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A SURVEY ON GRID CONNECTION AND INTEGRATION OF OFFSHORE WIND ENERGY: TRENDS AND CHALLENGES

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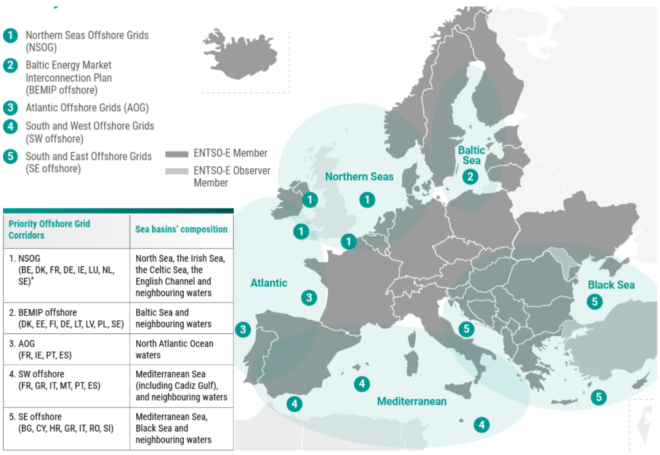
Abstract: Offshore wind energy is a clean, endogenous and efficient renewable source (RES) which will play an important role for the energy transition in Europe. Grid connection and integration of offshore wind energy is critical from a Transmission System Operator (TSO) viewpoint since there is an urgent need for offshore transmission grid development while onshore RES development is in intensive progress. The additional offshore RES capacity must be securely connected to the onshore grid while the energy must be efficiently integrated into the energy interconnected system. The paper investigates general technoeconomic aspects on connection solutions and integration for medium-scale size offshore wind farms (OWFs) while the authors discuss challenges and trends in preliminary planning of grid connection infrastructure to the HV and EHV transmission grid, as well as integration aspects. Finally, the survey paper will provide cited references; recently published bibliography for further reading and discussion.

Keywords: Offshore wind energy, power system, connection, integration, challenges

INTRODUCTION

The European Union (EU), with its 5 sea basins as depicted in Figure 1, has a significant potential for offshore wind energy. Renewable energy sources (RES) from the seas can be exploited by a great variety of technologies, making it a cornerstone of the green energy transition. The EU is investing in offshore wind energy to deliver on the energy and climate goals increasing the competitiveness and affordability of electricity and ensure security of energy supply. In line with EU countries' regional cumulative offshore goals of 86-89 GW by 2030 and 355-366 GW by 2050, offshore renewables are poised to become a main pillar of Europe's future electricity mix.



Priority Offshore Grid Corridors	Sea basins' composition
1. NSOG (BE, DK, FR, DE, IE, LU, NL, SE)*	North Sea, the Irish Sea, the Celtic Sea, the English Channel and neighbouring waters
2. BEMIP offshore (DK, EE, FI, DE, LT, LV, PL, SE)	Baltic Sea and neighbouring waters
3. AOG (FR, IE, PT, ES)	North Atlantic Ocean waters
4. SW offshore (FR, GR, IT, MT, PT, ES)	Mediterranean Sea (including Cadiz Gulf), and neighbouring waters
5. SE offshore (BG, CY, HR, GR, IT, RO, SI)	Mediterranean Sea, Black Sea and neighbouring waters

Figure 1: Offshore grid corridors and Sea basins in Europe according to ENTSOe.

To make sure that offshore renewable energy can help reach the EU's ambitious energy and climate targets for 2030 and 2050, the European Commission (EC) published a dedicated EU strategy on offshore renewable energy in 2020 by proposing specific ways forward to support the long-term sustainable development of the sector. Setting the targets for an installed capacity of at least 60 GW of offshore wind by 2030, and 300 GW, respectively, by 2050. EU countries have exceeded these targets, both in the short and long term. The strategy addresses a broad range of areas, such as maritime spatial planning, coordinated grid planning and development, improving the regulatory framework, mobilising investment and EU funding, research and innovation and developing supply chains.

