponding PV output surplus "E_{surp}" (unused PV generation when the battery is full, which may be used for low priority or deferral loads) are computed, according to the following equations (2) and (3).

$$E_{dem} = E_{pv} + E_{bat} + E_{d} \quad (2)$$

$$E = E_{pv} + E_{bat} + E_{loss} + E_{surp} \quad (3)$$

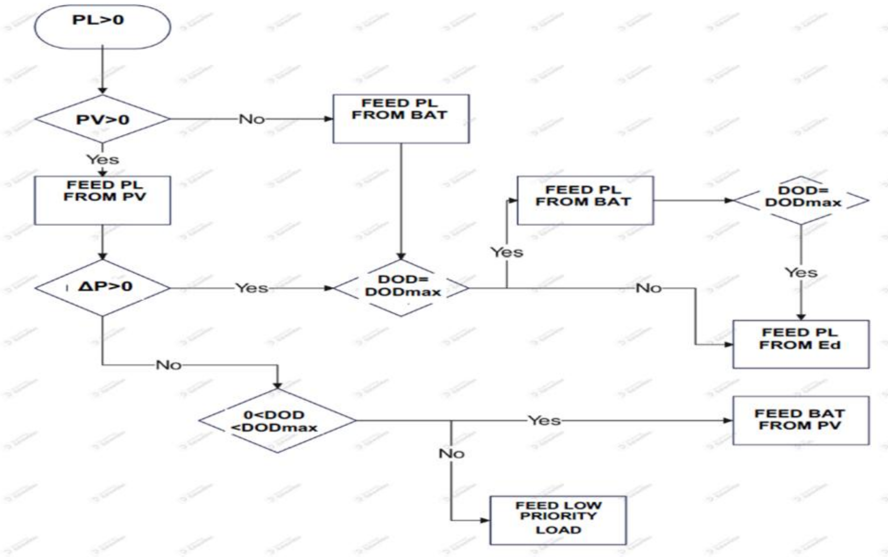


Figure 6: Energy Management Diagram of PV-Battery-Diesel Algorithm

4. CALULATION RESULTS

The energy coverage of the desalination plant is assessed through a parametric analysis of the photovoltaic (PV) generator rated power (P_o) in the range 400–600 kW_p with step of 50 kW_p. The associated lithium-ion storage capacity (E_{ss}) is considered between 0.5 and 0.8 MWh, under assumptions of 85% round-trip efficiency and 80% maximum depth of discharge (DOD_{max}). PV array losses are assumed equal to 15% of gross DC production, while conversion losses from inverters and chargers are approximated at 10%.

For each (P_o–E_{ss}) pair, a two-year time-series simulation (2022–2023) was performed. The supervisory control algorithm prioritizes direct PV supply to cover the desalination demand. Surplus production is stored in the battery system until full state of charge (SOC=100%) is reached, whereas demand exceeding PV output is supplied by discharging the batteries. TPS units are dispatched only when both PV production and the available storage are insufficient (i.e., $DOD \rightarrow DOD_{max}$).

Figure (7) presents the annual energy balance of the hybrid PV – battery – TPS configuration. The desalination demand varies seasonally between 40–50 MWh/month in winter and up to 90–100 MWh/month in summer. In the case of a 600 kW_p PV generator combined with 0.8 MWh storage, more than 98% of the annual desalination load is covered by renewable energy, with TPS contribution dropping below 2%. In this configuration, direct PV coverage accounts for ~82%, battery discharge ~16%, and the residual demand ~2% from TPS. With a reduced storage capacity (0.7 MWh), direct PV participation decreases slightly to 79%, and the storage contribution decreases to ~15%, increasing TPS participation to ~7%.

Smaller PV systems exhibit lower renewable penetration. For example, a 400 kW_p PV with 0.55 MWh storage achieves 71% renewable coverage direct from the PV station and 12% from the storage system while TPS unit is covering 16% of the desalination load.

In Figure (7) the results of the parametric analysis of the above-described algorithm are presented.

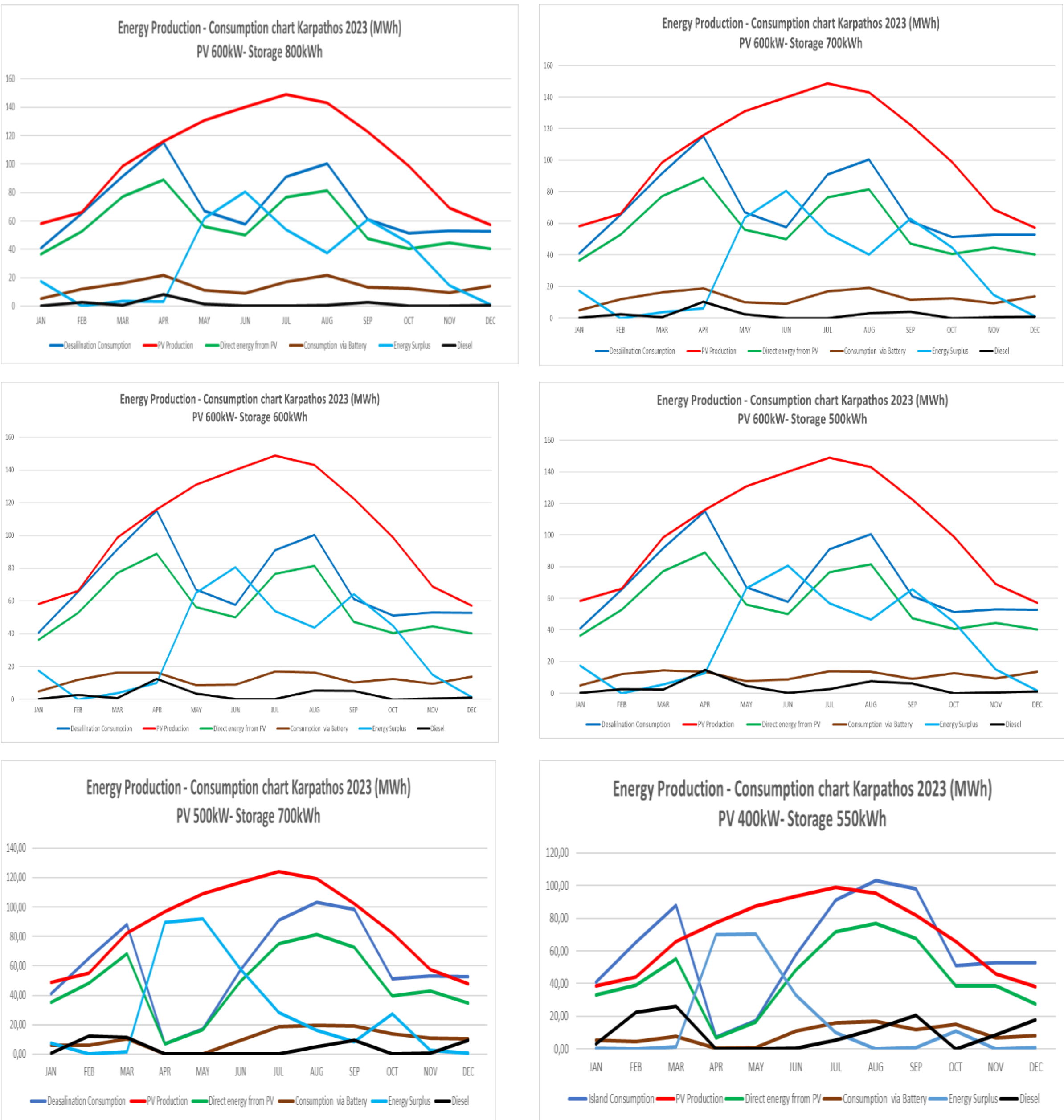


Figure 7: Energy Analysis of Selected Configurations Analyzed for the Desalination Plant In Karpathos

These results demonstrate that properly dimensioned PV – battery systems can reliably cover the energy needs of desalination plants while drastically reducing fossil fuel dependency. Beyond operational reliability, the proposed hybrid systems contribute to economic savings and significant CO_2 emission reductions, strengthening the resilience of insular water supply infrastructures.

In order to provide a clear representation of the hybrid system's energy balance, Figure (8) illustrates the annual energy analysis for 2023 across six representative PV–battery configurations. The first case corresponds to a 600 kW_p PV installation combined with battery storage capacities of 0.8 MWh, representing the configuration with the largest PV capacity investigated. According to the results of the supervisory algorithm, the required diesel contribution ranges between 16% and 2%, depending on the storage size. In all the configurations the maximum power input is coming directly from the PV station, since we choose to operate the desalination plant during daytime when there is energy production from the PV station.

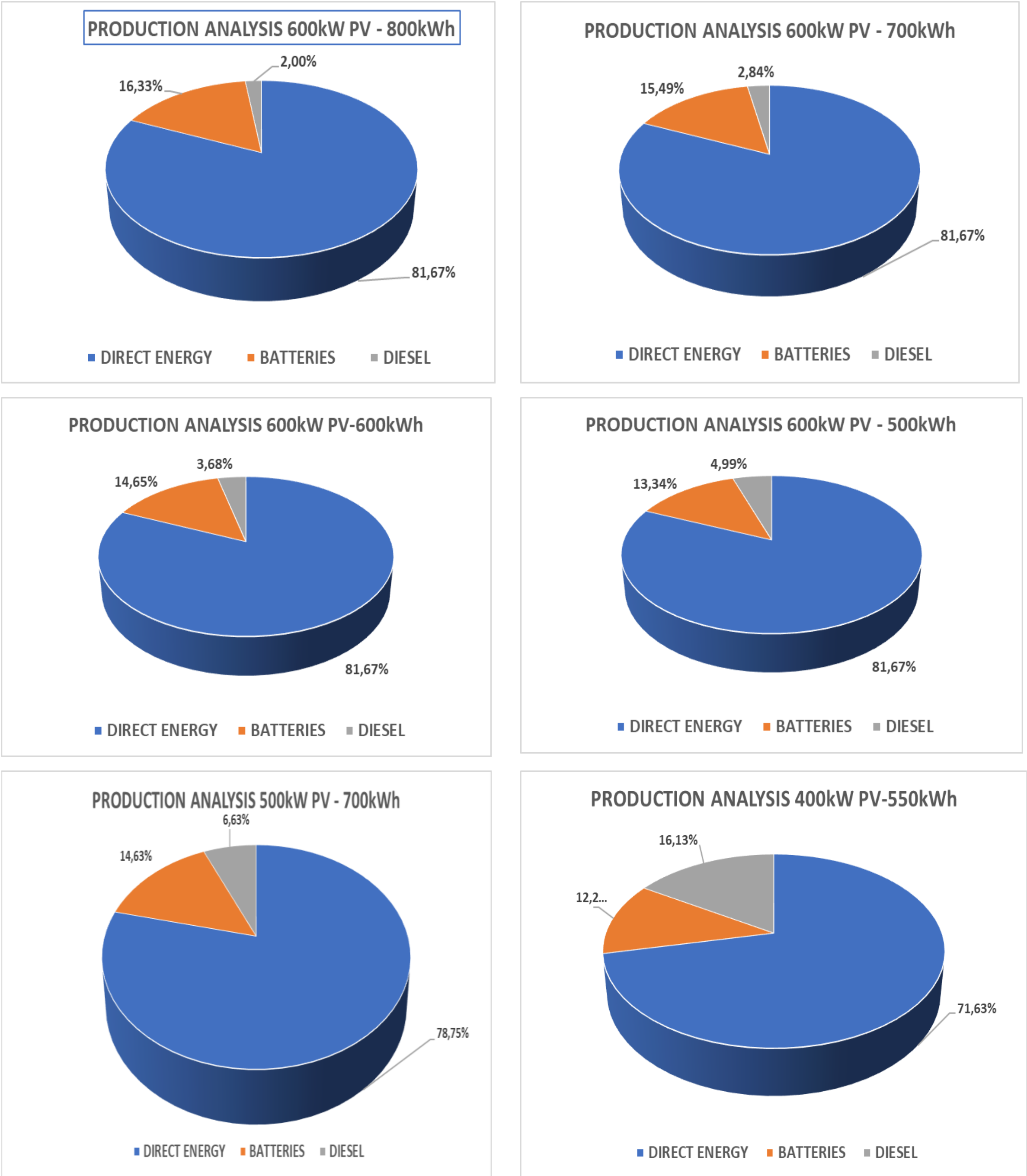


Figure 8: Annual Energy Consumption Analysis of Selected Configurations for the Desalination Plant in Karpathos

The simulation outcomes indicate that the direct photovoltaic (PV) contribution to the desalination demand ranges between 500 and 700 MWh/year, reflecting the temporal concurrence between electricity generation and load consumption. As the storage capacity increases, a notable enhancement in renewable coverage is achieved through the utilization of stored solar energy. Specifically, the battery contribution rises from approximately 100 MWh/year with a nominal capacity of 0.55 MWh, to nearly 160 MWh/year when the storage capacity is expanded to 0.8 MWh. Consequently, the reliance on the local thermal power station (TPS) decreases substantially, from over 117 MWh/year in the baseline case to only 17 MWh/year under the most optimized configuration [10].

