Journal of Energy

VOLUME 75 Number 2 | 2026

journal homepage: http://journalofenergy.com/

Potential Assessment and Techno-Economic Analysis of Offshore Wind Farm in Croatia

Andrija Mustapić, Juraj Havelka

***Summary* — The aim of the paper is to assess the technical and energy potential of offshore wind farms in the Adriatic Sea and to conduct a techno-economic analysis of their feasibility. The paper is based on the hypothesis that the Adriatic Sea possesses significant, but spatially and technically constrained, potential for offshore wind development, the realization of which depends on technological progress, the regulatory framework, and integration into the national power system. The structure of the paper includes an overview of the theoretical and technical foundations of offshore technology, an analysis of the natural and spatial characteristics of the Adriatic, a methodology for assessing energy potential, the development of a techno-economic model, and the interpretation of results, along with consideration of limitations and recommendations for further research.**

***Keywords* — offshore wind farm, techno-economic analysis, Adriatic Sea, Croatia.**

I. Introduction

Accelerated energy transition at the level of the European Union and the rest of the world has, in recent decades, resulted in a strong increase in investments in renewable energy sources, with wind energy playing a prominent role in the decarbonization of the power sector. Momentum has been observed in the development of offshore wind farms, which, due to more favorable and stable wind conditions, larger installed turbine capacities, and reduced spatial constraints, achieve higher capacity factors compared to onshore projects. In the European context, technological and market development is led by projects in the North Sea, where standards for design, construction, and operation have been established that today serve as a reference model for emerging markets. Republic of Croatia, as a member of the European Union, has committed to implementing climate and energy targets that include increasing the share of renewable energy sources in gross final energy consumption and reducing greenhouse gas emissions. Therefore, the Adriatic Sea represents a potentially significant, yet so far insufficiently explored, energy resource. The specific characteristics of the Adriatic—its relatively shallow northern part, greater depths in the central and southern areas, pronounced seasonality of winds (bura and jugo), the sensitivity of marine ecosystems, and the importance of tourism and maritime transport—require an interdisciplinary approach when considering the possibilities for offshore wind farm development.

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The assessment of offshore wind potential in the Adriatic cannot be based solely on the analysis of wind speed and frequency, but must also include spatial planning, technical, environmental, and socio-economic factors. Technical feasibility depends on sea depth, geotechnical characteristics of the seabed, distance from the coast and grid connection points, while the economic viability of projects arises from the relationship between investment and operational costs, expected electricity production, market electricity prices, as well as the regulatory framework and incentive mechanisms. A particular challenge lies in aligning energy projects with existing economic activities, environmental protection, and spatial planning of coastal and marine areas.

Techno-economic analysis represents a key tool for the objective assessment of the profitability of potential projects. It includes determining installed capacity and expected annual energy yield, estimating capital expenditure (CAPEX), operational expenditures (OPEX), and calculating indicators such as net present value (NPV), internal rate of return (IRR), and levelized cost of energy (LCOE).

In this paper, we make the following original contributions. First, we perform an integrated spatial-technical assessment of the Croatian part of the Adriatic Sea for bottom-fixed offshore wind, combining wind resource data, bathymetry, seabed properties, visual impact zones, existing concessions, environmental constraints and maritime traffic to identify practical potential areas of interest (Section III). Second, we link this spatial analysis with the planned development of the Croatian transmission network, with a particular focus on the Istria Program and the role of the future 400/110 kV Vodnjan substation, in order to evaluate grid integration constraints for offshore wind (Section III.G). Third, we develop and apply a detailed techno-economic model of a reference 150 MW offshore wind farm at a selected site in the northern Adriatic, using high-resolution wind data and the IEA 10 MW RWT turbine, to quantify energy production, losses, LCOE, NPV and IRR under Croatian cost and price assumptions (Sections IV and V). Finally, we carry out a sensitivity analysis on the electricity selling price to identify the revenue conditions under which the first offshore wind project in Croatia becomes financially viable, and we derive policy-relevant implications for support schemes and network planning (Section V.A).

Andrija Mustapić, Juraj Havelka, Potential Assessment and Techno-Economic Analysis of Offshore Wind Farm in Croatia, Journal of Energy, vol. 75 Number 2 (2026), 40–56

https://doi.org/10.37798/2026752747

II. Offshore Wind Farms Current Situation in Europe and the World

Europe currently has a total of 291 GW of installed wind power capacity, of which 254 GW is onshore and 37 GW offshore. The European Union accounts for 236 GW in total, with 215 GW onshore and 21 GW offshore. The leading countries in terms of installed offshore capacity are primarily those bordering the North Sea. According to statistics for the end of 2024, the largest installed capacity is in the United Kingdom (16 GW), followed by Germany (9 GW) and the Netherlands (4.7 GW). They are followed by Denmark (2.7 GW), Belgium (2.3 GW), and France (1.5 GW) [1]. In Figure 1, projects in operation are shown in red, while planned projects are shown in blue. Globally, the leading country in wind power generation is China, with approximately 480 GW of installed wind capacity, of which around 38 GW is offshore [2].

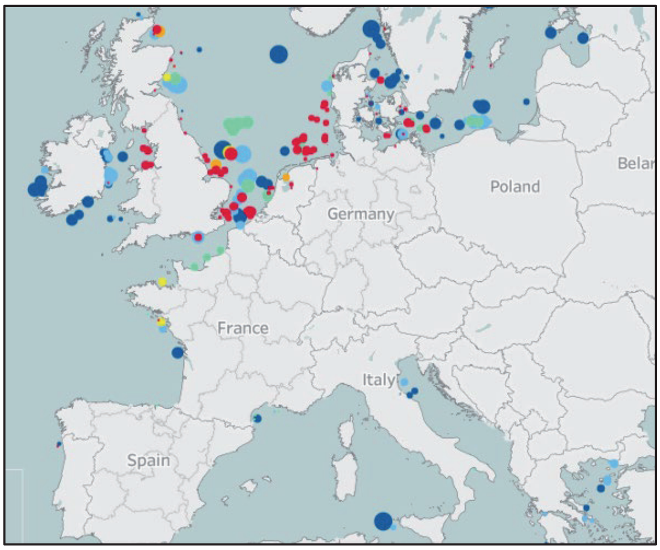

Fig. 1. Overview of currently installed and planned offshore projects in Europe [3]

In 2024, renewable energy sources accounted for a record 50.4% of total electricity generation in the United Kingdom. Offshore wind farms, which harness the significant wind potential of coastal areas, contributed more than 58% of total wind power generation. Figure 2 below shows electricity generation from renewable sources in 2024, expressed in GWh [4].

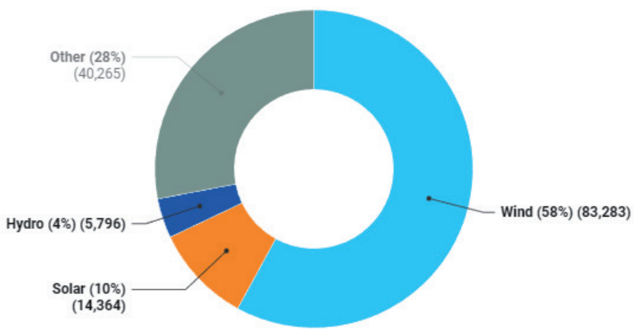

Fig. 2. Electricity generation from renewable energy sources in 2024 [4]

Dogger Bank currently represents the largest offshore wind farm project under construction in the world, located in the UK sector of the North Sea, approximately 130 km from the coast of the United Kingdom. The site is a vast submerged sandbank in the central part of the North Sea, with average depths of only 15 to 30 meters. The project is being developed in three phases—Dogger Bank A, Dogger Bank B, and Dogger Bank C—each with a planned installed capacity of approximately 1.2 GW, for a total of about 3.6 GW. Dogger Bank A began supplying electricity to the grid in 2023 and is in the process of gradual commissioning to full operation. Phase Dogger Bank B is in the final stage of construction and gradual grid connection, while Phase Dogger Bank C is in an advanced stage of development, with completion planned for the second half of the decade [5].

The project utilizes wind turbines with large individual capacities (on the order of 13–14 MW), thereby reducing the number of required installed units and optimizing overall energy production. Electricity is collected via inter-array cables and transmitted to offshore substations, from where it is delivered to the onshore power grid using a high-voltage direct current (HVDC) system. Slower electrification dynamics, congestion in the power system, and lengthy and administratively demanding permitting procedures in certain countries have resulted in slower wind energy development than planned national targets. Additional constraints arise from insufficient grid connection capacity, limited port infrastructure, and a shortage of specialized vessels required for the installation and maintenance of offshore facilities [6].

One of the most significant trends in the offshore wind energy industry, which has greatly contributed to reducing the LCOE, is the continuous increase in the rated power of wind turbines. During the 1990s, the average installed capacity of individual turbines was less than 1 MW. Significant technological progress was achieved in the early 2000s, after which the average turbine capacity gradually increased, reaching approximately 3 MW by 2010.

Since 2015, there has been a notably accelerated increase in the capacity of turbines installed in offshore projects. For comparison, the average rated capacity of onshore wind turbines installed across Europe in 2024 was 4.6 MW, while the average rated capacity of offshore wind turbines connected to the grid in 2024 was 10.1 MW, representing an increase from 9.7 MW in 2023 [3][7]. Figure 3 illustrates this growth in wind turbine capacities over the years.

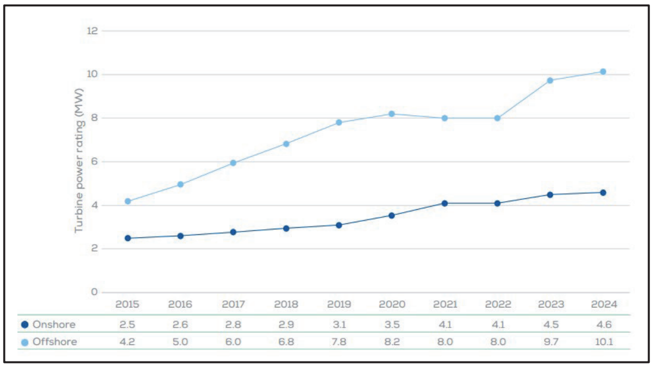

Fig. 3. Graph showing a comparison of the growth in average capacity of offshore and onshore wind turbines [3]

It is also important to highlight the higher capacity factor of offshore wind farms compared to onshore ones, primarily due to more frequent and stable wind conditions at sea, while the larger installed capacity of individual turbines plays a secondary role. Offshore projects in Europe achieve average capacity factors of around 35%, with the highest reaching up to 45%, which is significantly higher than typical values for onshore wind farms, which achieve average capacity factors of around 25% [3].

A. Types of Wind Turbine Foundations

Depending on seabed conditions, offshore wind project developers typically choose between monopile and jacket foundations.

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Monopiles are the most common, accounting for approximately 81% of all offshore wind turbine foundations in Europe, followed by jacket foundations.

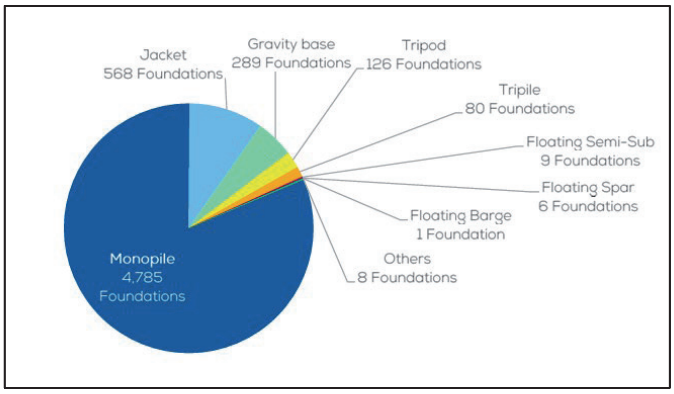

Fig. 4. Number of different installed foundation types in Europe [3]

On the one hand, monopile foundations are expected to maintain their dominant position (Figure 4); however, their market share may decrease in favor of lattice structures (jacket foundations), primarily due to the increasing average water depths at which new projects are being developed. On the other hand, further industrialization of monopile manufacturing and the proven ability of these structures to adapt to greater depths while maintaining relatively low costs could enable them to retain their dominant position in the long term, and potentially even increase their market share. Monopile foundations are most commonly used for depths of up to 30 m, while jacket foundations are typically used for greater depths, up to around 60 m. Figure 5 shows various types of foundations currently in use.