The actions proposed in the EU strategy by the Members primarily have been implemented or are well under way. In 2023, the Commission adopted a Communication on the delivery of the EU Offshore Strategy (COM/2023/668). It outlines the achievements on the strategy's implementation and also includes further actions and areas of focus for the Commission, such as

- supporting national authorities in the streamlining of permitting procedures
- establishing regional maritime spatial planning per sea basin
- strengthening the resilience and protection of offshore infrastructure
- cooperating on cybersecurity
- supporting the revision of the European Technology and Innovation Platform (ETIP) strategic agenda on wind energy

A key deliverable of the strategy was to revise the Regulation on Trans-European Energy Networks (TEN-E)

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to better consider offshore renewables and grids. It includes infrastructure categories for hybrid offshore grids and radial lines, as well as permitting provisions to accelerate the scale-up of offshore grids. In addition, the TEN-E Regulation supports regional cooperation between EU countries to define, with support from the Commission, non-binding regional goals for offshore renewable deployment within each sea basin, to be revised every 2 years. In December 2024, EU countries concluded such regional agreements for the second time, updating the first regional agreements of January 2023. Based on the ambitions expressed by EU countries, TEN-E calls for ENTSO-E to develop offshore network development plans (ONDPs) for each EU sea basin. ENTSO-E published the first ONDPs in January 2024, to be revised every 2 years [1-6].

As a subsequent TEN-E deliverable, the EC adopted in June 2024, Guidance on collaborative investment frameworks for offshore energy projects to support EU countries, national regulatory authorities and transmission system operators in their discussions on cost-sharing agreements for achieving their regional offshore renewable targets. ENTSO-E will accordingly apply this Guidance to the ONDPs by mid-2025. The Ten-Year Network Development Plan (TYNDP) is ENTSO-E's network planning tool or, in other words, the European electricity infrastructure development plan. Mandated by Regulation (EU) 2022/869, it provides a pan-European vision of the future power system and investigates how power links and storage can be used to make the energy transition happen in a cost-effective and secure way. The Offshore Network Development Plan (ONDP) is a new component of the TYNDP, focused on needs for offshore transmission infrastructure. It translates the EU Member States' non-binding agreements on offshore goals from January 2023 into offshore transmission corridors, transmission equipment needs and related costs. ONDP is mandated by the TEN-E Regulation (2022/869 EU Reg Art 14.2) [1-6].

Offshore wind energy is expected to be an important part of the European energy transition and a key contributor to reach the targets of the EU Green Deal. The electricity market design should ensure the efficient utilisation of resources by providing efficient price signals (incentives) to producers, consumers, storage and infrastructure operators both for short term operations and for long-term investments. A key issue is how to integrate massive amounts of offshore wind generation to the onshore markets in the most efficient manner.

The remaining of this article is structured as follows: Section 2 describes connection and integration of offshore wind to the synchronous continental grid. Section 3 is devoted to offshore wind in Greece and the role of the TSO. The experiences of offshore grid deployments in Greece are promoted in Section 4. The challenges of the offshore wind projects are discussed in Section 5, while the article closes with the conclusions. Finally, the bibliography section provides references for further reading.

1. CONNECTION AND INTEGRATION OF OFFSHORE WIND

The connection of offshore wind farm is continuously evolving due to many factors. The dominant voltage level of the turbine transformer is 66 kV while there are new projects with 132 kV as depicted in Figure 2. The size of the wind farm as well as the distance from the grid connection point is critical for the selection either HVDC or HVAC transmission technology [7-16]. It is declared that the scope of the paper is not to explain in detail the HVDC technology but to provide basic information about the connection of 200~300 MW minimum sized wind parks mainly with ac-technology planned in Greece. Regarding the inter-array cabling system, the developers decided to select up to 3 types of cross-sections.

