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Energy Production and Economic Impact in the Black Sea Blue Economy

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ABSTRACT: The generation of energy production obtained with the help of renewable resources contributes to the reduction of carbon emissions and to the consolidation of energy security in the area, as well as to the development of the necessary infrastructure for socio-economic development in the coastal and offshore area. The objectives of paper are specific to a certain location in the Black Sea, namely: obtaining wind energy production using an efficient design of a pilot floating system, using a wind dataset for optimized design floating system, calculation of the levelized cost of electricity for wind energy (LCOE) and impact with market value of wind energy production in the Black Sea Blue economy. The methods used are: the Froude scaling methodology was used for design of pilot floating system, metocean analytics for obtained metocean data (wind, waves, currents), monitoring the state of pilot floating system components using Digital Twin Technology (DT), economic modeling of technology-specific LCOE of renewable technologies (Specific Investment Cost-CAPEX, Operating Cost-OPEX) in comparison with respect to the current level of LCOE at local conditions in the Black Sea and PESTEL analysis (Political, Economic, Social, Technological, Environmental and Legal impact).The final data obtained for the achievement of the proposed objectives are results obtained during the implementation of the BLOW project: an optimized design for the study location with reduced costs for operation and maintenance, optimized parameters using metocean data, societal, environmental and economic impact assessment with barriers and obstacles. The conclusion is that globally, the development of a floating offshore wind energy market is emerging rapidly as experience and knowledge is gained from pilot projects.

1 INTRODUCTION

The costs of electricity production are a significant factor, being different depending on the applied and construction technology, as well as operational expenses for each power generation plant design. In the last 15 years, costs for renewable energy technologies have dropped considerably, due to technological innovations such as the use of cheaper and more efficient materials. These led to the reduction of the amount of materials used, to more efficient production processes, to an improvement in the production of system components [1].

In another order, hydrogen-based energy production comes to balance the fluctuating supply from renewable sources and the energy mix becomes more and more important in the future.

Mixed power generation in the Black Sea region is among the biggest carbon consumers in Europe. Some renewable energy sources (wind energy, wave energy, solar energy) can help reduce the region's dependence on fossil fuel-based energy generation. At the same time, they can contribute to regional energy security and strengthen the infrastructure necessary for the socio-economic development of coastal areas. Simultaneously with the capitalization of these energy potentials, the potential of adjacent energy production with low carbon emissions can be capitalized [2, 3,4,5].

In recent years, installations for the production of electricity from wind sources have spread in all the countries of the world involved in the development of the projects aimed at production of electricity from renewable sources. Between the years 1997 and 2004, the world power production capacity of the CEE a increased by 26.1%. By developing technology and moving from onshore wind power plants (CEE) to the offshore ones, the energy produced by the latter has become the main source of worldwide interest in the development of renewable sources [6].

Energy transformation and supply it involves both technical and economic efforts. The costs of electricity production are a significant cost factor, varying with technology and according to construction and operational expenses of each electricity production facility [7,8].

In the Black Sea, an experimental floating wind farm with a capacity of 5 MW can be implemented and developed (**B**lack Sea f**L**oating **O**ffshore **W**ind, BLOW project) [9,10]. It can constitute an open-access test platform for future offshore wind pilots floating in the Black Sea. The industrial feasibility of floating wind turbines required for mass industrialization must be compatible with local production capabilities and provide a pathway to mass industrialization.

To integrate a floating wind turbine pilot system and, subsequently, to establish a floating wind farm, in the context of industrial clusters in region, a close collaboration with local partners must be created and carry out an analysis to identify the existing barriers and obstacles (technical, economic, financial, institutional, social, cultural, etc.) in order to implement floating wind systems in Black Sea. At the same time, a weighted ranking and evaluation of the barriers will be made and the legal recommendations regarding their removal will be scored. For the first time, the strong growth of wind and solar energy has determined the share of renewable sources in the global mix of electricity over 30%. More than 102 countries have generated 30% more energy from renewable resources. Currently, 39.4% of global electricity now comes from low-carbon sources. [11, 12, 13, 14].