From the energy balance point of view, it seems that the most promising system configuration includes a 0.6 MW_p PV generator based on ~850 bifacial panels of 700 W_p each, supported by 6 inverters of 100 kVA (nominal AC output of ~0.6 MW), and a battery bank of 0.8 MWh consisting of 4 Li-ion modules of 0.2 MWh each. This arrangement ensures that desalination demand is reliably covered during most of the year, with the TPS operating only in rare periods of prolonged low irradiance.

The PV panels are assumed to be mounted on adjustable metallic frames, oriented north–south with a variable tilt between 15° and 35° to optimize seasonal solar collection [9]. Although a detailed financial analysis of the proposed installation is beyond the scope of this work, the preliminary investment cost is estimated around 1 M€. The corresponding annual savings from avoided diesel fuel consumption are on the order of 0.35 M€. Moreover, the reduction in greenhouse gas emissions is projected at nearly 400 tons of CO_2 per year, a figure that highlights both the environmental and socio-economic benefits of the proposed system [5,7,12].

5. CONCLUTIONS

A data-driven methodology has been applied to assess the electrification of desalination facilities in Karpathos through the integration of photovoltaic (PV) generation and lithium-ion battery storage. The analysis demonstrates that appropriately sized hybrid systems can reliably cover more than 80–90% of the desalination units electricity demand, while the contribution of the local thermal power station (TPS) reduced to less than 10% annually, mainly out of the summer period. These results confirm that renewable-based desalination can substantially decrease fossil fuel dependency, mitigate greenhouse gas emissions, and enhance energy and water security for remote islands.

While several system configurations were found to be technically effective, the identification of a single "optimal" solution requires updated financial data and a holistic evaluation of investment costs against operational savings and environmental externalities. Nonetheless, the findings highlight the viability of PV–battery systems as a cost-effective and sustainable pathway for island water supply.

An additional challenge arises from the significant surplus of PV energy observed during the summer period (May–October), when average excess generation can exceed 40 MWh per month. This clean energy surplus represents an opportunity to further increase desalinated water production, thereby reducing dependence on groundwater wells without incurring additional operational costs. Future research should investigate the systematic integration of this surplus into water management strategies, as well as its potential contribution to ancillary services such as local mobility and grid stability.

ACKNOWLEDGEMENTS

This research was carried out in the framework of the projects NHSOS and JustRedDI.

REFERENCES

[1]. Kyriakarakos, G., Papadakis, G., & Karavitis, C. A.: ‘’Renewable energy desalination for island communities: Status and future prospects in Greece’’. Sustainability, 2022, 14(13), 8176. https://doi.org/10.3390/su14138176

[2]. Shahid, M. K., Mainali, B., Rout, P. R., & Choi, Y.: ‘’A review of membrane-based desalination systems powered by renewable energy sources. Membranes’’, 2023, 13(5), 439. https://doi.org/10.3390/membranes13050439

[3]. Janowitz, D.: ‘’Photovoltaics powered seawater desalination by reverse osmosis. Desalination’’, 2025, 593, 117221. https://doi.org/10.1016/j.desal.2025.117221

[4] Kaldellis J.K.: "Optimum Techno-Economic Energy-Autonomous Photovoltaic Solution for Remote Consumers throughout Greece", Journal of Energy Conversion and Management, 2004, Vol.45(17), pp.2745-2760.

[5] Kaldellis J.K., Ktenidis P.: "The Clean-Green Decarbonization of Remote Islands. The GReco-islands concept", 16th COMECAP-2023, Athens, Greece, Environmental Sciences Proceedings, 26, 208.

[6] Dimionat, T. (2017). Detailed map of Karpathos, Greece [online map]. Available at: https://greece-map.net/greece-karpathos-maps/ (Accessed: 19 August 2025).

[7] Cross S., Padfield D., Ant-Wuorinen R., King P., Syri S.: ´´Benchmarking Island power systems: Results, challenges, and solutions for long term sustainability´´ Renew. Sustain. Energy Rev. 2017, 80, 1269–1291.

[8] Kaldellis J.K., Kapsali M., Kavadias K., 2014,"Temperature and Wind Speed Impact on the Efficiency of PV Installations. Experience Obtained from Outdoor Measurements in Greece", Renewable Energy, Vol.66, pp.612-624.

[9] Kaldellis J.K., 2014, "Photovoltaic-energy storage systems for remote small islands". In Solar Energy Storage, Sørensen, B. (ed.), Academic Press, 13.

[10] Kaldellis J.K.: "Integrated electrification solution for autonomous electrical networks on the basis of RES and energy storage configurations", Energy Conversion and Management, 2008, Vol.49(12), pp.3708-3720.

[11] Kaldellis J.K., Kavadias K., Zafirakis D., 2012, "Experimental Validation of the Optimum Photovoltaic Panels' Tilt Angle for Remote Consumers", Renewable Energy, Vol.46, pp.179-191.

[12] Kaldellis J.K., Zafirakis D., Kavadias K.: "Techno-economic comparison of energy storage systems for island autonomous electrical networks", Renewable and Sustainable Energy Reviews, 2009, Vol. 13(2), pp.378-392.

FROM CONCEPT TO PRACTICE: LOCAL COMMUNITIES' PERCEPTIONS TOWARDS OFFSHORE WIND FARMS ON GREEK ISLANDS

Lydia Avrami[1], Antoinetta Capella[1], Nicolas Demertzis[1]

[1]National Centre for Social Research
e-mail: lavrami@ekke.gr

ABSTRACT

The development of offshore wind farms remains at the core of the Greek energy transition strategy, as outlined in the relevant National Programme, which has already encountered the strong skepticism of a significant number of local communities, reflecting the broader socio-political challenges in renewable energy governance. The paper aims to map and analyze the attitudes and perceptions of local communities and stakeholders towards the potential environmental, social and economic impacts of the planned offshore wind farm, focusing on the case of the Diapontian Islands. The sea area of the Diapontian Islands, a small island complex of the Ionian Sea, northwest of Corfu Island, has been selected as one of the potential areas for offshore wind farms installation. We identify the key factors contributing to local resistance or acceptance of offshore wind farms by using qualitative data collected through in-depth interviews with informants selected from local authorities, the private sector, and civil society organizations in Corfu and the Diapontian Islands during September 2024.

Our findings indicate that perceived negative impacts on biodiversity and local economic activities - especially tourism and fisheries- along with mistrust or distrust towards public authorities, fuel the widespread opposition to the planned offshore wind farm in the area, even though local stakeholders acknowledge the need for and the national benefits of energy transition and renewable energy sources (RES) development. It seems that top-down and non-deliberative decision-making feeds into "fake news" and the perceptions for lack of governance transparency. Engaging local communities in stakeholder consultation during decision making and planning of offshore renewable energy projects, mapping the latters' potential socioeconomic impacts on those communities and adopting policy measures that will offset the adverse effects of such projects for both the environment and society seem to be essential for addressing public concerns and building trust around energy transition strategies.

Keywords: Offshore wind farms; renewable energy governance; local perceptions; social acceptance; blue economy; Greek islands; Diapontian Islands.

1. INTRODUCTION

The development of offshore wind farms remains at the core of the Greek energy transition strategy, as outlined in the relevant National Programme, which has already encountered the strong skepticism of a significant number of local communities, reflecting the broader socio-political challenges in renewable energy governance. Given the numerous human activities developed in marine and coastal areas, offshore wind farm development strategies are often accompanied by concerns about the coexistence and synergies of existing economic activities with the proposed offshore renewable energy projects. It is commonly accepted that Marine Spatial Planning can ensure the management of conflicts between human activities and enhance the implementation of the offshore renewable energy development plans.

Even though, in April 2025 the Greek Ministry of Environment and Energy announced the establishment of the National Spatial Strategy for the Marine Space (NSSMS), which is presented as specifying and mapping the country's Marine Spatial Planning (MSP), it is worth noting that this Act of the Council of Ministers (Government Gazette Issue - FEK Δ 227/17.04.2025) merely delineates the marine areas of the MSP and the general guidelines and parameters that should be followed for marine spatial planning of human activities. Moreover, given that it does not include analysis, allocation and mapping of human activities and uses in these marine areas to achieve ecological, economic, and social goals, it cannot be considered as a completed MSP, according to the Directive 2014/89/EU, which defines in Article 6 the setting-up of maritime spatial plans as follows: "When establishing and implementing maritime spatial planning, Member States shall set up maritime spatial plans which identify the spatial and temporal distribution of relevant existing and future activities and uses in their marine waters".

Recent studies highlight the potential negative environmental and social impacts of the development of offshore wind farms. These impacts are mainly related with the social justice and the displacement of populations and/or activities, the phenomenon of "ocean grabbing", the degradation of the marine environment and the ecosystem services provided, the adverse impacts on fishermen, the lack of access to marine resources by certain users, the social and cultural impacts due to the alteration of traditional activities, landscapes and settlements, the infringement of the rights of indigenous peoples, as well as the lack of participatory governance processes for offshore RES projects [1].

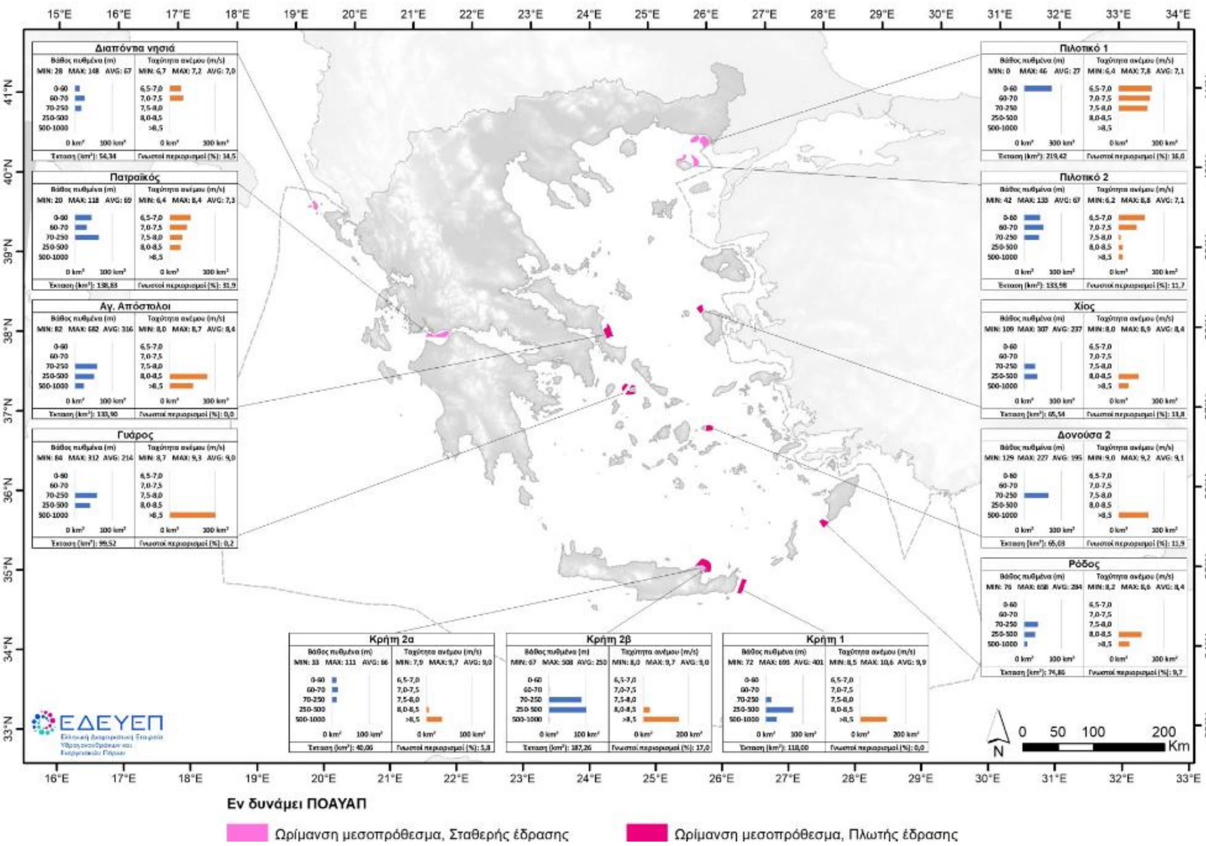
The paper aims to map and analyze the attitudes and perceptions of local communities and stakeholders towards the potential environmental, social and economic impacts of the planned offshore wind farm, focusing on the case of the Diapontian Islands. The sea area of the Diapontian Islands, a small island complex of the Ionian Sea, northwest of Corfu Island, has been selected as one of the potential areas for offshore wind farms installation. We identify the key factors contributing to local resistance or acceptance of offshore wind farms by using qualitative data collected through in-depth interviews with 21 informants selected from local authorities, the private sector, and civil society organizations in both Corfu and the Diapontian Islands during September 2024.

2. THE NATIONAL DEVELOPMENT PROGRAMME FOR OFFSHORE WIND FARMS: THE CASE OF DIAPONTIAN ISLANDS

The development of offshore wind farms remains at the core of the Greek energy transition strategy, as outlined in the National Development Programme for Offshore Wind Farms. This National Program and the relevant Strategic Environmental Impact Assessment (SEIA) drafted in late 2023 by the Hellenic Hydrocarbons and Energy Resources Management Company (HEREMA)[1] and the Ministry of Environment and Energy aims to delineate specific zones for the development of offshore wind farms in Greece [2]. In order to safeguard environmentally sensitive areas and marine activities in the Greek territory, HEREMA applied 20 exclusion criteria. These criteria include, among others, issues of national security and passenger navigation, airports, minimum distance from coastline, areas of environmental and cultural importance, tourist activities, aquaculture areas and other uses.