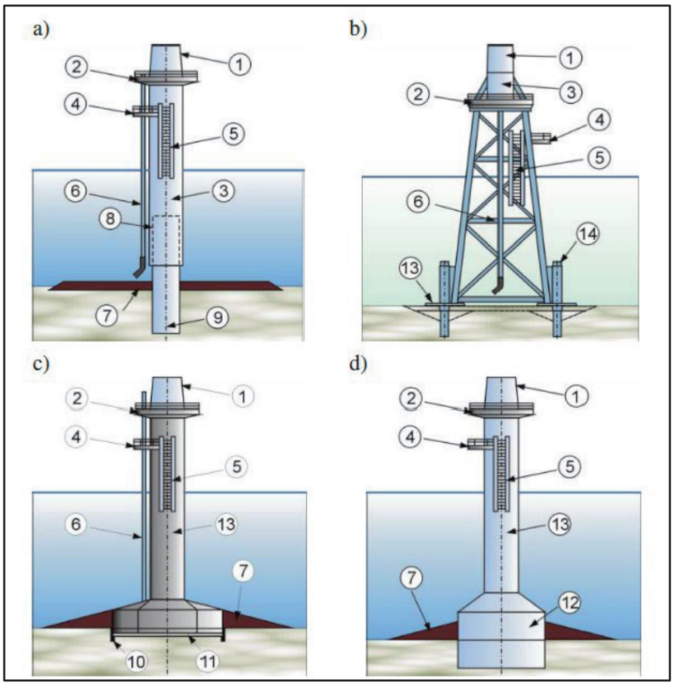

Fig. 5. a) Monopile b) Jacket foundation c) Gravity-based foundation d) Suction foundation [3]

Since floating wind technology is currently in a pre-commercial stage of development, a pronounced learning curve effect is expected in the coming period. For projects at the global level, the application of various types of floating foundations is anticipated, with the choice of solution depending on local and project-specific constraints such as environmental conditions, available infrastructure, and the maturity of the supply and logistics chain [8].

In terms of water depth limitations, floating wind farms have a significant advantage over conventional offshore wind farms with fixed-bottom foundations. Their application enables installation at depths greater than 60 m, thereby opening up the possibility of harnessing stronger and more stable winds in more distant offshore areas compared to nearshore zones.

From an installation perspective, floating wind farms offer certain operational advantages. Structures can largely be assembled in ports or shipyards onshore and then towed to the designated location, which can result in reduced installation costs and lower dependence on specialized installation vessels. Despite these advantages, floating wind farms are currently more expensive than conventional offshore installations with fixed foundations. This is mainly due to the limited number of large-scale commercial projects in Europe and worldwide.

There is no single, standardized foundation design for floating wind farms. The choice of solution depends on a number of factors, including wind conditions, turbine size and capacity, water depth, wave and current regimes, and the geological characteristics of the seabed. Figure 6 illustrates various types of floating wind turbine foundations.

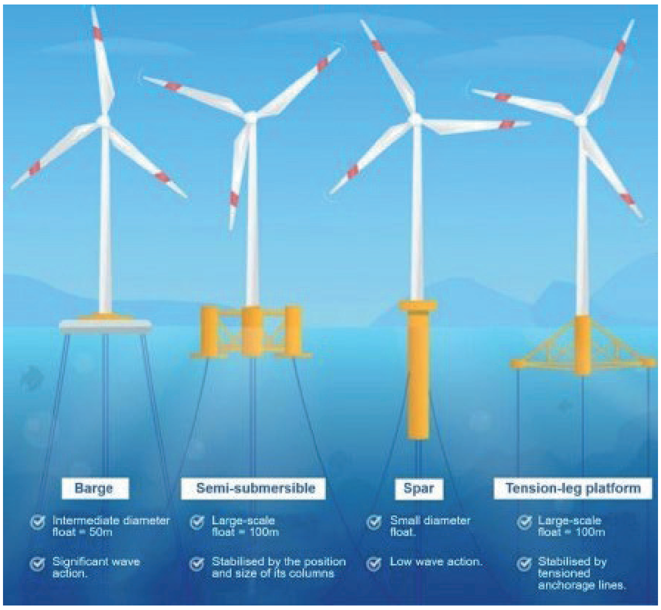

Fig. 6. Types of foundations for floating wind farms

According to available data, in 2021 Europe had approximately 113 MW of installed floating wind capacity. The largest project was Kincardine in the United Kingdom, with an installed capacity of 50 MW. In addition to the United Kingdom, floating wind capacity has also been developed by countries such as Portugal, Norway, Spain, and France [10].

Given that floating wind farms are still in their early stages of development, with numerous pilot projects worldwide, they remain significantly more expensive than fixed-bottom wind farms. Therefore, this thesis will focus on wind farms with fixed foundations.

B. Grid Connection Methods

B.I. Offshore Substation

Offshore substation represents the central element of an offshore power system. A typical offshore wind farm consists of four main components: wind turbines, the internal (inter-array) network, the

https://doi.org/10.37798/2026752747

offshore substation, and the external (export) network. Electrical energy generated at low voltage (around 690 V) is first transformed to a medium-voltage level (33 or 66 kV) using a transformer located within the wind turbine. It is then transmitted through the medium-voltage internal network, while at the substation the voltage is stepped up to high-voltage transmission levels (110/150/220 kV), suitable for further transmission to the onshore power grid.

Due to harsh environmental conditions, offshore substations are most commonly designed as enclosed structures fixed to the seabed. Their construction is conceptually based on oil platforms, with certain technical adaptations specific to electrical power applications. The platform is designed to accommodate main power and grounding transformers, switchgear, and other auxiliary equipment required for the safe and reliable operation of the system.

The electrical equipment of an offshore substation depends on whether alternating current (AC) or direct current (DC) is used. Accordingly, HVAC and HVDC offshore substations are distinguished, with technical configurations and functional characteristics adapted to the selected transmission system.

The main electrical equipment of HVAC offshore substations includes power transformers, auxiliary (station service) transformers, grounding transformers, gas-insulated high-voltage and medium-voltage switchgear (GIS), backup generators, grounding resistors and AC filters.

The primary purpose of HVDC offshore substations is to convert alternating current (AC) into direct current (DC) for the efficient transmission of electrical energy over long distances. Compared to HVAC substations, HVDC installations include additional specific components: IGBT converters with associated cooling systems and direct current (DC) filters. These components enable the conversion, stabilization, and filtering of direct current, thereby ensuring reliable and high-quality transmission of electrical energy to the onshore grid. The operating conditions of electrical equipment (including cooling systems, required insulation clearances, and other technical requirements) must be adapted to the specific offshore environment. It is also necessary to provide appropriate conditions for the operation of auxiliary systems and personnel accommodation, including technical rooms, HVAC systems, living quarters, and supporting infrastructure. Special attention is given to safety, navigation, signaling, and rescue systems, including fire protection systems, lightning protection, evacuation procedures, and other measures necessary for safe operation in a marine environment [11].

Structural design of offshore facilities faces a number of specific challenges. Among the most important are environmental influences, including wind, sea currents, waves, and sea level variations, which cause significant static and dynamic loads on the structure. In addition, careful consideration must be given to the mass of installed equipment on the platform and the distribution of the center of gravity, as these parameters directly affect platform stability and safety. Particular attention must be paid to corrosion protection due to the highly aggressive marine environment. Prolonged exposure to saltwater and humidity can lead to material degradation, making the application of appropriate protective systems essential for maintaining structural integrity. Geotechnical investigations of the seabed are also crucial to ensure adequate foundation bearing capacity and structural stability throughout the entire service life. An important aspect of design also involves planning marine operations, including transportation, assembly, and installation of the structure, which must be aligned with weather conditions and safety constraints of the marine environment. The technical lifetime of such structures is typically planned for a period of 20 to 25 years. Figure 7 shows the structure of an offshore substation and its foundations, while Figure 8 presents a specialized vessel for the installation of offshore components and the assembly of an offshore substation.

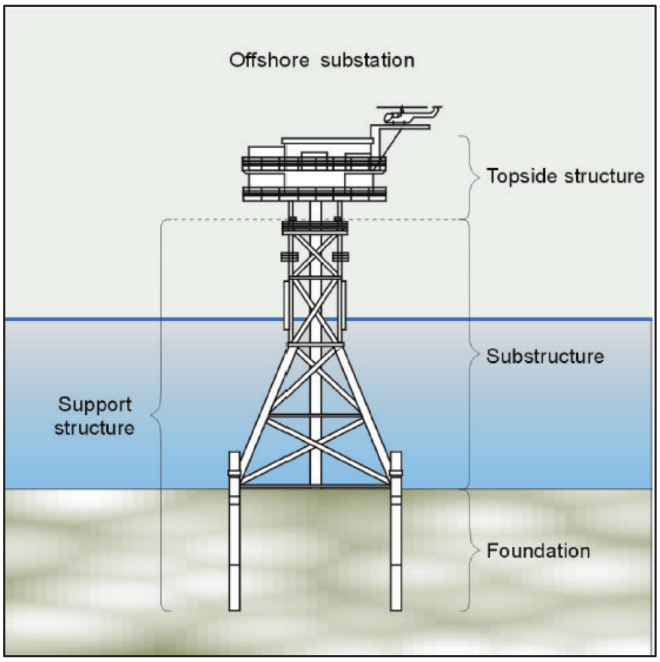

Fig. 7. Structure of an offshore substation

Fig. 8. Installation of an offshore substation [33]

B.II. Submarine Cables

Submarine cable systems have been in use for nearly a century and, depending on the type of system in which they are applied, are divided into alternating current (AC) and direct current (DC) cables. DC submarine cables are used in situations where the use of AC cable systems is not technically or economically justified. The limitations of AC submarine cables are primarily related to the occurrence of high capacitive currents, increased short-circuit currents, the inability to directly connect power systems of different frequencies, and increased transmission losses over long distances.

In the past, submarine cables were predominantly used to connect mainland and island power systems, whereas today their application has expanded significantly to include the connection of offshore wind farms to the power grid. In this context, various connection concepts can be applied, primarily depending on the distance of the wind farm from the shore and the installed capacity of the plant. For shorter distances (approximately 5–20 km) and lower capacities, medium-voltage cable systems with rated voltages from 10 to 66 kV are most commonly used, directly connecting wind turbines to an onshore substation. For longer distances, offshore platforms with substations are constructed to step up the voltage level, while transmission to shore is carried out using high-voltage (>110 kV) submarine cables.

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With the development of large-capacity projects and increasing distances from the coast, high-voltage direct current (HVDC) cable systems, with converter stations located both offshore and onshore, are increasingly being used. Such solutions enable reduced transmission losses and optimization of investment costs for long-distance transmission. An additional technical challenge is presented by floating offshore wind farms, where cable connection methods must be adapted to accommodate continuous movement of the structures.

The choice between HVAC and HVDC submarine cable systems primarily depends on the route length. For shorter distances, typically up to 80–100 km, HVAC cables are commonly used due to lower investment costs and satisfactory technical performance. At greater distances, HVDC systems offer several advantages, particularly in terms of reduced losses, limitation of short-circuit currents, and the ability to connect power systems with different frequencies. Furthermore, in HVAC cables, capacitive currents become a limiting factor as the route length increases.

According to their construction, submarine cables can be classified into three main categories:

- single-core AC submarine cables,
- three-core AC submarine cables with common armoring,
- high-voltage direct current (HVDC) submarine cables (single-core or bipolar).

The choice between three-core and single-core AC cables depends on several factors, including seabed route characteristics, cable length, and installation feasibility. Three-core cables are advantageous in situations where minimizing the occupied seabed corridor is important, as single-core cable systems may require spacing between individual cores of more than 20–30 m. Although installation at smaller distances is possible, it is generally avoided due to the risk of simultaneous damage to two or more cables. On the other hand, installing three-core cables is technically more demanding due to their larger dimensions. An advantage of three-core cables with common armoring is reduced losses, primarily due to the symmetrical arrangement of phase conductors. In single-core submarine cables, these losses may be more pronounced, although part of this advantage is offset by increased heating caused by the proximity of phase conductors within a three-core structure [12][13].

B.III. Components of Submarine Cables

The conductor of a submarine cable is made of aluminum or copper. Although copper is significantly more expensive than aluminum, it is often used in submarine cables due to the possibility of using a smaller cross-section for the same transmission capacity. A smaller conductor cross-section reduces the amount of material required for other structural layers (insulation, armoring, and sheath), which can have a beneficial impact on the overall cable mass, as well as on installation and maintenance costs. However, there is no universally optimal choice of conductor material, and combined aluminum–copper solutions are sometimes used in practice for specific sections of the cable system.

