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SET Wind

The SET Plan Implementation
Working Group for Offshore Wind

2nd SET Plan Implementation Plan for offshore wind

March 2022

1. Executive summary

The Offshore Wind Implementation Working Group (IWG) is composed of representatives from relevant European countries (member states, governmental agencies from NL, BE, DE, EE, ES, FR, IT, NO, TR and UK) and stakeholders, representing both industry and academia with interests in offshore wind, as well as from representatives of the European Commission (DG RTD, DG ENER, JRC). Since the first version of the SET-Plan Implementation Plan for Offshore Wind was published in 2018, the IWG has continued its work in collaboration with the EU-funded project SETWind. This collaboration has led to this updated version of the SET-Plan Implementation Plan for Offshore Wind. The updated Implementation Plan has been developed in close coordination with ETIPWind and EERA JP Wind.

The SET Plan is nested in an EU policy context consisting of the EU Energy Union, the European Green Deal, the EU Fit for 55 package and a set of strategy papers touching directly on the issue of offshore wind, namely the EU Strategy for Offshore Renewable Energy (Nov 2020), the EU Strategy for Energy System Integration (July 2020) and the EU Strategy for Hydrogen (July 2020).

The main elements of the first 2018 Implementation Plan were the cost targets for floating and bottom fixed offshore wind and the nine R&I priority actions. Both elements have been updated in the present 2022 Implementation Plan. The targets have been expanded from two to four while the priority actions have been reduced from nine to six.

The 2018 Implementation Plan stated the need for a total of €1000 million to be invested in offshore wind energy by 2030. However, an analysis by ETIPWind shows that the combined private and public investment in wind energy reached €1994 million in 2018[1]. While industry spending dwarfs public investments in wind energy R&D, the combined investments of industry and public funding bodies in wind energy R&D remains essential to bring new innovations from academia and RTOs to the industry, as well as to provide a fertile environment to educate and train thousands of future employees in the wind energy sector.

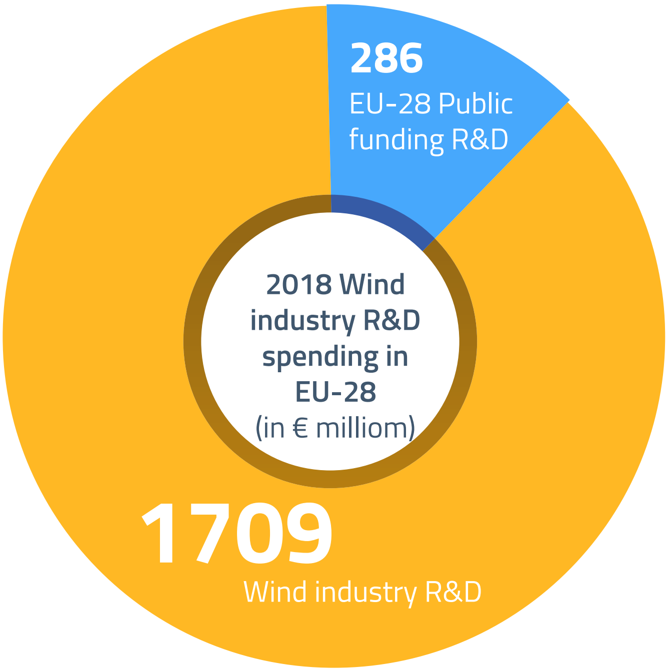

Figure 1. ETIPWind calculations of wind energy R/D spending in Europe

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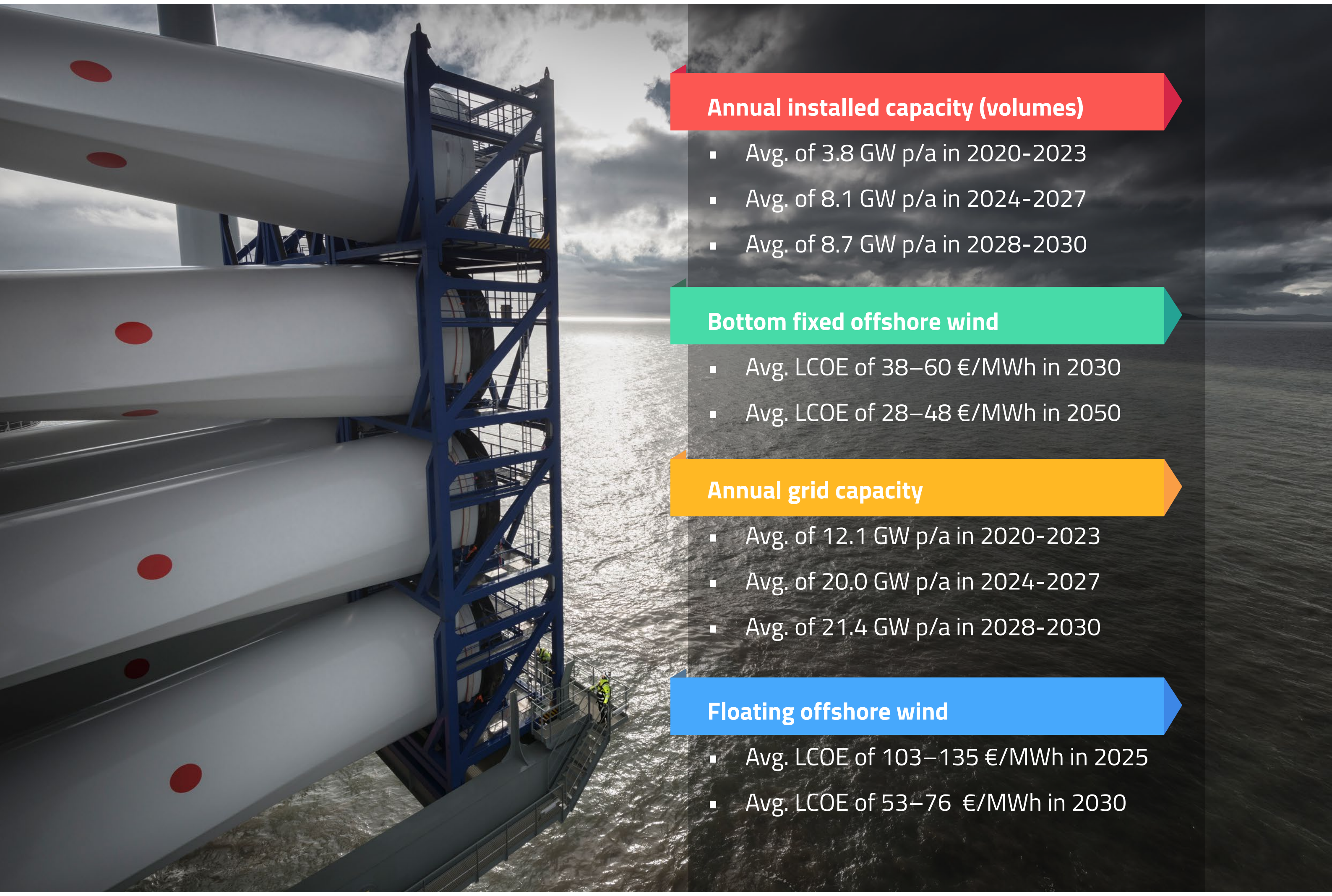
[1] Analysis by ETIPWind based on figures from the 2020 WindEurope report *Wind energy and economic recovery in Europe* (https://windeurope.org/data-and-analysis/product/wind-energy-and-economic-recovery-in-europe/)

Updated Implementation Plan targets

The updated Implementation Plan targets include the required annual installed capacity of wind power and grids towards 2030 to achieve the upper target of 450 GW offshore wind by 2050. The range in the cost reduction targets for bottom fixed and floating offshore wind reflects the effect of high and low installation scenarios. The less installed capacity, the slower the price will drop.



Annual installed capacity (volumes)

- Avg. of 3.8 GW p/a in 2020-2023
- Avg. of 8.1 GW p/a in 2024-2027
- Avg. of 8.7 GW p/a in 2028-2030

Bottom fixed offshore wind

- Avg. LCOE of 38–60 €/MWh in 2030
- Avg. LCOE of 28–48 €/MWh in 2050

Annual grid capacity

- Avg. of 12.1 GW p/a in 2020-2023
- Avg. of 20.0 GW p/a in 2024-2027
- Avg. of 21.4 GW p/a in 2028-2030

Floating offshore wind

- Avg. LCOE of 103–135 €/MWh in 2025
- Avg. LCOE of 53–76 €/MWh in 2030

Source: Getting fit for 55, ETIPWind 2021

The updated priority actions

The R&I priority actions have been updated in consultation with ETIPWind, EERA JP Wind and referring to the IEA Wind TCP Grand Challenges. This led to the following result, which combines insights from the different priority areas to establish a balanced set of priority actions:

ETIPWind	EERA JP Wind	IEA WInd Strategic Work Plan	**SET Plan Implementation Plan Priority Actions**
Next Generation Technologies	Next Generation Wind Turbine Technology & Disruptive Concepts	Advanced Technology	**Next Generation Wind Turbine Technology**
Grid & System Integration	Grid Integration & Energy Systems	Energy Systems with High Amount of Wind	**Offshore Wind Farms & System Transformation**
Floating Wind	Offshore Wind (Bottom Fixed + Floating)		**Floating Offshore Wind & Wind Energy Industrialisation**
Operation & Maintenance	Operation & Maintenance	Resource and Site Characterisation	**Wind Energy Operation, Maintenance & Installation**
Digitalisation, electrification, industrialisation & human resources	Sustainability, Social Acceptance, Economics & Human Resources	Social, Environmental, and Economic Impacts	**Ecosystem, Social Impact & Human Capital Agenda**
Offshore Balance of Plants		Communication, Education, and Engagement	
	Fundamental Wind Energy Science	Deeper Understanding of the Physics of Atmospheric Flow	**Basic Wind Energy Sciences**

Lighthouse initiatives

Achieving Europe's ambitions for offshore wind requires ambitious R&D efforts. Complementing the national programmes, Horizon Europe and the Proposal for a Clean Energy Transition Partnership, the SETWind project has conducted an extensive consultation with stakeholders to identify two main areas for a European Lighthouse initiative. These are:

- **Floating offshore wind technology**, being the new frontier in offshore wind energy development, which offers a huge potential to exploit wind resources over deep water. The overall goal is to make floating offshore wind cost-competitive.
- **Integration of large-scale offshore wind energy,** to enable the future reliable operation of the power system with zero emission of CO_2.

Social sciences and humanities research for offshore wind

In collaboration with SETWind, the H2020 project Energy-SHIFTS, EERA JP E3s and the EERA JP Wind sub-programme for socio-economic and environmental issues[2], a set of recommendations drawing on the social sciences and humanities are outlined in the Implementation Plan.

The recommendations reflect the EU Green Deal's emphasis on the EU as a *fair and prosperous society*, protecting the health and well-being of citizens through a just and inclusive green transition while also acknowledging the need for citizens to get behind the massive transition of the energy system needed to stay within the Paris targets of 1.5%.

The three recommendations are related to:

- **Fostering co-creation and public engagement**
  By enabling earlier engagement of citizens and stakeholders and providing tools to empower their contribution.
- **Stimulating fair prospects for all**
  By balancing the distribution of cost and benefit to the whole range of offshore stakeholders.
- **Strengthening the implementation of UN SDGs through harvesting heterogeneous data**
  By implementing FAIR data principles and linking data to the UN SDGs.

New assessment criteria for evaluating the impact of offshore wind energy R&I

Based on a SETWind expert workshop organised in January 2020, the Implementation Plan includes an outline of recommendations for how to assess R&I projects in the context of the challenges outlined above (cost, value, sustainability and innovations for regional conditions).

The R&I assessment criteria (metrics) developed within a framework of moving *Beyond LCOE* are categorised in the following way:

- Cost of energy (the classical LCOE)
- The financial and regulatory requirements/potentials
- The energy system interplay with the environment and people

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[2] https://energy-shifts.eu/ ; https://www.eerajpwind.eu/ ; https://www.eera-e3s.eu/

2. Message from the Chair

Bob Meijer.