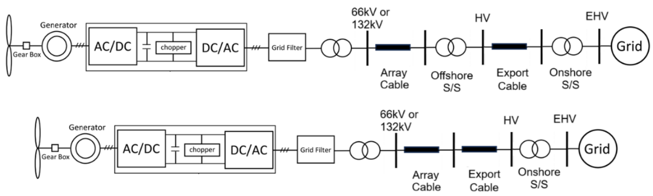
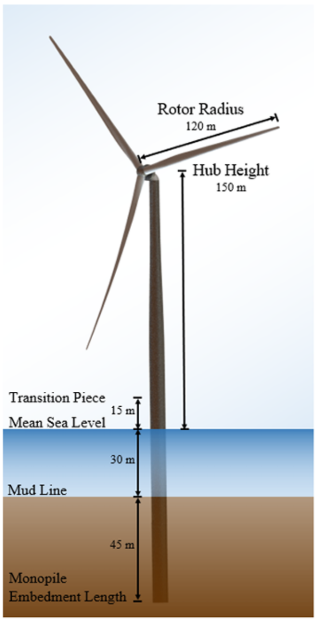


Figure 2: A typical connection of a wind farm to the continental grid with HVAC transmission technology. Notably, the 15 MW rated power offshore wind turbine with 66kV output voltage is considered.

The industry has introduced offshore wind turbines of 15 MW rated power [17] with rotor diameters more than 200 m as shown in Figure 3 presenting in the attached table the assumed characteristics.



Parameter	Units	Value
Power rating	MW	15
Turbine class	-	IEC Class 1B
Specific rating	W/m^2	332
Rotor orientation	-	Upwind
Number of blades	-	3
Control	-	Variable speed Collective pitch
Cut-in wind speed	m/s	3
Rated wind speed	m/s	10.59
Cut-out wind speed	m/s	25
Design tip-speed ratio	-	9 0
Minimum rotor speed	rpm	5.0
Maximum rotor speed	rpm	7.56
Maximum tip speed	m/s	95
Rotor diameter	m	240
Airfoil series	-	FFA-W3
Hub height	m	150
Hub diameter	m	7.94
Hub overhang	m	11.35
Rotor precone angle	deg	-4.0
Blade prebend	m	4
Blade mass	t	65
Drivetrain	-	Direct drive
Shaft tilt angle	deg	6
Rotor nacelle assembly mass	t	1,017
Transition piece height	m	15
Monopile embedment depth	m	45
Monopile base diameter	m	10
Tower mass	t	860
Monopile mass	t	1,318

deg degrees; rpm revolutions per minute
m meters; t metric tons
m/s meters per second; W/m^2 watts per square meter

Figure 3: The IEA Wind 15 MW offshore reference wind turbine [7].

Let's assume an hypothetical 2×300 MW=600 MW offshore wind farm, so the typical interconnection scenaria to the mainland grid will preliminarly be investigated. Followingly, it is assummed that:

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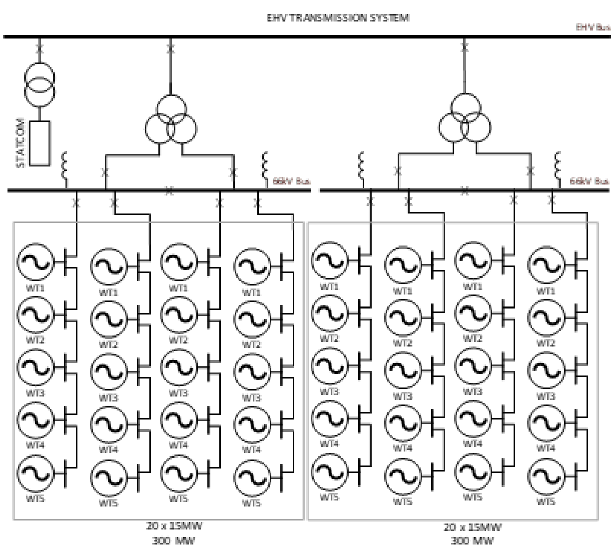
- the developer propose 8 organized clusters of 5 wind turbines per export cable (5×15MW=75MW)
- a total number of 8 export cables of 1×3×630 mm^2 Cu is assumed with maximum power capacity of 90MVA per cable