The insulation layer provides an electrical barrier between the high-voltage conductor and the surrounding medium. In modern practice, cross-linked polyethylene (XLPE) is most commonly used due to its favorable electrical and mechanical properties. Outdated technologies, such as oil-filled or gas-insulated cables, are generally avoided today, although they are still present in certain cases. For DC submarine cables, proven technologies using impregnated paper insulation are often applied.

Semiconductive layers are placed around the conductor and insulation to ensure a uniform electric field and to prevent local concentrations of electrical stress that may arise due to surface irregularities or protrusions. This increases the reliability of the insulation system and reduces the risk of partial discharges. The thickness of semiconductive layers typically ranges from 1 to 2 mm.

The metallic sheath of a submarine cable is most commonly made of lead, and less frequently of aluminum or copper. Its primary function is to protect against moisture ingress and mechanical damage, as well as to conduct fault currents. A disadvantage of metallic sheaths is the potential occurrence of circulating currents and additional heating when the sheath is grounded at both ends. The sheath thickness typically ranges from 2 to 5 mm, depending on application and operating conditions. In three-core cables, configurations with separate metal sheaths for each core (SL – single lead sheath) or a common sheath are possible, with SL configurations more commonly used in practice.

Armoring is applied to protect the cable from mechanical stresses and damage in the marine environment, for example due to anchoring or contact with rocky seabeds. It is typically made of steel wires or tapes, often arranged in two helically wound layers. Since armoring is usually made of steel, additional losses due to eddy currents and hysteresis may occur. In single-core submarine cables, these losses can significantly reduce transmission capacity, while in three-core cables they are less pronounced.

Polyethylene is most commonly used as the outer protective layer. Although it is not resistant to high temperatures, it provides high resistance to moisture ingress. Its primary function is to protect the armoring and metallic sheath from corrosion caused by seawater and other external influences.

Submarine cables, whether three-core or single-core, often integrate optical fibers for telecommunications and data transmission between wind turbines and the substation. Optical fibers enable remote control and continuous monitoring of wind farm operation from a control center, ensuring reliable system management and timely detection of operational disturbances. These optical conductors may be additionally protected by a metallic sheath or other mechanical protection elements within the cable structure [14][15]. The described components are shown in the cross-section of a three-core submarine cable in Figure 9.

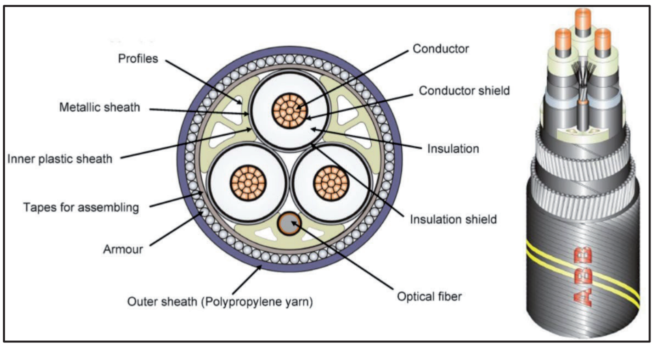

Fig. 9. Example of a three-phase submarine cable [15]

C. Design and Installation of Submarine Cables

The design of submarine cables represents a fundamental phase in the overall engineering process of their construction. This process includes systematic analysis and planning aimed at defining the optimal cable route, selecting appropriate materials and equipment, organizing the installation procedure, and ensuring the safety and long-term protection of the cable during and after installation.

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The entire engineering process of submarine cable construction can be divided into several successive phases. In the initial, preliminary (conceptual) phase, the approximate cable route is determined and basic seabed surveys are conducted. The results of this phase often serve as a basis for investment decisions. This is followed by the conceptual design and technical solution development phase, during which more detailed geophysical and geotechnical investigations are carried out, and the route is defined more precisely. At this stage, technical documentation is prepared, and based on the description of the planned installation, the necessary approvals and permits are obtained.

The detailed engineering phase includes the elaboration of technical solutions related to the cable itself and its installation process, including the selection of vessels, tools, and auxiliary equipment. This phase forms the basis for the execution of actual installation activities in the field. The final phase refers to the period after cable laying, when an assessment of the completed works is carried out. At this stage, the level of cable protection is verified, the availability of spare parts for potential repairs is assessed, and the system's readiness for transition into operational mode is evaluated.

International standards and recommendations, such as those issued by IEC, IEEE, and CIGRÉ, play an important role in ensuring compliance with technical norms and industry guidelines. These standards define requirements related to testing, qualification, and quality control of cable systems, thereby ensuring their technical reliability and safety of application.

The method of laying submarine cables largely depends on the characteristics of the seabed, with various methods and specialized tools available. In the case of hard and rocky seabeds, ploughs or similar tools are most commonly used to mechanically cut a trench into the substrate. In contrast, sandy seabeds allow for simpler execution, where a subsea jetting device can be used to move along the entire cable route and create a trench approximately one meter deep. After installation, the cable is placed into the formed trench and, under the influence of sea currents and natural sedimentation, gradually becomes buried and stabilized on the seabed [14].

D. *Maintenance*

Compared to onshore wind farms, offshore wind farms benefit from more favorable and stable wind energy potential. Nevertheless, high operational costs remain one of the key constraints to their more intensive development. In particular, operation and maintenance (O&M) costs stand out, being more than twice as high as those of onshore wind farms. Furthermore, as the distance of installations from the coast increases—especially under deep-sea conditions—the costs of carrying out maintenance activities grow proportionally with distance, further affecting the overall economic viability of such projects [16].

Given the significant exposure of foundations and transformer installations to the corrosive marine environment, regular inspections are of particular importance. Damage to protective coatings, seal degradation, or the onset of corrosion can lead to substantial financial and technical consequences if not detected in time. For this purpose, unmanned aerial vehicles (UAVs), remotely operated underwater vehicles (ROVs), and advanced visual inspection systems are increasingly being used, reducing the need for direct manual access to structures and improving personnel safety. The digitalization of operational processes, the development of predictive maintenance, and the integration of logistics systems are gradually transforming the management and maintenance segment of offshore wind farms, enabling more efficient monitoring, extending equipment service life, and reducing downtime and operational costs. Additional support for the development of these practices comes from the long-standing experience of the oil and gas industry in conducting safe offshore operations.

Repair activities include both interventions due to unplanned failures and the planned replacement of components at the end of their designed service life. More extensive interventions on turbines, such as the replacement of blades, gearboxes, or generators, require the engagement of specialized installation or service vessels equipped with high-capacity cranes. On the other hand, smaller corrective interventions—such as sensor replacement or minor hydraulic and electrical repairs—are usually carried out on-site using crew transfer vessels or service operation vessels. Repairs also apply to elements of the electrical infrastructure, where, depending on the complexity of the intervention, specialized equipment such as ROVs, lifting systems, and auxiliary vessels is employed, often through external specialized contractors. Effective coordination and timely execution of repairs are crucial for minimizing downtime and ensuring continuity of electricity production [17].

III. Potential in Croatia

A. *Winds in Croatia*

The two main winds in the Croatian part of the Adriatic Sea are the bura and the sirocco (jugo). The bura is a strong, dry, and cold wind with an average speed of 15 m/s. Wind gusts can reach up to 70 m/s. It develops over the high coastal mountains (Velebit, Mosor, Biokovo, etc.), is most frequent in winter, and blows in gusts (directions: N, NE, E – wind direction is defined by the direction from which the wind blows)[18][19].

The average speeds of the sirocco range between 10 m/s and 30 m/s (directions: S, SE). It is strongest over the open sea, where it generates large waves. It can blow for several consecutive days and occurs more frequently in winter than during the warmer part of the year. In summer, it usually does not last longer than three days, while in winter it can persist for up to ten days, and sometimes, with short interruptions, even up to three weeks. It typically develops in the southern Adriatic during winter and in the northern Adriatic during spring. In addition, numerous Croatian islands act as obstacles, reducing wind speed and increasing atmospheric turbulence [19].

Figure 10 shows the mean annual wind speed at a height of 80 m above ground. The presented wind speed is the result of a numerical atmospheric model and represents the average value within a 2 km × 2 km grid cell [20].

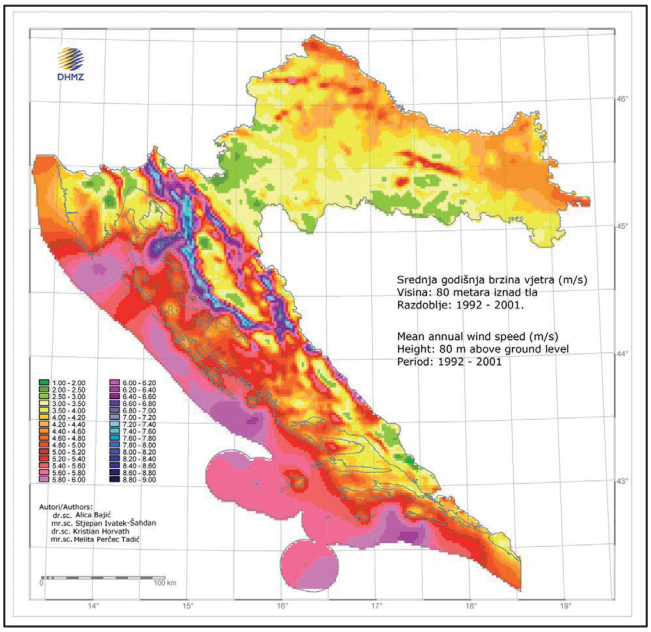

Fig. 10. Map showing the mean annual wind speed at a height of 80 m above ground [20]

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However, with the increasing hub heights of offshore wind turbines, there is a need for additional wind measurements. Currently, several studies on wind speed in the Adriatic are underway. INA is conducting wind speed measurements on two gas platforms in the Adriatic: Izabela North and Ivana A (northern Adriatic).

B. Seabed Properties

Sediments predominantly range from sandy and sandy-silty in the northern and western parts, to silty and sandy-gravelly in channels and around islands such as Kvarner, the Rab Channel, and Pag. Rocky seabeds are characteristic of coastal zones. Figure 11 shows the composition of the Adriatic seabed, indicating that the area of interest south of Istria is mostly sandy [21].

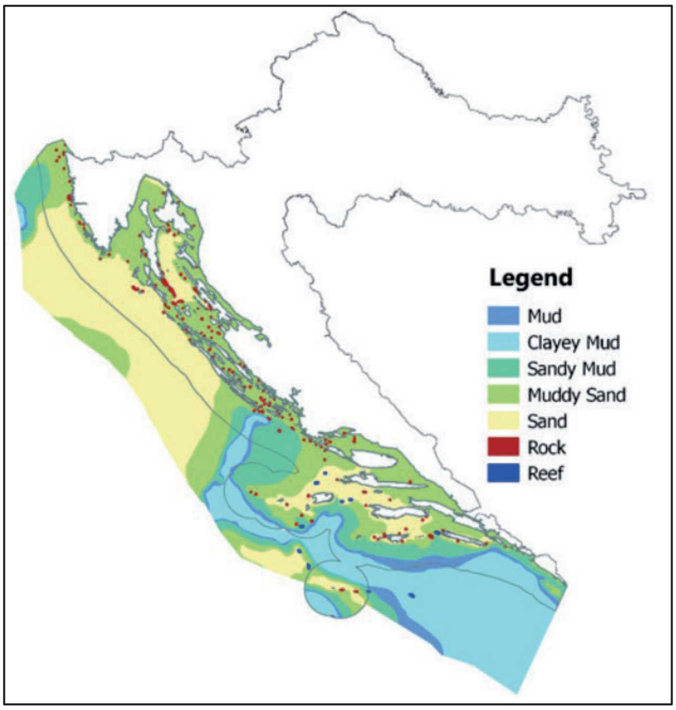

Fig. 11. Composition of the Adriatic Sea seabed [21]

C. Sea Depth

The Adriatic Sea is divided into two parts by the Palagruža Sill. The northernmost part of the Adriatic consists of a shallow (up to 100 m), flat, sandy or silty seabed. An exception is the Kvarner channels, which are deeper than 100 meters. The second section of the northern Adriatic has an average depth of 200 m and extends 130 km along its longitudinal axis and 40 km in width, reaching as far as the Palagruža Sill.

South of the Palagruža Sill, the seabed descends steeply to the deepest point in the Adriatic Sea at a depth of 1,233 meters. The deepest area—the South Adriatic Basin—is located between the Palagruža Sill and the Strait of Otranto (743 m). The Strait of Otranto also represents the outlet of the Adriatic Sea. The seabed structure in this part consists of mixed sedimentation.