With the accelerated energy transition, the targets for offshore are changing rapidly. Over the past years spectacular cost reductions have been achieved and ambitions for rolling out offshore wind in Europe have increased. We are witnessing a shift in focus, from mainly cost reduction to the wider requirements needed to scale towards 2050 targets. Research and innovation is required to address the challenges related to the integration of offshore wind power in the energy system, spatial planning and ecology, offshore infrastructure as well as the societal costs.

In this new and updated Implementation Plan for Offshore Wind, the Implementation Working Group has taken on board these changes. We differentiate between the various basins and regional cooperations; lighthouse initiatives for floating wind energy and system integration put a focus on important themes; and the role of the social sciences and humanities in offshore wind also has a strong position in the plan.

With this we are confident that the Implementation Plan is fit for the next phase.

We are also happy to see the launch of the SET Plan Implementation Plan for HVDC. This technology will play a key role in enabling large-scale, cost-effective deployment of offshore wind, and we look forward to collaborating with the new working group on this shared challenge.

3. EU policy framework for the Implementation Plan

The EU Energy Union

In 2015 the European Commission adopted the Framework Strategy for a Resilient Energy Union with a Forward-looking Climate Change Policy (Energy Union)[3]. The Energy Union was built to improve the security, sustainability and competitiveness of the EU's energy sector.

The main aim of the Energy Union is to ensure the EU delivers on its 2020 targets. These include a 20% reduction in greenhouse gas (GHG) emissions compared to 1990, a share of 20% of renewable energy in the energy mix and a 20% improvement in energy efficiency. It also paves the way towards a more sustainable EU economy by 2030. The Energy Union strategy put forward a 40% GHG emission reduction compared to 1990 levels and promised to provide new 2030 targets for renewables and energy efficiency.

The strategy also spelled out the need for more research and innovation in renewables, and in particular in solar and wind energy[4]. Since the strategy was adopted, the EU has had the ambition to become "number one in renewable energy". Delivering this would require more efforts and coordination in R&I at EU and Member State level. An update of the Strategic Energy Technologies Plan (SET Plan), which had been the centre of the EU's energy innovation strategy since 2008, would help steer these efforts.

The Integrated SET Plan

The same year a new Integrated SET Plan provided a new framework for energy research. It placed renewable energy technologies at the heart of the energy transition. The plan was built around ten key actions to accelerate the EU energy system transformation in a cost-effective way. Becoming number one in renewables was key action one[5]. The new SET Plan identified five renewable energy technologies, including offshore wind energy, as a strategic priority. For each of these technologies, Temporary Working Groups were set up.

The Temporary Working Groups brought together representatives from Member States, European Institutions and the private sector, represented by the European Technology & Innovation Platforms (ETIPs). They identified sector-specific targets in line with the EU's climate and energy ambitions and developed detailed implementation plans to deliver on those targets. They are now formally recognised as the SET Plan Implementation Working Groups.

The EU's 2030 climate & energy ambition

In recent years the EU's climate and energy ambition has increased significantly. In 2017 the EU adopted the Clean Energy Package, which included a binding 40% GHG emission reduction target and binding targets for 32% renewables and 32.5% energy efficiency improvements. These targets were binding at EU level; there were no binding targets for each individual Member State.

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[3] COM/2015/080 final
[4] https://eur-lex.europa.eu/legal-content/EN/LSU/?uri=COM:2015:80:FIN
[5] https://setis.ec.europa.eu/actions-towards-implementing-integrated-SET Plan

Two years later, in 2019, the new Commission President, Ursula Von Der Leyen, presented the European Green Deal. This promised to make Europe the first climate-neutral continent by 2050[6]. In December 2019, the Council of the European Union formally endorsed the goal of EU climate neutrality by 2050[7].

The new long-term target also affected the EU's 2030 ambitions. In July 2021, the European Commission tabled its Fit for 55 package[8]. The name reflects the new proposed 2030 GHG reduction target of 55% compared to 1990 levels. The package includes proposals to make existing legislation more ambitious. For instance, in 2022 there will be an update to the renewable energy directive, including a new EU-27 renewable energy target of at least 40%. In addition, the package includes proposals for new EU legislation.

As part of the Green Deal and the new climate and energy ambitions the European Commission developed several strategies, of which the most relevant for offshore wind are highlighted below.

- **Energy System Integration Strategy**. This strategy highlights the importance of renewables-based electrification to deliver on the 2030 and 2050 targets. The strategy states that the share of electricity in final energy consumption must grow from 23% today to at least 30% in 2030, and 50% by 2050. By 2030, renewables should provide between 55% and 60% of Europe's electricity. By 2050 this should be at least 80%. The strategy highlights the enormous potential of offshore wind, citing 300-450 GW of potential, and stresses the need to reinforce the transmission and distribution networks[9].

- **Hydrogen Strategy**. This strategy makes the development of hydrogen production from renewable electricity an EU priority. Where direct electrification is not possible, renewable hydrogen (hydrogen produced from electrolysers powered by renewable energy) can help the EU's hard-to-decarbonise sectors to become climate neutral by 2050. The strategy sets a gradual trajectory to scale up renewable hydrogen. By 2024 the goal is to have at least 6 GW renewable hydrogen electrolysers installed, producing 1 million tonnes of renewable hydrogen. By 2030 this should be at least 40 GW, to produce 10 million tonnes. By 2050, 18% of Europe's energy demand could be met with renewable hydrogen and its derivatives (e.g. ammonia)[10].

- **Offshore Renewable Energy Strategy.** This strategy outlines the road to achieve 60GW offshore wind by 2030, and 300GW offshore wind in EU waters by 2050. The strategy highlights the importance of regional development in all EU sea basins. Spatial planning will be key to ensure environmental protection and enable better multi-use of the sea. Extensive development of the grid infrastructure, including hybrid systems and energy islands, will require investments, while robust methodologies for allocating costs as well as an efficient market design will need to be put in place.

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[6] https://ec.europa.eu/commission/presscorner/detail/e%20n/ip_19_6691

[7] https://www.consilium.europa.eu/media/41768/12-euco-final-conclusions-en.pdf

[8] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC0550&from=EN, COM (2021) 550 FINAL

[9] COM(2020) 299 final

[10] COM(2020) 301 final

Member States and the new climate & energy targets

To ensure achievement of the 2030 targets in the Regulation on the Governance of the Energy Union, Member States have prepared National Climate & Energy Plans (NECPs) that spell out how they would contribute to the delivery of EU targets over the next ten years (2021-2030). The plans should include detailed actions and policies for the deployment of renewable energy technologies. Member States also had to indicate how their research and innovation policies and instruments would advance the clean energy transition[11].

The European Commission's assessment of the NECPs was that they would deliver on the then current agreed targets of 40% GHG reduction and 32% renewable energy at EU level. But the plans were lacklustre. Some Member States would not be able to deliver their 'fair share' with the measures proposed. NECPs in general fail to identify the immense potential of offshore renewables. The European Commission highlights the renewable energy financing mechanism[12] as a way to accelerate offshore energy technologies and to help Member States achieve their 'fair share'[13].

In addition, the NECPs fail to specify clear and detailed actions on the research and innovation needed to deliver the climate and energy objectives. The European Commission notes "the overall decrease in national budgets devoted to research and innovation in clean energy technologies" and the severe lack in long-term planning for research and innovation. Where the SET Plan is mentioned, Member States fail to back up their commitment to the SET Plan with concrete budgets[14].

The governance regulation stipulates that Member States will need to submit a second NECP in 2023. These will also have to account for the new, more ambitious, climate and energy targets. The NECPs will require thorough updates and improvements to be 'Fit for 55' and deliver EU climate neutrality by 2050.

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[11] Regulation (EU) 2018/1999 of the European Parliament and of the Council on the Governance of the Energy Union and Climate Action.

[12] Renewable Energy Financing Mechanism C(2020)612

[13] COM(2020) 564 final

[14] COM(2020) 564 final

Offshore wind at the heart of EU climate & energy policy

Wind energy is an essential element of Europe's energy system. In 2020, Europe had 220GW of installed wind power capacity, of which 25 GW was offshore. 14.5 GW of Europe's offshore wind capacity was installed within the EU-27. Wind energy provided for 16.4% of Europe's electricity demand in 2020[15]. The offshore wind sector already provides for 77,000 jobs across Europe. By 2030 this could grow to 200,000 jobs, provided the NECPs are fully implemented[16].

Full implementation of the new 2030 target of 55% GHG reduction would demand more renewable energy. The European Commission states the EU-27 needs 453 GW of wind energy by 2030. 374 GW of that would be onshore wind and 79 GW offshore wind. Wind would provide for 30% of the EU's energy demand[17]. By 2050 this would need to be 300 GW of offshore wind and 1,000 GW of onshore wind. In this case wind would provide for 50% of EU electricity[18]. However the current NECPs would only help deliver 60 GW of offshore wind by 2030[19].

Developing more offshore wind is therefore a priority for the EU. It is the first of the priority technologies included in the European Commission's reports on the progress of clean energy competitiveness. The first report calls on Member States to step up their ambitions for offshore wind to deliver the 2030 targets[20]. The second report highlights the need for further investments in floating technology and suitable port infrastructure. In addition, the report calls for building a future offshore grid around hybrid projects[21].

Several Member States have already started to scale up their ambitions for offshore wind by 2030. Belgium will now develop up to 5.8 GW of offshore wind, up from 4.4 GW as stipulated in the NECPs. Spain announced it wants to develop 3 GW of offshore wind. And the coalition agreements in the Netherlands and Germany will translate to 22 GW (up from 11.5 GW) and 30 GW (up from 20 GW) respectively.

How to fund and mobilise investments for the European Green Deal and Fit for 55

In January 2020, the European Commission put forward their proposal for how to finance the Green Deal. The Sustainable Europe Investment Plan would have mobilised €1 trillion of investments from 2020 to 2030, of which more than 50% would come from the EU budget. However, only a few weeks later COVID-19 hit Europe and plans had to be revised.

In July 2020, the Council of the European Union agreed on the need for a dedicated European recovery plan, saying such a plan should place the ambitions of the European Green Deal at the heart of Europe's recovery. The plan calls for a new €750 billion programme, Next Generation EU. Together with the EU budget for 2021-2027, this will be the main investment vehicle for delivering the European Green Deal. The combined budget should place over €1.8 trillion, with a mandatory target for climate action spending of 30%[22].

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[15] WindEurope Wind energy in Europe – 2020 statistics and the outlook for 2021-2025, (2021)
[16] WindEurope, Wind energy and economic recovery in Europe (2020)
[17] European Commission, SWD(2021) 307 final, CTP MIX scenario.
[18] Ibid.;
[19] COM(2021) 952 final
[20] COM(2020) 953 final
[21] COM(2021) 952 final
[22] https://www.consilium.europa.eu/en/press/press-releases/2020/07/21/european-council-conclusions-17-21-july-2020/

The EU budget 2021-2027 programmes play an essential role in accelerating the deployment of renewables, including offshore wind. The most relevant programmes are:

- **Horizon Europe**. The EU's framework programme for research and innovation. It has a budget of €95.5 billion, of which 5.4 billion is from Next Generation EU. 35% of the budget must support climate action. There is a dedicated cluster on Climate, Energy & Mobility with a total budget of €15 billion. There will also be a public-public co-funded partnership on the clean energy transition.
- **Connecting Europe Facility (CEF).** The EU's energy infrastructure investment programme. It has a budget of €22.4 billion. €5.8 billion will be allocated to energy infrastructure, which includes both gas and electricity networks. There will be a new investment window for cross-border renewable energy projects. It will have a budget of up to 15% of the CEF Energy budget, or €875 million.
- **Just Transition Fund.** A new programme to tackle the social and economic impacts of energy transition. It has a budget of €17 billion: €7.5 billion from the EU budget and €10 billion from Next Generation EU. The funding will be allocated directly to Member States. Special attention will be given to skills and (re-)training of workers in fossil fuel-based industries.
- **InvestEU.** The EU's internal investment support mechanism. It has a budget of €2.8 billion, with the aim to lever a multiple of that from other public and private investors.