Offshore wind is currently one of the most cost-efficient, clean and scalable power sources. There are more publications confirming the potential of floating wind in Black Sea for EU member states. An estimated total potential natural capacity of 94 GW for Romania's offshore wind sector, out of which 75% would be floating wind [15]. The offshore wind potential in the north of the Bulgarian Black Sea coast would be more than 116 GW. In the Shabla region alone, capacities of at least 6 GW can be built in a few years [16, 17].). Floating offshore has a lot of potential at the pan European level, but it is also a very promising source for EU member states. Beyond the usual high wind speed markets (UK, Japan, Norway, France, etc), low to medium markets similar to the Black Sea are notably South Korea with huge ambitions (the Korean government's target of 12GW of offshore wind by 2030.

Floating Offshore Wind Turbines (FOWT) can help reduce the region's reliance on fossil fuel-based power generation, contribute to regional energy security and drive infrastructure reinforcement for the socio-economic development of coastal areas, as well as the potential of adjacent low-carbon production, such as renewable hydrogen. Indeed, the technical potential for offshore wind estimated in the Black Sea is 166 GW, and about its half is located in Romania and Bulgaria, where the floating offshore potential represents 78% of the technical market [18].

In the following chapters, the manuscript relates to a significant and timely topic with potential contributions to the field. The authors explore the potential of offshore floating wind energy in the Black Sea region, emphasizing its role in reducing carbon emissions, enhancing energy security, and fostering socio-economic development. In the content it is proposed an optimized design for a pilot floating wind system tailored to the region's wind conditions and discusses its economic implications within the blue economy framework. The originality and novelty of the work consists in the fact that the regional focus (Black Sea) is new and, unfortunately, underexplored in the literature. Furthermore, the idea of combining energy production with economic development under the umbrella of the Blue Economy is relevant and aligned with EU policy objectives.

2 METHOD AND RESEARCH

In this paper we propose for study some points to obtain wind energy production with a pilot floating system, the efficient design of floating system, a cost-effective floating unit design optimized for a wind dataset obtained with metocean analysis [4,19], environmental impact assessment, impact on LCOE (the levelized cost of electricity)[1], economic impact (market value of floating offshore wind power with a specific focus on the Black Sea Blue economy), societal impact and contribution towards carbon neutrality & energy security [20].

2.1 *The location of study*

The location of study is near Varna, Bulgaria (Fig. 1) [1,4].

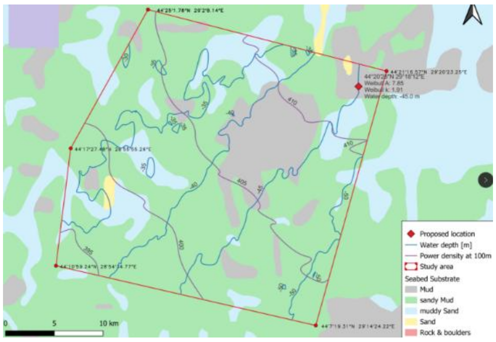

Figure 1. Location of study [1,4]

The proposal for installation of pilot floating system is in according with marine administration (Fig. 2)[21].

Figure 2. Location of general assembly [21]

Wind system location established 21,5m height from sea level on the platform Galata (Fig. 3)[9,10].

Figure 3. Location of wind system [9,10]

Waves and currents monitoring system will be mounted attached to one leg of the platform Galata, in the exterior, take account the main currents/waves direction.

Data are collected for all months of the one year on Galata (2023-2024). The collected data were compared with data from ERA5, Galata platform, EuxRo01, EuxRo03 and CG Meteo sensors.

For location point of study the statistic was computed [22,23]. The statistical analysis period is 2007-2022, and the analyzed distributions are: wind and wave distribution rose for significant wind speed and significant wave height at point of study, the wind speed field, monthly joint probability distribution of significant wave height and wave spectral peak period at point of study, etc [23,24].

2.2 *Key Technical Considerations for Wind Energy Capture*

In order to obtain an effective design of the pilot floating system, the following aspects must be taken into account:

– development of a disruptive and cost-effective floating unit design optimized for low and medium speed areas;
– advanced operation, control and maintenance through digitalization (the state of the pilot system components will be monitored through a Digital Twin Technology, DT) (Figure 4)[25, 26, 27]