Figure 12 shows the depth of the Adriatic Sea, indicating that in the area of interest, south of Istria, the sea depth ranges from 40 to 60 m [22].

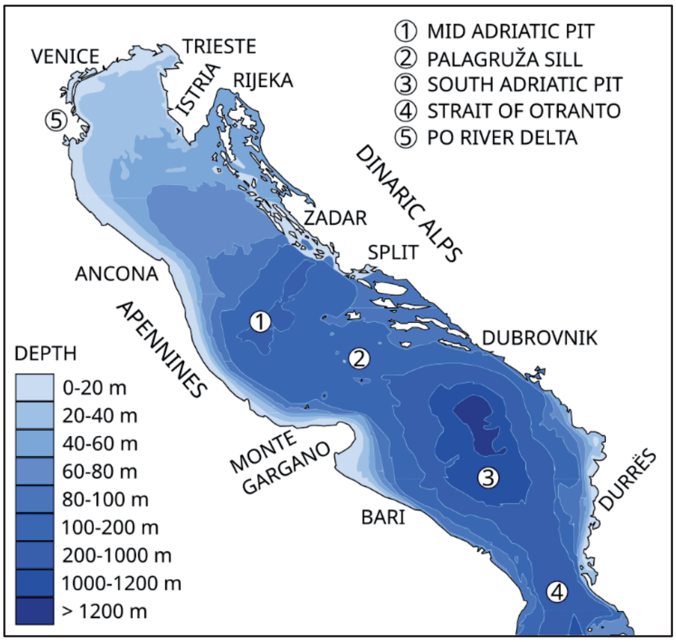

Fig. 12. Map showing the depth of the Adriatic Sea [22]

D. Visual Impact

The visual impact of offshore wind farms in the marine environment is primarily determined by the height of the wind turbines, their distance from the coast, the topographical features of the surrounding terrain, and weather conditions. The intensity of spatial perception varies depending on these parameters. For example, a wind turbine with a height of 150 meters, under conditions of good visibility, can be seen from the coast at a distance of approximately 20 to 30 kilometers. During nighttime, the structures themselves are not visible, but the aviation warning lights on the turbines can be noticed from considerable distances.

Given the significant contribution of tourism to the Croatian economy, the issue of visual exposure of offshore wind farms requires systematic analysis. In this context, it is necessary to consider

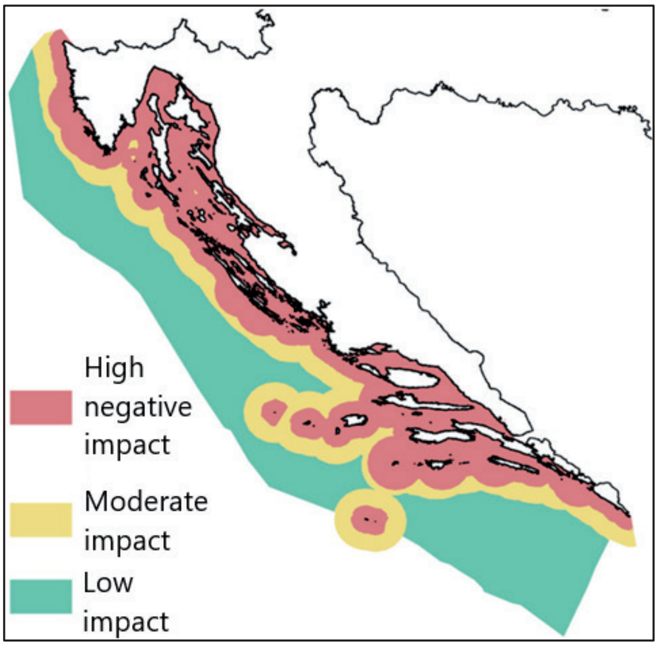

Fig. 13. Visual impact of offshore wind farms in the Republic of Croatia [9]

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spatial visibility zones and the intensity of their potential impact.

Figure 13 shows a map of the visual impacts of offshore wind farms, developed based on defined parameters of distance and spatial sensitivity. The largest zone of negative impact includes a belt extending up to 10 kilometers from the coast along the entire observed area, with an additional buffer zone of 20 kilometers around national parks, nature parks, and other frequently visited cities and locations.

The zone of moderate impact extends up to 20 kilometers from the coast. In this area, offshore wind farms are likely to be visible from land, but their visual perception will generally be weaker, often hazy, and not necessarily easily noticeable.

The low-impact zone includes areas located more than 20 kilometers from the coast. This area is considered sufficiently distant from the shoreline such that potential visual impacts on the landscape are minimized or negligible [9].

E. Various Constraints and Potential Locations

A spatial analysis of potential areas of interest (PAIs) for the development of offshore wind farms was conducted, taking into account a range of technical, environmental, and spatial constraints. One of the primary criteria defined was the maximum allowable sea depth for installation, set at 60 meters, ensuring the technical feasibility of using bottom-fixed foundations.

Additionally, potential areas must be located outside existing concession zones for hydrocarbon exploration and exploitation, in order to avoid conflicts with ongoing energy activities. To minimize impacts on maritime traffic, it is necessary to avoid traffic separation schemes and major shipping routes. Furthermore, the analysis excludes protected marine areas and Natura 2000 ecological network sites, as well as important bird migration corridors, in order to preserve biodiversity and reduce negative environmental impacts. Finally, one of the criteria relates to visual impact on the coastal and marine landscape. Potential areas of interest must have minimal visual impact or be located at least 20 km from the coast, thereby reducing their visibility from land.

An additional important constraint within the spatial analysis was the exclusion of the channel areas of the Croatian sea. The reason for this lies in the intensive use of these areas for maritime transport, fisheries, and marine tourism, as well as their pronounced biodiversity and heterogeneous marine habitats. However, these areas should not be entirely excluded from future considerations, especially in the context of potential limited offshore renewable energy development, if such projects would be of interest to local communities on remote islands with underdeveloped energy infrastructure.

The calculated surface areas of potential areas of interest obtained through this spatial analysis should be considered approximate values, given the available data and the applied methodology.

The northern part of the Adriatic Sea under Croatian jurisdiction, spanning from the southern part of the island of Mali Lošinj to the northern tip of the Istrian Peninsula, has been identified as the only suitable area of interest based on the criteria of maximum allowable sea depth and relatively short distance from the coast. Accordingly, further analysis has been focused on this defined area, as shown in Figures 14 and 15.

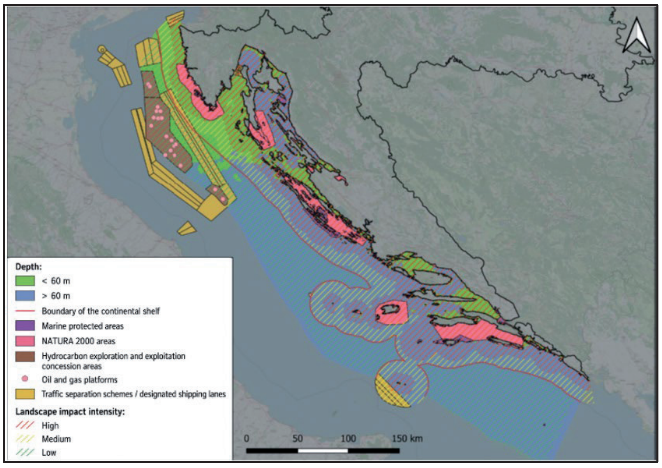

Fig. 14. Analysis of possible PPIs for the construction of offshore wind farms in the Republic of Croatia

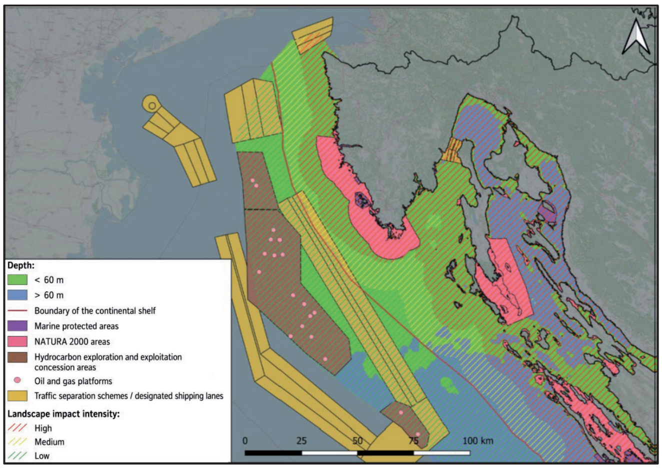

Fig. 15. Area of focused analysis of possible PPIs for offshore wind farms

Taking into account the constraints related to sea depth and distance from the coast, as well as the need to avoid existing hydrocarbon exploitation concession areas and designated shipping routes, four potential areas of interest have been identified, as shown in Figure 16. It should be emphasized that, due to the limited spatial resolution and accuracy of the available bathymetric data, sea depths up to 60 meters have been determined approximately.

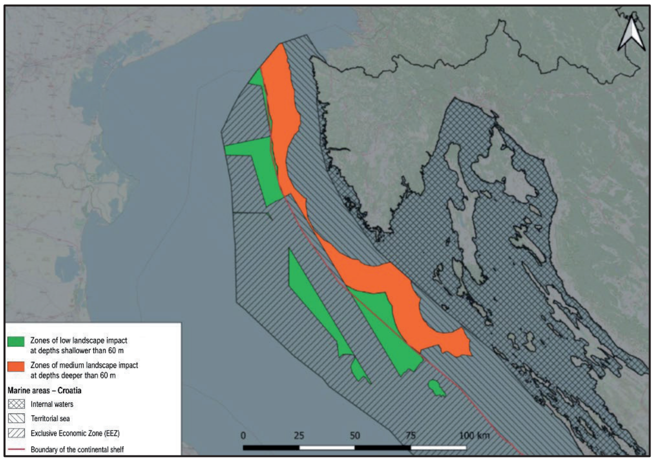

Fig. 16. PPI zones for offshore wind farms with low and moderate impact on the landscape and seascape

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Table I

Surface Areas of Suitable Areas for Offshore Wind Farms

Type of impact	Territorial Sea [km²]	Exclusive Economic Zone [km²]	Total [km²]
Low	205	1.055	1.260
Medium	1.602	-	1.602
Total[km2]	1.807	1.055	2.862

An additional potential marine zone for the development of offshore wind farms includes already allocated concession areas for hydrocarbon exploration and exploitation, with a total area of approximately 2,181 km², excluding a 500-meter safety zone around existing and planned production platforms (Table I). The possibility of developing offshore wind farms within these areas is conditioned by the provisions of concession agreements concluded between INA and the Republic of Croatia, i.e., it depends on the legal framework governing the use of these concession fields.

As previously stated in this paper, floating wind farms are not the focus of this study; however, Figure 17 illustrates the significant potential area for their future deployment once the technology becomes more mature and cost-effective.

Although this study restricts the techno-economic modelling to bottom-fixed turbines (sea depths $\leq$ 60 m), floating offshore wind technology could unlock a much larger technical potential in the deeper central and southern Adriatic. As indicated in Fig. 17, these areas combine greater depths with generally stronger and more stable wind regimes. Once floating foundations reach wider commercial deployment and more robust cost benchmarks become available, a comprehensive reassessment of Croatian offshore potential should explicitly include floating wind, with dedicated spatial criteria (depth > 60 m, wave climate, port infrastructure) and adapted techno-economic assumptions. This represents an important direction for future extensions of the present work.

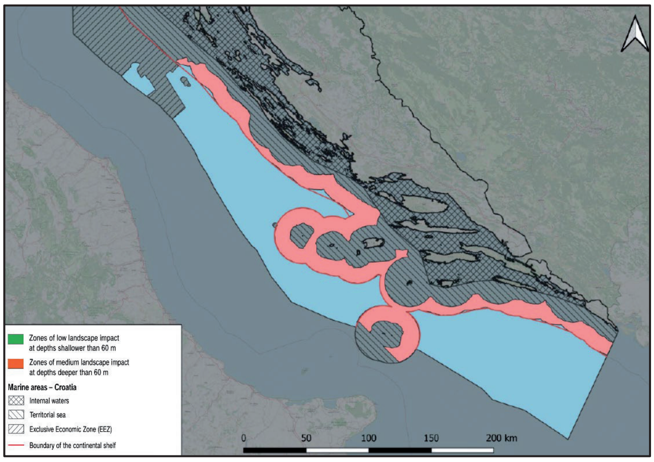

Fig. 17. Zones for the potential development of floating offshore renewable energy sources with low and moderate impact on the landscape and seascape

F. Regulations and Legislation

Developers of offshore renewable energy (RES) projects must follow the development steps defined for RES in the *Guide for the Development and Implementation of Renewable Energy Projects in Croatia*.