Offshore wind energy in Europe

Wind energy is an essential element of Europe's energy system. Europe now has 220GW of installed wind power capacity: 194 GW onshore and 25 GW offshore[23]. These wind energy installations provided for 15% of the EU's electricity demand in 2019.

With full implementation of the NECPs' wind energy, EU-28 could see 397 GW of wind energy by 2030. Offshore wind would account for 111 GW, up from 22 GW in 2019. Wind would provide for 30% of the EU's energy demand[24]. BBy 2050, Europe would need between 300 and 450 GW in order to deliver climate neutrality. In this case, wind would provide for 50% of EU electricity, and offshore wind alone would provide for 30%[25].

Offshore wind in particular is a European priority. It is the first of five priority technologies in the European Commission's report on the progress of clean energy competitiveness. Europe is a world leader in offshore wind technology. This is due to sustained efforts in research and innovation and a strong European market. Close to 93% of the total offshore capacity installed in Europe in 2019 was produced by European manufacturers. The report notes that Member States need to step up their ambitions for offshore wind to deliver the 2030 targets. Investments in offshore wind will strengthen the local European supply chains[26]. The offshore wind sector already provides for 77,000 jobs across Europe. By 2030 this could grow to 200,000 jobs, provided the NECPs are fully implemented[27].

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[23] WindEurope "Wind energy in Europe – 2020 statistics and the outlook for 2021-2025", (2021)
[24] WindEurope, Wind energy and economic recovery in Europe (2020)
[25] European Commission Long Term Strategy (2018)
[26] COM(2020) 953 final
[27] WindEurope, Wind energy and economic recovery in Europe (2020)

4. Opportunities and challenges for offshore wind in Europe

Offshore wind represents a significant future opportunity: resources are stable and abundant, and public acceptance is increasing. Europe is the leader in offshore wind, and the sector is continuously growing with new and improved technologies as well as growing investments from both private and public actors. In the North Sea and Baltic Sea, most experience has thus far been gained from bottom fixed turbines, but more and more initiatives are emerging to accelerate the development of floating devices, such as pre-commercial floating projects in the Mediterranean Sea and Atlantic as well as the Black Sea.

In the framework of the EU Green Deal, the EU Strategy for Offshore Renewable Energy adopted in November 2020 identifies key areas for fostering a massive cost-effective and sustainable scale-up of offshore renewable energies in the whole EU:

- Long-term planning and development of offshore and onshore electricity grids.
- Market arrangements and favourable and predictable frameworks for investors and operators.
- Regional cooperation, in particular around the various sea basins and addressing maritime spatial planning.
- Development of key technologies and innovations (renewables and grid).
- Energy demand management and Energy System Integration (hydrogen, power to gas).

Within R&I, the areas below are highlighted as particularly important

- For mature technologies such as offshore wind, the emphasis is on optimising existing manufacturing processes, for example regarding wind turbine and blade production[28].
- Near-commercial technologies such as floating platforms, which can help to harness the potential of EU countries with deeper waters.
- Research on environmental impact and optimal use of marine space.
- Infrastructure and grid development, including research into HVDC technologies, and offshore conversion, storage and transport of other energy carriers (e.g. hydrogen) will be key to the successful integration of offshore wind.

Addressing these challenges, the EU Strategy underlined that offshore wind will be instrumental in achieving its carbon emission reduction targets for 2030 and becoming climate neutral by 2050, but should also play a prominent role in the recovery phase, as it has great potential for generating domestic jobs, value chains and related industrial, research and service capacity.

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[28] It should be noted here that the Implementation Working Group Offshore Wind questions the description of offshore wind as a mature technology. The working group considers offshore wind a maturing technology, which still has significant room for improvement across the value chain.

Four key challenges for offshore wind energy

Based on current developments in industry, policy and research, the IWG Offshore Wind has identified the following four main challenges to be addressed by offshore wind energy R&I in the coming decade:

1. **Cost**

   The scale of installation and a stable policy framework are key drivers in reducing the cost of offshore wind, but R&I can contribute significantly to cost reduction. The six R&I priority actions outlined in this Implementation Plan cover a range of important R&I areas that will drive down the cost of offshore wind farms from design to decommissioning.

2. **Value**

   Cost reductions in wind power must go hand-in-hand with a focus on increasing the value of wind. Energy system integration and sector coupling is key to this, as it enables greater scale and flexibility in the market for green electricity. Power-to-X, including the potential for off-grid production of hydrogen and the recent ambitions for energy islands (e.g. hub and spoke), should be mentioned here. In the offshore environment, synergies with the reorienting oil and gas sector, other offshore renewables and cooperation with blue economy sectors have to be found to utilise both infrastructure and knowhow.

3. **Sustainability**

   The offshore wind energy sector needs to fully integrate sustainability considerations both environmentally and socially. With the massive build-out of offshore wind underway, the impact on the marine environment and the multiple users of the sea needs to be addressed, for example by conducting cumulative environmental impact assessments. Onshore, active engagement with communities that are affected positively and negatively by the installation of offshore wind farms, power lines, production and logistic facilities but also the jobs created must be addressed. At the technology level, circularity by design is a key topic to address.

4. **Regional conditions**

   Offshore wind energy is currently dominated by the development in the North Sea, but other regions are now following suit with ambitious plans for offshore wind power. Offshore is not one uniform environment. Water depth influences the choice of technologies (floating or bottom fixed), but weather conditions, multiple users of the sea and environmental and societal conditions also influence the design choices for wind power systems.

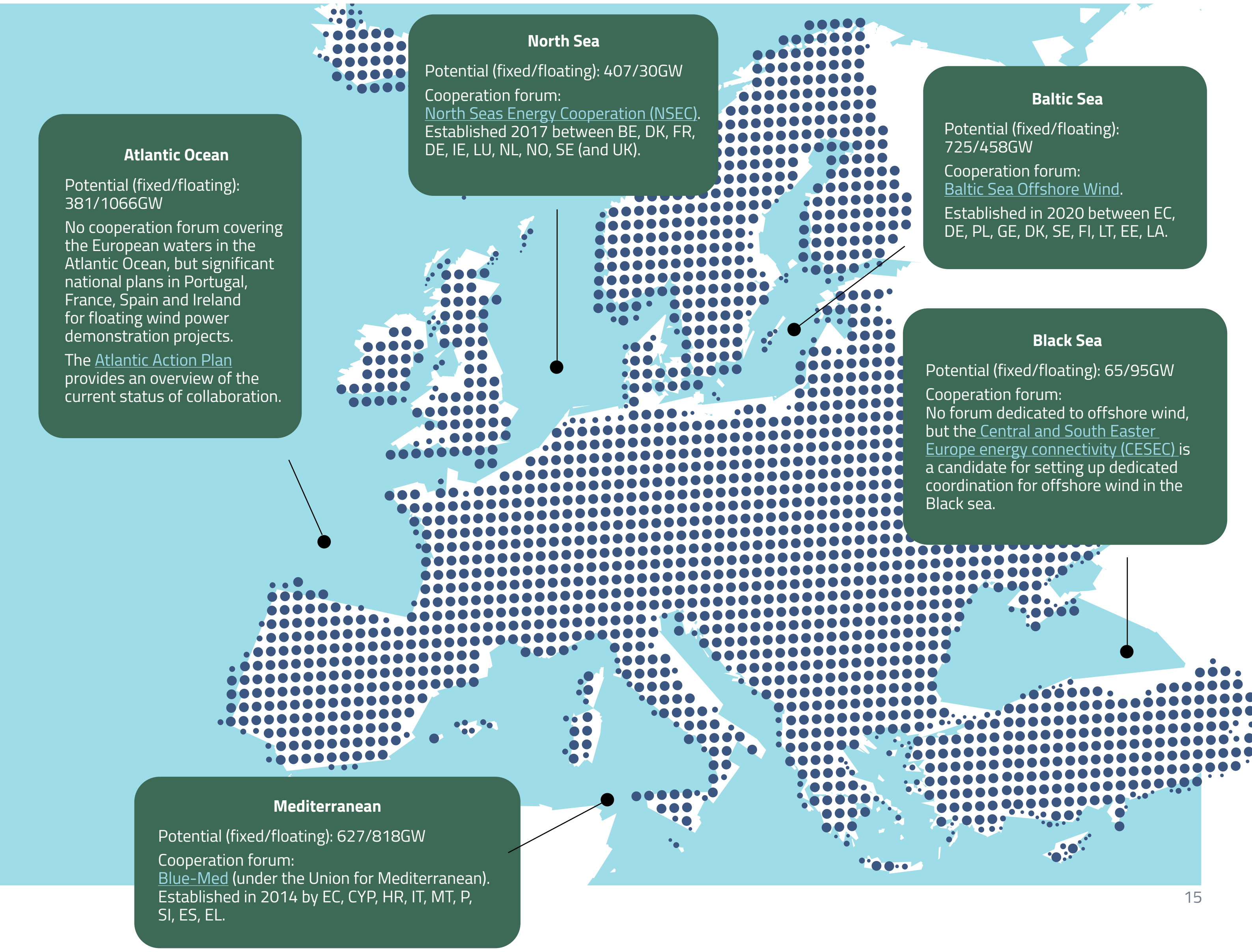
5. Regional cooperation

The 2018 Implementation Plan for Offshore Wind had a section dedicated to the 2016 North Sea Energy Cooperation between the countries in the region. In addition, it recommended dedicated actions promoting offshore wind in the Mediterranean. As such, it reflected the state of affairs when the Implementation Plan was drafted in 2017-2018. Over the past three years the cost of offshore wind energy has come down, and ambitions in European countries have gone up. Lower prices and commitments to fight climate change are turning offshore wind energy into a Europe-wide endeavour.

The widening scope for offshore wind in Europe is reflected in the EU Strategy for Offshore Renewable Energy. Governments have set or are setting ambitious targets for offshore wind from the northwest of Norway to the Black Sea in the southeast.

The geographical expansion of offshore wind offers is critical for Europe's ambition to curb CO_2 emissions, but it also poses a number of new challenges as the industry moves into new operating conditions for designing, planning, installing and operating large offshore wind farms.

This chapter starts by providing a brief overview of the different elements needed to develop offshore wind. This is followed by a short review of the potential and challenges for wind energy in each of the five EU sea basin areas. For each of the five sea basins, examples of R&D challenges are outlined to demonstrate how different geographic locations require different considerations when planning and building offshore wind farms.



Atlantic Ocean

Potential (fixed/floating): 381/1066GW

No cooperation forum covering the European waters in the Atlantic Ocean, but significant national plans in Portugal, France, Spain and Ireland for floating wind power demonstration projects.

The Atlantic Action Plan provides an overview of the current status of collaboration.

North Sea

Potential (fixed/floating): 407/30GW

Cooperation forum:
North Seas Energy Cooperation (NSEC).
Established 2017 between BE, DK, FR, DE, IE, LU, NL, NO, SE (and UK).

Baltic Sea

Potential (fixed/floating): 725/458GW

Cooperation forum:
Baltic Sea Offshore Wind.

Established in 2020 between EC, DE, PL, GE, DK, SE, FI, LT, EE, LA.

Black Sea

Potential (fixed/floating): 65/95GW

Cooperation forum:
No forum dedicated to offshore wind, but the Central and South Easter Europe energy connectivity (CESEC) is a candidate for setting up dedicated coordination for offshore wind in the Black sea.

Mediterranean

Potential (fixed/floating): 627/818GW

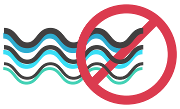
Cooperation forum:
Blue-Med (under the Union for Mediterranean).
Established in 2014 by EC, CYP, HR, IT, MT, P, SI, ES, EL.