[1] According to the law 4964/2022, HEREMA is state-owned company responsible for managing Greece's exclusive rights to explore and identify suitable areas for offshore wind farms, acting on behalf of the Greek state.

This programme identifies 10 eligible areas for offshore wind energy projects to be developed by 2030, reffered to as Organised Areas for Offshore Wind Farm Development (OWFODA), with a total capacity of approximately 4.9 GW, using mainly floating wind technology. More precisely, the OWFODA[2] designated for the medium-term development phase are located in the following areas: Eastern Crete, Southern Rhodes, the Central Aegean, the Evia-Chios axis, and the Ionian Sea (see Map 1).

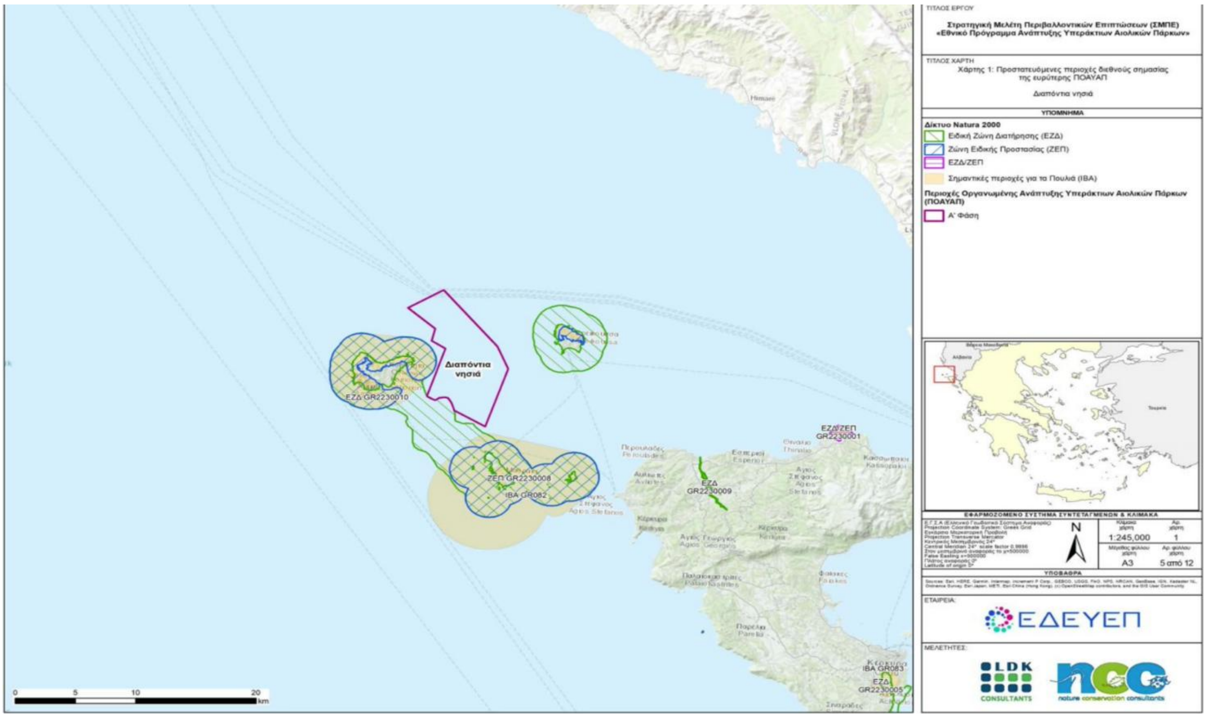


Map 1. Organised Areas for Offshore Wind Farm Development (OWFODA): Medium-term planning by 2030 (Source: HEREMA 2023b).

Thus, the sea area of the Diapontian Islands, a small island complex of the Ionian Sea, located at the westernmost point of Greece and approximately 10 km from Corfu Island, has been selected as one of the potential areas for offshore wind farms installation. The Diapontian Islands consist of three larger islands and several smaller islets. Othoni, Erikoussa and Mathraki are the three islands with most permanent residents, ranging from 330 to 500. They are rich in fauna and flora and a very large part of them belongs to the Natura 2000 network or has been recognized as an important area for birds (see below Map 2). According to the National Programme, the planned offshore wind farm will be installed in the sea area between the islands of Othoni, Erikoussa and Mathraki, with the installation of dozens of wind turbines with a rotor diameter of 236 meters and a height of up to 280 meters. As outlined in the SEIA [3], the planned offshore wind farm will cover a total area of 54 km^2, including fixed-base wind turbines with a proposed total capacity of 270 MW and situated at a distance of 1890.92 meters from the coastline.

The uniqueness of the area, along with the scale and type of the proposed wind energy project, poses huge challenges for local communities and the environment, which have led to unanimous opposition from local stakeholders. Local and regional public authorities, representatives of fishery and tourism sectors, as well as civil society organizations have officially expressed their concerns regarding the planned offshore wind farm in the area.

[2] These areas do not include the marine area between Evros-Samothraki, which is defined as an area for the development of pilot OWF projects, according to Law 4964/2022.



Map 2: Diapontian Islands, nature protection regime and Organised Area for Offshore Wind Farm Development (Source: HEREMA 2023a).

It is worth noting that Map 2 reveals the low wind potential[3] of the Diapontian Islands area, compared with other delineated areas. This issue was also underlined by the representatives of national agencies[4] involved in the planning and implementation of offshore wind energy projects, who have pointed out that the wind speed is considered insufficient in this area, making such an investment non-viable. Therefore, the investment interest remains extremely low.

It seems that Diapontian Islands in the Ionian Sea may be permanently excluded from the planning for midterm and long-term offshore wind energy development after the reactions of the local communities and agencies of the wider region, while the two regions northeast of Crete (Crete 2a and Crete 2b) are coming out of the first phase of development of the national programme and have been postponed until after 2032, probably beyond 2035 [4]. However, it is important to note that there is no official relevant decision. In fact, in August 2024, the Ministry of Culture approved the Strategic Environmental Impact Study for the National Offshore Wind Farm Development Programme, which includes the Diapontian Islands in the planning.

[3] Low wind potential refers to areas or conditions where the wind speed considered insufficient for conventional wind turbines to operate efficiently or even start up, typically below their cut-in speed (around 10-15 km/h). In these cases, specialized technology may be required, which making the project more complicated and costly [5].

[4] Following the interviews with the local stakeholders, we also conducted in-person interviews with representatives of national agencies directly or indirectly involved to the planning and implementation of the offshore wind energy development in Greece, aiming to capture their views and opinions regarding specific issues and challenges that accompany the planned project in the Diapontian Islands and draft policy proposal that will minimize the potential impacts and maximize the benefits of the RES development in the area [6].

3. LOCAL COMMUNITIES' PERCEPTIONS TOWARDS OFFSHORE WIND FARMS: FINDINGS OF THE ON-SITE QUALITATIVE RESEARCH IN CORFU AND DIAPONTIAN ISLANDS

3.1. . Level of knowledge about renewable energy sources and attitudes towards res projects

The research analysis reveals that all respondents had sufficient information about wind energy and other renewable energy sources, as well as good practices and potential environmental, economic and social impacts of RES development in Greece and other European countries. Most of the respondents recognize the need to increase green energy production and acknowledged its associated benefits. More specifically, they acknowledge the positive impacts of RES production for reducing energy costs and environmental footprint of energy consumption, while enhancing energy security. However, almost all local stakeholders who participated in the research, remain skeptical and express strong concerns about the potential impacts of offshore wind farms in the sea area of the Diapontian Islands, such as aesthetic and environmental degradation, negative impacts on local economic activities -especially tourism and fisheries-, non-consultation with local communities and their limited participation in decision-making, despite the critical nature of the project for their area.

Therefore, local stakeholders in Corfu and the Diapontian Islands underline the need for all RES projects, and especially offshore wind farm planning, to be adapted to the specific characteristics of each region and to ensure the quality of life of local communities along with the protection of cultural heritage and natural environment. Despite the concerns, there is a moderate acceptance of small-scale photovoltaic power plants, which are considered as having less negative social and environmental impacts and therefore could be a better solution for energy self-sufficiency of the Diapontian Islands,especially in Erikoussa, where there are frequent power outages.

3.2. Perceived impacts of the planned offshore wind farm in the diapontian islands

Our findings indicate that perceived negative impacts on biodiversity, local economic activities -especially tourism and fisheries- and marine transportation, along with mistrust or distrust towards public authorities, fuel the widespread opposition to the planned offshore wind farm in the area. Almost all the local stakeholders in Corfu and Diapontian islands who participated in the research, assess the potential effects of the operation of an offshore wind farm in the region as very negative (detrimental) for the quality of life of residents.

As recorded from the interviews conducted, but also from the formal protest resolutions of local bodies and authorities, the planned location of the offshore wind farm and the type of wind turbines proposed for installation are perceived as likely to maximize the negative impacts on both local communities and the natural environment. In particular, as already mentioned, according to the National Development Plan for Offshore Wind Farms, the offshore wind farm is planned to be installed in the sea area of three small islands -Othonoi, Erikoussa and Mathraki- and just 1,4 nautical miles from the coastlines of these islands [2]. The planned installation of offshore wind turbines with fixed foundations into the seabed[5] (rather than floating ones), whose height (approximately 280 meters) will exceed the highest natural peaks of Erikoussa and Mathraki, as stated by the local stakeholders, is considered as a "violent intervention" in this virgin natural landscape, with devastating consequences for the natural beauty and aesthetic value of the area.

Even though, specific criteria for exclusion of areas were applied to ensure "environmentally sensitive areas and marine activities in the Greek territory", as stated in the National Development Plan for Offshore Wind Farms, many participants in the survey believe that the selection of this specific area was based on "different" criteria and less transparent procedures, aiming to facilitate and attract private investments as the waters in this specific area are shallow (approximately 70m) and, therefore, the installation of offshore wind farms with fixed foundation is less costly.

More specifically, the potential negative impacts of the planned offshore wind farm, as indentified by local stakeholders, include the destruction of islands' coastal beauty, the environmental degradation and loss of biodiversity, the loss of coastal and marine tourism attractiveness (both for North Corfu and the Diapontia islands), the increasing challenges for maritime transportation, the impacts on other maritime and coastal economic sectors such tourism and fisheries. Strong concern was also

[5] Offshore wind farms with fixed foundations are the most common type of installation, the most mature and cheapest of the offshore renewable technologies. However, this type is suitable for shallow waters, typically less than 60 meters deep.

expressed by several participants about the environmental impacts of the activities required to install the wind turbines, but also about their lifespan and their end-of-life management, given the fact that the distance of the proposed wind farm is just 247,03 meters from the two protected areas[6] of the Natura 2000 network established in the area of Diapontian islands. Moreover, they point out the impacts on the birdlife of the area, due to the increasing risk of bird collisions with wind turbine blades, as the area is a corridor for migratory birds.

Visual nuisance emerge as one of the main concerns regarding the operation of the planned offshore wind farm in the area, as highlighted by all participants in the survey. With the aim to clarify what is considered visual nuisance for the local stakeholders, participants were given four archive images of a proposed offshore wind farm in United Kingdom, with varying distances from the coastline, ranging from 13km to 44km and involving 20MW wind turbines with a tower height of 190 meters from the sea and a total height of approximately 300 meters (including the blade). Given that both the distances from the coastline and the type of wind turbines depicted are similar to the proposed wind farm in the sea area of Diapontian islands, these images can act as “photo simulations”, offering a visual representation of hypothetical scenarios and helping the participants to clearly understand and visually assess the potential nuisance of the proposed offshore wind farm in a real environment. Then, the participants were asked to select “the photo that does not constitute a visual nuisance to them” without initially being informed of the exact distances from the coastline.

Figure 1 (13km from the coastline)

Figure 2 (24km from the coastline)

Figure 3 (35km from the coastline)

[6] Special Protection Area for birds-GR2230008 and Special Conservation Area "Marine area of Diapontian Islands" -GR2233001.

Figure 4 (44km from the coastline)

Although the degree of visual nuisance caused by offshore wind farms is subjective and it is difficult to establish a commonly accepted threshold for minimizing potential visual impacts, the vast majority of local stakeholders from both Corfu and Diapontian islands perceived all, or at least the first three images (i.e. offshore wind farm's distance 13 to 35km from the coastline), to be visual nuisance. Only few survey participants declared that the fourth image, depicting an offshore wind farm located 44km from the coastline, did not constitute a visual nuisance to them.

In addition, local stakeholders pointed out the negative impacts of the proposed project on maritime transportation, particularly regarding the connection between Corfu and Diapontian islands. According to their claims, the existing ferry line intersects almost vertically the delineated area of the planned offshore wind farm. Therefore, the daily connection of the islands may need to be rerouted and served through an alternative ferry line, leading to increased transportation costs and travel time, both of which are considered critical, especially for Diapontian islands, where reliable and efficient maritime connectivity is of vital importance.