The current procedure for the use of maritime areas in Croatia is highly complex and, in principle, does not guarantee that a project developer will achieve their objectives within the desired timeframe. In cases involving the use of marine areas that require construction (and thus additional permits), the procedure becomes even more complicated. Two overarching laws regulate the use of maritime areas:

- The *Maritime Domain and Seaports Act*, which governs the methods of using maritime domain and the procedure for granting concessions
- The *Physical Planning Act*, which defines the initial step in obtaining a concession—the process of acquiring a location permit and the detailed spatial planning procedure

The absence of a National Spatial Development Plan represents the first obstacle, as the process of obtaining a location permit requires alignment with spatial plans for the specific area. In general, the Ministry of Physical Planning, Construction and State Assets and the Ministry of the Sea, Transport and Infrastructure are responsible for this domain, but many details remain unclear regarding which law applies and which ministry is competent for each step. For example, construction permits for oil platforms were issued by the Ministry of Physical Planning, Construction and State Assets under the Mining Act, which cannot be directly applied to offshore RES projects. Approvals, preliminary studies, and research within the Exclusive Economic Zone, as well as concessions for cables and electricity transmission from territorial waters to land, are issued by the Ministry of the Sea, Transport and Infrastructure.

The first step in obtaining a concession for maritime domain is securing the legal interest of the concession grantor to initiate the location permit procedure, which is determined by the level of the spatial plan regulating its use. If there is no national spatial development plan for marine areas, the county is responsible for granting concessions as defined by the county spatial plan.

A project developer who has expressed interest and obtained all required documentation (including the location permit) must still compete in a public tender for the concession. This introduces a degree of legal uncertainty, particularly considering the time required to obtain all necessary permits.

For state-level concessions, the maximum duration is 50 years, while counties may grant concessions for up to 20 years. State-level concessions are granted by the Croatian Parliament, whereas regional-level concessions are granted by the county assembly. After completion of the concession procedure, selection of the concessionaire, and signing of the concession agreement, construction may begin, and the concession agreement is considered the legal basis for obtaining a construction permit.

Offshore wind farms often have marine concessions lasting 40 to 60 years, which allows for "repowering" at the same site after the initial turbines reach the end of their design life (typically 25 to 30 years). This enables the reuse of existing infrastructure (grid connection, cabling, and often foundations), instead of fully abandoning the location [23].

G. Istria County and Energy Infrastructure

Istria County maintained relative energy self-sufficiency over a long period by relying on fossil fuels, primarily hard coal used in two units of the Plomin Thermal Power Plant. Since 2017, Unit A has been out of operation, reducing electricity generation in the area solely to the operation of Unit B.

The currently operational Unit B only marginally meets the existing annual electricity demand of Istria County, which amounts to approximately 1.4 TWh, with a continuous upward trend in consumption. At the same time, following the shutdown of Unit A, the remaining generation capacity is far from sufficient to meet peak system loads. Part of the required capacity is compensated by re-

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newable energy production, primarily solar power plants installed within the county. However, the stability of the power system is largely ensured through a 220 kV transmission line connecting Istria to the rest of Croatia, along with an additional lower-capacity line toward Slovenia. In general, insufficient interconnection capacity—both in terms of the number of transmission routes and their transfer capability—represents one of the key limitations of the Istrian power system.

The need to redefine the region's energy concept is further emphasized by the planned closure of Unit B of the Plomin Thermal Power Plant in 2033. This raises concerns regarding long-term security of electricity supply and highlights the necessity of developing new generation capacities.

The Croatian part of the Adriatic Sea has a limited number of locations suitable for offshore wind farm development, with the most favorable area, in terms of sea depth, being the northern Adriatic along the Istrian coast. However, due to existing economic activities in this area, offshore wind farm planning must be carried out in an integrated manner, taking into account the interests of all relevant sectors and ensuring the preservation of the marine ecosystem.

An additional constraint is the fact that Croatia still lacks a clearly defined regulatory framework that would enable the systematic development of offshore wind farms. Such projects are currently not envisaged in existing spatial plans, nor have specific marine areas been designated for wind farm development.

The construction of adequate infrastructure capacity, particularly 400 kV transmission lines, is a prerequisite for the realization of offshore wind farms in Istria, as the existing grid capacity is insufficient to accommodate new generation facilities. At the same time, the development of transmission infrastructure is currently the only way to ensure the fundamental objective of the power system—full security of electricity supply, regardless of the regional availability of energy sources.

In this context, the ten-year development plans of the transmission system operator are relevant, as they foresee the completion of the (400) 220/110 kV Vodnjan substation and its connection to the 400 kV Melina–Divača transmission line by the end of 2034. These planned developments play a significant role in creating the prerequisites for the future expansion of generation capacity in the Istria region [24].

G.I. Ten-Year Transmission Network Development Plan of HOPS

In accordance with Regulation (EU) 2022/869 on guidelines for trans-European energy infrastructure (TEN-E), the Republic of Croatia has defined non-binding targets for the development of offshore wind energy, amounting to 510 MW of installed capacity by 2030 and 1,200 MW by 2040. These targets provide a framework for long-term planning of offshore capacity development within the national energy system.

One of the key challenges in the implementation of the green transition is ensuring sufficient transmission and distribution capacity to accommodate a large number of new high-capacity generation facilities. The existing power system network was originally planned and dimensioned according to a different structure of electricity generation and consumption, both in terms of installed capacity and connection locations. Therefore, within a relatively short timeframe, it is necessary to carry out extensive reconfiguration of the Croatian, as well as the broader European, power grid to enable accelerated integration of renewable energy sources while maintaining system reliability and security of supply.

The increased share of non-dispatchable energy sources, such as wind and solar power plants, generates additional requirements for power system management. Such generation depends on weather conditions and is variable and less predictable, which necessitates the installation of network elements that enable dynamic real-time power flow management, as well as more optimal utilization of existing transmission capacities.

The Croatian Transmission System Operator has developed four programs for the expansion of the 400 kV transmission network to facilitate the integration of renewable energy sources in Croatia: the Lika Program, the Istria Program, the Southern Domestic Corridor Program, and the Slavonia Program (Figure 18).

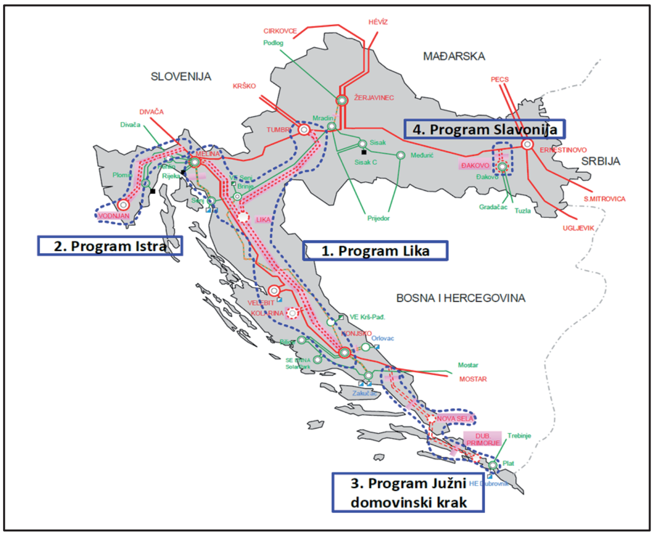

Fig. 18. HOPS – 4 development programs of the 400 kV transmission network [25]

These programs are aimed at strengthening transmission infrastructure in areas with expected growth in renewable energy generation capacity. It is important to emphasize that the implementation timeline for transmission network investments is generally longer than the time required to construct generation facilities and connect them to the grid. For this reason, it is crucial to initiate the preparation, planning, and implementation of investments in the 400 kV transmission network in a timely manner, in order to avoid system bottlenecks and ensure a coordinated development of generation and grid capacities [25].

G.II. Istria Program

To enable the integration of renewable energy sources and accommodate the expected increase in load in the Istria region, the construction of the (400) 220/110 kV Vodnjan substation is planned, with a loop-in/loop-out connection to the existing 400 kV Melina–Divača transmission line. This development creates the necessary conditions for connecting new generation capacities and strengthening the transmission infrastructure in the region.

The Istria Program is designed so that the new 400/110 kV Vodnjan substation is connected using the loop-in/loop-out method to the transmission line toward Divača, thereby enabling maximum utilization of the potential for connecting new renewable energy sources in Istria. However, achieving this goal also requires prior implementation of the Lika Program, specifically the construction of a new transmission line from Lika toward the Zagreb area (TS Tumbri), which would relieve the existing Melina–Divača line.

It is estimated that, with the implementation of the Istria Program and part of the Lika Program (the new transmission line

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toward TS Tumbri), up to 960 MW of new renewable energy capacity could be connected to the grid without the need for permanent curtailment. This capacity represents an estimate, as the actual connection potential depends on the locations of generation units; in some cases, additional reinforcement of the 110 kV network or cross-border transmission lines may be required.

Currently, the only major system node for electricity supply and evacuation in Istria is the 220/110 kV Plomin substation, connected via double 220 kV transmission lines to Melina and Pehlin. This indicates that there are presently no technical conditions in Istria to accommodate large-capacity generation units, making the extension of the 400 kV transmission network to the region essential. The proposed construction of the (400) 220/110 kV Vodnjan substation, with a loop-in/loop-out connection to the 400 kV Melina–Divača line, represents a technical solution that enables secure transmission of electricity from planned facilities. At the same time, this investment enhances the security of supply for existing grid users, particularly during summer evening hours when renewable generation is low.

The potential shutdown of Plomin 2 Thermal Power Plant would further negatively impact the security of supply in Istria. In such a scenario, the construction of a new 400 kV transmission line and a new 400/x kV substation would have a positive effect on maintaining supply security at an acceptable level. To implement the Istria Program and complete the 400 kV transmission network within the planned timeframe (by the end of the ten-year period, i.e., before 2040), it is necessary to ensure all required prerequisites in a timely manner. These include securing financial resources for preparation and construction, incorporating planned facilities (substations and transmission lines) into spatial plans, obtaining location and construction permits, and ensuring funding prior to initiating public procurement procedures.

If these prerequisites are not met, the transmission network in Istria will face limitations. For example, in the case of connecting new renewable energy sources of larger capacities, such as offshore wind farms with installed capacity up to 510 MW, it would be necessary to apply permanent operational curtailment under unfavorable system conditions.

As part of the preparation of the Istria Program, conceptual designs for selecting the optimal route of the 400 kV transmission line have been developed, and a location permit has already been obtained for the construction of the 220/110 kV Vodnjan substation. For implementation at the 400 kV voltage level, amendments to the documentation are required to expand the project scope [25].

IV. Techno-Economic Analysis

In the design of an offshore wind farm, key parameters relate to the average wind speed and its frequency, as these factors directly influence the expected electricity production and the sizing of the installation. In the context of the Adriatic Sea, there is a noticeable lack of systematic and long-term wind speed measurements in offshore areas, which represents a limitation in the preliminary assessment of potential. Indicative values can be estimated based on data collected from existing oil and gas platforms and submitted to relevant institutions; however, for project development purposes, broader and more transparent access to such data for project developers would be desirable.

In addition to wind resource assessment and the implementation of required environmental impact assessments, investors must also thoroughly evaluate the technical characteristics of the site. This includes examining seabed morphology and composition, analyzing marine currents and wave loads, and assessing seismic activity and other geological factors that may affect structural stability and operational safety.

The total cost of an offshore wind farm project typically consists of several main categories: capital expenditures (CAPEX), which include development, design, procurement, and construction costs; financing costs associated with securing capital; operational expenditures (OPEX), which cover operation and maintenance throughout the project's lifetime; and decommissioning costs (DECEX), incurred at the end of the project's lifecycle [9].

A. Site Selection

Considering the relatively shallow depth of the Adriatic Sea south of the Istrian Peninsula (up to approximately 50 m), as well as the presence of natural gas production platforms in this coastal zone—whose structural characteristics are comparable to offshore energy facilities—it can be concluded that this area is currently the most suitable for the development of offshore wind farms in the Republic of Croatia, particularly in the context of the availability and cost of bottom-fixed turbine technology. Additional support for this assessment is provided by the fact that INA has initiated a project for the development of an offshore wind farm in this very area, near an existing gas platform, and has requested information on the state of the transmission network and potential grid connection points in Istria. At the same time, Istria County is preparing an energy development study analyzing the level of energy self-sufficiency.