Offshore wind implementation a general overview

In the coming years, the energy system will require a considerable amount of renewable energy, and a central part of this expansion is expected to come from offshore wind energy. Several cross-sector planning and development steps are necessary to implement offshore wind in a sustainable, social and cost-efficient way. Furthermore, there is a need for innovation and R&D to bring down the cost of the technology to compete with onshore wind and more traditional energy sources. With a focus on innovation in design and standardisation to upscale manufacturing capabilities, the cost of energy is expected to reach the current price of onshore wind in a decade.

To understand the development in offshore wind it is important to understand the different conditions to address when planning offshore wind. These are divided into four categories.

Planning restrictions



The sea is used by many different stakeholders for transport, fishery, military purposes or resource extraction. Use of the marine space can be divided into the following categories:

- Vessel routes: corridors for vessels must be secured to avoid collisions
- Fishing areas: securing breeding areas and areas for fishing
- Military areas: zones for training with ammunition are generally large
- Resources: raw materials such as gravel need to be secured

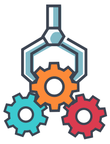
Each of these uses imposes limitations on where wind farms can be constructed. Furthermore, a number of cultural and environmental considerations need to be taken into consideration. This is done through a set of assessments that includes: *Marine archaeological assessment*, to secure areas of historical interest. *Environmental assessment* ensures that wind farms can co-exist with fish, mammals, birds and their habitats. *Areas of unexploded ammunition UXO* pose a severe threat during the construction of wind farms and must be explored in areas where there is a potential risk of leftovers from World War II. In addition to the above planning restrictions, near-shore areas are exposed to demands for social acceptance, as such areas often are associated with tourism and beautiful landscapes, and are also important for residents.

Geophysical conditions

To de-risk the capital investments and lower the cost of producing wind energy, it is necessary to determine the geophysical conditions with as low an uncertainty as possible to reduce the design uncertainties of a wind farm. The most critical geophysical conditions for de-risking the design of a wind farm are:

- *Wind resources*: absolute levels of wind potentials with uncertainties of less than 5% are required, including the modelling of both the atmospheric flow and wind farm wake, including interaction with nearby wind farms.
- *Wind conditions*: levels of turbulence and extreme wind speeds need to be known to secure a robust design.
- *Met-ocean conditions*: joint distributions of wave and wind, including current, extreme waves and wave climate need to be known for the design of both floating and fixed foundations.
- *Physical conditions:* these include bathymetry in 3D geotechnical investigations of the seabed, to establish knowledge of the soil conditions.

Infrastructure



Offshore wind requires large-scale infrastructure. This includes the vessels and harbours that can handle large wind farm components and service facilities, which are essential for constructing and operating wind farms. It also includes the electrical infrastructure with transformer stations, electrical cables and connection points. A common electrical HVDC grid requires standardisation of the interoperable electrical components to be developed.

People and capabilities

The green transitions require extensive education to train and educate the people who will construct and operate not just the offshore wind farms, but also expand and operate ports, design and operate electrical infrastructures for offshore wind, and develop appropriate market designs and good regulatory framework in countries. This capability has been built up in the North Sea area during the past 30 years, but will now need to be developed at a much faster pace in other European regions.

The area of the Baltic Sea

he wind resources in the Baltic Sea are high, ranging from 950 W/m^2[29] in the Baltic Sea to approximately 750 W/m^2 in the Bothnian Bay. It is one of the areas with the most wind farms, with several countries developing ambitious plans for offshore wind.

The Baltic Sea has potential for both fixed bottom and floating offshore wind, as approximately 50% of the areas have depths of 0-60 m and the remaining 50% have depths of 60-600 m. The Baltic is surrounded by different countries, and flow modelling is challenging due to land-sea transitions creating low–level jets and complex flow patterns.

Specific challenges call for research, development and innovation towards 2030 and 2050

The Baltic Sea is surrounded by a number of countries that have or are developing ambitious plans for offshore wind. It is important to develop a coordinated multi-use ocean plan to accommodate heavy shipping traffic, military interests and fisheries. The plan needs to include considerations regarding the construction of energy islands and areas with plans for a dense population of wind farms.

Developing a common grid is another domain that offers significant potential for cost savings. This will require the development of AC/DC converter technology with multivendor interoperability through standardisation.

Improved understanding of geophysical conditions can help de-risk the finance decision by modelling wind climate and met-ocean conditions precisely. In the Baltic Sea, modelling is challenging due to the land-sea transition. These transitions are characterised by the large shift temperature of the surfaces and the surface roughness, often requiring high-resolution modelling.

The occurrence of ice as well as the local seabed conditions have a large influence on the turbine foundation systems and need to be investigated.

Collaboration forum for the Baltic Sea

In September 2020, the Baltic Sea offshore wind Joint Declaration was signed by Denmark, Germany, Estonia, Latvia, Lithuania, Poland, Finland, Sweden and the European Commission[30].

The efforts will be coordinated via the Baltic Energy Market Interconnection Plan (BEMIP) High-level Group, which is tasked "to adopt, in the Spring of 2021, a work programme for offshore wind development taking into account national policy plans of every Baltic Sea Region country set in their National Energy and Climate Plans and the EU policy developments in relation to renewable energy production."[31]

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[29] In the following, a 3.4 MW wind turbine has been used and wind conditions from the Global Wind Atlas applied at the specific location https://globalwindatlas.info/

[30] https://ec.europa.eu/energy/sites/ener/files/signature_version_baltic_sea_offshore_wind.pdf

[31] https://ec.europa.eu/energy/sites/ener/files/signature_version_baltic_sea_offshore_wind.pdf, p.3

The North Sea

With 20.5 GW of grid connected wind power, the North Sea is home to 2/3 of the globally installed capacity of offshore wind (2020). Wind resources are generally very high, ranging from 1350 W/m^2 in the north to 1050 W/m^2 in the south of the North Sea. There is mixed potential for both floating and bottom fixed, as the North Sea area has an average depth of 95 m, whereas the Norwegian Sea has an average depth of 1750 m, and is thus suitable for floating wind. In the North Sea itself, 50% of the area is ideal for bottom fixed.

Specific challenges call for research, development and innovation towards 2030 and 2050

Due to the installed GWs of wind power in the North Sea, one specific task is to create a European coordinated multi-use plan, addressing both infrastructure and regulatory and market barriers to coordination across borders. A specific focus point is enabling the grid expansion required by the construction of energy islands. Similar to the Baltic Sea, AC/DC converter technology needs to have multivendor interoperability through standardisation to reduce costs and utilise the potential of the energy islands. Another specific focus is the development of off-grid hydrogen-producing turbines, which it is estimated will have a strong potential for cost savings when used in connection with the planned energy islands[32].

Another area that will become increasingly important is the development of multiphysics models that include wind farm-to-atmosphere and farm-to-farm interactions to de-risk the siting of enormous wind farms in closer proximity to each other.

Collaboration forum for the North Sea

The North Sea Energy Cooperation (NSEC) was established in 2016 between Belgium, Denmark, France, Ireland, Luxembourg, the Netherlands, Norway, Sweden, Germany and the European Commission. In July 2020, the NSEC released a joint declaration focusing on five elements of the continued collaboration[33]:

1. Joint and hybrid projects
2. Maritime spatial planning
3. Support framework and finance
4. Delivering 2050
5. Alignment of technical standards

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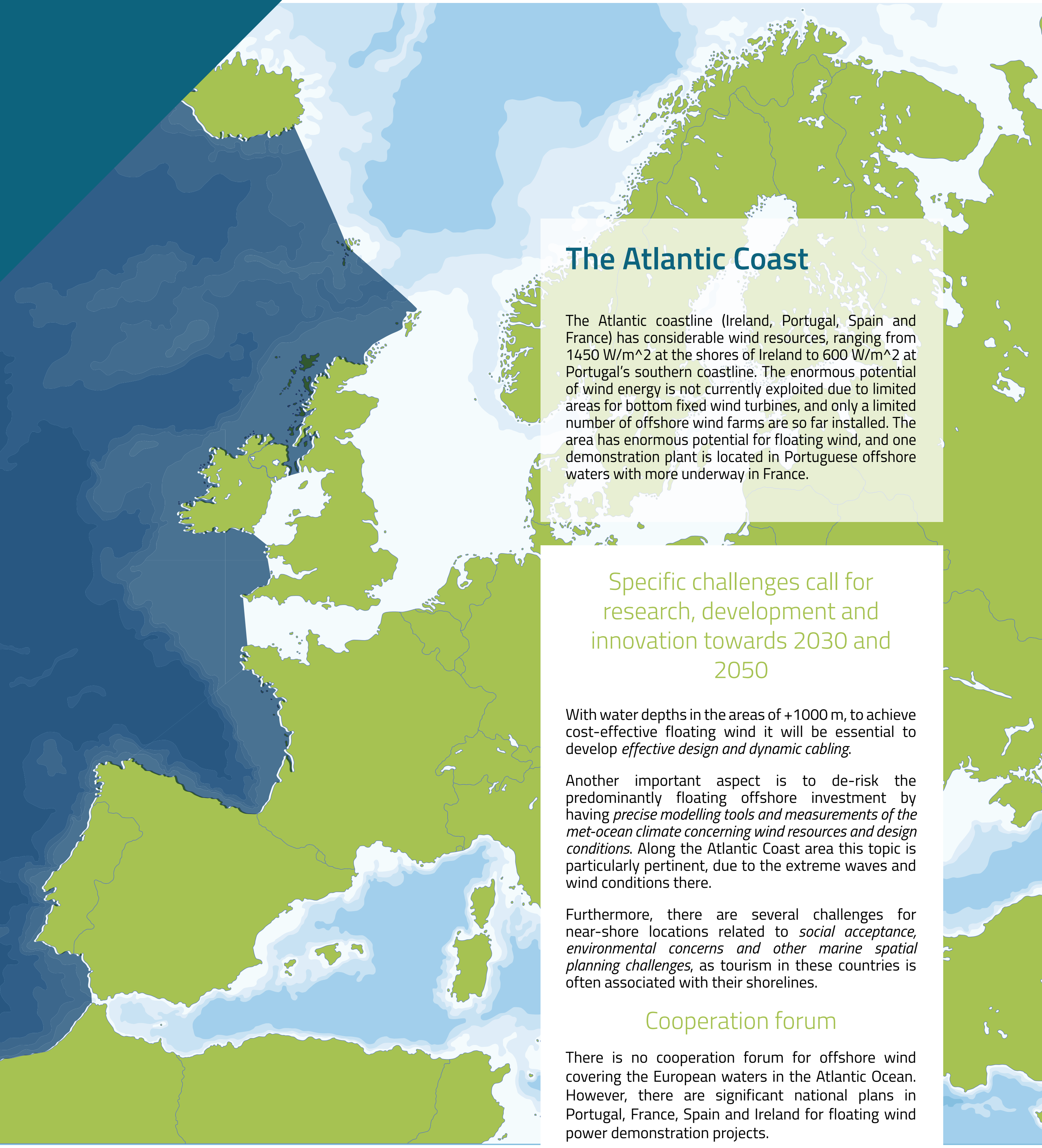
[32] Alessandro Singlitico, Jacob Østergaard, Spyros Chatzivasileiadis (2021). Onshore, offshore or in-turbine electrolysis? Techno-economic overview of alternative integration designs for green hydrogen production into Offshore Wind Power Hubs. (2021)

[33] https://www.bmwi.de/Redaktion/EN/Downloads/M-O/nsec-joint-statement.pdf?__blob=publicationFile&v=2



The Atlantic Coast

The Atlantic coastline (Ireland, Portugal, Spain and France) has considerable wind resources, ranging from 1450 W/m^2 at the shores of Ireland to 600 W/m^2 at Portugal's southern coastline. The enormous potential of wind energy is not currently exploited due to limited areas for bottom fixed wind turbines, and only a limited number of offshore wind farms are so far installed. The area has enormous potential for floating wind, and one demonstration plant is located in Portuguese offshore waters with more underway in France.

Specific challenges call for research, development and innovation towards 2030 and 2050

With water depths in the areas of +1000 m, to achieve cost-effective floating wind it will be essential to develop *effective design and dynamic cabling*.