Two basic study connection scenaria as depicted in Figure 4 can be easily defined:

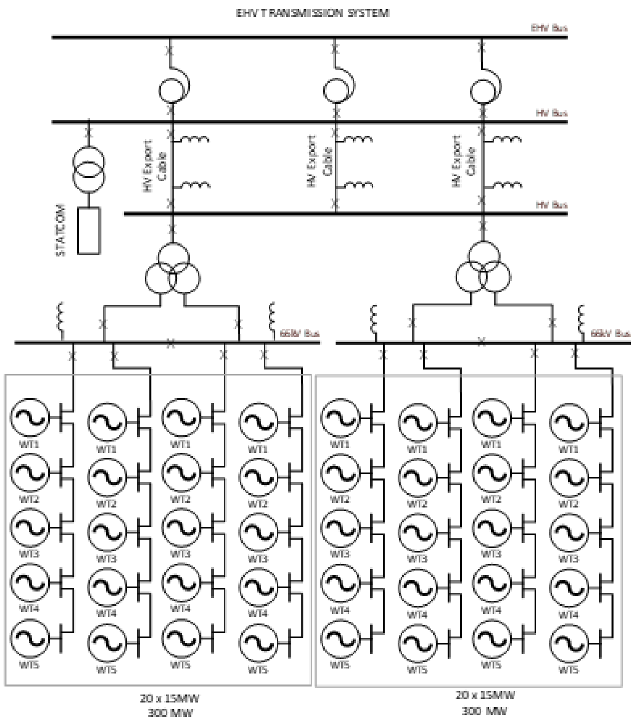
Scenario 1. The offshore wind power is transfered directly to the mainland grid connection point with 8 submarine export cables at 66kV. Two 320MVA step-up power transformers 66/400kV with dual windings at 66kV side (2×160MVA) are at least necessary for the connection to the EHV grid.

Scenario 2. There is an intermediate offshore (or on-island) substation 66/150kV with three 280MVA step-up power autotransformers 66/150kV and three 150kV submarine export cables 1×3×800 mm^2 Cu are needed with maximum power capacity of 220MVA per cable. Of course, there is a need for an addtional three 280MVA step-up power autotransformers 150/400kV or alternatively two 320MVA step-up power autotransformers 150/400kV.

The two offshore wind farms 66kV busbar systems can coupled as well either by a third sectionalizer bay or via cable (two bays are necessary). Of course, there is a need for reactive power compensation with fixed/variable shunt reactors at 66 kV busbar and 150kV cables as well as probably a need for a Static Sychronous Compensator (STATCOM) that special study will outcome. These scenaria can be studied in details while the maturity of the offshore project will be performed. Of course, the standarization of the connection schemes can be beneficial both for a TSO and a developer.



a) Scenario 1



b) Scenario 2

Figure 4: Single line diagrams of connection topologies for two general scenaria of a 2x300 MW offshore wind farm connection.

The optimal integration of offshore wind power is guaranteed only via the Grid Codes while an offshore wind farm is assumed as a typical power plant i.e. offshore wind power plant (OWPP) providing grid services. The following aspects are covered:

- Frequency and voltage tolerance requirements.
- Active power and frequency control. This control contributes to the frequency stability of wind power plants. According to the ENTSO-E Network Code “Requirements for Generators” NC-RfG, frequency control has three operation modes: limited frequency sensitive mode – overfrequency (LFSM-O), limited frequency sensitive mode – underfrequency (LFSM-U), and frequency sensitive mode (FSM).
- Reactive power control which contributes to the voltage stability of the grid. Reactive power control is usually achieved by various types of reactive power compensation equipment, such as (fixed/variable) shunt reactors and STATCOM, together with generator’s PQ capability. The control is performed in a direct manner by receiving external set points in reactive power and power factor control modes or in an indirect way with a voltage reference and predefined V-Q slope in voltage control mode.
- Fault ride-through (FRT) capability which includes two parts: low voltage ride-through (LVRT) and high-voltage ride-through (HVRT).
- Power quality requirements like flicker and harmonics.