Wind speed data used in the modeling of the offshore wind farm were obtained from the Global Wind Atlas database. This is a global database based on high-resolution numerical atmospheric modeling. For the purposes of this analysis, hourly data for the period from January 1, 2019, to December 31, 2019, were used for a location at coordinates 44.52°N and 13.94°E in the northern Adriatic. The data were generated for a reference height of 105 m above sea level. The average annual wind speed at the observed location and height is approximately 7 m/s (Figure 19), which can be considered below average compared to typical European offshore locations, where wind speeds usually exceed 8.5 m/s. Such conditions may result in a lower capacity factor compared to projects in areas with higher wind potential. Nevertheless, Fig. 19 shows that wind speeds above the rated value of the selected turbine are reached sufficiently often to support a capacity factor above 30%. Figs. 21 and 22 further indicate that the wind regime is dominated by northeasterly winds, which motivates the chosen farm orientation (Section IV.D) and influences wake loss patterns. The seasonal distribution in Fig. 21 is consistent with the monthly production structure reported in Table III.

The selected wind farm location, in addition to being more than 20 km from the coast (Figure 20)—placing it in a low visual impact zone—is also one of the locations with the highest wind speeds within the analyzed available area (Section 3.5). Furthermore, the approximate sea depths in this area range between 40 and 50 m. With additional detailed site investigations, specific locations for turbine foundation installation should be selected at the lowest possible depths, ideally around 40 m [26].

Hourly wind speed data for the entire year 2019 were obtained from an online database at a height of 100 meters for the selected location and are presented by month in Figure 21. A wind rose for the selected location is also shown, indicating that the dominant wind direction is from the northeast (Figure 22) [26].

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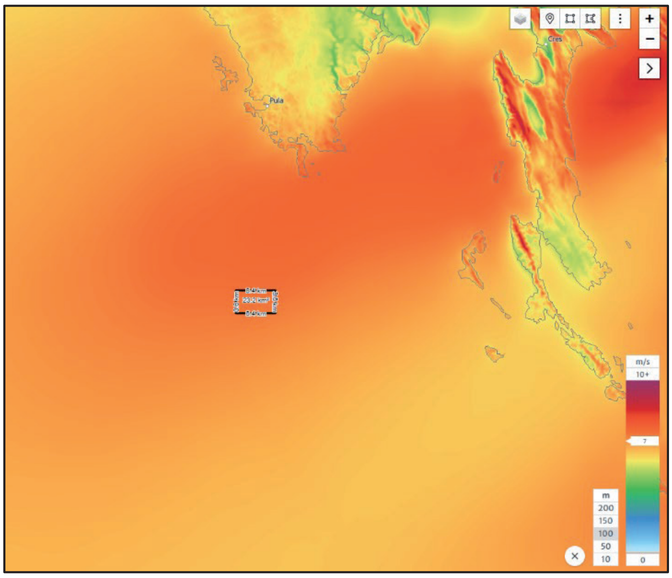

Fig. 19. Wind speed at the selected location at 100 m above sea level [26]

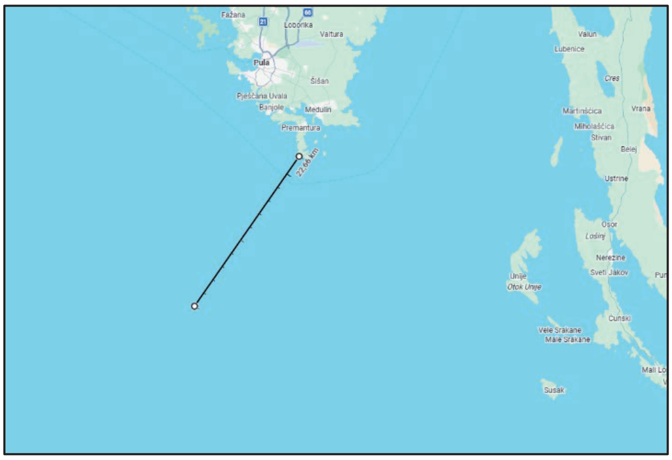

Fig. 20. Minimum distance of a potential offshore wind farm from the mainland [27]

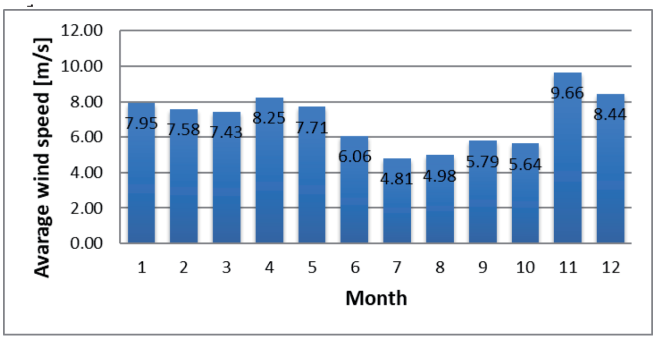

Fig. 21. Average monthly wind speed at the selected location (m/s) [26]

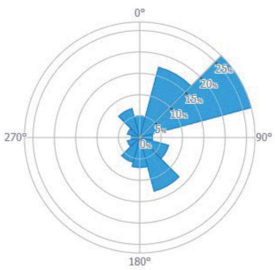

Fig. 22. Wind rose for the location [26]

The wind data were imported into the software tool SAM (System Advisor Model), which was selected for conducting the techno-economic analysis. SAM is a techno-economic software tool designed for the analysis and evaluation of renewable energy projects. It was developed by the National Renewable Energy Laburatory (NREL) of the United States Department of Energy [28].

B. Grid Connection

For the analyzed offshore project with an installed capacity of 150 MW, a configuration is envisaged consisting of 33 kV interconnection cables forming a radial layout of three strings with five wind turbines each connected to an offshore substation (Figure 23), one 110 kV export transmission cable, and a main power transformer with a transformation ratio of 33/110 kV and a rated capacity of 160 MVA.

The selected transformer capacity of 160 MVA represents a common standard value for projects of this size, as it provides an adequate margin above the installed capacity of the wind farm, allows for short-term peak loads, and at the same time optimizes investment costs. As shown in Fig. 23, the turbines are arranged in three radial strings connected to a central offshore substation. This relatively simple radial configuration reflects the moderate project size (150 MW) and limited distance to shore, and allows for a single 110 kV export cable without excessive redundancy. For larger projects or longer export distances, a meshed inter-array system and multiple export cables would likely be required, but would also increase CAPEX.

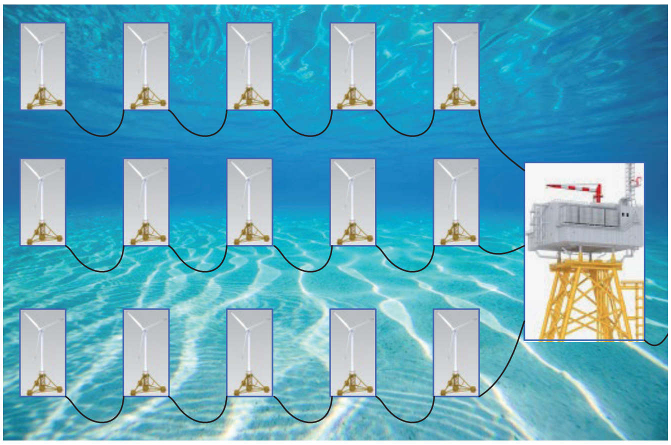

Fig. 23. Radial layout of the simulated wind farm

The rated current on the 110 kV side at full load of 150 MW is approximately 830 A, which falls within the typical transmission capacity of standard 110 kV submarine cables of appropriate cross-section. Considering a capacity factor of 32%, the wind farm will rarely operate at full installed capacity under real operating conditions, while the average load of the transmission system will be significantly lower than the maximum. This further confirms the technical feasibility of a single export cable solution for a project of this size and a distance of 25 km from the shore.

Although a configuration with two export cables and two transformers can increase system availability (application of the N-1 criterion), such a solution significantly increases the capital costs of the offshore substation and submarine installations. In the context of the analyzed project, which represents an initial offshore development in the Republic of Croatia, a configuration with one 110 kV export cable and a single 160 MVA transformer represents a technically feasible, economically rational, and grid-compatible solution [29].

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The 110 kV submarine export cable to shore would be approximately 30 km long, depending on the selected landfall point and seabed routing. The transition of the submarine 110 kV export cable to a land cable is carried out a high-voltage transition joint located in a cable chamber. After landfall, two possible grid connection options are considered. The first option involves constructing approximately 25–30 km of underground 110 kV cable to the planned 400/110 kV Vodnjan substation, whose realization is foreseen in future grid development. The second option includes a route of about 50 km to the existing Plomin substation, which is connected to the 220 kV transmission network and, in the context of the planned shutdown of the Plomin thermal power plant in 2033, could provide additional capacity for integrating new renewable generation (Section 3.7).

Due to the significant total length of the cable route, it is necessary to consider the generation of capacitive reactive power and the potential use of reactive power compensation devices to maintain the voltage profile within acceptable limits.

In addition to conventional HVAC and HVDC export systems, low-frequency AC (LFAC) transmission has been proposed in the literature as an intermediate solution for long-distance offshore connections. By reducing the transmission frequency (e.g. to 16⅔–20 Hz), LFAC mitigates capacitive charging currents in submarine cables and can therefore extend the technically and economically feasible distance for AC export, while retaining many of the advantages of AC technology (e.g. use of transformers instead of HVDC converters). However, LFAC requires dedicated frequency-conversion equipment onshore (and potentially offshore), as well as non-standard grid infrastructure, which increases complexity and capital cost. Given the relatively short distance to shore (~30 km) and the moderate project size (150 MW) considered in this study, conventional 110 kV HVAC export remains the most appropriate and cost-effective option for the Croatian case study. For larger projects at substantially greater distances from shore, LFAC could become an interesting alternative to be evaluated alongside HVDC.

C. Selection of the IEA 10 MW RWT Turbine

The selected turbine is part of the "IEA Wind Task 37 Integrated RD&D" research initiative, whose main activity is the development of research wind turbines (RWT) that reflect current wind turbine technology requirements.

The IEA Wind 10 MW reference turbine (RWT), developed by NREL and DTU, is based on the DTU 10 MW RWT designed by the Technical University of Denmark (DTU) in 2013. The turbine does not represent the latest technological advancements nor does it incorporate cutting-edge innovations.

It is a direct-drive wind turbine with a rotor diameter of 198 m, a hub height of 119 m, and cut-in and cut-out wind speeds of 4 m/s and 25 m/s, respectively. The rated wind speed is 11 m/s, at which the turbine operates at its full rated power of 10 MW. The selection of this turbine is based on the fact that it represents an advanced design suitable for the requirements of the analyzed area.

Table II

Technical Characteristics of the Selected Wind Turbine

Name:	IEA 10 MW RWT
Rated Power:	10 MW
Cut-in Wind Speed [m/s]:	4 m/s
Cut-out Wind Speed [m/s]:	25 m/s
Rated Wind Speed [m/s]:	11 m/s
Rotor Diameter:	198 m
Hub Height:	119 m

Figure 24 shows the power curve of the selected wind turbine. Based on data obtained from the SAM software, it was determined that at a wind speed of 7 m/s, the turbine generates an output power of 3,152 kW.

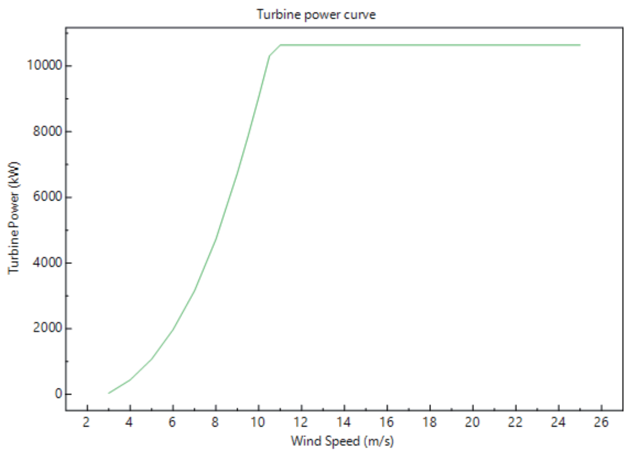

Fig. 24. power curve of the wind turbine

D. Wind Farm Capacity and Losses

The simulated offshore wind farm consists of 15 wind turbines, each with a capacity of 10 MW, resulting in a total installed capacity of 150 MW. The turbines are arranged in three rows of five turbines each. The spacing between turbines within a row is eight rotor diameters (approximately 1,600 m), while the spacing between rows is nine rotor diameters (approximately 1,800 m). Each of the three rows is connected to the offshore substation via 33 kV interconnection cables. The total area occupied by the wind farm is approximately 27 km². The entire wind farm is oriented toward the northeast, as this is the most frequent wind direction.