Another important aspect is to de-risk the predominantly floating offshore investment by having *precise modelling tools and measurements of the met-ocean climate concerning wind resources and design conditions*. Along the Atlantic Coast area this topic is particularly pertinent, due to the extreme waves and wind conditions there.

Furthermore, there are several challenges for near-shore locations related to *social acceptance, environmental concerns and other marine spatial planning challenges*, as tourism in these countries is often associated with their shorelines.

Cooperation forum

There is no cooperation forum for offshore wind covering the European waters in the Atlantic Ocean. However, there are significant national plans in Portugal, France, Spain and Ireland for floating wind power demonstration projects.

The Mediterranean

This area consists of the Mediterranean Sea and seven neighbouring seas and basins. The wind resources are generally medium to low, at an average of 400 W/m^2, with a few places with high wind resources due to local weather phenomena, e.g. in France at the Mediterranean Sea, where the mistral gives 1300 W/m^2; Croatia at the Adriatic Sea, with the bora at 750 W/m^2; the Aegean Sea with the etesian winds at approx. 950 W/m^2). The Mediterranean is, in general, a very deep sea at approximately 5500 m. 80% of the area is deeper than 1000 m, while 15% is in the range of 60 to 1000 m. This makes floating wind the only option for large-scale deployment of wind power in the area.

> “De-risking floating wind projects requires the development of atmospheric models that can tackle land-sea transitions”

Specific challenges call for research, development and innovation towards 2030 and 2050

The Mediterranean area is important due to its historical heritage. There is consequently a need for careful planning to establish a peaceful *co-existence with tourism, archaeological sites and the environment*.

Due to the extreme water depth in the area, there are significant challenges with *the spatial footprint of floating mooring systems*, as these will extend far out from the floating foundations. Innovative solutions are required to tackle these challenges.

De-risking the floating wind projects requires precise predictions of the energy yield, which requires *the development of atmospheric models that can tackle land-sea transitions*, including thermic flows and complex terrain. It is necessary to model the mistral, bora and etesian winds specifically.

Cooperation forum

The Union for Mediterranean has a specific action for the energy transition[34]. The BlueMed initiative has outlined an implementation plan which includes a priority on how to “Promote the role of marine renewable energies (MRE) in the energy transition phase”[35]. The priority has a strong focus on floating wind and the multi-use of sea including interactions with marine ecosystems and socio-economic studies.

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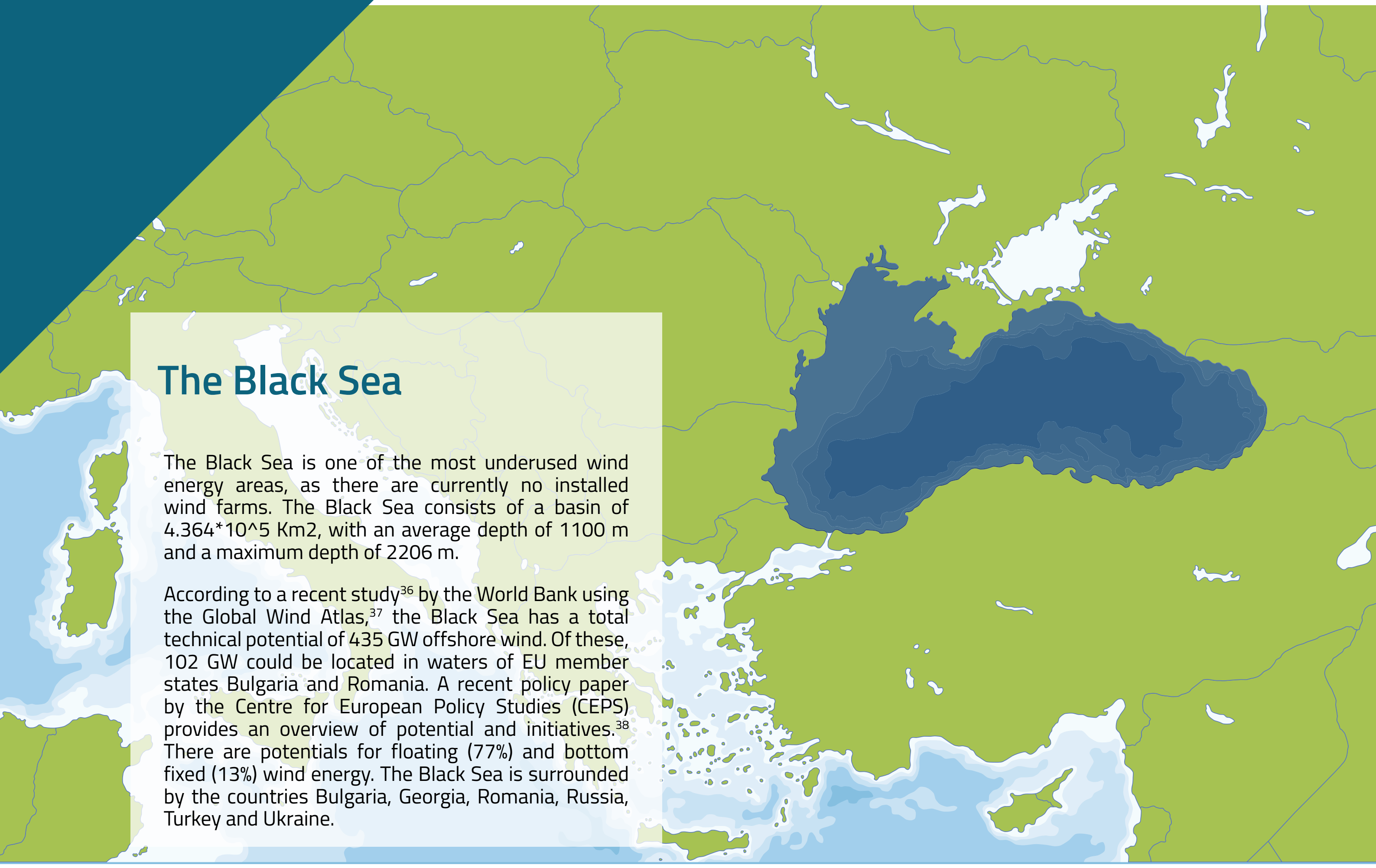
[34] https://ufmsecretariat.org/what-we-do/energy-and-climate-action/

[35] http://www.bluemed-initiative.eu/wp-content/uploads/2020/07/bluemed-preliminary-implementation-plan.pdf



The Black Sea

The Black Sea is one of the most underused wind energy areas, as there are currently no installed wind farms. The Black Sea consists of a basin of 4.364*10^5 Km2, with an average depth of 1100 m and a maximum depth of 2206 m.

According to a recent study[36] by the World Bank using the Global Wind Atlas,[37] the Black Sea has a total technical potential of 435 GW offshore wind. Of these, 102 GW could be located in waters of EU member states Bulgaria and Romania. A recent policy paper by the Centre for European Policy Studies (CEPS) provides an overview of potential and initiatives.[38] There are potentials for floating (77%) and bottom fixed (13%) wind energy. The Black Sea is surrounded by the countries Bulgaria, Georgia, Romania, Russia, Turkey and Ukraine.

Specific challenges call for research, development and innovation towards 2030 and 2050

The Black Sea has vast wind power potentials, but with relatively low wind speeds averaging 450 W/m^2, compared to 1450 W/m^2 along the Atlantic Coast.[39] Low wind sites have a much higher uncertainty for wind speed and turbulence assessment. This results in the need to *develop models able to capture local phenomena driven by heat differences and local topography.* Validated tools will help to reduce uncertainty for investments, annual production and maintenance.

Due to lack of water current exchange, the Black Sea is characterised by an anaerobic underwater environment at +200 m below the surface. This can cause problems with corrosion in metal installations such as the mooring systems for floating wind power.

The Black Sea currently lacks the infrastructure in the form of ports and grid system to enable a large-scale deployment of wind power. Research and assessments are needed to optimise the planning of these very costly investments to enable wind power in the area.

Cooperation forum

There is currently no forum dedicated to offshore wind, but the Central and South Eastern Europe Energy Connectivity (CESEC) is a candidate for setting up a dedicated group for offshore wind.[40]

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[36] http://documents1.worldbank.org/curated/en/718341586846771829/pdf/Technical-Potential-for-Offshore-Wind-in-Black-Sea-Map.pdf

[37] https://globalwindatlas.info/

[38] https://www.ceps.eu/ceps-publications/how-black-sea-offshore-wind-power-can-deliver-a-green-deal-for-this-eu-region/

[39] The reference turbine here is a 3.45 MW turbine from the Global Wind Atlas (https://globalwindatlas.info/)

[40] https://ec.europa.eu/energy/topics/infrastructure/high-level-groups/central-and-south-eastern-europe-energy-connectivity_enack sea

6. SET Plan strategic targets

Updating the targets for the SET Plan Implementation Plan for offshore wind

The European Commission has set a target of at least 300 GW of offshore wind by 2050 to power Europe's green transition. Offshore wind can deliver on these ambitions, but it will require a substantial scale-up of research, innovation and agile adaptation of the regulatory frameworks to drive the scale and volume needed by 2050.

To deliver at least 300 GW, cost reductions in offshore wind will need to continue. Cost reductions can only be achieved through technology improvements and large-scale investment and deployment. Targeted R&I must help deliver technologies and science needed to accelerate deployment and bring down costs. Here, it is important to be aware of where in the offshore wind value chain particular R&I actions are needed.[41]

To reach at least 300 GW of offshore wind, the installation rate needs to increase dramatically. Such an acceleration of the deployment rate can only be achieved through:

Increased demand for clean and renewable electricity

- Increased shares of electricity in the energy mix through renewables-based electrification of heat, transport and industrial activities. New electric technologies will drive demand for the bulk renewable electricity that offshore wind can provide.
- For hard-to-abate sectors, indirect electrification or wind power-to-X is a solution.
- Improved transmission infrastructure and technology to maximise the use of clean renewable energy produced by wind energy where and when needed.
- Increased reliability of renewable power production and security of supply through stable infrastructure and increased R&I.

Investment visibility

- Stable commitments of member states (NECPs) to deliver targets on time.
- Clear and coordinated pipeline of offshore wind auctions to ensure companies have enough time and planning security to make the necessary investments.
- Integrated maritime spatial planning to develop a holistic plan for offshore wind development in Europe and ensure all maritime sectors can co-exist and make the best use of the available maritime space and resources

> “Targeted R&I must help deliver science and technologies to accelerate deployment”

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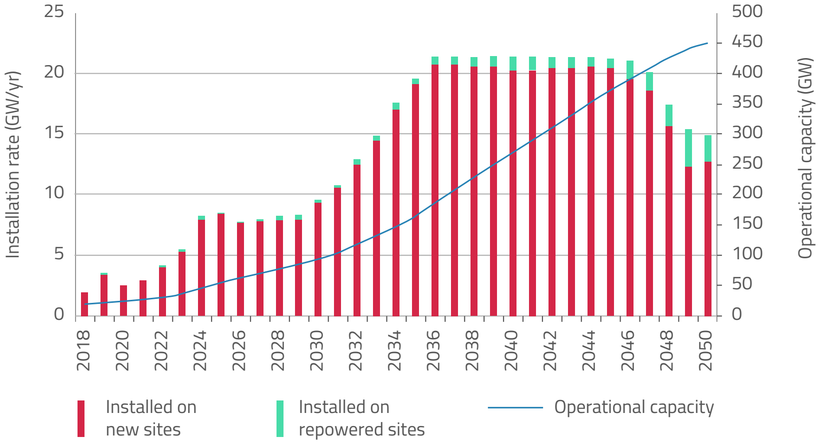
[41] The recently published Competitiveness Progress Report and its underpinning analysis provide additional information on EU competitiveness of offshore wind and other clean energy technologies' value chains: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1602695747015&uri=COM:2020:953:FIN

Targeted R&D efforts to

- Increase performance and yield of wind turbines, since this represents up to 45% of total installed costs of offshore wind.[42]
- Standardise and optimise logistics for large-scale deployment, while taking into account their cumulative impact on the marine environment.
- Lower the cost of installing offshore wind turbines.
- Lower the number of manned operation and maintenance interventions (e.g. with robotics).
- Facilitate EU-wide coordination of system integration of wind and other offshore renewable energy to optimise grid connections, ensuring interoperability and harmonisation of technical standards.
- Increase reliability of offshore wind power production and transmission.
- Industrialise floating substructures with an eye to faster deployment in various European water basins.
- Research and develop offshore conversion, storage and transport capabilities for other energy carriers such as hydrogen.
- Address sustainable decommissioning, re-use and recycling of wind turbine components, through circularity by design, improving the efficiency and lifetime of both existing and new technologies.