These difficulties in maritime transportation, along with the destruction of the natural landscape, the visual nuisance and the noise that will be caused by the operation of the offshore wind farm, are considered to have irreversible impacts on coastal and marine tourism in the area, and therefore on the wellbeing of local communities. In addition, most of the respondents underlined the economic impacts for local fisheries, clarifying that the delineated area of the proposed wind farm is a traditional fishing area. Therefore, the prohibitions and limitations on fishing activities will pose major challenges for the economic survival of the sector in Corfu and Diapontian islands. Strong concerns were also expressed regarding the potential decline of fish stocks in the area, which may result from the disruption of the balance of the marine ecosystem and the seabed. Moreover, dominant is the position that none from the public authorities will care about the 150 professional fishers, who may suffer economic devastation. It should be noted that, according to the National Development Programme for Offshore Wind Farms, fishing activities will be considered as an evaluation criterion in the subsequent studies for the final location of the projects.

As most of the survey participants mentioned, the economic impacts of the planned project and the increasing difficulty of the connection of these small islands with Corfu, will lead many people to leave the islands. Given their strategic location at the westernmost point of Greece, stakeholders express concerns that the constant decrease of residents and the ageing population of Diapontian islands raise risks of national importance,related mainly to the national sovereignty and jurisdiction over territorial waters and other designated maritime zones.

3.3. Trust, consultation and information deficit

The research analysis shows that the lack of trust in institutions is evident and increases the skepticism of survey participants against the offshore wind energy planning and more specifically about the selection criteria of the specific sea area. It seems that the trust of local stakeholders towards public authorities is undermined by: a) insufficient information and consultation with local stakeholders, b) doubts about the transparency and reliability of the selection criteria and procedures used to delineating the Organized Areas for Offshore Wind Farm Development, c) uncertainty surrounding the potential reciprocal benefits of the offshore wind farm for local communities, d) ambiguity of the project management by the competent companies and e) the 'feeling' that there is no provision and strategic plan for the long-term future of the Diapontian islands, ensuring the minimization of potential negative impacts on the local society and economy.

All survey participants, including representatives of public authorities, stated that they have never been invited to discuss with the competent agencies regarding the planning and the development of such a project in their area. According to their views, the lack of official information and consultation has created a sense of alienation, feeding into “fake news” and reinforcing perceptions of a lack of governance transparency. As a result, a prominent opinion within the local community is that the involved companies act solely with the aim of profitability and that the broader RES planning serves other interests, rather than addressing the needs and priorities of the local population.

Local communities feel that they are being "sacrificed", shouldering the negative consequences of RES projects, which do not offer them any substantial benefits in return. They referred to experiences from other Greek regions where RES projects were developed, claiming that although promises for significant social and economic benefits were made, these never turned into reality. Therefore, they are almost convinced that the promised reciprocal benefits of the planned project will never be seen in practice.

4. CONCLUSIONS

Our findings indicate that perceived negative impacts on biodiversity and local economic activities - especially tourism and fisheries- along with mistrust or distrust towards public authorities, fuel the widespread opposition to the planned offshore wind farm in the area, even though local stakeholders acknowledge the need for and the national benefits of energy transition and RES development. It seems that top-down and non-deliberative decision-making feeds into “fake news” and the perception of a lack of governance transparency. Engaging local communities in stakeholder consultation during the decision making and planning of offshore renewable energy projects, mapping the potential socioeconomic impacts of such projects on affected communities and adopting policy measures that will offset their adverse effects on both the environment and society, seems to be essential for addressing public concerns and building trust around inclusive, equitable, and sustainable energy transition strategies.

The non-delimitation of the Exclusive Economic Zone (EEZ) in Greece still poses significant limitations on the planning and development of offshore RES projects. This is because offshore wind farms should be located close to the coastline, increasing visual nuisance and making planning for the harmonious coexistence of different maritime economic activities more complex.

The completion of Marine Spatial Planning in Greece remains a crucial prerequisite for managing conflicts between human activities, creating synergies and therefore enabling the effective implementation of the offshore renewable energy development plan. Socioeconomic impact assessment of planning and actual consultation with local stakeholders are more than necessary for minimizing the socioeconomic and environmental impacts on local communities as well as building an advocacy coalition of green transition at local level. Even though not all issues that trigger local reactions, such as visual nuisance, can be fully resolved, trust, communication, and mutual understanding can be built through co-decision and co-design procedures, involving all interested parties. In this way, the foundations could be laid for a common culture for the green transition, which will leave no room for fake news and will focus on win-win solutions. The planning process should be transparent and open to all interested parties, and the reciprocal benefits of the planned offshore RES projects should be clearly defined and measurable at the first stage of the decision making so as to motivate local communities to be involved.

REFERENCES

[1] Bennett, N.J., Cisneros-Montemayor, A.M., Blythe, J., Silver, J.J., Singh, G., Andrews, N., Calo, A., Christie, P., Franco, A.D. and Finkbeiner, E.M., 2019, “Towards a sustainable and equitable blue economy”, Nature Sustainability, 2, pp. 991-993.

[2] HEREMA, 2023a, “National Development Program for Offshore Wind Farms”. Available online: https://herema.gr/

[3] HEREMA, 2023b, “Strategic Environmental Impact Assessment”, Available online: https://herema.gr/

[4] Liangou, Ch., 2023, “Offshore wind farm review”, Kathimerini newspaper. Available: https://www.ekathimerini.com/economy/energy/1241375/offshore-wind-farm-review/#:~:text=According%20to%20information%2C%20the%20Diapontia%20islands%20in,of%20planning%20(midterm%20and%20long%2Dterm)%20after%20the

[5] Nizamani, Z., Muhammad, A.K., Ali, M.O.A., Wahab, M.A., Nakayama, A., and Ahmed, M.M., 2024, “Renewable wind energy resources in offshore low wind speeds regions near the equator: A review”, Ocean Engineering 311(4):118834.

[6] Avrami, L., Demertzis, N., Kaminiaris, O., Capella, A., Mela, K., Syrou, D. and Frangiskou, A., 2025, “Green Transition and Blue Economy: Synergies and incompatibilities”, TAEDR-0537352, Greece 2.0–Next Generation EU. Athens: National Centre for Social Research. Available: https://www.justredi.gr/galazia-oikonomia

ANALYZING OFFSHORE WIND PARKS ENERGY PERFORMANCE IN NORTHERN EUROPE. PROSPECTS AND CHALLENGES FOR SE MEDITERRANEAN

John K. Kaldellis[1], Louiza Moutafi[1], Emilia M. Kondili[2]

[1]Soft Energy Applications & Environmental Protection Laboratory
[2]Optimisation of Production Systems Laboratory
Dep. of Mechanical Engineering, University of West Attica
e-mail: jkald@uniwa.gr

ABSTRACT

Offshore wind parks (OWPs) show continuously growing installed capacity all around the globe, with Europe and China representing more than 90% of the 85 GW_e of wind power operating in open seas. Of particular interest is the increased activity of OWPs implementation in the north of Europe, where the strong wind potential and the relatively limited depth of the region's seas ensure utilization factors (Capacity Factors-CF) at the levels of 50% and a rational initial investment cost for the given conditions. In this context, the present work investigates initially the long-term energy performance of Northern European OWPs, using open access data concerning the monthly energy yield of more than 40 parks in the two major European offshore wind markets, i.e. UK and Germany. According to the current analysis, the average CF for all the installed OWPs in UK is higher than 40% for the period 2010-2024. Similar situation exists also in Germany, although the CF values achieved for OWPs are slightly lower. The success story of N. Europe OWPs attracts investors and governments in S. Europe planning to develop also OWPs in the Mediterranean Sea. To this end, the present research attempts to utilize the experience from the implementation of OWPs in Northern Europe in order to investigate the prospects of implementing corresponding investments in the Greek seas as well. According to the revised final National Energy and Climate Plan (NECP) the installation and operation of 1900 MW_e of new OWPs is expected by 2030. However, issues like the necessary zoning framework for OWPs siting has not yet been completed. Moreover, in almost all the areas where OWPs have been planned, significant public reaction has been expressed. At the same time, the problem of defining the proprietary rights in several regions of SE Mediterranean Sea has emerged on top of the techno-economic risk concerning the implementation of such big and novel for the area investments. For this purpose, the long-term experience of the OWPs of N. Europe may provide significant know-how and protect the new OWPs investments from "early infant" problems.

Keywords: Wind Power, Investment Cost, Electricity Interconnection Cost, Utilization Factor, NECP, Sea siting, Annual Energy Yield

1. INTRODUCTION

The wind energy exploitation is one of the main electricity providers of our planet contributing by more than 2500 TWh_e of clean energy. Actually, the installed wind power around our planet is almost 1200 GW (end of 2024), while increased interest is shown recently about offshore wind parks (OWPs). According to most recent results [1.2], offshore wind parks (OWPs) present continuously growing installed capacity all around the globe, with Europe and China representing more than 90% of the 85 GW_e of wind power operating in open seas, Figure (1).

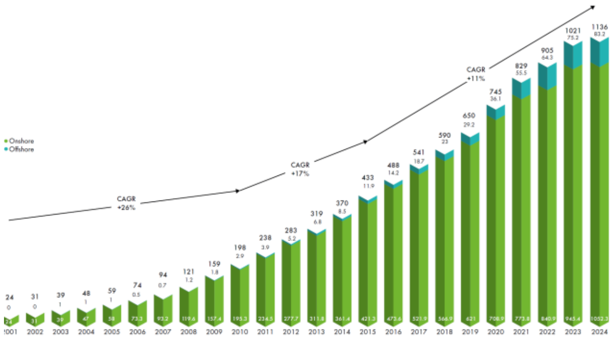


Figure 1a: Historic development of global WE installations (GW), [1]

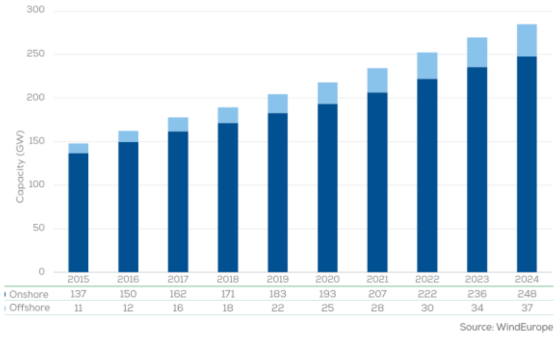


Figure 1b: Installed WE capacity in Europe, 2015-2024. [2]

In this context, the present work investigates initially the long-term energy performance of Northern European OWPs, using open access data concerning the monthly energy yield of more than 40 parks in the two major European offshore wind markets, i.e. UK and Germany. According to the current analysis of the annual CF of OWPs in UK, the average CF for all the installed OWPs is higher than 40% for the period 2010-2024. Similar situation exists also in Germany, although the CF values achieved for OWPs are slightly lower than the corresponding values in UK.

The high performance of N. Europe OWPs attracts investors and governments in S. Europe planning to develop also OWPs in the Mediterranean Sea. For this purpose, the present work describes the experience from the implementation of OWPs in Northern Europe in order to encourage interested investors to implement OWPs in the Greek seas as well. According to the revised final Greek National Energy and Climate Plan (NECP) the installation and operation of 1900 MW_e of new OWPs in the Greek seas by 2030 is expected [3]. However, issues like the necessary zoning framework for OWPs siting has not yet been completed. Moreover, in almost all the areas where OWPs have been planned, significant public reaction has been expressed, pressing the central and local governments to abandon the installation of OWPs in these specific locations. Furthermore, the problem of defining the proprietary rights in several regions of SE Mediterranean Sea has emerged on top of the techno-economic risk concerning the for the first-time implementation of such big and novel for the area investments. To this end, the long-term experience of the OWPs of Northern Europe should be taken into consideration in order to protect the new OWPs investments from any "early infant" problems.