2. OFFSHORE WIND DEVELOPMENT IN GREECE

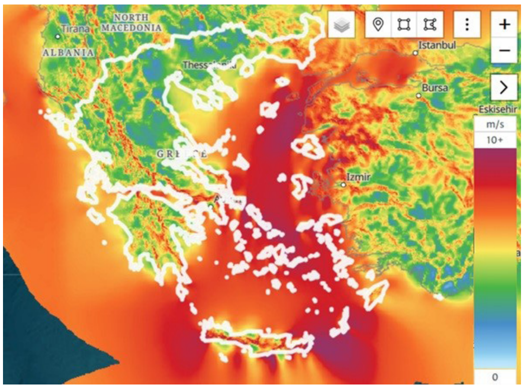
With offshore wind resources in Greece considered among the most attractive for energy production in Europe – characterised by strong and constant winds throughout the year – the potential of the sector cannot be overemphasized. Although onshore wind continues to dominate global wind energy production, the saturation of exploitable sites, a lower comparative energy capacity, and visual and noise disturbances are just a few of reasons behind the current international surge in offshore wind farm (OWF) development.In July 2022, in a landmark move that officially kick-started the deployment of offshore wind development in Greece, the Hellenic Parliament approved the first law on OWFs (Law 4964/2022, GGI A' 150/30.07.2022). As a result, the Hellenic Hydrocarbons and Energy Resources Management Authority (HEREMA) [17] was appointed – on behalf of the Greek state – as the authority responsible for the management of these rights with respect to the research, exploration, and identification of OWF Organized Development Areas (OWFODA), in addition to the assignment of research rights to third parties within said development areas. The Greek government set an ambition to deliver at least 2 GW of offshore wind energy capacity by 2030 as part the National Energy and Climate Plan (NECP).

HEREMA's responsibilities include the preparation of the National OWF Development Programme based on the results of a multi-criteria technical study launched by the Ministry of Environment and Energy as well as the respective Strategic Environmental Impact Assessment (SEIA). Moreover, HEREMA conducts all technical studies and corresponding SEIA for designating the specific zones where OWF will be developed (referred to as "OWF Organised Development Areas"). Finally, the Authority will evaluate the bids submitted by potential investors based on professional, technical, and financial criteria, and issuance of Exploration and Survey Licenses for OWF development and issuance of Exploration Licenses. A key role is the participation as a member of the Coordination Committee for the Connection and Development of OWF Projects.

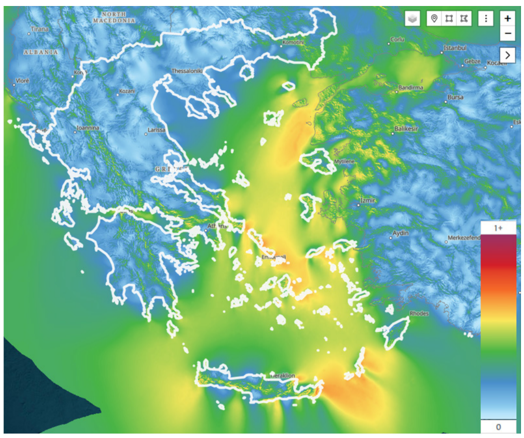
The Draft National Development Programme for Offshore Wind Farms and the Strategic Environmental Impact Assessment were presented in October the 31st, 2023. The presented programme defines the eligible OWFODA and estimates the capacity of OWF projects that can be developed, in the mid-term (up to 2030-2032) and long-term (after 2030-2032) horizon. The draft National Programme for the Development of OWF includes 25 areas, covering a total area of 2,712 km2 and with an estimated minimum capacity of 12,4 GW. The majority of the proposed offshore areas are suitable for floating technology. 20 exclusion criteria applied in total in order to safeguard environmentally sensitive areas and marine activities in the Greek territory. These criteria take into account, 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.

Figure 5 presents the wind potential and capacity factor in offshore regions of Greece as well as bathometer map and potential areas for offshore wind development. Moreover, wind distributions are provided as well.