The Implementation Working Group for Offshore Wind consisting of Member States (NL, BE, DE, EE, ES, FR, IT, NO, TR and UK), supported by its stakeholders ETIPWind and EERA JP Wind recommends the following metrics to assess the delivery of offshore wind in Europe and its contribution towards a total installed capacity of up to 450 GW needed for a climate neutral economy by 2050.

Installation rate required to achieve 450 GW by 2050



Annual installed capacity (volumes)

- Avg. of 3.8 GW p/a in 2020-2023
- Avg. of 8.1 GW p/a in 2024-2027
- Avg. of 8.7 GW p/a in 2028-2030

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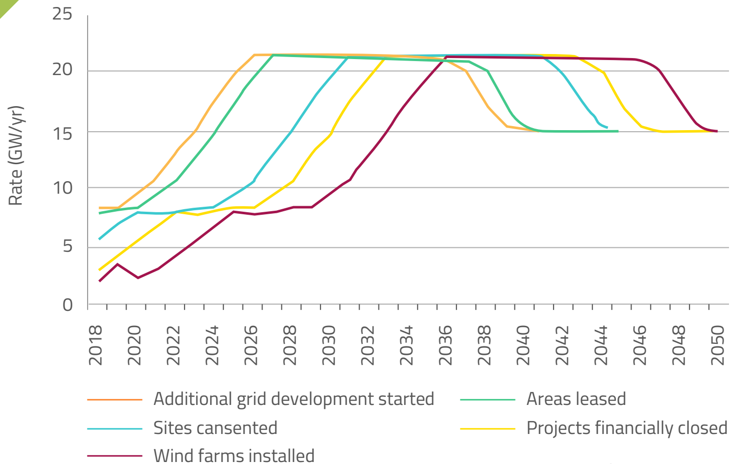
[42] IRENA, Future of wind: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation paper), International Renewable Energy Agency, Abu Dhabi, 2019

Grid development, leasing, consenting, financial closure and installation rates required to achieve 450 GW by 2050

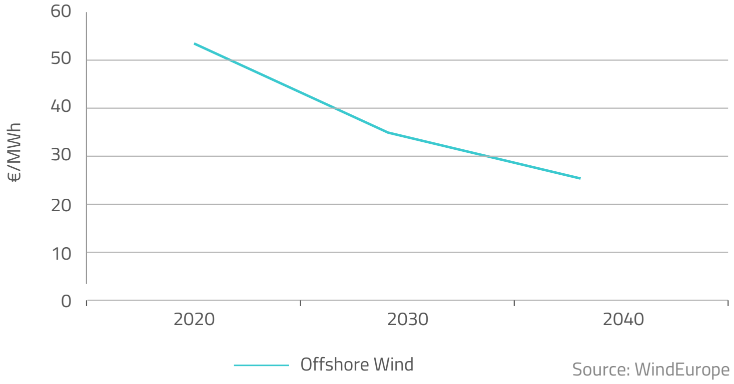


Source: BVG Associates for WindEurope

Annual grid capacity[43]

- Avg. of 12.1 GW p/a in 2020-2023
- Avg. of 20.0 GW p/a in 2024-2027
- Avg. of 21.4 GW p/a in 2028-2030

Cost of wind energy

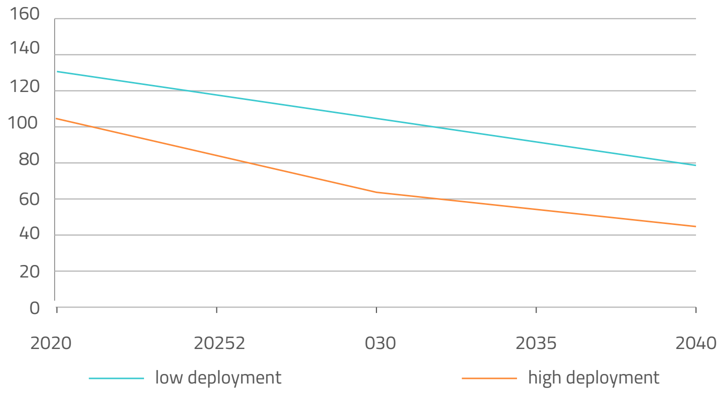


Source: WindEurope

Bottom fixed offshore wind

- Avg. LCOE of 38–60 €/MWh in 2030
- Avg. LCOE between 28 and 48 €/MWh in 2050

LCOE development for Floating wind power



Floating offshore wind

- Avg. LCOE of between 103and 135 €/MWh in 2025 (dependent on 1.5 GW installed capacity)
- Avg. LCOE of between 106 and 62 €/MWh in 2030 (dependent on 6 GW installed capacity)

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[43] This electrical grid capacity is needed to deliver the goals of the energy transition. It is important to note that a parallel out-build of pipelines will be needed to deliver green hydrogen and green ammonia to industry; power generation, steel mills, chemical plants; transport and agricultural sectors.

7. Social sciences and humanities in offshore wind R&I[44]

The European Commission and Member States have rightly emphasised the importance of the social sciences and humanities in enabling the green transition, increasing acceptance of transformation pathways and actively involving society. This is also true for offshore wind energy.

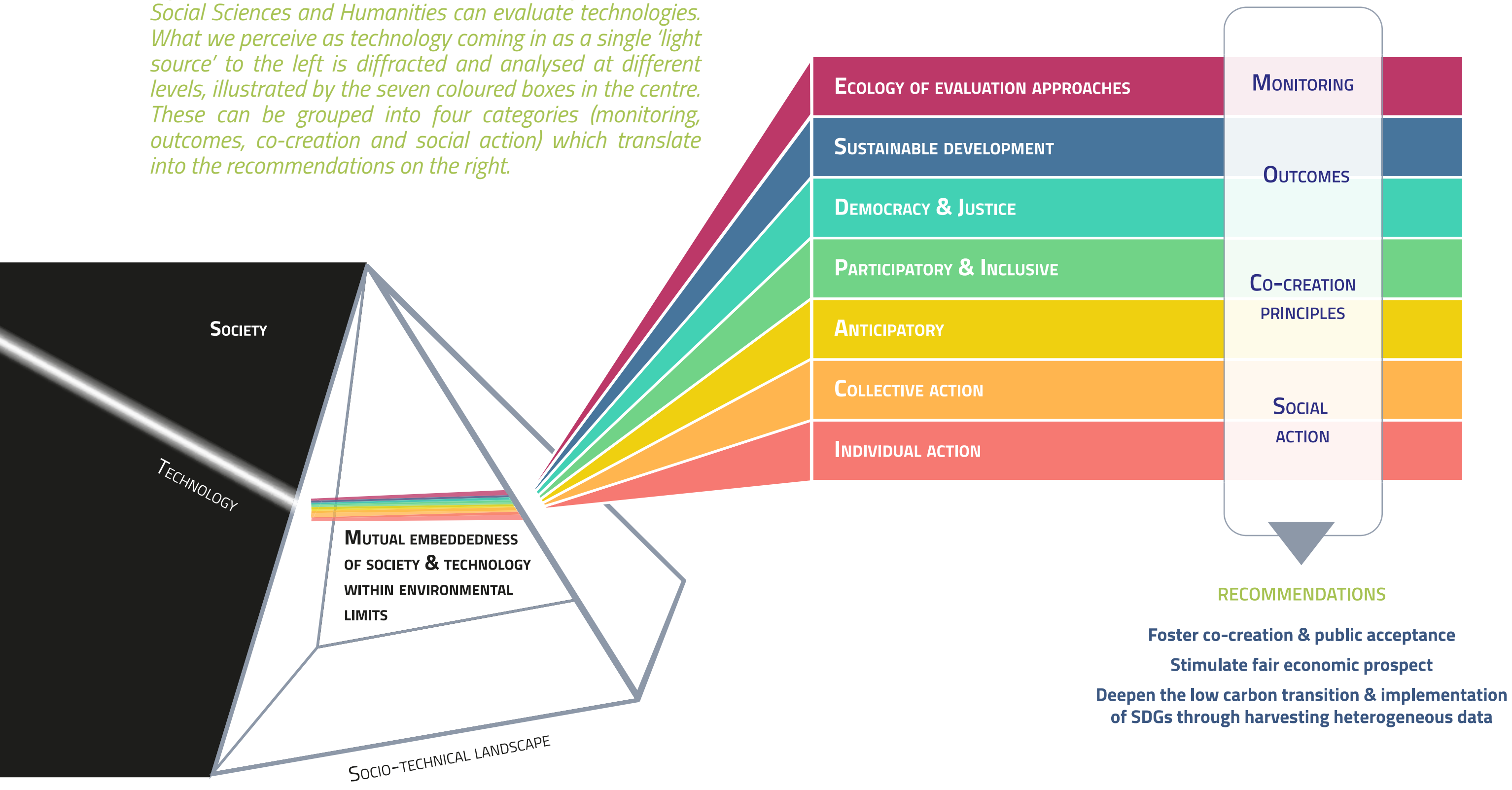
The energy system does not only consist of technologies and services; it also consists of the people employed to develop and manage the system, the people using its output, and the people who are affected by its presence both positively and negatively. While it is understandable that we tend to think of the already hugely complex energy system primarily as the system of technology and services, we must think of energy system integration as a system including people and society. Only in this way can we ensure that we achieve a comprehensive and fully sustainable transformation of our energy system.

As the legacy fossil fuel-based system shrinks and the renewably based system grows, the points of interaction between people and renewable technologies grow. At the same time, ICT technologies and the reform of energy markets promote new market actors and new forms of local value creation, and create new opportunities for involvement. More wind turbines, PV-panels, electrolysers, transport and logistics hubs, smart technologies, dynamic incentivisation of production and consumption, but also local benefits, jobs and additional revenues – all of these are points of contact between the technology and people.

Leverage points for effective short and long-term policies in support of the large-scale deployment of offshore wind technology rest upon a proper understanding of the structure and resulting behaviour of the energy sector and its interconnectedness with other human-environment systems across time and space.

Social Sciences and Humanities (SSH) offer a broad range of methods, tools and solutions that allow us to better think, test and act such that the energy system contributes to the wider benefit of society. Figure 2 below conveys the different levels of analysis that the SSH tradition can contribute.

Figure 2 shows the different layers through which the Social Sciences and Humanities can evaluate technologies. What we perceive as technology coming in as a single 'light source' to the left is diffracted and analysed at different levels, illustrated by the seven coloured boxes in the centre. These can be grouped into four categories (monitoring, outcomes, co-creation and social action) which translate into the recommendations on the right.



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[44] This section of the Implementation Plan was drawn up in collaboration with the EERA Joint Programme E3s and the Energy-SHIFTS project funded under Horizon2020 (https://energy-shifts.eu/).

SSH recommendations for offshore wind

The following recommendations summarise three dimensions in the development of offshore wind where an SSH approach contributes to supporting the role of offshore wind in the green transition.

1st recommendation. Foster Co-creation & public engagement:

Co-creation starts with how we organise ourselves (e.g. in R&D and policy organisations) and how we seek to engage others. Processes allow for both problems and solutions to be inclusively deliberated and co-produced with a wide range of interconnected stakeholders. A co-creation process begins at the start of the process, not at the end of it.