2. OFFSHORE WIND IN UNITED KINGDOM

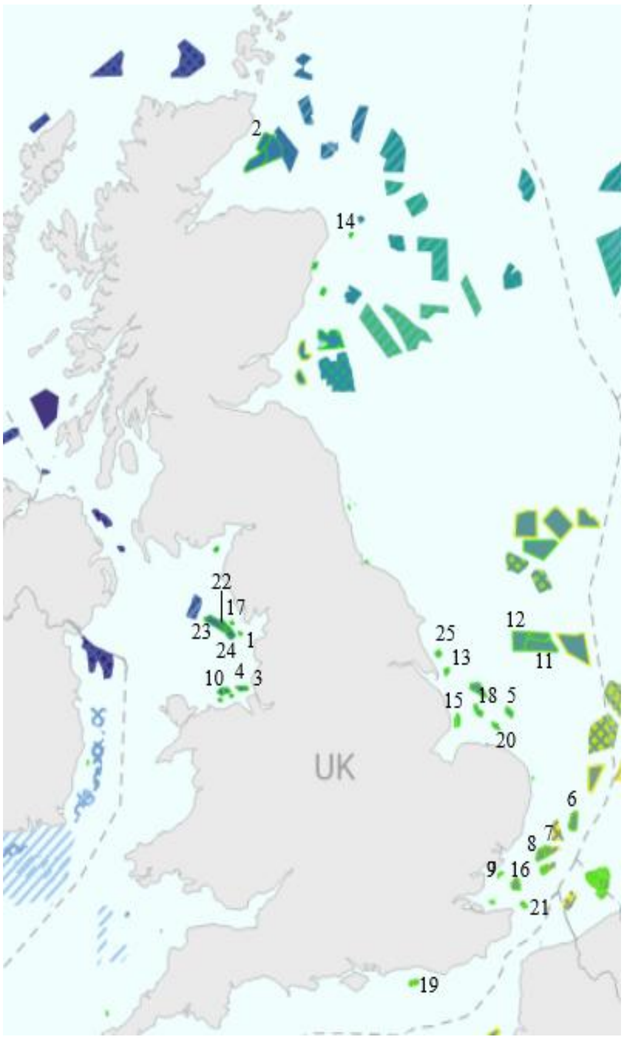


Figure 2: Map of operational offshore wind parks in United Kingdom, 2024 [4]

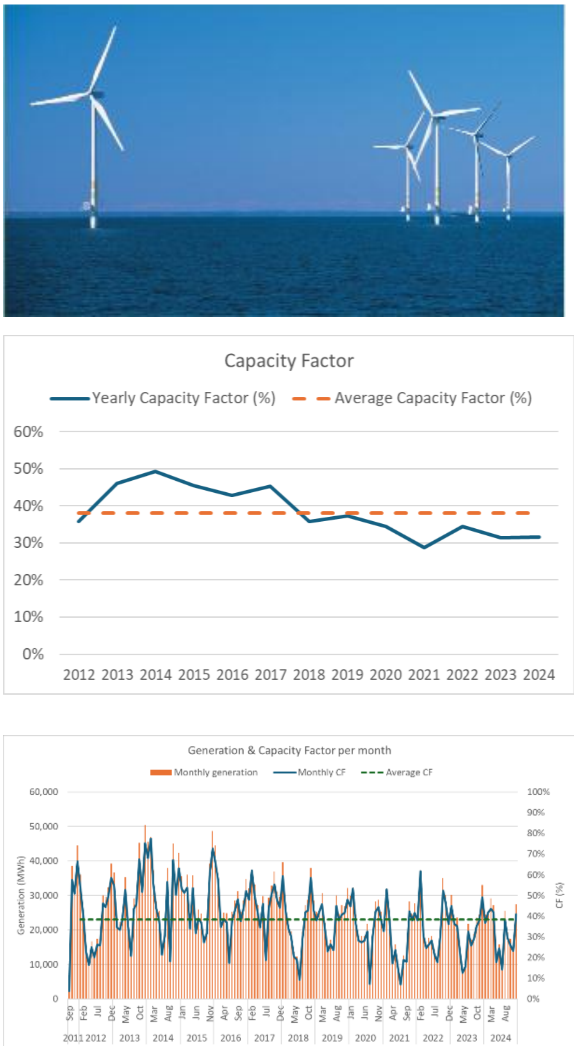


Figure 3: The first WP of UK. The Barrow WP data presentation [4]

The United Kingdom is characterized as the European leader in offshore wind energy, with a significant number (~45) of large-scale wind farms operating in its coastal waters, while its total offshore wind power capacity exceeds 16 GW. During the last ten years, offshore wind capacity continues to expand, supported by technological improvements, favorable government policies, and the country's commitment to achieving net-zero emissions. The geographical distribution of offshore wind farms in the UK is presented in Figure (2), highlighting the concentration of projects primarily in the North Sea. This specific area is characterized by favorable wind conditions and water depths that allow for fixed-bottom foundations. The deployment of floating wind technology has also begun, with projects like Hywind Scotland demonstrating strong performance in deep waters.

More specifically, the UK has over two decades of experience in offshore wind development, with some projects operating for nearly 20 years. One of the earliest commercial offshore wind farms, Barrow, has been operational since 2006, highlighting the country's longstanding expertise in managing and maintaining offshore assets. The OWP of Barrow is based on 30 3MW Vestas-90 WTs (nominal power 90 MW), presenting a long-term (2012-2024) capacity factor value equal to 38%, see also Figure (3). Recently, the Hornsea-1 and Hornsea-2 WPs have been installed, being among the world's largest offshore wind farms, with capacities of 1,218 MW (i.e. 174 Siemens Gamesa SWT-7.0-154) and 1,320 MW (i.e. 165 Siemens Gamesa 8.0-167 DD), respectively. In Figure (4) one can see the high CF values of these two huge WPs, approaching 46% on annual basis. Finally, the Hywind

Scotland is the UK's first floating offshore WP (2017) with nominal power 30 MW (i.e. 5 Siemens SWT-6.0-154), operating at water depth of 120 m, demonstrating the feasibility of floating wind technology.

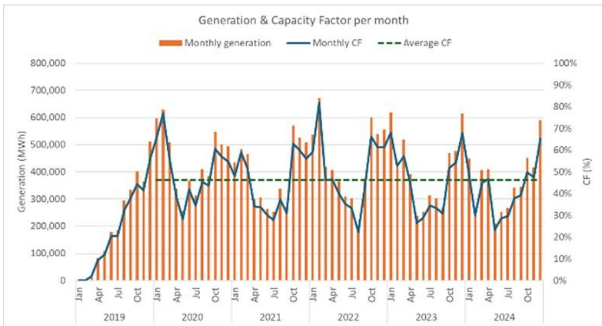


Figure 4a: Hornsea-1 Energy Performance

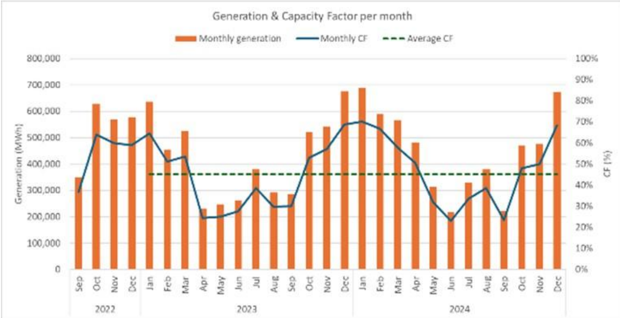


Figure 4b: Hornsea-2 Energy Performance

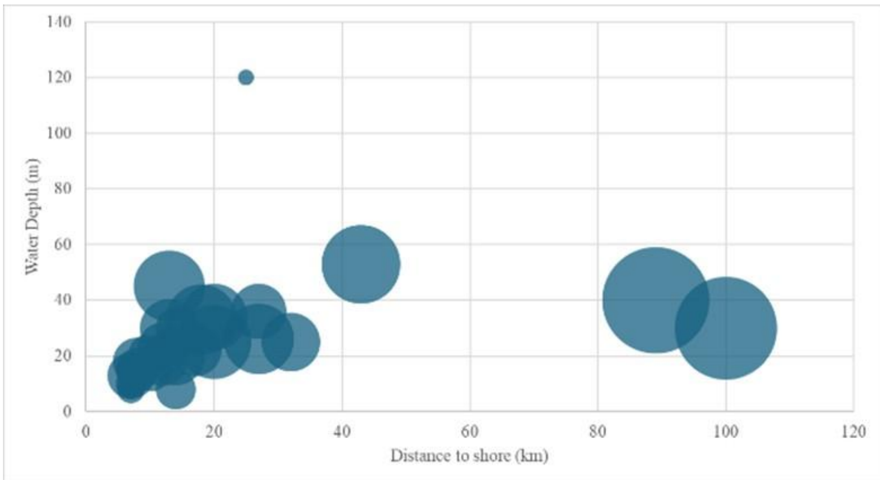


Figure 5: Distance to shore and water depth of analysed OWPs [4]

Another key characteristic is the correlation between water depth and distance to shore. For the analyzed UK offshore wind farms, this correlation is presented in Figure (5). Most of the examined wind farms are situated 20 km to 40 km from shore, in water depths ranging from 10 m to 40 m. However, recent offshore developments are being constructed at significantly greater distances. Projects like East Anglia One extend beyond 40 km offshore, while Hornsea 1 & 2 are located nearly 100 km from the coast, operating at depths of up to 60 m. In Figure (5), bubble sizes represent the installed capacity of each offshore wind farm, highlighting the trend of larger-scale projects being deployed further from shore.

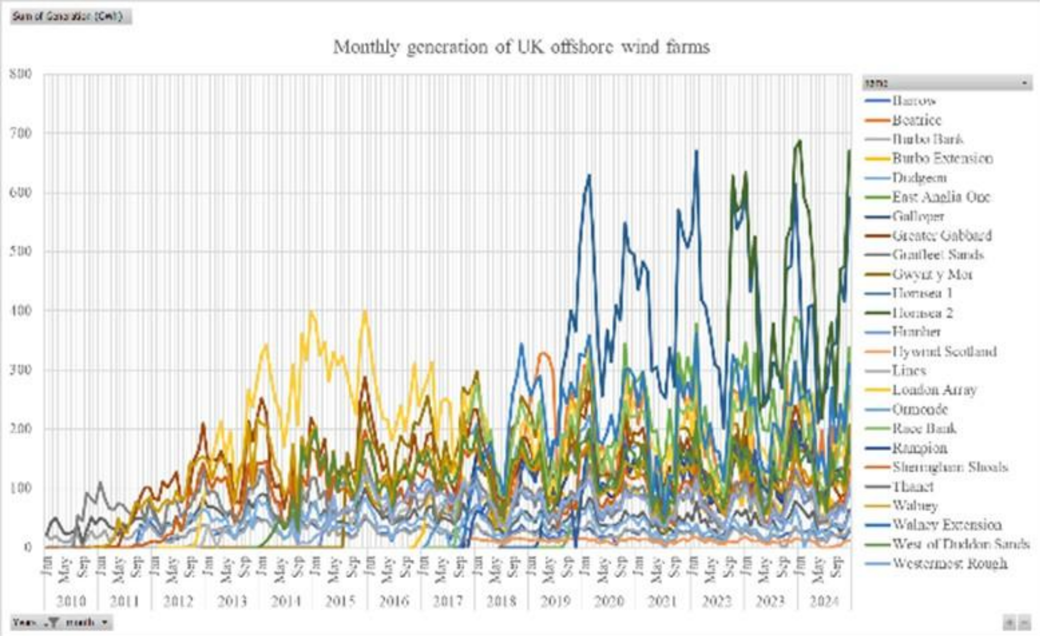


Figure 6: Monthly generation of UK offshore wind farms

The monthly electricity generation of UK offshore wind farms, presented in Figure (6), reveals distinct seasonal variations. These fluctuations are primarily driven by changes in wind speeds throughout the year, with peak generation typically occurring during the winter months and lower outputs observed in the summer. This pattern aligns with the UK's prevailing wind conditions, where stronger winds are common from October to March, leading to higher electricity generation. Conversely, wind speeds tend to be lower during the summer, resulting in reduced output. Recapitulating, all this experience has provided valuable insights into turbine performance, maintenance strategies, and infrastructure scaling, helping the UK optimize its wind power generation over time [5].

The UK offshore wind sector continues to expand, with almost 8 GW new offshore wind capacity currently (2025) under construction and additional projects (around 6 GW) having secured government's support through Contracts for Difference (CfD). These CfDs provide long-term price stability for developers, ensuring financial viability and accelerating project deployment. Notable projects include those awarded CfDs in the latest auction rounds, which will contribute to the UK's ambitious offshore wind targets [5].

3. OFFSHORE WIND IN GERMANY

Germany is the leader of wind energy exploitation in Europe with more than 72 GW wind power installed and a key leader in offshore wind energy as well (9.1 GW by the end of 2024) [2]. The German wind farms are primarily concentrated in the North Sea and the Baltic Sea. As of 2024, German offshore wind capacity continues to grow, contributing significantly to the country's renewable energy targets. Large projects have been awarded in the latest tenders and contribute to the country's ambitious offshore wind targets. Germany foresees 30 GW of offshore wind capacity in 2030. As wind penetration continues to grow, strategies such as demand-side response, interconnections with neighboring electricity markets and large-scale battery storage will become increasingly crucial to mitigate the effects of seasonal fluctuations [6].

Moreover, since 2023, curtailments have been imposed in the North Sea WPs, significantly affecting offshore wind farms due to grid congestion and transmission bottlenecks. These curtailments primarily occur when wind generation exceeds grid capacity, leading to temporary reductions in power output despite favorable wind conditions. This issue has particularly impacted high-capacity wind farms located far from shore, where grid infrastructure has not expanded at the same rate as offshore wind development. The impact of curtailments is visible in the capacity factor reductions for specific wind farms. DanTysk and Sandbank, which historically achieved capacity factors around 49%, saw a drop to 34% in 2023 due to increasing curtailments [4].