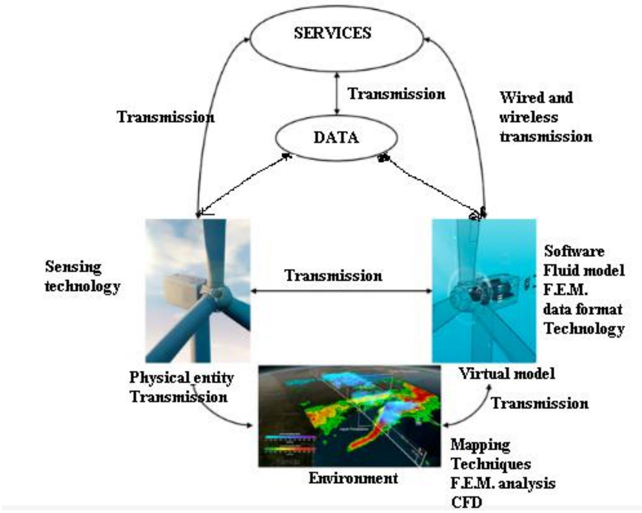

Figure 4. DT of a wind turbine [27]

– industrial feasibility of floating wind system for mass industrialization compatible with local production capabilities. The main objective is to achieve a higher Annual Energy Production (AEP) than a higher rated power to increase the market value. The pilot system will target a specific power of around 300 W/m², which is well suited for low to medium offshore wind speeds, but is also compatible with high wind speed locations. Local mass industrialization for production will be assessed and designed, including the possibility of automation, onshore assembly and offshore deployment. The reduction of LCOE-Levelized Cost of energy (targeting a value of up to 50 EUR/MWh by 2030), and an automated and optimized production process is considered.

The methods used are: the Froude scaling methodology was used for design of pilot floating system, metocean analytics for obtained metocean data (wind, waves, currents), monitoring the state of pilot floating system components using Digital Twin Technology (DT), economic modeling of technology-specific LCOE of renewable technologies (Specific Investment Cost-CAPEX, Operating Cost-OPEX) in comparison with respect to the current level of LCOE at local conditions in the Black Sea and PESTEL analysis (Political, Economic, Social, Technological, Environmental and Legal impact).

2.3 *Design of pilot floating system*

Regarding the design of pilot floating system, the Froude scaling methodology was used, which guarantees that the dynamic behaviour of the floating wind system is well represented, assuming that the wave height and wind speed are also properly scaled. This prototype will be made on a scale to experimentally with stand the wind conditions specific to the study site [4, 24]. Consequently, the technical feasibility for the desired installed power can be assessed. Such pilot projects are mentioned in the specialized literature [28, 29, 30].

We propose for the pilot floating system a design adapted to low and medium wind speeds (we use the information of wind speed from ERA5 data from 1996 to 2022, corrected to compute 6.5m/s over the GALATA area at 100m), using a 140m diameter rotor, aiming for a power density of 300 W/m²(Fig.6)[21].

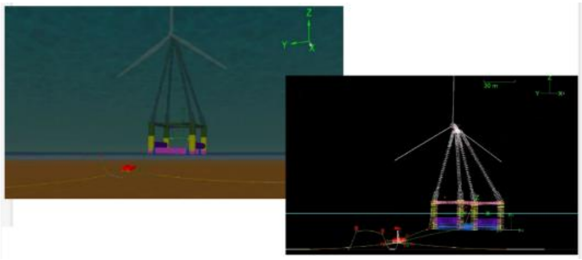

Figure 6. The pilot floating system design [21]

The pilot system will be equipped with advanced controllers that control and increase energy production by reducing the load on the floating wind system and extending its life (up to 30 years). In order to improve the reliability of the system, a grid formation controller is also considered, which allows the wind system to operate in the island system, making it responsible for the grid creation.

The pilot system proposed for analysis aims at a lighter structure (approx. 30%), with 10% additional energy generated by the longer blades due to the specific shape recommended by the specialized literature [21]. The goal is to reduce CAPEX (Capital expenditures), while targeting a 300 W/m² turbine design optimized for low and medium wind speed areas. For these purposes, the LCOE must be calculated.

2.4 *Calculation of the levelized cost of electricity for wind energy*

As a result, from a technical point of view, an exact calculation of the levelized cost of electricity for wind energy (LCOE) is required (in a realistic scenario for 2030 the LCOE for fixed offshore wind power in the Romanian region of the Black sea will be €71/MWh, while for the later development of floating offshore wind the LCOE would be €94/MWh; the LCOE in 2045 is projected to be between 5.0 and 8.3 €cents/kWh;), which involves certain commercial steps [1]:

- first of all, the design of a credible and robust design of a floating wind system according to the statistical data of the wind and wave velocity fields;
- in assembly line and heavy logistics processes, feasibility and optimization from a mass production perspective will be ensured;
- infrastructures will be specified (cranes, automated welding, etc.).