1. Policymakers at regional, national and EU level need to work across silos to ensure a holistic approach to offshore wind development.
2. The SSH research community has a range of available tools and methods to support policymakers in planning and decision-making, but this requires up-front engagement.
3. Cross-European and/or regional initiatives should ensure that stakeholders (including citizens) have an active voice in the early phase of new offshore wind projects, rather than imposing pre-identified agendas that local communities must 'accept'.

2nd recommendation. Stimulate fair prospects:

In line with the EU Green Deal, offshore wind must contribute to a just and fair transition for all citizens. This includes the distribution of costs and benefits, but also a shared understanding of the need to speed up the transition and consequently also the build-out of offshore wind.

1. Create awareness and understanding in the wider community that the green transition requires substantial build-out of renewable generation sources.
2. Balance the distribution of cost and benefits to the whole range of stakeholders in offshore wind development, including the local communities that are affected. This includes a better understanding of the full impact of offshore wind at local-regional level.
3. Increase efforts to ensure training and education for the workforce in areas where offshore wind development is starting to take off.

3rd recommendation. Deepen the low carbon transition & implementation of SDGs through harvesting heterogeneous data:

The achievement of the UN 2030 Agenda and the Paris Agreement require monitoring and reporting systems at different scales, also extending towards business reporting and regulatory compliance. Their effectiveness relies on measurable goals, indicators and high quality data. The latter include both quantitative and qualitative data.

1. It is recommended that the value offered by heterogeneous data is systematically linked to the political processes for implementing the SDG agenda.
2. Furthermore, to foster the full potential offered by digitalisation and Industry 4.0, it is recommended that the offshore wind industry implements open and FAIR data standards along the entire supply chain. This enables transparent and effective monitoring, reporting and evaluation.

8. Lighthouse R&I initiatives for offshore wind

Two offshore wind lighthouse initiatives are in development by the SETWind project, following an extensive consultation process with the stakeholder community including ETIPWind and EERA JP Wind.

The term 'lighthouse initiative' refers to a visionary, science-driven large-scale initiative with a significant budget (tens of millions of euros) and duration (5 years or more) that will address grand scientific and technical challenges crucial to the further advancement of offshore wind energy, providing new knowledge and a basis for innovation.

The two lighthouse initiatives address two areas:

- **Floating offshore wind technology**, being the new frontier in offshore wind energy development that offers a huge potential to exploit wind resources over deep water. The overall goal is to make floating offshore wind cost-competitive.
- **Integration of large-scale offshore wind energy,** to enable the future reliable operation of the power system with zero emission of CO_2.

The motivations to focus the lighthouse initiatives on these two areas are:

- Offshore wind has the potential to deliver 18 times the global electricity demand of 2017, but 80% of the global offshore wind resource is over deep water.[45] Thus, it is essential to develop floating offshore wind technology to be able to utilise this huge untapped resource.
- Large-scale utilisation of offshore wind energy is identified as crucial for reaching climate goals. The most ambitious scenario for Europe includes a total of 450 GW of offshore wind capacity in 2050[46] tto supply 30% of the electricity demand. This requires new solutions for the integration of offshore wind energy to provide for efficient and reliable operation of the power system.

Within both areas, there are great opportunities for industrial development, creation of new jobs and innovation, and there are grand science and engineering challenges that must be addressed.

The two lighthouse initiatives are in support of the UN sustainability goals, in particular: 7: Affordable and Clean Energy, 9: Industry, Innovation and Infrastructure, 11: Sustainable Cities and Communities and 13: Climate Action.

The science and engineering challenges are well documented, see for example the ETIPWind research and innovation roadmap[47] and the EERA JP Wind R&I strategy.[48] These include a long list of topics from which a selection can be made to constitute a lighthouse research project. This should mainly focus on low TRL research upto qualification on laboratory scale. The idea behind this is that there are some fundamental research questions that need to be addressed to enable the development of wind energy to its full potential. Three such grand challenges are described in a recent article in Science[49] by a group of highly acclaimed wind energy experts from the IEA Wind TCP. The challenges are:

- Improved understanding of atmospheric and wind power plant flow physics. This is vital both to enable the development of cost-competitive floating wind technology and to be able to properly operate wind farms to support the energy system.
- The interaction between aerodynamics, structural dynamics and hydrodynamics of enlarged floating wind turbines.
- Systems science for integration of wind power plants into the future electricity grid.

An attractive lighthouse initiative should include the elements above but ensure that it can be applied and work with the industry. It is important to use measurement from experiments, both lab and full-scale, and to link with industry initiatives. Access to open data is a crucial point, and the creation of research infrastructure to provide for such open data can be an important part of a successful lighthouse initiative.

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[45] IEA Offshore Wind Outlook, 2019

[46] https://windeurope.org/about-wind/reports/our-energy-our-future/

[47] www.ETIPWind.eu

[48] www.eerajpwind.eu

[49] Paul Veers et al, 2019, Grand challenges in the science of wind energy, Science Vol. 366, Issue 6464, https://science.sciencemag.org/content/366/6464/eaau2027/tab-pdf

9. Impact assessment of wind energy R&I

A number of factors drive the adoption of renewable energy, such as wind and solar PV, in electricity systems and markets. From providing security of fuel supply to addressing climate change, wind energy is poised to become the foundation of the 21st electricity system. However, even as the levelised cost of wind energy (LCOE) continues to fall and make it competitive with fossil fuel and other conventional generation, new concerns are developing around the value of wind energy in systems with high variable renewable energy shares.

Large shares of wind energy in a system have been shown to have an inverse correlation with average energy prices. Going forward, wind farms will increasingly participate in low-subsidy and even subsidy-free markets and the value of the energy will be just as important as the LCOE. Thus, throughout the entire wind energy value chain, from manufacturers to developers to policy makers, there is a need to go 'Beyond LCOE' and address the value that wind energy brings to electricity systems and society more broadly.

The important message is that Beyond LCOE is not coming: it is here. For industry in particular, the need to evaluate technologies and projects for metrics Beyond LCOE is essential. Many projects are already expected to participate in low-subsidy and subsidy-free electricity markets where high shares of variable renewable energy are even now placing downward pressure on electricity prices, and thus realisable project revenue. Industry has urged the research community to move forward quickly to identify metrics and develop tools for their assessment that can be used by industry in the near term.

Understanding these metrics will be essential for assessing the quality of future R&I projects at all levels from industry to regional, national and EU level. New business opportunities but also new societal value creation needs to be properly understood by evaluators.

Beyond LCOE metrics for assessing the potential impact of R&I projects will need to include three dimensions:

- **Cost of energy (the classical LCOE)**

  Continuing the reduction of LCOE remains important to wind energy, and as indicated by the SET Plan strategic targets, continued cost reductions are expected through a combination of deployment and advances in R&I and industrialisation.

- **The financial and regulatory requirements/potentials**

  The potential impact of R&I will also need to be assessed in the context of financial and regulatory requirements to wind energy. This includes the adaptation to markets and regulatory frameworks in diverse global markets.

- **The energy system interplay with the environment and people**

  The installation, operation and decommissioning of wind farms influence the surrounding environment and citizens. The effect on natural habitats, tourism sites, other users of the sea and citizens in the case of near-shore offshore wind needs to be considered when assessing the potential of new R&I.

10. Priority actions for offshore wind

The process to redefine R&I priority actions

The core of the Implementation Plan is a selection of R&I activities to be funded and carried out by the Member States, stakeholders from industry and academia, and the European Commission, in order to reach the targets set in the Declaration of Intent as well as the updated targets as described earlier in this document.

In the previous version of the Implementation Plan, the defined priority actions reflected the context and potential for offshore wind as it was considered at the time. However, the rapid development of the offshore wind sector combined with new demands and strategies at regional, European and global level has shown that priorities for offshore wind cannot be considered static, and that a different approach is needed to keep up with the changes in priorities. In this updated version, the priority actions have therefore been revised to follow the 'rolling agenda' for the offshore wind sector. The rolling agenda takes into account that offshore wind is at a stage where short and medium-term targets and priorities are ever-changing and therefore need continuous revision. The rolling agenda concept is supported by the SETWind project, through a series of workshops addressing emerging topics.

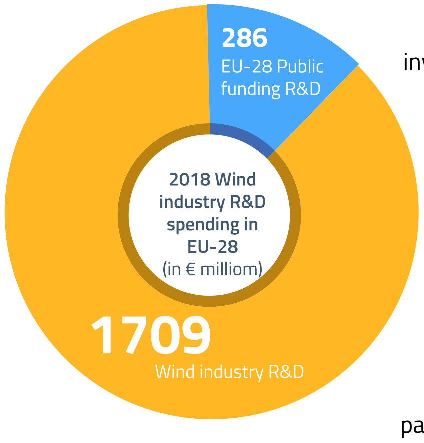
For the definition of the priority actions, strategies from the European Technology and Innovation Platform on Wind Energy (ETIPWind), the sub-programs of the European Energy Alliance Joint Programme on Wind Energy (EERA JP Wind) and the International Energy Agency Wind Energy Technology Collaboration Programme (IEA Wind TCP) have been considered. Below can be seen the 2019 R&I priorities from ETIPWind, EERA JP Wind, and IEA Wind TCP respectively. The updated priority actions in the right-most box have been formulated based on these strategic inputs

ETIPWind	EERA JP Wind	IEA WInd Strategic Work Plan	**SET Plan Implementation Plan Priority Actions**
Next Generation Technologies	Next Generation Wind Turbine Technology & Disruptive Concepts	Advanced Technology	**Wind Turbine Technology**
Grid & System Integration	Grid Integration & Energy Systems	Energy Systems with High Amount of Wind	**Offshore Wind Farms & System Transformation**
Floating Wind	Offshore Wind (Bottom Fixed + Floating)		**Floating Offshore Wind & Wind Energy Industrialisation**
Operation & Maintenance	Operation & Maintenance	Resource and Site Characterisation	**Wind Energy Operation, Maintenance & Installation**
Digitalisation, electrification, industrialisation & human resources	Sustainability, Social Acceptance, Economics & Human Resources	Social, Environmental, and Economic Impacts	**Ecosystem, Social Impact & Human Capital Agenda**
Offshore Balance of Plants		Communication, Education, and Engagement	
	Fundamental Wind Energy Science	Deeper Understanding of the Physics of Atmospheric Flow	**Basic Wind Energy Sciences**

Who should invest in offshore wind R&I?

A key question addressed to the IWG Offshore Wind has been who should invest in the required research at different levels. A recent analysis by ETIPWind shows that the annual investment in wind energy R&D is close to €2 billion annually.

While the overall investments are dominated by industry due to the very high cost of developing new technologies, the picture looks different when we spread it out at low, medium and high TRL.



Despite the relatively small investments from the European Commission compared to national and industry investments, it should be noted that the EU Framework programme represents approximately 35% of publicly available competitive funding. Horizon Europe and other EU investment tools therefore play a pivotal role in ensuring R&I development at a European scale. This is particularly relevant for lower to medium TRL research, where the whole stakeholder community benefits from large, coordinated efforts where results can be disseminated widely.