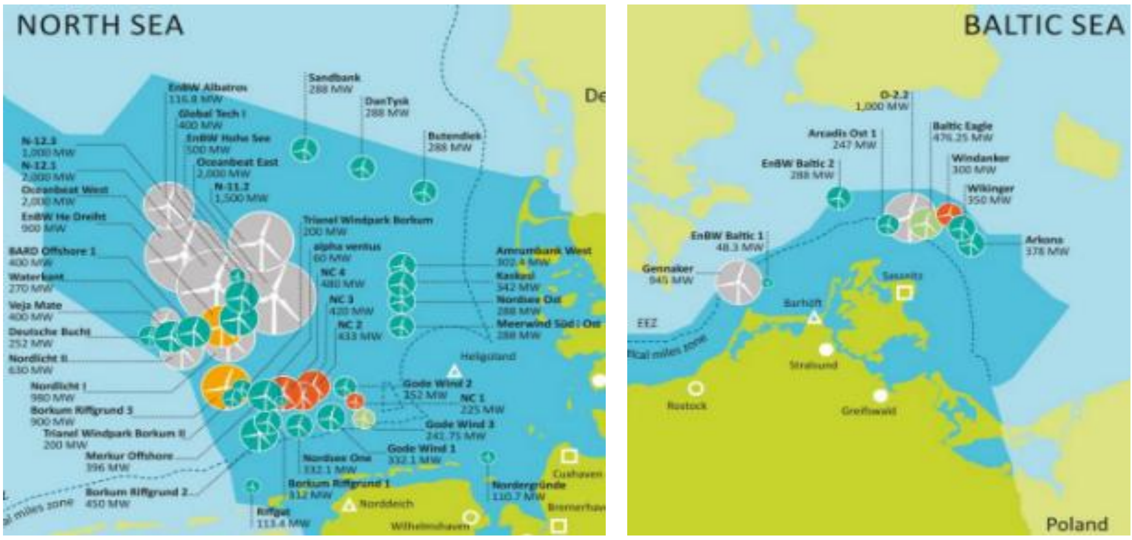


Figure 7: Map of German offshore wind farms, 2024. [6]

The geographical distribution of operational offshore wind farms in Germany is shown in Figure (7), highlighting their strategic locations in areas with strong and consistent wind resources. The North Sea hosts the majority of Germany's offshore wind capacity due to its stronger and more consistent wind speeds, allowing for the deployment of larger-scale projects such as Hohe See, DanTysk, and Amrumbank West. On the other hand, the Baltic Sea having generally lower wind speeds, offers more stable weather conditions and reduced wave effect, which has facilitated the development of projects like Baltic 1 & 2. These differences in environmental conditions influence turbine technology, foundation types and capacity factors. North Sea WPs typically achieve higher energy output but face more challenging installation and maintenance conditions compared to those in the Baltic Sea.

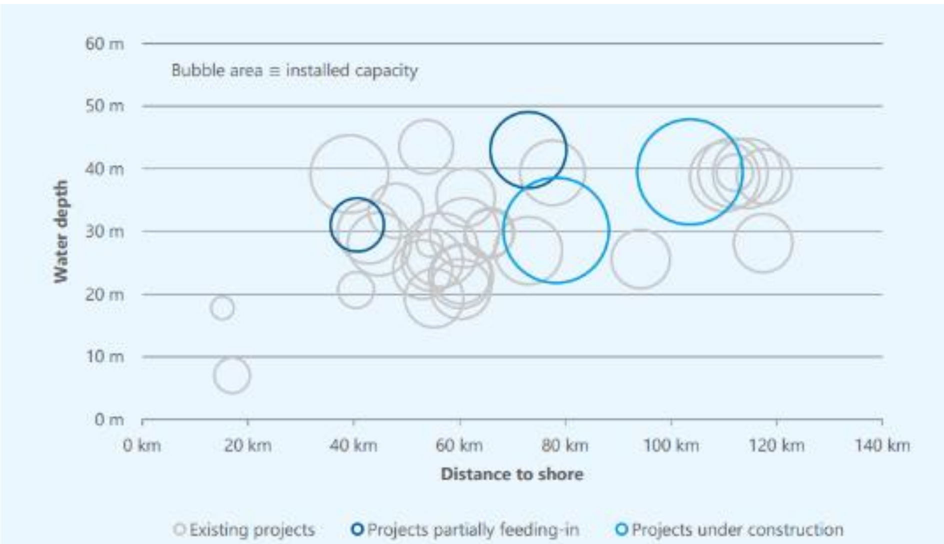


Figure 8: Water depth vs distance to shore of the German offshore wind farms [6]

The relationship between water depth and distance to shore for German offshore wind farms is presented in Figure (8). Most of the analyzed wind farms are situated between 40 km and 70 km from the shore, with water depths ranging from 20 m to 40 m. However, recent offshore wind developments, such as Hohe See and Gode Wind III, extend even further offshore, reaching depths of up to 50 m. The bubble size in the same Figure (8) represents installed capacity, illustrating the increasing scale of new projects. Notably, larger installations such as Hohe See (497 MW) and Arkona (385 MW) reflect the ongoing trend of developing higher-capacity wind farms in deeper waters.

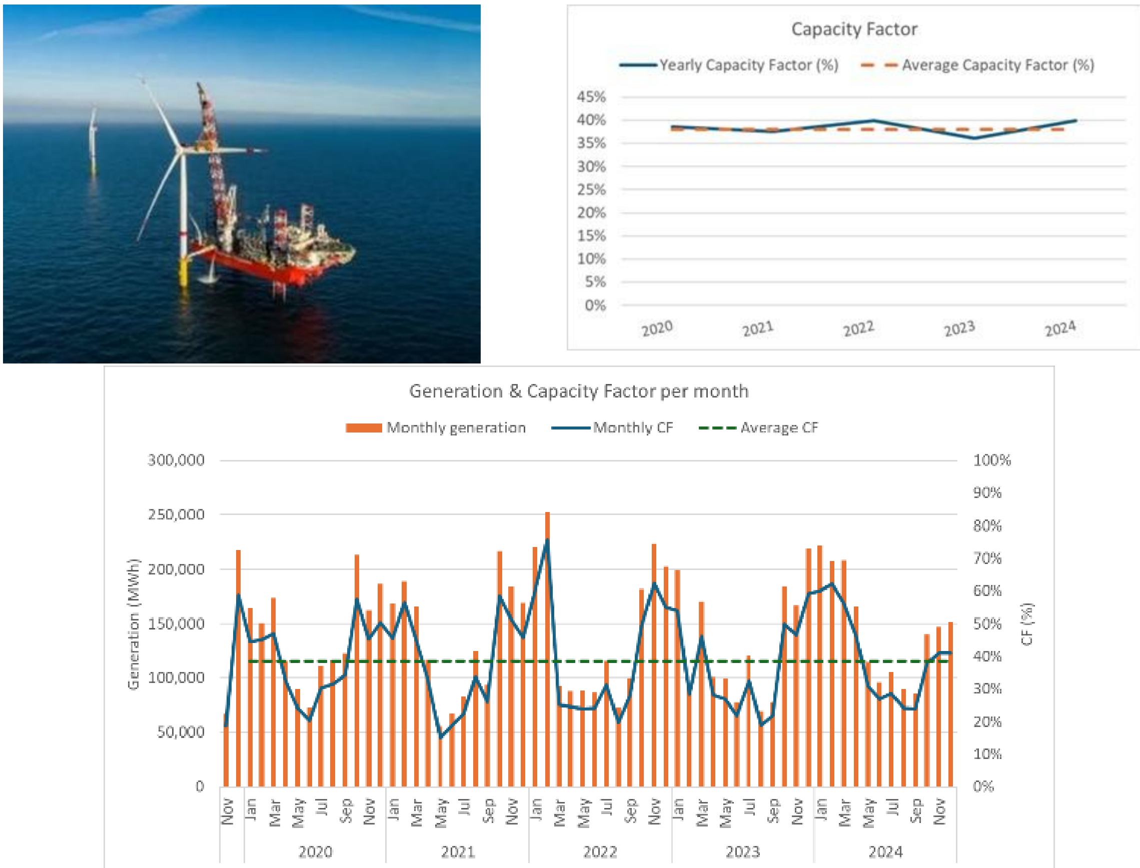


Figure 9: The North Sea Hohe See WP data presentation

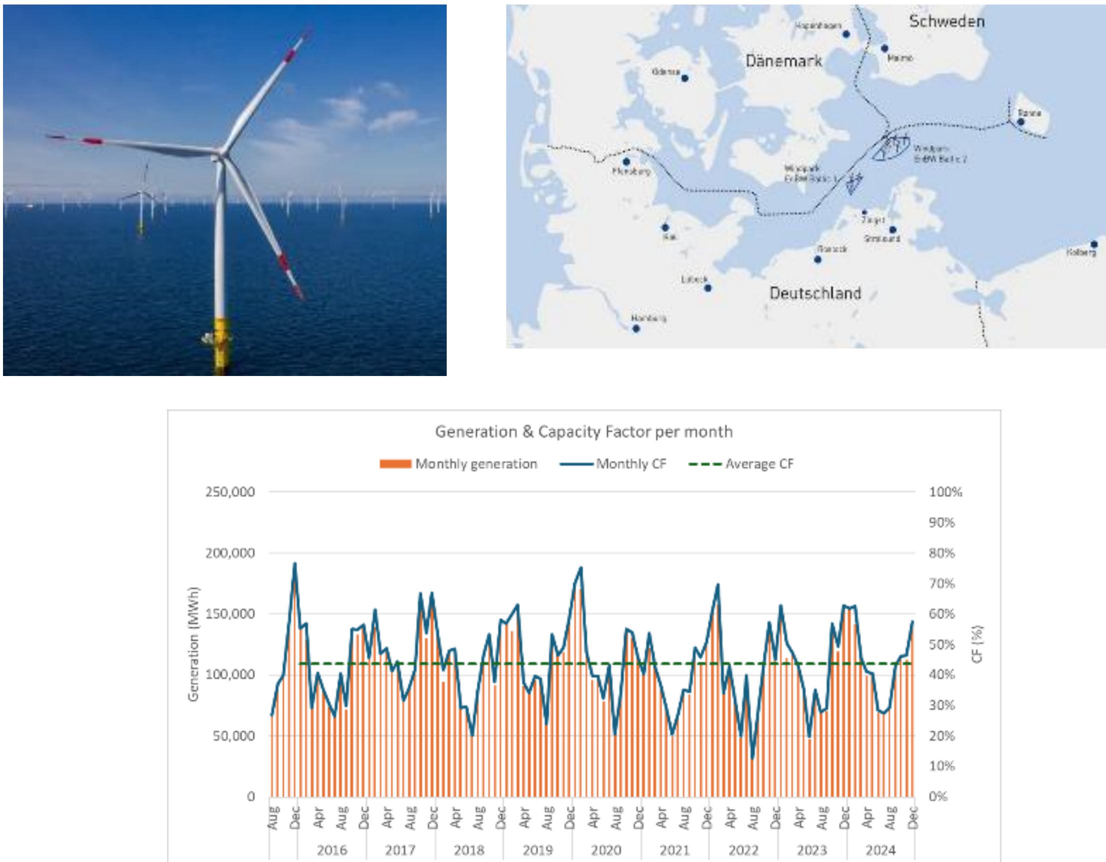


Figure 10: The Baltic-1 WP data presentation

Hohe See is one of the biggest (497 MW) WPs of North Sea, based on 71 Siemens SWT-7.0-154, Figure (9). Its annual average CF is approximately 40%, while it has been installed almost 95 km away from the nearby shore. Other interesting German WPs are the Baltic 1 & 2 ones, with installed total wind power (336.3 MW), including 21 Siemens SWT-2.3-93 and 80 Siemens SWT-3.6-120 WTs, Figure (10). The corresponding WPs are in operation since 2015, presenting long-term average CF equal to 44%. Moreover, Baltic Sea offshore wind farms have been less affected by curtailments. The monthly electricity generation of German offshore WPs is also illustrated in Figure (10), revealing a clear seasonal variation in energy output. Peak generation typically occurs in the winter months (December to February), aligning with Germany's weather conditions. On the contrary, the lowest generation levels are observed during the summer months (June to August), when wind speeds are generally lower.

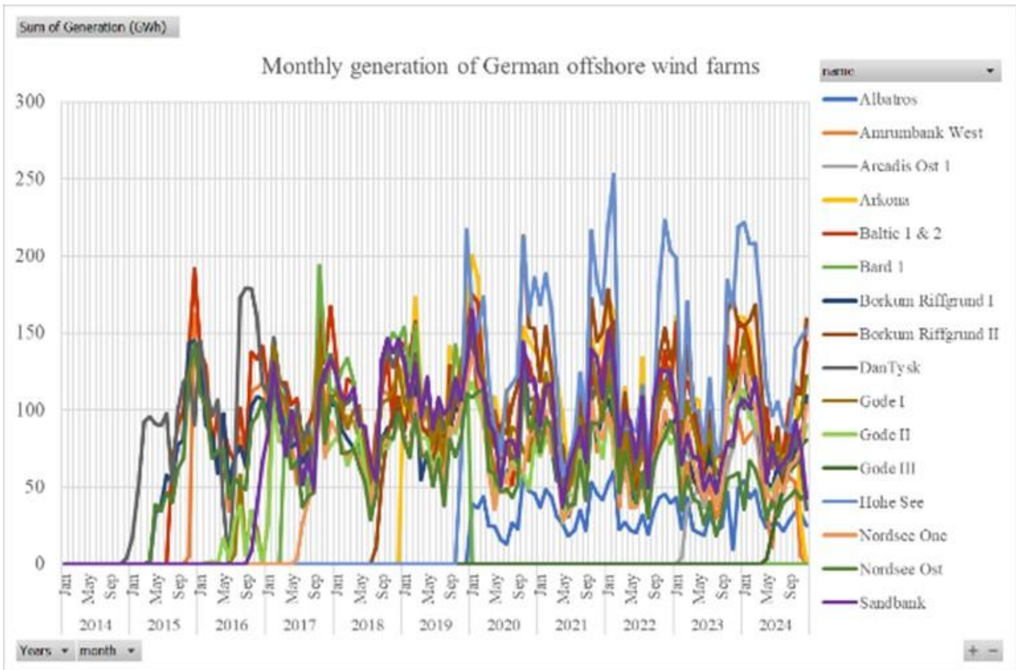


Figure 11: Monthly generation of German offshore wind farms [4]

The North Sea hosts the majority of Germany's offshore wind capacity due to its stronger and more consistent wind speeds, allowing for the deployment of larger-scale projects such as Hohe See, DanTysk, and Amrumbank West. On the other hand, while the Baltic Sea has generally lower wind speeds, it offers more stable weather conditions and reduced wave effect, which has facilitated the development of projects like Arkona and Baltic 1 & 2.