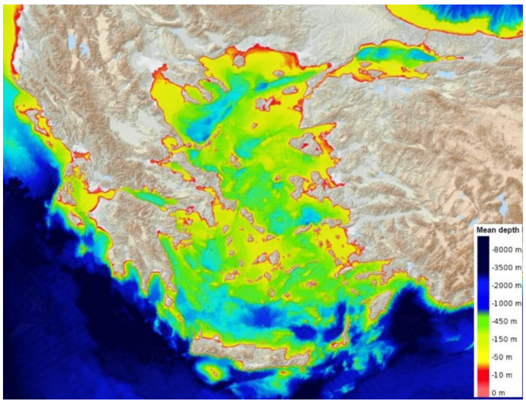
Other key organisations within the development of the sector include the Independent Power Transmission Operator (IPTO) and the Regulatory Authority for Energy, Waste and Water (RAAEY) which are also members of the Coordination Committee. IPTO is responsible for the development of interconnection between the transmission grid and OWFs, including the design, development, installation, and operation of interconnections between the Hellenic Electricity Transmission System (HETS) to the OWF Organised Areas Development (OWFODA). RAAEY, on the other hand, is in charge of organising a competitive tender process for the granting of operational aid for each OWFODA. It should be noted that the offshore area extending south of the coastline of the Regional Unit of Evros and north-northeast of Samothrace Island is being prioritised as an Organised Area for OWF Development, as it was designated by Law 4964/2022 as a pilot area for OWF development with a total capacity of up to 600 MW.



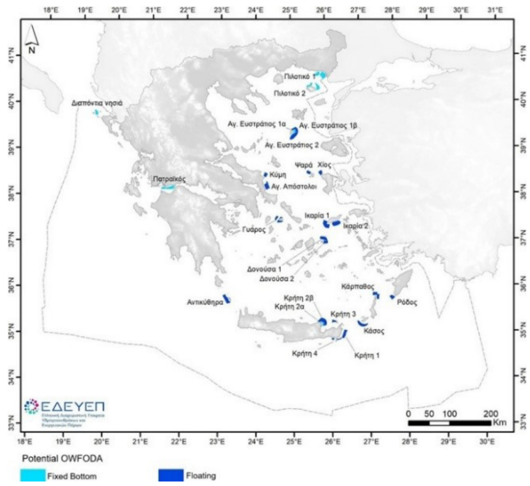
a) Wind speed map



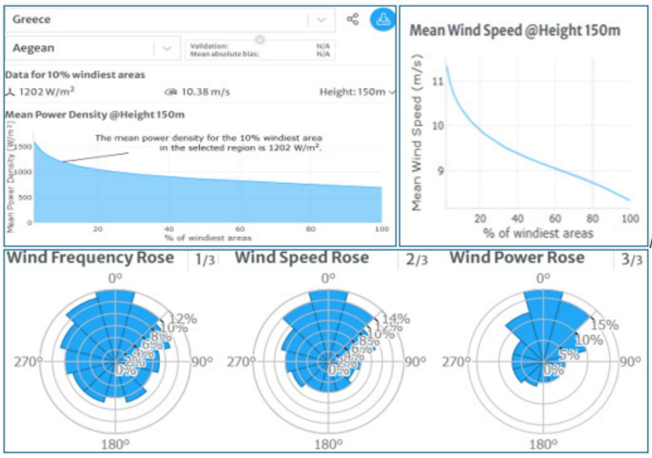
b) Capacity factor map for IEC Class I wind generator



c) Bathymetry map



d) Potential offshore wind farms organized development areas



e) Wind characteristics at Aegean Sea at 150m height from sea level

Figure 5: Main characteristics of offshore wind in Greece a) wind speed, b) capacity factor for Class I wind generator, c) bathymetry map, d) potential bottom-fixed (cyan) and floating (blue) offshore wind farms organized development areas (OWFDA) proposed in the Draft Plan by HEREMA (2023), and e) wind characteristics at Aegean Sea at 150m height from sea level [19,20].