The LCOE of renewable energy systems will be significantly lower than the operating costs of conventional power systems. LCOE for offshore wind turbines in comparison with LCOE for onshore turbines are much lower, with a decreasing trend until 2045, from 10.2 to 5.5 €cents/kWh, depending on location and wind speed distribution.

In our study LCOE is calculated by comparison all costs incurred during the lifetime of the power plant for construction and operation and the total amount of energy generated. For the calculation of the LCOE for a pilot floating system, the following applies [31]:

LCOE = (Sum of costs over lifetime)/(sum of electricity produced over lifetime), (1)

In literature LCOE [EUR/kWh] depends on :
Io - investment expenditure [EUR];
A_t -annual total cost[EUR/per year, t];
$M_{t,el}$ - produced amount of electricity[kWh/per year,t];
real interest rate [%];
n- economic lifetime [years];
t- year of lifetime (1, 2, ...n).

The total annual costs are composed of fixed and variable costs for the operation of the power plant, maintenance, servicing, repairs and insurance payments. That means the total annual costs A_t is

A_t = fixed operating costs + variable operating costs (+ residual value/ disposal of the power plant) (2)

Formula which generates LCOE is:

LCOE = (CAPEX+OPEX)/yield. (3)

where:
CAPEX: capital expenditure;these expenses assume the total investment for the purchase of components necessary for the installation of the pilot floating system (includes all investments, as well as those allocated for the labor force responsible for installing the system);
OPEX: operating expenses; this amount refers to the expenses necessary for the maintenance of the floating pilot plant (includes all taxes, operating and maintenance costs of the pilot floating system).
Yield;this variable refers to the energy output harvested by the system during its use.

The cost of electricity production sums up the following values:

- capital and investment costs: sums up losses from interest on borrowed capital and loss of income from equity capital;
- purchase and installation costs: figures the total expenses incurred for the purchase of parts, components and for their actual installation;
- operating costs: totals the expenses required in the maintenance, repair, cleaning and periodic control of the electricity generation system;
- fuel costs: where applicable, fuel procurement costs (such as fossil fuels or fuel rods) are also added.

For our pilot floating system the CAPEX are total costs for: development, wind turbine delivered to shipyard, substructure, turbine - substructure assembly (onshore), station keeping system, cabling system, transport & installation, contingency (10%) (Table 1). OPEX was calculated [33].

Wind and wave conditions, tidal ranges and tidal flows also impact LCOE. Higher mean wind speeds increase cost but have a net benefit for LCOE due to increased energy production.

A major impact on LCOE is the development of technology in the design and manufacture of floating substructures. This cost element is specific to the offshore floating pilot wind system and represents a very large proportion of the CAPEX.

Table 1. CAPEX details

Item group	Concept	Cost (k€)
Development	Grid connection	60
	Design	300
	Certification	474
	Consenting process & surveys	650
	Project management (HSE, legal...)	900
	Admin	158
	Legal	307
	Communication	278
	Travels	120
	Insurance (CAR)	400
Wind turbine delivered to shipyard	5MW turbine: rotor, nacelle, generator, tower based control cabinets, converters and cables	1.400
	Transformer	93
	Auxiliary transformer, harmonic filter and MV cables	235
	Transport from China to Black Sea area	570
	Tool needed to transport and install the RNA	300
Substructure	Float manufacturing	8.503
	Ancillaries procurement	1.400
Turbine - substructure assembly (onshore)	Yaw and gearbox removal + RNA installation	3.164
Station keeping system	Mooring procurement	2.130
	Buoy: lower part + slipring + slipring connectors + upper part + bearing (yoke)	1.000
Cabling system	2 dynamic cables (300m total) + static cable (21.9km) + onshore cables (3x900m) + cable hardware	4.840
Transport & installation	Port entrance fees and deck rental for floater + mooring system T&I	63
	Mooring installation (including SPM buoy)	1.160
	FOWT towing from production to site	955
	FOWT Hook up	998
	Offshore cables	5.150
	Fuel cost variation	150
	Transition, onshore cables and connection to grid	400
Contingency	TOTAL	36.158
	10%	3.616
	TOTAL WITH CONTINGENCY	39.774

OPEX:
A= 71000 GPB/MW/year
Inflation 2%
Total OPEX=415350€/year
where OPEX=A*1,17*5

2.5 *Impact assessments*

A PESTEL (**P**olitical, **E**conomic, **S**ocial, **T**echnological, **E**nvironmental and **L**egal) analysis for the project is carried out. The PESTEL analysis which is a conventional tool has been performed to determine the existing risk on the pilot floating system.