Summarizing the German OWPs energy generation analysis, one can say:

- North Sea wind farms (e.g., DanTysk, Amrumbank West, Sandbank) follow the expected seasonal trend, with strong winter generation and a noticeable decline in summer.
- Baltic Sea wind farms (e.g., Baltic 1 & 2, Arkona) show a less pronounced seasonal effect, possibly due to more stable wind conditions in that region.
- Older wind farms (e.g., Borkum Riffgrund I & II, Nordsee Ost) experience slightly more erratic generation trends, which may be influenced by maintenance schedules and aging infrastructure.
-

4. OFFSHORE WIND IN GREEK SEAS

The EU target of zero GHGs emissions until 2050 raises the need to increase the installed renewable energy capacity in Greece and enhance the energy security. Given that there is saturation of several suitable onshore areas of high wind potential, Greece -like most nations- holds increasing interest in offshore wind installations. Compared to other EU's countries, Greece is in the early stages of offshore wind development. In fact, during the last five years, the Greek State has been working on creating a comprehensive regulatory framework that addresses the complexities of offshore wind projects. This framework includes site identification, environmental assessments, permitting, and grid connections. Additionally, a solid legislation will attract international investment, facilitate technological innovation and ensure sustainable development while minimizing environmental impacts. According to the last official National Energy and Climate Plan (NECP) of Greece, the government set the target of 1.9GW of offshore wind capacity to be installed in the country until 2030 [3]. This ambitious target needs a well-organized strategic plan in order to be accomplished. In the next 20 years, from 2030 to 2050, the national plan prescribes circa six times more installed offshore wind capacity in Greece, Figure (12).

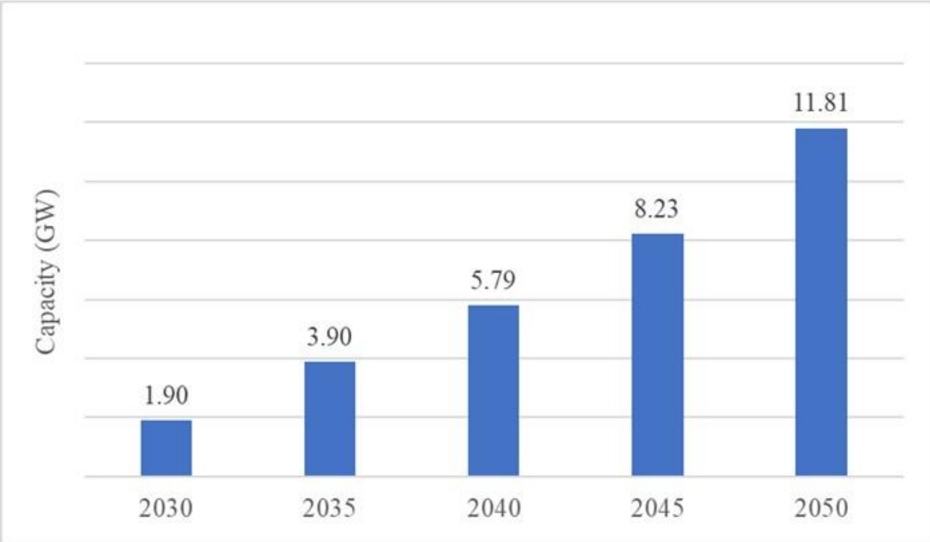


Figure 12: Final NECP targets for offshore wind in Greece [3]

In this context, Greece promotes the offshore wind energy, prioritizing this plan and organizing the relevant entity to be responsible of the development of the offshore wind farms. Hellenic Hydrocarbons and Energy Resources Management Company (HEREMA), which is the responsible state entity, has taken a proactive role in shaping Greece's offshore wind future [7]. In fall 2023, HEREMA announced a draft National Offshore Wind Farm Development Programme, which outlines strategic objectives and actions to boost the sector. This plan involves detailed mapping of Greek maritime areas to identify optimal sites for wind farms, considering factors such as wind resource potential, water depth, seabed conditions, and environmental sensitivities. HEREMA's initiative aims to create a robust foundation for offshore wind development, ensuring alignment with national energy goals and EU climate targets [7].

However, the process of creating a comprehensive regulatory framework hides many challenges. First of all, the mapping of the suitable and appealing sea areas is not an easy exercise. The criteria for the eligible Organized Development Areas (ODA) are numerous including environmental, social, touristic, as well as safety and security reasons. Additionally, another important stage required for the offshore wind development is the licensing process. After locking the eligible maritime areas that offshore wind farms can be built, the investors can participate in tenders for exploration licensing. The exploration licenses expire after 3 years from the issued date. The final developments will be decided launching a competitive bidding process in which the investors will provide bids in order to gain the license, develop their assets and operate them. Moreover, the connection to the grid needs to be considered before the offshore wind plan begins to be implemented. The Greek Transmission System Operator, IPTO, is responsible for the transmission grid and the substations needed for the operation and connection of the projects. The design and the installation of the interconnections will be held by IPTO.

When all these have been decided, more data should be collected for the selected areas. Several pilot projects are currently being initiated to assess the feasibility and performance of offshore wind farms in Greek waters. At this moment, exploration licenses have been offered for two pilot regions between the Samothrace island and Alexandroupolis, Figure (13), These projects aim to gather essential data on wind speeds, marine conditions and environmental impacts, which will inform large-scale development in the future.

HEREMA tries to finalize the National Offshore Wind Farm Development Programme, deciding the eligible sea areas and overcoming the public opposition. Ten areas have been initially decided to be in the short-term plan for the development. However, since there are objections from the public consultation, the size of the regions has been revisited. In Figure (13), with pink color appear ten areas proposed to be developed in short-term and other thirteen with green for long-term development.

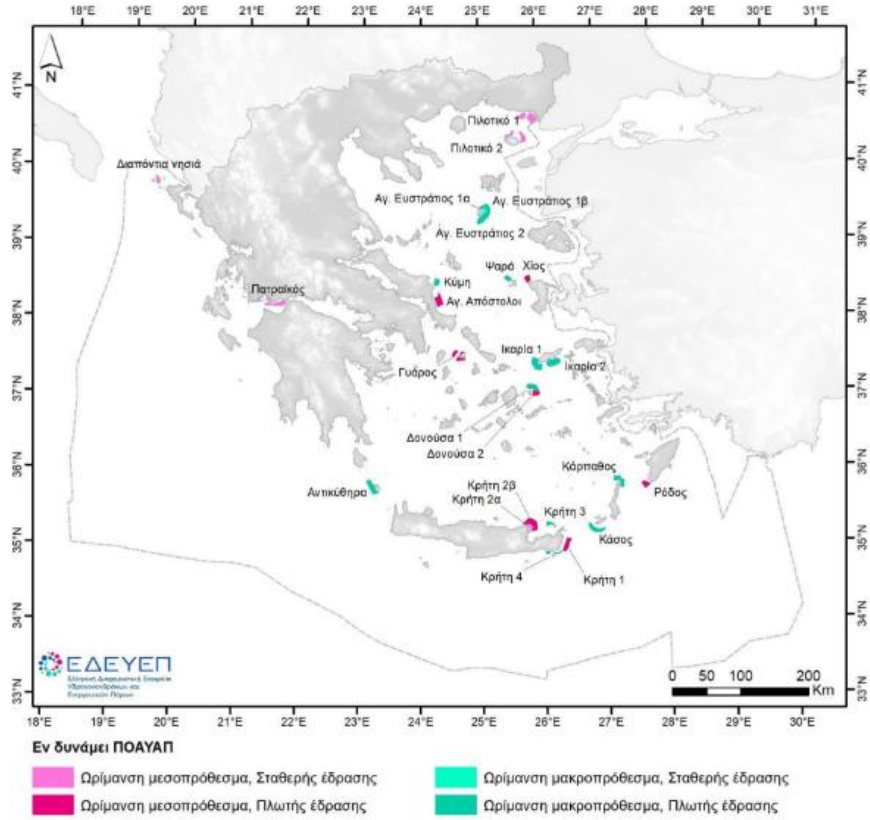


Figure 13: Map of the possible areas of offshore wind development [7]

Media sources reveal that Crete 1 and Gyaros will be the first designated areas for offshore wind farm development beyond the initial pilot zones [4]. Furthermore, recent articles speculate that offshore wind auctions could take place around 2027, setting the foundation for commercial offshore wind projects in Greek waters. If these timelines hold, the first large-scale offshore wind farms are expected to be operational by 2032, marking a significant milestone in Greece's transition to offshore renewable energy. However, WindEurope's latest forecast [2] does not allocate any offshore wind capacity to Greece by 2030, in contrast to the 1.9 GW target set in the country's NECP [3]. This disparity suggests a potential delay in implementation, possibly due to regulatory, administrative or infrastructural bottlenecks. The omission of Greece in regional forecasts [2] highlights the need for decisive and timely policy action to align ambitions with realistic deployment trajectories [8].

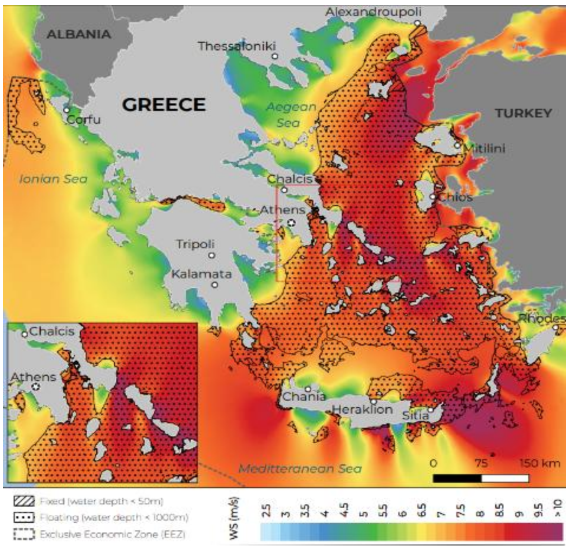


Figure 14: Offshore wind potential in Greece [9]

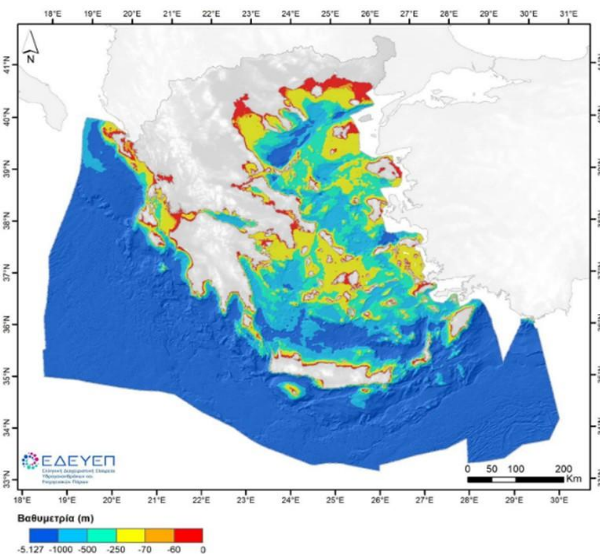


Figure 15: Bathymetric map of Greek seas [7]

According to the available data [9], Greece is characterized by high and very promising wind potential in the sea areas, especially in the Aegean Sea. In specific sea areas, Figure (14), the mean wind speed exceeds 9m/s at 100m height. These favorable conditions of strong and consistent wind speeds present a significant opportunity for offshore wind energy generation. On the other hand, Greek seas are characterized by steep seabed slopes and deep waters, often exceeding 50m even at relatively short distances from the coastline [7]. As demonstrated in Figure (15), significant portions of the Aegean and Ionian Seas reach depths well beyond 100m, making floating offshore wind technology essential for large-scale deployment. The seabed composition varies across regions, with areas of rocky, sandy, and clay-based substrates, which will play a crucial role in determining the most suitable foundation types for offshore wind turbines [10].