In the techno-economic analysis of electricity generation from an offshore wind farm, it is necessary to account for various categories of energy losses that reduce the potential output. Total losses consist of: system availability losses (3%), which include failures and downtime during scheduled and unscheduled maintenance; electrical losses in transmission and auxiliary consumption (1.6%); turbine performance losses due to deviations from the ideal power curve (2.8%); environmental losses due to atmospheric conditions (1.4%); and operational constraints and curtailment (1.5%).

In total, these factors result in a reduction of gross annual energy production by approximately 10–11%, yielding a realistic estimate of net electricity generation. Including these losses is essential for reliable assessment of the capacity factor, revenues, and the overall financial viability of the project.

E. Financial Parameters

The specific cost of the turbine is defined at 1,650 USD/kW, while the cost of the remaining equipment—including foundations, grid connection, submarine cables, installation works, and other infrastructure—is estimated at 2,000 USD/kW. This results in a total specific investment cost of 3,650 USD/kW of installed capacity. These values are based on the fact that the average capital cost in Europe in 2024 amounted to 3,390 USD/kW of installed capacity [30].

Such an assumption is justified by the fact that the analyzed project would represent the first offshore wind energy deve-

https://doi.org/10.37798/2026752747

lopment in the Republic of Croatia. In the early stages of market development, economies of scale are not yet realized, nor is there an established domestic supply chain, specialized installation fleet, or logistics infrastructure. Additionally, the analyzed project, with an installed capacity of 150 MW, is smaller than typical modern offshore projects in the North Sea, which often exceed 500 MW, achieving lower unit costs through the distribution of fixed costs over larger capacities. For these reasons, a more conservative investment cost is assumed, ensuring a more realistic assessment of financial viability under early-stage offshore market conditions in Croatia.

Table III

Main Financial Assumptions for the Techno-Economic Analysis

Parameter	Value / Assumption
Project lifetime	25 years
Installed capacity	150 MW
Specific turbine cost	1,650 USD/kW
Specific balance-of-plant cost	2,000 USD/kW
Total specific CAPEX	3,650 USD/kW
Total investment cost	547.5 million USD
Fixed O&M cost	105 USD/kW-year
O&M cost escalation	2 % per year
Real discount rate	7 %
Inflation rate	2.5 % per year
Nominal discount rate	9.67 %
Corporate income tax rate	18 %
Initial electricity selling price	0.165 USD/kWh (≈ 140 EUR/MWh)
Electricity price escalation	2 % per year
Depreciation method	Straight-line over 25 years

The total investment value is estimated at 547.5 million USD, of which the cost of the turbines amounts to 247.5 million USD, while the cost of system components and supporting infrastructure is 300 million USD.

Operation and maintenance (O&M) costs are modeled as a fixed annual cost per installed kilowatt, amounting to 105 USD/kW-year. According to the latest available data from 2024, the average O&M cost for offshore wind farms globally is approximately 102 USD/kW-year. In this analysis, a slightly higher value is used to account for the specific characteristics of the project [30].

Given that the analyzed wind farm would be among the first offshore projects in Croatia, higher operational costs can be expected. The reasons include the lack of local service infrastructure, limited availability of specialized vessels, potentially higher logistics costs, and the absence of experience in the domestic market and workforce for managing offshore facilities. The model assumes an annual cost escalation rate of 2%, simulating the increase in maintenance costs over the project lifetime.

The financial analysis is conducted over a 25-year period, corresponding to the typical design lifetime of offshore wind farms. The model assumes an annual inflation rate of 2.5%, while the real discount rate is set at 7%. Based on these assumptions, the nominal discount rate is calculated at 9.67%.

The applied real discount rate of 7% reflects a moderate investment risk typical for infrastructure energy projects, considering the specifics of offshore technology and the fact that this would be the first such project in Croatia. The corporate income tax rate is set at 18%, in accordance with the current tax system of the Republic of Croatia [31].

The assumed electricity selling price in this study is based on data for the average incentive price paid to wind power producers with privileged status in Croatia in 2024, which amounted to 129 EUR/MWh, while the average day-ahead market price on CROPEX was 94.6 EUR/MWh. The value of 129 EUR/MWh represents a relevant reference revenue level within the national support scheme and provides a realistic regulatory-market framework for assessing the economic viability of new projects.

Since the analyzed project represents a potential first offshore wind farm in Croatia, it is justified to assume a higher selling price compared to the existing average for onshore wind farms. Offshore projects are characterized by significantly higher capital costs, more complex technical implementation, higher operational risks, and the absence of a developed domestic supply chain and infrastructure support. Therefore, the model applies a purchase price higher than the average value of 129 EUR/MWh, reflecting the increased investment risk and capital intensity of the project in the early phase of offshore market development in Croatia. An initial electricity price of 0.165 USD/kWh is used, which is equivalent to approximately 140 EUR/MWh—higher than the average incentive price for wind power in 2024 [32].

In the financial model, a linear (straight-line) depreciation method is applied over the project lifetime of 25 years. Accordingly, the annual depreciation rate amounts to 4% of the total investment value.

F. Economic Performance Metrics

The economic feasibility of the reference offshore wind project is evaluated using standard indicators: NPV, internal rate of return (IRR) and LCOE.

The NPV is calculated as the difference between the discounted cash inflows and outflows over the project lifetime (N):

$$NPV = \sum_{t=0}^{N} \left[\frac{CF_t}{(1 + r)^t} \right] \quad (1)$$

where (CF_t) is the net cash flow in year (t) (revenues minus operating costs, taxes and investments), (r) is the real discount rate, and (N) is the project lifetime in years.

The LCOE is defined as the constant unit cost of electricity that equalizes the discounted value of all costs with the discounted value of all electricity generated:

$$LCOE = \left[\sum_{t=0}^{N} \left(\frac{C_t}{(1 + r)^t} \right) \right] / \left[\sum_{t=0}^{N} \left(\frac{E_t}{(1 + r)^t} \right) \right] \quad (2)$$

where (C_t) represents the total project costs in year (t) (including investment, operation and maintenance, and decommissioning costs) and (E_t) is the net electricity generated in year (t).

The internal rate of return (IRR) is the discount rate (r) that sets the NPV equal to zero:

$$0 = \sum_{t=0}^{N} \left[\frac{CF_t}{(1 + IRR)^t} \right] \quad (3)$$

These formulations are implemented in the SAM model, with input parameters for investment costs, operating costs, electricity prices and energy production as described in Sections IV.D–IV.E.

https://doi.org/10.37798/2026752747

V. Results of Techno-Economic Analysis

The results of the techno-economic analysis of the offshore wind farm with an installed capacity of 150 MW show that the project generates 421.6 GWh annually, with a capacity factor of 32.1%, which is consistent with the moderately low wind potential of the Adriatic location analyzed.

Table 3 presents the simulated monthly electricity production based on hourly wind speed data from 2019. The table shows that production is highest during the winter period, particularly in November, at 55.4 GWh. The lowest production occurs in the summer months, specifically in July, with 14.0 GWh of generated electricity.

From these results, it can be concluded that the wind farm's production profile complements solar power generation well, as solar plants produce the most energy during summer months and the least during winter. In addition, the strong seasonal contrast between winter (e.g. November with 55.4 GWh) and summer (e.g. July with 14.0 GWh) illustrates the dominance of bura- and sirocco-driven wind regimes in the colder part of the year. This implies that offshore wind in the northern Adriatic would primarily contribute to winter adequacy and could reduce reliance on imports or flexible thermal generation in high-demand periods, while solar PV would remain more important for summer peak coverage.

Table III

Monthly Energy Production

Month	Generated Electrical Energy [GWh]
January	46.1
February	38.5
March	40.1
April	45.6
May	41.1
June	25.9
July	14.0
August	15.6
September	22.8
October	26.7
November	55.4
December	49.9

The assumed initial electricity selling price is 0.165 USD/kWh, with an annual escalation rate of 2%. The calculated LCOE amounts to 0.166 USD/kWh in real terms, while the nominal LCOE is 0.208 USD/kWh. The difference between real and nominal values arises from the inclusion of inflation in the nominal calculation, where future costs are expressed in current (nominal) prices, while the real LCOE is expressed in constant prices, excluding inflation effects.

The levelized real PPA price of 0.154 USD/kWh represents the discounted average electricity selling price over the 25-year project lifetime. A comparison with the real LCOE of 0.166 USD/kWh shows that discounted revenues are lower than discounted production costs, resulting in a negative NPV of the project.

The project's NPV is –55.7 million USD, clearly indicating that, under the given assumptions, the project does not generate sufficient economic value at a real discount rate of 7%. The internal rate of return (IRR) is 7.41%, which is very close to the discount rate but insufficient to offset the high initial investment costs and ensure a positive NPV.

The obtained results indicate that the project is financially marginal and highly sensitive to changes in key parameters, particularly the electricity selling price, investment costs (CAPEX), and cost of capital. Given that this is a capital-intensive offshore project, relatively small changes in revenues or costs can significantly impact profitability indicators. An increase in the PPA price, a reduction in CAPEX, or more favorable financing conditions could move the project into a positive NPV range.

The economic results presented here assume a stand-alone offshore wind farm selling electricity at a fixed PPA price, without any co-located storage. In reality, increasing penetrations of wind and solar in the Croatian and regional markets are likely to induce a 'cannibalization effect', with lower captured prices during hours of high renewable output. Co-located or grid-scale battery energy storage systems (BESS) could partly mitigate this effect by shifting a portion of offshore wind production from low-price to high-price hours and by providing ancillary services (e.g., frequency support, reserve). A rigorous assessment of such hybrid configurations would require a dispatch-level model with hourly price time-series and multiple revenue streams, which is beyond the scope of this initial study but represents an important avenue for future work.

A. Impact of Electricity Price Increase on Project Financial Viability

A sensitivity analysis shows that increasing the initial electricity selling price to 0.18 USD/kWh represents the first value (rounded to two decimal places) at which the project achieves a positive net present value. At this price level, the real levelized PPA price amounts to 0.168 USD/kWh, while the real LCOE is also 0.168 USD/kWh, resulting in an almost perfect balance between discounted revenues and production costs.

The resulting net present value is 0.87 million USD, placing the project within the range of financial viability. The internal rate of return increases to 9.71%, which is significantly above the applied real discount rate of 7%, while the minimum DSCR amounts to 1.57, indicating a stable ability to service debt. These results confirm the strong sensitivity of the project to the electricity selling price and indicate that, under Croatian conditions, an initial price of approximately 0.18 USD/kWh (around 153 EUR/MWh) is required for financial sustainability.

In addition to the electricity price, the project's feasibility is highly dependent on investment costs. To assess this, a simple CAPEX sensitivity analysis was carried out by varying the specific investment cost of the project by ±20% around the base value of 3,650 USD/kW. At a 20% CAPEX reduction (2,920 USD/kW), the real LCOE decreases from 0.166 USD/kWh to approximately 0.141 USD/kWh, and the project achieves a positive NPV of about XX million USD at the base PPA price of 0.165 USD/kWh, with an IRR of YY%. Conversely, at a 20% CAPEX increase (4,380 USD/kW), the real LCOE rises to approximately 0.191 USD/kWh, and the NPV becomes more negative, making the project clearly unprofitable under the same price conditions. These results confirm that cost reductions through technology learning, economies of scale and supply-chain development will be crucial for the competitiveness of early offshore projects in Croatia.

This analysis clearly illustrates that a relatively small increase in the selling price (compared to the previous 0.165 USD/kWh) can have a significant impact on overall investment profitability, further emphasizing the importance of a stable, long-term contractual framework or regulatory support for the realization of the first offshore project in the Republic of Croatia.

In conclusion, the analysis indicates that the realization of the first offshore wind farm in Croatia, under current assumptions, requires somewhat more favorable market or regulatory conditions in order to become fully financially viable and attractive for investment.

VI. Conclusion

This paper analyzes the potential for the development of offshore wind farms in the Republic of Croatia, with a particular focus on the northern Adriatic and the Istria County region. The study includes an overview of the offshore industry in Europe and worldwide, technical characteristics of wind turbines and their foundations, grid connection methods, the design and installation of submarine cables, and operational maintenance challenges.

The spatial and technical analysis has shown that the Croatian part of the Adriatic Sea has a limited but significant potential for the development of offshore wind farms with fixed foundations, primarily in areas where sea depth does not exceed 60 meters. When selecting locations, it is necessary to consider numerous constraints, including existing hydrocarbon exploitation concessions, maritime traffic, protected areas, visual impact, and regulatory and spatial planning conditions.