Political barriers: there are no critical expected barriers regarding political issues. Conversely, the EU is pushing forward to ensure the proper penetration of Renewable Energy. However, there is the need to get agreements on international waters, and how it may be an advantage for floating offshore wind.

Economic barriers: the low cost of fossil-based power generation, which may slow down the need for renewable energy integration and its investments. Eexisting market rules and technical regulations were made to accommodate conventional generating technologies.

Social barriers: the social acceptance and the visual impact.

Technological barriers: innovative technological developments - the "Innovation Death Valley"; and making the technology cost-competitive [9].

Environmental barriers: impact of mooring lines and power cables on marine mammals and fish, the potential impact of materials on sea-life in general.

Legal barriers: the regulation and ownership of shared waters, cross-border interconnections, and different normative and regulations, a high number of different regulatory authorities involved and complex regulatory procedures.

2.5.1 Environmental and societal impact assessment

Local environmental impacts must be studied after collecting the data [4,24,29]. For wind data (wind distribution rose, wind speed extreme, monthly mean vertical profile of wind speed) was used special equipment (WindCube, Vaisala, sensors) and for waves and currents was used a Doppler velocimetry (SeaGuard II, Andeera). Wind data collected from different sources was processed later with metocean methodology [4, 24]. In order to ensure an efficient design of the floating wind system, a statistical wind analysis must be done [4,6,12,14,17].

The installation of a pilot floating wind system in the study location involves analysing the types of barriers with an impact on the environment that can be done with the PESTEL analysis (Political, Economic, Social, Technological, Environmental and Legal)[23], which is a conventional tool has been performed to determine the existing risks. This floating pilot system greatly contributes to the increased sustainability of renewable energy and renewable fuel value chains, taking full account of social, economic and environmental aspects in line with the European Green Deal priorities. The most direct impact is related to unlocking the potential of offshore floating wind energy in the Black Sea. The goal is to increase the renewable energy sector in order to decarbonize (the Black Sea region is among the largest carbon consumers in Europe (between 300 and 450 gCO_2eq/kWh). The carbon impact of a floating offshore wind project (avoided CO_2

emissions) is about 10 times higher in Bulgaria or Turkey, than France or Norway [17,28,32]. Another concrete impact in the short-term is pilot system potential contribution to the development of carbon capture and storage in Bulgaria. Pre-feasibility studies are currently being carried out for the exploitation of the Galata gas field as a carbon storage option. Partnerships have already been started for the exploitation of the Galata deposit, whose storage capacity is estimated at 10-20 Mt of CO_2. Other saline aquifers in the area offer much greater potential, making the region an excellent candidate for CO_2 storage not only from large emitters in Bulgaria, but also potentially from emitters in neighbouring countries. Another major societal impact of installing such a pilot system would be its contribution to energy security around the Black Sea. Indeed, the energy transition in the region would reduce dependence on foreign imports.

The location of a pilot floating wind system and the prospective development of a floating wind farm in this area can contribute to reducing air pollution in the long term, thus improving health conditions. This problem is paramount in countries such as Bulgaria and Romania, which belong to the most polluted countries in Europe. This is mainly due to coal-fired power plants and domestic burning of solid fuels for heating. Floating offshore wind systems can also contribute to coastal protection by creating nature recovery sanctuaries; the wind farm areas can be protected from any fishing activity. At the same time, this floating offshore system can contribute to the extensive monitoring of the environment thanks to the on board sensors. It also contributes strongly to the development of aquaculture in the area.

2.5.2 Economic impact and market value of floating wind potential focus on the Black Sea Blue Economy

The offshore wind market is huge. An increase of more than 235 GW of new offshore wind capacity is expected to be added over the next decade, bringing total offshore wind capacity to 270 GW by 2030. Floating offshore wind systems contribute to this growth, being a sizable, homogeneous emerging global market (€78 billion CAPEX expected in 2035) with very strong growth potential over the coming decades. Global installed capacity is expected to reach 7-10 GW by 2030 and 70 GW by 2040. Developing such a project on a cost-effective commercial scale will drive market trends. The global offshore wind market continues to mature and shows signs of accelerating growth in the near future. Europe is expected to lead the growth of the market, taking advantage of its very large marine territory. Due to the advancement of technologies, breakthrough innovations and constant cost reductions, floating wind power will be implemented in areas where the technology is not yet competitive [4, 25] . And this is especially the case in areas of low to moderate wind speed. This means that the electric generator, rotor and turbine are optimized for the wind speeds they are most likely to encounter. The wind class of each turbine is assigned as I, II or III based on its rated power density, as specified in the last column of Table 2.