3. OFFSHORE GRID EXPERIENCES IN GREECE

The Greek TSO (IPTO) [21] has gained a great experience in developing and operating offshore grid specifically from the mainland to the islands. Initially, the first island interconnections were completed in Ionian Sea where the depth as well as the distance were acceptable for the available technologies and means. Since the establishment of IPTO in 2011, numerous interconnection projects have been planned, constructed and are currently in operation as depicted in the grid map of Figure 6.

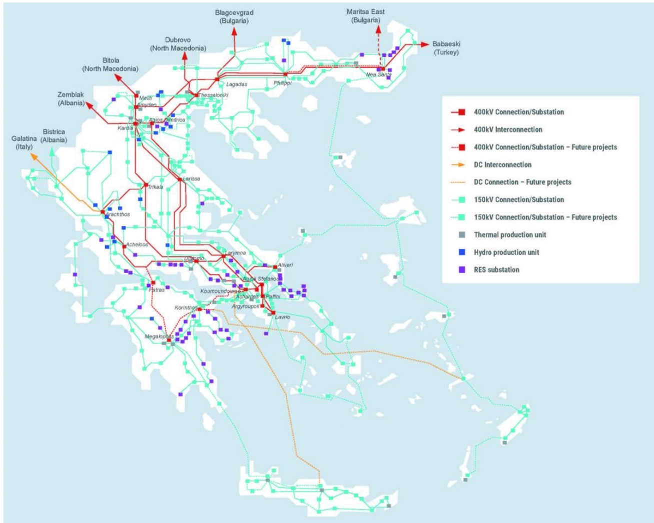


Figure 6: The grid map of islands interconnection in Greece.

The project of the Interconnection of Cyclades Islands was a technically complex project, completed in three phases, which have ensured reliable, economic and sufficient supply of electricity to the islands of Syros, Paros, Tinos, Mykonos and Naxos. Nowadays, the interconnection program foresees the interconnection of the rest southeastern islands: Serifos, Milos, Folegandros and Thira (Santorini). This offshore transmission system is comprised of 150kV submarine cables, GIS substations in all islands, as well as reactive power compensation of all cables and Static Var Compensators (in Syros and Thira).

The interconnection of Crete with the Peloponnese constitutes the first phase of the interconnection of Crete with the Hellenic Electricity Transmission System (HETS). The project consists of the construction of 150 kV AC 2x200 MVA interconnection between the island of Crete and peninsula Peloponnese. The project includes two new submarine cables with the length of 135 km each, upgrades of the existing and construction of new transmission lines, underground cables and substations in the Peloponnese and Crete, static synchronous compensator on Crete. The landing points of the submarine cables are in the Kissamos Bay (Crete) and the Malea peninsula (Peloponnese). The second phase is the direct Crete-Attica interconnection marks Greece's largest and most complex electricity transmission project. It involves the interconnection of Crete to the mainland system (Attica) with a 1GW transmission capacity link, utilizing direct current (DC) technology. The project is one of the few worldwide employing innovative VSC (Voltage Source Converters) technology for AC to DC conversion and ranks among the world's top three in terms of sea depth (1000m).

The TYNDP for the next decade 2025 – 2034 of IPTO forsees finally the interconnection of Dodecanes islands (Kos, Rhodes, and Karpathos) as well as Northeastern Aegean (Skyros, Lesvos, Limnos, Chios, Samos). Notably, a second 1GW VSC-HVDC interconnector has been planned from Korinthos directly to Kos.

4. CHALLENGES

The interconnection and integration [22-24] of offshore wind power is critical to a TSO. Numerous of challenges are identified specifically in the era of global energy transition.

4.1. Supply chain

At this moment, the global supply chain faces a huge demand. Wind turbines components - like turbines, blades, nacelles, and foundations – array and export cables, as well as offshore and onshore GIS substation equipment demand is beyond the manufacturing capacity and scalability. Thus, most of the developers as well as the TSOs decide to announce tender procedures aiming framework-agreements for submarine and underground cables as well as GIS substations equipment. Specifically, it is worth noting that the HVDC market has a great demand for new projects. Supply chain disruptions—whether from geopolitical tensions, mining limitations, or price volatility—can hamper production or/and press the cost as well as special vessel shortages exacerbate installation delays.