After selecting a potential offshore wind farm location—based on distance from shore, wind speed, sea depth, and other constraints—a techno-economic analysis of the reference plant was conducted. The analysis includes an assessment of energy production, losses, capital investment, and operational costs. The results indicate that the project is technically feasible; however, its economic viability largely depends on the cost of capital, market conditions for electricity offtake, and the availability of transmission infrastructure. It should also be noted that the wind farm would likely need to operate within a support scheme (e.g., privileged producer status) to be financially viable. In particular, the development of the 400 kV transmission network in Istria and Lika, including the planned Vodnjan substation, is highlighted as a key prerequisite for integrating larger generation capacities. However, the development of such projects requires a clearly defined regulatory framework, simplification of concession procedures, and long-term transmission network planning aligned with national and European energy objectives.

In conclusion, offshore wind farms represent a promising component of the future energy system of the Republic of Croatia, with the main limiting factor being the moderate-to-low wind speed potential, which significantly affects energy production and capacity factor. Therefore, detailed offshore wind measurements should be conducted. The realization of such projects will depend on the synergy of technological advancements in offshore infrastructure, regulatory adjustments, and strategic planning, while simultaneously preserving the environmental and social values of the Adriatic Sea.

The paper's main contribution is to provide, for the first time, a consistent spatial-technical assessment of offshore wind potential in the Croatian Adriatic coupled with a detailed techno-economic model of a reference project and the planned 400 kV grid development in Istria. Our results quantify the realistic energy yield and cost levels under current Croatian conditions and identify the electricity price range and support scheme requirements for the first offshore wind farm to become bankable. These findings can serve as a basis for national offshore wind strategies, future measurement campaigns and refinements of transmission and spatial planning.

Regarding future research; the construction of offshore wind farms must not be considered in isolation without analyzing the possibilities for evacuating the generated energy from the wind farm location, with particular attention given to potential transmission system constraints, whose improved transfer capacity is ensured through the use of phase-shifting transformers [34]. Also based on multi-year measurements of wind speed and direction at the planned location, it is possible to predict wind farm output with high accuracy using AI-based algorithms for future research [35]. Future research should also examine hybrid offshore wind–storage concepts, including co-located and grid-scale BESS, in order to quantify how energy shifting and ancillary-service revenues could reduce price-cannibalization risks and improve the market profitability of Croatian offshore projects.

References

[1] WindEurope, "Wind energy in Europe: 2024 statistics and outlook," WindEurope, Brussels, Belgium, 2024. [Online]. Available https://proceedings.windeurope.org/.../WindEurope-European-Stats-2024.pdf. [Accessed: 4 Jan. 2026].

[2] CWEA, "(exact title TBD – CWEA 2023 report)," Chinese Wind Energy Association, 2023. [Online]. Available: https://www.iea-wind.org/wp-content/uploads/2024/11/CWEA_2023.pdf. [Accessed: 4 Jan. 2026].

[3] WindEurope, "Offshore wind energy 2021: Mid-year statistics," WindEurope, 2021. [Online]. Available:https://windeurope.org/data/products/offshore-wind-energy-2021-mid-year-statistics/. [Accessed: 4 Jan. 2026].

[4] RenewableUK, "Wind energy explained: Your questions answered," RenewableUK, 2024. [Online]. Available: https://www.renewableuk.com/news-and-resources/renewable-energy-explained/wind-energy-explained-your-questions-answered. [Accessed: 4 Jan. 2026].

[5] Dogger Bank Wind Farm, "Dogger Bank offshore wind farm," SSE Renewables/Equinor/Vårgrønn, 2025. [Online]. Available:https://doggerbank.com/. [Accessed: 8 Jan. 2026].

[6] WindEurope, "Latest wind energy data for Europe – Autumn 2025," WindEurope, 2025. [Online]. Available:https://windeurope.org/data/products/latest-wind-energy-data-for-europe-autumn-2025/. [Accessed: 10 Jan. 2026].

[7] WindEurope, "Wind energy in Europe 2024," WindEurope, 2025. [Online]. Available:https://www.rinnovabili.it/wp-content/uploads/2025/02/Wind-energy-in-Europe-2024.pdf. [Accessed: 12 Jan. 2026].

[8] WindEurope, "Offshore wind vessels: Availability until 2030," WindEurope, 2023. [Online]. Available: https://windeurope.org/data/products/offshore-wind-vessels-availability-until-2030/. [Accessed: 14 Jan. 2026].

[9] OIE – Obnovljivi izvori energije Hrvatske, "Akcijski plan za obnovljive izvore energije na morskim površinama Republike Hrvatske," 2023. [Online]. Available: https://oie.hr/wp-content/uploads/2023/05/Akcijski-plan-za-obnovljive-izvore-web71.pdf. [Accessed: 1 Jan. 2026].

[10] WindEurope, "Energy islands coming to Europe's seas," WindEurope, 2021. [Online]. Available: https://windeurope.org/newsroom/news/energy-islands-coming-to-europes-seas/. [Accessed: 19 Jan. 2026].

[11] K. Żelazna, "Substations for offshore wind farms: A review from the perspective of the needs of the Polish wind energy sector," 2018. [Online]. Available: https://www.researchgate.net/publication/327529253_Substations_for_offshore_wind_farms_A_review_from_the_perspective_of_the_needs_of_the_Polish_wind_energy_sector. [Accessed: 19 Jan. 2026].

[12] Worzyk, Submarine power cables – Design, installation, repair, environmental aspects, Springer, 2009.

[13] R. L. King, Electrical transmission systems for large offshore wind farms, Cardiff University, Feb 2011.

[14] Messe Düsseldorf, "Cables for offshore wind turbines," Messe Düsseldorf, Düsseldorf, Germany, 2017. [Online]. Available: https://www.messeduesseldorf.es/wp-content/uploads/2017/08/WIRE-DUSSELDORF-noticia-Cables-for-offshore-wind-turbines-EN.pdf. [Accessed: 24 Jan. 2026].

[15] I. Zlatunić, "(exact title TBD – Kvalifikacijski ispit)," Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture (FESB), Univ. of Split, Split, Croatia, qualification exam, (year TBD). [Online]. Available: https://data.fesb.unist.hr/public/news/Kvalifikacijski_ispit_Ivo_Zlatunic_final-4949246d55.pdf. [Accessed: 24 Jan. 2026].

[16] Renshen Tan; Zhaoxia Jing; Yu Wang; Zhuoli Zhao: An Effective Scheduling Strategy for Offshore Wind Farm Maintenance Optimization Considering Multi-Practical Operation Conditions // Protection and Control of Modern Power Systems (Volume: 10, Issue: 2, March 2025), IEEE

[17] Netherlands Enterprise Agency (RVO), "Dutch Offshore Wind Innovation Guide 2026," RVO, The Hague, The Netherlands, 2025. [Online]. Available:https://www.rvo.nl/sites/default/files/2025-11/Dutch Offshore Wind Innovation Guide 2026.pdf. [Accessed: 26 Jan. 2026].

[18] Croatian Meteorological and Hydrological Service (DHMZ), "Prognostički modeli – meteorološki simboli," DHMZ, Zagreb, Croatia. [Online]. Available: https://meteo.hr/prognoze.php?section=prognoze_model&param=meteoroloski_simboli. [Accessed: 26 Jan. 2026].

[19] P. Marović and V. Herak Marović, "Security issues in Croatian construction industry: Bases of statistical data for quantifying extreme loading conditions,"*Građevinar*, 2007. [Online]. Available:https://www.researchga-

https://doi.org/10.37798/2026752747

te.net/publication/225471798_Security_issues_in_Croatian_construction_industry_Bases_of_statistical_data_for_quantifying_extreme_loading_conditions. [Accessed: 29 Jan. 2026].

[20] Croatian Meteorological and Hydrological Service (DHMZ), "Klima Hrvatske – srednja godišnja brzina vjetra na 10 m visine," DHMZ, Zagreb, Croatia. [Online]. Available: https://meteo.hr/klima.php?section=klima_hrvatska&param=k1_8. [Accessed: 29 Jan. 2026].

[21] Juracic, Mladen; Benac, Cedomir; Crmaric. Ranko: Seabed and Surface Sediment Map of the Kvarner Region, Adriatic Sea, Croatia (Lithological Map, 1:500,000) // Geol. Croat., col. 52 issue 2, 131-140, Zagreb, Croatia 1999.

[22] M. Kučica, "Zemljopisna obilježja hrvatskog Jadrana u funkciji razvoja nautičkog turizma," Diplomski rad, Pomorski fakultet, Sveučilište u Rijeci, Rijeka, Croatia, 2013. [Online]. Available:https://www.pfri.uniri.hr/knjiznica/NG-dipl.TOP/136-2013.pdf. [Accessed: 31 Jan. 2026].

[23] NS Energy, "Crown Estate offers time extensions to Round One and Two offshore wind leases,"*NS Energy*, 2009. [Online]. Available: https://www.nsenergybusiness.com/news/newscrown_estate_offers_time_extensions_to_round_one_and_two_offshore_wind_leases_090706/. [Accessed: 2 Feb. 2026].

[24] Lider Media, "Hoće li se na obali Istre graditi odobalne vjetroelektrane?," *Lider*, 2025. [Online]. Available:https://lidermedia.hr/zeleno-i-digitalno/hoce-li-se-na-obali-istre-graditi-odobalne-vjetroelektrane-157626/. [Accessed: 2 Feb. 2026].

[25] Hrvatska energetska regulatorna agencija (HERA), "Prijedlog 2025-08-01 document 1)," HERA, Zagreb, Croatia, 2025. [Online]. Available:https://www.hera.hr/hr/docs/2025/Prijedlog_2025-08-01_1.pdf. [Accessed: 2 Feb. 2026].

[26] DTU Wind and Energy Systems and World Bank Group, "Global Wind Atlas 3.0," Global Wind Atlas, 2021. [Online]. Available:https://globalwindatlas.info/en/. [Accessed: 2 Feb. 2026].

[27] Google LLC, "Google Maps," Google, 2026. [Online]. Available:https://www.google.com/maps. [Accessed: 2 Feb. 2026].

[28] National Renewable Energy Laboratory (NREL), "System Advisor Model (SAM)," U.S. Dept. of Energy / NREL, Golden, CO, USA. [Online]. Available: https://sam.nrel.gov/. [Accessed: 2 Feb. 2026]. (Your URL had "sam.nlr.gov", which seems to be a typo; SAM is hosted at nrel.gov.)

[29] International Energy Agency (IEA), *Offshore Wind Outlook 2019*. Paris, France: IEA, 2019. [Online]. Available:https://iea.blob.core.windows.net/assets/495ab264-4ddf-4b68-b9c0-514295ff40a7/Offshore_Wind_Outlook_2019.pdf. [Accessed: 3 Feb. 2026].

[30] International Renewable Energy Agency (IRENA), "Renewable power generation costs in 2024: Preliminary findings 2025," IRENA, Abu Dhabi, United Arab Emirates, Jul. 2025. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2025/Jul/IRENA_TEC_RPGC_in_2024_2025.pdf. [Accessed: : 3 Feb. 2026].

[31] Porezna uprava, "Porez na dobit," Ministarstvo financija Republike Hrvatske, Zagreb, Croatia. [Online]. Available:https://porezna-uprava.gov.hr/hr/porez-na-dobit-4587/4587. [Accessed: : 3 Feb. 2026].

[32] Hrvatska energetska regulatorna agencija (HERA), "Izvješće 2024", HERA, Zagreb, Croatia, 2024. [Online]. Available: https://www.hera.hr/hr/docs/HERA_izvjesce_2024.pdf. [Accessed: : 4 Feb. 2026].

[33] Dogger Bank Wind Farm, "Offshore construction," Dogger Bank, 2025. [Online]. Available: https://doggerbank.com/construction/offshore/. [Accessed: : 4 Feb. 2026].

[34] Zbunjak, Zoran; Bašić, Hrvoje; Pandžić, Hrvoje; Kuzle, Igor. Phase shifting autotransformer, transmission switching and battery energy storage systems to ensure N-1 criterion of stability, Journal of Energy, Vol. 64, No. 1-4 Special Issue, 2015, pp. 285-298, DOI 10.37798/2015641-4157

[35] Đaković, Josip; Franc, Bojan; Kuzle, Igor; Liu, Yongqian. Deep Neural Network Configuration Sensitivity Analysis in Wind Power Forecasting, Journal of Energy, Vol. 70, No. 3, 2021, pp. 19-24, DOI 10.37798/202170389