Table 2. The wind class of turbine

IEC wind Class	Annual average wind speed [m/s]	Power density [w/m^2]
III	<7.5	300-350
II	>8.5	350-450
I	>10	>450

The proposed floating pilot system specifically targets Class III areas, covering a significant part of the technical offshore wind potential in two of the four European sea basins: the Mediterranean and the Black Sea [32]. In the Black Sea area, the average wind speed in the areas of interest varies from 7 to 8 m/s, and the World Bank study (March 2020) states a huge technical potential for floating offshore wind of 166 GW; of which 54 GW are in Romania and 24 GW in Bulgaria.

This pilot floating system is a source of job creation and local content. There are studies that show that 1GW/year (80 turbines) generates about 10,000 jobs [34]. Our estimate is slightly lower, leading to 5000 Full Time Equivalent (FTE) +/-50%. Our hypothesis considers:

- CAPEX target 2M€/MW, grid-connection to the shore included;
- 40% of local content, and even 60% if turbines are produced locally;
- 20 to 40% of the Investments are driven to wages with 80k€/y/FTE including running costs and State taxes. This is considering the labor cost in Western Europe, which is much higher than in Eastern Europe and in the countries around the Black Sea, where the local impact can be much higher (increase of the working conditions and/or broader impact through the creation of local value, e.g., by contributing to the Blue Economy .

The target is to mitigate infrastructural investments while keeping some local content.

This pilot floating system and offshore renewables can contribute to protecting coastal communities, fauna & flora, and decarbonizing the power system (societal impact), but can also foster the creation of a local Blue Economy through five different sectors: Oil & Gas, Shipping, Aquaculture, Desalination and Cooling[32, 35, 36].

Oil & Gas operators can provide early market development opportunities for floating offshore wind towards full utility-scale farm deployment. Besides, floating offshore wind deployment can leverage on existing technical capacities and skills from the offshore Oil & Gas industry (logistics, maritime knowledge, financial capacity, legal capacity, etc.), while Oil & Gas operators can use floating offshore as a pathway to decarbonize their industry and - in the medium term - shift their business towards e.g., offshore renewable energy production.

Other fields of application in the sectors of the Blue Economy include: shipping [32, 36], aquaculture, desalinization, seawater air conditioning technology[37].

In sector of shipping, the International Maritime Organization has set as its main objective the reduction of global emissions from maritime transport by at least 50% by 2050 [36]. Ships can reduce their footprint if they are powered by advanced biofuels, renewable hydrogen-based fuels, synthetic fuels or electric propulsion. Floating offshore wind farms, combined with existing offshore infrastructure, can serve to produce hydrogen that can be deployed in nearby ports or serve directly as offshore charging stations for ships [32].

In sector of aquaculture, most floating aquaculture farms are highly dependent on fossil fuels (intensive carbon consumption), which involved high transport and maintenance costs [38]. Floating offshore wind industry can exploit synergies with this sector.

Process of water desalination is a very energy-intensive process . Seawater air conditioning (SWAC) is a technology that can provide efficient cooling((an energy-intensive process expected to triple globally by 2050) [39,40, 41].

3 CONCLUSIONS

This floating offshore wind system can contribute to the availability of disruptive renewable energy technologies and systems and renewable fuels in 2050 to accelerate the replacement of fossil-based energy technologies. This impact is particularly relevant as electricity generation in the Black Sea region is one of the biggest carbon consumers in Europe. It can also contribute to de-risking renewable energy and fuel technologies towards their commercial exploitation and net zero greenhouse gas emissions by 2050, and to reducing costs and improving the efficiency of renewable energy and renewable fuel technologies and their value chains by unlocking the potential of the Black Sea's floating offshore wind.

In addition, the pilot system and offshore renewables can help protect coastal communities, fauna and flora and decarbonise the energy system, but can also encourage the creation of a local blue economy through five different sectors: oil and gas, shipping, aquaculture, desalination and cooling [25, 26].

Oil & Gas operators are ideal candidates to help accelerate the development of floating wind, given the existing cost of energy offshore (usually over 150€/MWh), as they mainly use diesel generators with heavy-carbon and cost undertaking.

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