4.2. Capacity allocation and Curtailments

The rapid deployment of RES – mainly PV and wind power – both in transmission system as well as in distribution network in the mainland as well as numerous applications for new project development has resulted in saturation of power generation. The power balance is expressed in (1):

$$P_S+P_N+I=E+L_S+L_N+S+Losses \quad (1)$$

where P_S and P_N is the summary power produced in System and Network, I are the summary of imports and E is the summary of exports, L_S and L_N is the load in System and Network respectively. When the generation is exceeded, the Operators have to proceed to curtailments. This phenomenon is very usual in Europe and numerous energy quantities are curtailed for keeping the System security. Notably, the authors have performed an extensive capacity allocation study for the first stage of 2 GW offshore in Greece.

4.3. Energy Storage

As it is noted at the previous subsection, energy storage is of cornerstone importance for high penetration of stochastic RES. At this moment in Greece there are only two hydro pumping stations of 700MW installed capacity in the mainland as well as two hybrid projects in Ikaria (pumping facility) and Tilos (battery system) islands. Moreover, there is a project for a 700MW hydro pumping in Amfilochia in western Greece. The national energy and climate plan foresees a plan for 3 – 4 GW storage mainly autonomous as battery energy storage stations for a scenario 80% RES penetration in 2030 horizon.

4.4. Flexibility and Demand response

Flexibility and Demand Response are both important concepts related to energy management, particularly in relation to how electricity systems balance supply and demand. Both wind and PV farms can operate as power plants with flexibility functions like thermal and hydro power plants. Moreover, demand response (DR) is a specific strategy used to manage demand for electricity. It involves encouraging consumers to adjust their electricity usage in response to supply conditions, typically to help balance the grid when demand is high or when there's a shortage of supply. It helps avoid blackouts, stabilize the grid, and can also reduce the need for peaking power plants. For this purpose, a lot of TSOs operate a dedicated RES control center in order to manage the RES plants.

4.5. Cross-border interconnections and Regional coordination and control

IPTO has a strategic vision in developing and promoting new cross border interconnections as well as upgrading the current ones, specifically the following projects are mentioned the second interconnection with Italy, the second interconnection with Albania, the second interconnection with Türkiye, upgrading of the interconnection with North Macedonia, the interconnection with Germany, the interconnection with Cyprus and Israel, the interconnection with Egypt as well as with Saudi Arabia. These interconnections can expand the transfer capacity of RES and accelerate the energy transition.

Due to the fact that power flows are not only directed from the low-price regions to the high ones but are defined by the energy demand mainly to central and northern industrial Europe, numerous grid bottlenecks appeared. The role of regional coordination and control centers are of major importance providing a set of services e.g. common grid model (CGM), coordinated security analysis (CSA), capacity calculation (CCC) an outage planning (OPC), short term adequacy (STA), and critical grid situation (CGS). Notably, the Southeastern Electricity Network Coordination Center (SEleNe CC) [25] conducts all the above-mentioned in the region.

5. CONCLUSION

Offshore wind energy is important for the global energy transition while numerous projects have been planned and operated in Europe. For Greece, which is characterized by special geographic and wind potential conditions, the development of this sector is of major priority. A framework for coordinated offshore grid development is necessary in order to successfully face the challenges. The TSO centric model for the connection of the offshore wind farms turns out to be successful and efficient and can improve the system reliability, the project constructability, project risk mitigation, minimization of potential environmental impacts minimization, and provide optimized technical solutions by flexibility, modularity and integration. A long-term study of an offshore network development can provide the identification of potential transmission expansion in the continental grid while the adoption of technological trends of offshore transmission can enhance the grid reliability and security of supply with high-RES penetration.

Disclaimer

This paper is a technical review. The opinions expressed in this publication are those of the authors. They do not purport to reflect the opinions or views of IPTO or other companies / organizations.

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BIOGRAPHY

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