Another key factor influencing offshore wind development in Greece is the proximity of potential sites to energy demand centers and existing grid infrastructure. Many of the strongest wind resource areas, particularly in the central and southern Aegean, are located far from mainland Greece, raising challenges in grid connectivity and transmission capacity. The current electrical grid infrastructure requires significant upgrades, especially in regions such as Crete, N. Aegean and the Cyclades, to support large-scale offshore wind integration. The planned interconnections prescribed in the "Ten-year Network Development Plan" of TSO [3, 8] are expected to play a critical role in enabling offshore wind expansion. While Greece is making progress with planned submarine interconnections - such as those connecting Crete, the Cyclades, and Dodecanese islands to the mainland grid- the current infrastructure remains inadequate to support large-scale offshore wind deployment [8]. Furthermore, offshore wind projects require high-voltage transmission systems, potentially including HVDC (High Voltage Direct Current) technology, to minimize losses over long distances. These systems involve complex technical, economic, and environmental planning, and their long permitting and construction timelines pose a risk of delaying offshore wind integration.

Additionally, the fragmented maritime geography of Greece complicates grid planning and system operation. The development of offshore substations, export cables and landfall points will need to account for a highly scattered set of potential project sites, which differs significantly from the more compact offshore clusters seen in the North Sea. This geographical complexity, combined with regulatory and administrative obstacles, means that offshore wind infrastructure in Greece should be approached with a long-term and strategically coordinated vision. Beyond technical aspects, environmental and maritime constraints [11] should also be considered when planning offshore wind development in Greek waters. The Aegean and Ionian Seas are home to diverse marine ecosystems, including protected areas under the Natura 2000 network. Careful environmental impact assessments (EIA) will be required to mitigate potential effects on biodiversity, fisheries and marine habitats [12].

Furthermore, Greek seas are among the busiest maritime routes in the Mediterranean, with heavy traffic from commercial shipping, passenger ferries and fishing vessels. Offshore wind farm siting will need to carefully consider navigational corridors and maritime safety regulations, ensuring minimal disruption to existing sea routes [11]. Finally, the problem of defining the proprietary national rights in several regions of SE Mediterranean Sea has emerged on top of the techno-economic risk concerning the implementation of such big and novel for the area investments.

Recapitulating, the Greek seas present highly favorable conditions for offshore wind energy, with strong wind potential and several maritime areas suitable for deployment. However, deep waters, grid limitations and environmental constraints should be carefully managed to ensure successful project implementation. The adoption of floating wind technology will be essential for unlocking the full potential of offshore wind in Greece, while strategic grid planning and environmental assessments will play a key role in shaping future developments [8].

5. DISCUSSION AND COMPARISONS

The analysis of offshore wind development in the UK and Germany provides valuable insights into the evolution of the sector, including technological advancements, policy frameworks and operational challenges [13]. Both countries are global leaders in the sector, supported by strong policy frameworks and decades of operational experience. However, their approaches differ significantly due to geographical, regulatory, and infrastructural factors. The UK's offshore wind sector is characterized by large-scale projects primarily located in the North Sea, with some developments in the Irish Sea. Germany, on the other hand, has distributed its offshore wind farms across both the North Sea and the Baltic Sea. While North Sea projects in Germany share some similarities with the UK in terms of scale and distance, developments in the Baltic are generally closer to shore and in shallower waters.

In terms of installed capacity, the UK has seen rapid growth, with a clear emphasis on gigawatt-scale developments and an active pipeline supported by Contracts for Difference (CfDs) [5]. Germany’s growth has been steady but somewhat slower, influenced by regulatory frameworks and spatial constraints. Performance metrics such as generation and load factors also reveal notable differences. The UK benefits from stronger and more consistent wind resources, particularly in the North Sea, contributing to higher average capacity factors. Germany’s capacity factors [6] are slightly lower, especially in the Baltic Sea, where wind speeds are more moderate. Moreover, seasonality plays a notable role in shaping the performance profiles of offshore wind farms in both the UK and Germany. In general, both countries experience higher generation during the winter months, driven by more frequent storms and stronger wind patterns, while summer months yield comparatively lower output.

Differences also exist in foundation technologies [10]. Monopile foundations remain dominant in both countries due to their cost-effectiveness and simplicity. However, Germany has adopted a wider variety of substructures, including jacket and tripod foundations, particularly in areas with softer seabed or greater structural demands. The UK has made significant strides in floating wind, positioning itself as a leader in this emerging segment with projects like Hywind Scotland demonstrating high performance in deep-sea conditions.

Overall, while the UK and Germany share common goals and face similar technical and environmental challenges, their divergent approaches provide valuable lessons for emerging offshore wind markets. Germany’s emphasis on centralized planning and maintenance discipline contrasts with the UK’s innovation-driven and market-oriented strategy. These insights are especially relevant for Greece as it prepares to develop its offshore wind sector. Greece, with its complex maritime geography and strong wind resources - especially in the Aegean Sea - should plan its offshore wind rollout carefully, learning from the tested models of its northern European counterparts.

Regarding site selection, Greece should assess not only the wind resource potential but also the technical and logistical feasibility of deploying projects across its fragmented island geography [8]. The Aegean and Ionian Seas offer promising wind speeds, but varying water depths and seabed conditions demand tailored solutions. Lessons from the UK’s experience in deep-water and far-from-shore deployments, as well as Germany’s success in shallow, structured environments, provide complementary strategies depending on the location. In terms of energy generation and load factors, Greece is expected to benefit from high wind potential in many offshore zones. However, detailed wind profiling and long-term measurement campaigns are needed to establish realistic capacity factor expectations. Seasonal wind patterns in Greece differ from northern Europe, and localized weather conditions could influence the design and operation of offshore assets.

From a technical standpoint, foundation selection in Greece will also need to be tailored to site-specific conditions. The relatively deep waters surrounding many of Greece’s most promising offshore zones suggest that floating foundations may be more viable in the long term, as demonstrated by the UK’s experience with Hywind Scotland. However, where depths are moderate and seabed conditions allow, fixed-bottom structures like monopiles or jackets may still play a role in early-stage projects. The regulatory and market framework will determine the pace of offshore wind development. Greece must provide long-term policy certainty, transparent auction mechanisms, and risk-mitigating financial tools [8]. Drawing from the UK’s CfD scheme and Germany’s structured bidding rounds, Greece can create a balanced framework to attract both domestic and international investors.

Grid infrastructure represents perhaps the most pressing challenge. Currently, Greece’s interconnection infrastructure is still under development, with many of the islands in the Aegean and southern parts of the country not yet connected to the mainland grid or operating under limited capacity. This poses a significant barrier to offshore wind deployment. Strategic planning will be essential to prevent grid saturation, as observed in parts of Germany’s North Sea region. Delays in grid reinforcement could significantly undermine the viability of early offshore projects.

In conclusion, Greece has the opportunity to build a high-performing offshore wind sector by learning from the established paths of the UK and Germany. By applying best practices across site selection, technology adoption, regulatory design and infrastructure planning, Greece can overcome its structural limitations and unlock the full potential of its marine wind resources.

6. CONCLUSIONS

The current work investigates the offshore wind energy development in two of the biggest European wind power markets, highlighting key trends in site selection, capacity evolution, load factors, seasonality and long-term performance. The UK has led the sector with large-scale offshore wind farms, particularly in deep waters, while Germany has focused on more nearshore projects with moderate depths and a centralised regulatory approach.

These two mature case studies may provide valuable insights that can guide Greece's offshore wind industry during its first step of development. Actually, this comparison between the UK and Germany revealed key differences in capacity scaling, technological choices, and market mechanisms, offering lessons for Greece in terms of grid integration, floating wind potential and policy design. By taking into consideration these perceptions, Greece can accelerate its offshore wind deployment while addressing potential challenges related to grid infrastructure, energy production curtailments, regulatory uncertainties and public reaction.

ACKNOWLEDGEMENTS

This research was carried out in the framework of the CLIMPACT-II project.

REFERENCES

[1] GWEC 2025, "GWEC's Global Wind Report 2025. The definitive guide to the wind industry", Available at: https://www.gwec.net/reports/globalwindreport (Accessed: 26 May 2025).

[2] WindEurope 2025, "Wind energy in Europe: 2024 Statistics and the outlook for 2025-2030", Available at: https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-2024-statistics-and-the-outlook-for-2025-2030/ (Accessed: 10 April 2024).

[3] Ministry of Environment and Energy, 2025, "National Energy and Climate Plan (NECP)", Athens, Greece. Available at: https://commission.europa.eu/publications/greece-final-updated-necp-2021-2030-submitted-2025_en (Accessed: 23 March 2025).

[4] Moutafi L., 2025, "Lessons learnt from the Operation of Offshore Wind Parks in North Europe - Prospects of the Offshore Wind Parks in Greece" MSc Dissertation Thesis, Supervised by J.K. Kaldellis, Joint Course of University of West Attica-Heriot Watt University, Athens.

[5] The Crown Estate, 2024, "Offshore Wind Report 2023", Available at: https://www.thecrownestate.co.uk/our-business/marine/offshore-wind-report-2023 (Accessed: 25 March 2025).

[6] Deutsche WindGuard, 2025, "Status of Offshore Wind Energy Development in Germany Year 2024", Available at: https://www.windguard.com/year-2024.html (Accessed: 30 March 2025).

[7] Hellenic Hydrocarbons and Energy Resources Management Company (HEREMA-ΕΔΕΥΕΠ), 2023, "ΕΘΝΙΚΟ ΠΡΟΓΡΑΜΜΑ ΑΝΑΠΤΥΞΗΣ ΥΠΕΡΑΚΤΙΩΝ ΑΙΟΛΙΚΩΝ ΠΑΡΚΩΝ", Available at: https://herema.gr/, in Greek (Accessed: 23 March 2025).

[8] Kaldellis J.K., Kondili E., 2024, " Offshore Wind Parks Implementation Prospects and Challenges in Greece", 13th National Conference for Soft Energy Resources, Athens, May 2024.

[9] GWEC, 2021, "Offshore Wind Technical Potential in Greece", Available at: https://gwec.net/wp-content/uploads/2021/06/Greece_Offshore-Wind-Technical-Potential_GWEC-OREAC.pdf.

[10] Kaldellis, J.K. and Kapsali, M., 2013, "Shifting towards offshore wind energy -Recent activity and future development", Energy Policy, Vol. 53, pp. 136–148. Available at: https://doi.org/10.1016/j.enpol.2012.10.032.

[11] Kaldellis J.K., Chrysikos T., 2018, "Wave Energy Exploitation in the Ionian Sea Hellenic Coasts: Spatial Planning of Potential Wave Power Stations", International Journal of Sustainable Energy, Vol.38(4), pp.312–332.

[12] Kaldellis J.K., Apostolou D., Kapsali M., Kondili E., 2016, 'Environmental and social footprint of offshore wind energy. Comparison with onshore counterpart', Renewable Energy, 92, pp. 543–556. Available at: https://doi.org/10.1016/j.renene.2016.02.018.

[13] M Dolores Esteban, José-Santos López-Gutiérrez, Vicente Negro, 2022, "Offshore Wind Power Basics", in Comprehensive Renewable Energy (Elsevier Second Edition-J.K. Kaldellis editor), Vol.2, pp. 628 – 643.

SUSTAINABLE SOLUTIONS FOR THE PRECIOUS ISLAND RESOURCES: HARD TIMES AND GREAT EXPECTATIONS

Emilia M. Kondili[1], John K. Kaldellis[2]

[1]Optimisation of Production Systems Lab.,
[2]Soft Energy Applications and Environmental Protection Lab.,
Dep. of Mechanical Engineering, University of West Attica,
e-mail: ekondili@uniwa.gr

ABSTRACT

The present work intends to set the ground for the whole conference and is dedicated to the unique environment of islands contributing to the core mission: their sustainable development.

The island environment – physical, social, economic…- is dramatically changing during the last years. It is a very complicated problem where not only one but a whole set of emerging issues are challenging the progress and the development of the islands. The energy, the water resources, the land use, the waste, the seashore, the landscape and the seascape, the built environment, the transportation, the harbor, the traffic… In fact, in the Greek islands all the global environmental and social issues are threatening a very sensitive and vulnerable ecosystem with its own biodiversity, local production and civilization that has been living for centuries a tranquil and self-sufficient in most cases life.

This paper is not another report for the tourism and the violated capacity of the islands. It is a work that emerges from our technical knowledge as well as our long-term experience from the life in these so precious areas. Our mission is to highlight the only – to our belief - approach that will really take these unique island ecosystems to the future. And this is the need to 're-think' and 're-design' the model of the island's development.

Since we want to really achieve measurable results, our work will focus in the integrated holistic solutions for the various facets of the current 'hard times' in energy, water, land, biodiversity, transportation and all the other issues towards a sustainable future that will exploit the knowledge, the technology and the available tools of today along with the economy where these places were based on in the past years.

In the above context we will also attempt to make a short revision of all the movements and organisations that have started appearing in the islands during the last years for the minimization of impacts and the protection of the environment; thus highlighting our expectations that the holistic approach with sound technical solutions is the only sustainable perspective.

Keywords: holistic solutions, islands resources

Laboratory of Soft Energy Applications & Environmental Protection (SEALAB)

Tel. 0030-2105381237 and 0030-2105381020

Optimisation of Production Systems Laboratory (OPS)

Tel. 0030-2105381430

Address: University of West Attica, Olive Grove Campus, P. Ralli and Thivon 250, Egaleo 12244 Websites: www.sealab.gr, www.ops.mech.uniwa.gr, www.mbaenergy.gr, www.oilgasmsc.gr **Nisyros Municipality**

www.nisyros.gr, tel : 00302242360501