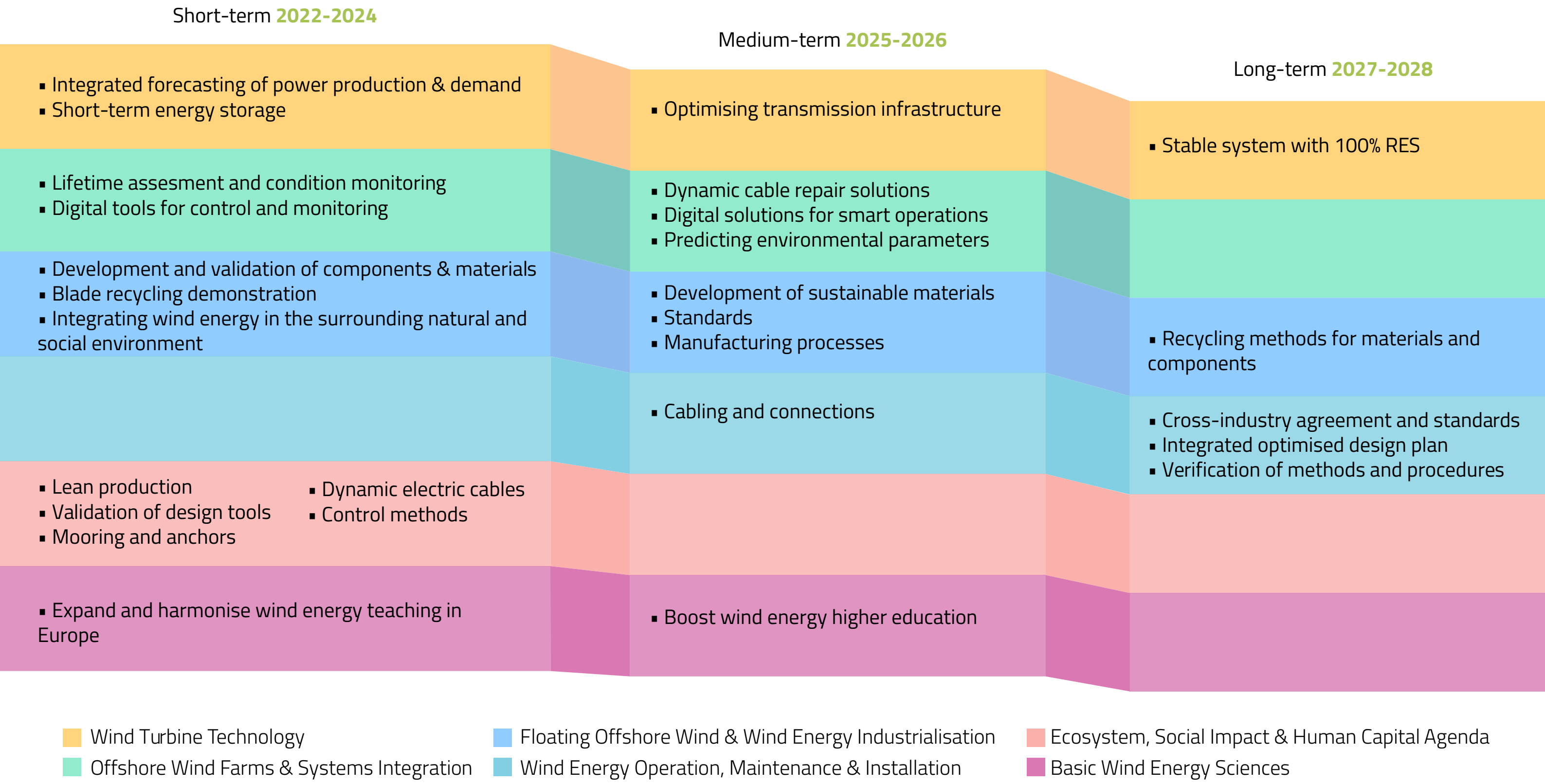
The R&I priority actions of the Implementation Plan for offshore wind 2022

The six priority actions of the Implementation Plan 2022 are:

1. Next generation wind turbine technology
2. Offshore wind farms & systems integration
3. Floating offshore wind & wind energy industrialisation
4. Wind energy operation, maintenance & installation
5. Ecosystem, social impact & human capital agenda
6. Basic wind energy sciences

Following the approach taken in the ETIPWind Technology Roadmap 2019[50], , the priority action sub-topics are listed as low/medium/high priority and short/medium/long-term. The priority reflects general tendencies, and might vary between industries, countries and regions.

- Short-term: 2022–2024
- Medium-term: 2025–2026
- Long-term: 2027–2028



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[50] https://ETIPWind.eu/files/reports/ETIPWind-roadmap-2020.pdf

1

NEXT GENERATION WIND TURBINE TECHNOLOGY

Description of the action

Large technology developments are being realised and foreseen while wind energy is being implemented in large numbers. The wind sector requires a strong scientific knowledge base to develop wind energy generators beyond its capabilities of today and tomorrow. New concepts contribute to the massive deployment but require major support at lower as well as higher TRLs to overcome the inertia of existing concepts.

Research gaps:

- Implementation of 300 GW wind power in Europe requires more cost-efficient, energy-efficient, low environmental impact, scalable wind energy converters.
- Degradation and damage mechanisms of materials and components.
- Unknowns in degradation mechanisms (such as wear in blades and drivetrain, erosion of blades) lead to unexpected behaviour and limited options for cures.
- Access to and data from a wind turbine research infrastructure.
- Upscaling of wind turbines and aiming for further cost reduction require validation of models and innovations to reduce uncertainties in design. Dedicated experiments and data sets are lacking.
- Interpretation and extrapolation of scaled, hybrid and component testing.
- The development of larger and larger turbines requires major development and innovations in certification and testing methodologies such as scaled testing and testing of components, together with virtual tests and development of international standardisation.
- Multi-purpose platforms integrating various options such as wind, solar, wave, tidal, seaweed etc., and suitable turbine technology for this.

Description of sub-topics

1. *Develop next generation test and validation methods* Development of external condition measurement methods, in addition or alternative to full-scale blade testing, test benches for drivetrain testing, tailor-made wind tunnel models and improvements in material testing. Testing and validation methods for components should be developed and proposed for international standardisation. Develop an integrated, full-scale international testing environment.	Priority: Short-term TRL: High
2. *Large rotor aerodynamics and structures, including interaction with turbulence* Development of smart rotor technology to reduce loads while increasing blade length, smart materials to reduce degradation, self-repair technology and intelligent, adaptive blade and turbine control.	Priority: Medium-term TRL: Medium
3. *Develop disruptive technologies* Investigating game changers and new technology solutions in rotor, drive train, support structures and electrical system, including technology developments in other disciplines and completely different concepts like large low induction rotors and high altitude wind power or integrated Hydrogen conversion.	Priority: Long-term TRL: Low
4. *New and smart materials* Introducing structural couplings, smart materials, such as nano-coatings, high-strength materials, anticorrosion materials and self-healing materials. Structural reliability methods need to be developed in order to better use materials, predicting damage and cracks in an enhanced way. Solutions for leading edge erosion need to be developed.	Priority: Short-term TRL: Medium
5. *Facilitate demonstration project towards 20+MW turbines* Barriers to blade design and testing, rotor-hub design and drivetrain design must be addressed, including the transportation and installation of large and heavy components.	Priority: Short to medium-term TRL: High

2

OFFSHORE WIND FARMS & SYSTEMS INTEGRATION

Description of the action

R&I must contribute to the transition towards 100% RES power systems, understanding the challenges and developing the required technical capabilities. This includes aspects such as dynamic stability of systems with very large penetration of converters, market designs and interactions with other energy systems, sector coupling, energy conversion and storage. *This action must be addressed in collaboration with the SET Plan Implementation Working Group on HVDC.*

Research gaps:

- Adaptation of electricity markets for 100% RES power systems. When production of wind and solar dominate the markets, their production characteristics must be matched by market design, including more local and short-term flexibility markets, with faster dispatch and adequate pricing.
- ▪ Validated energy systems models for assessing the value of wind power with 100% variable renewable energy supply. Various scenarios/hourly time step models exist, but with more or less crude assumptions, e.g. for wind variation, balancing capabilities, regional transportation bottlenecks etc.
- ▪ Degradation and failure mechanisms of cables, transformers and power electronic converters call for extensive research and testing to be fully understood and to enable reliable grid solutions, including mitigation measures.
- ▪ Behaviour and control of large HVDC connected clusters is vital for enabling the future development of large interconnected offshore grids, serving to connect wind farms to different national markets and offshore loads, as well as power/energy exchange between regions. Essential aspects are strategic grid planning, optimal power flow, reliable operation and protection schemes and supporting the interconnected terrestrial grids.
- ▪ Dynamic performance of very large wind power clusters needs to maintain power quality and stability in offshore wind farm grids that are fully based on power electronic converters in order to guarantee reliable and efficient wind farm operation.
- ▪ Advanced system services from wind power, providing reserve power for frequency support, reactive power for (dynamic) voltage support, mitigation or active compensation of harmonics for maintaining power quality and providing black start (grid forming operation) for increasing security of supply and helping system restoration etc.

Description of sub-topics

1. *Design and control of wind power plants and HVDC grids for power system with zero CO_2 emissions* Technical solutions to enable wind power plants to allow safe and efficient power system operation in power systems with large renewable generation and zero CO_2 emissions ▪ Advanced system services from offshore wind farms, providing reserve power for frequency support, reactive power for (dynamic) voltage support, mitigation or active compensation of harmonics for maintaining power quality and providing black start (grid forming operation) for increasing security of supply and helping system restoration etc. ▪ Operation and control in concert with HVDC grid, enabling future development of large interconnected offshore grids, serving to connect wind farms to different national markets and offshore loads, as well as power/energy exchange between regions.	Priority: Medium to long-term TRL: Medium
2. *Increased performance of wind power and grid via digitalisation* Use of field data, big data analytics and AI combined with system modelling for monitoring, control and performance optimisation of wind power in the energy system. ▪ Digital solutions including big data analytics and AI combined with system modelling for improved control and performance with provision of ancillary services from the future large offshore wind farms. ▪ Bring forward digital twin models that give a real-time estimate of time to failure of key components, in wind farms and grids, such as cables, transformers and converters, to enable reliable operation and supply of electricity.	Priority: Short to medium-term TRL: Medium to high

3. *Sustainable hybrid solutions, storage, and power to X* Combining offshore wind with other renewables, using complementary generation patterns, contributes to improving the security of supply and lowering grid integration costs. Onshore and offshore power–to-X (e.g. to hydrogen), storage and transport are essential to realise the required generation flexibility and security of supply, both in the short term as well as seasonally. Furthermore, integration of these solutions into offshore wind farms is required to facilitate their large-scale and economic integration, including off-grid approaches, i.e. using gas or other alternative energy carriers. ▪ Validate hybrid solutions, in which offshore wind is combined with other offshore renewable generation such as wave energy and PV. ▪ Assess storage and power-to-X solutions that will contribute to generation flexibility and security of supply, both short-term and seasonally. ▪ Validate integration of these solutions in offshore wind farms, including off-grid approaches, e.g. isolated offshore wind farms producing hydrogen.	Priority: Short to medium-term TRL: High
4. *Markets & financing* The energy system transition requires the development of tools for energy management, taking into account wind forecast uncertainty, and supporting the interaction between wind power, other generation, conversion and storage, demand-response and grid capacity limitations. Furthermore, it will need to account for opportunities to enable the general public to be part of the business through investment options. ▪ Validated energy systems models for assessing alternative developments of offshore energy transmission systems, including electricity and hydrogen. ▪ The models should be developed to consider relevant timescales, wind variations, balancing capabilities, regional transportation bottlenecks, etc.	Priority: Short-term TRL: Low/ medium
5. *Experiment for validation of design* Define and execute experiments and measurement campaigns for validation of technologies, models and hypotheses. To the degree possible, data should be made open access to accelerate learning in the entire sector.	Priority: Short-term TRL: High

3

FLOATING OFFSHORE WIND & WIND ENERGY INDUSTRIALISATION

Description of the action

Massive offshore implementation of wind power requires R&I to further reduce risks and costs, and thus to accelerate deployment. Developments will occur further offshore and in deeper water, requiring floating wind power. Integrated design methods need to be developed, which include wind and waves, electrical infrastructure, environment, substructures, control, logistics and risks.

Research gaps:

- New concepts and validation of integrated design models for floating wind plants are required to ensure cost-effective designs and to maximise the opportunities for optimisation of floating foundations based on wind turbine load control technology.
- ▪ Efficient multi-disciplinary optimisation offers to achieve cost-effective and reliable foundations, accounting for a wide range of design parameters, and needs research and maturing. Platform and mooring line design, construction and maintenance strategy.
- ▪ Offshore physics (soil damping, breaking waves, soil-structure-fluid interaction, air-sea interaction). The limited understanding of physics phenomena and model uncertainties affecting offshore balance of plant technology prevents accurate design models and optimal cost-effective designs. Proper data sets are lacking.
- ▪ Site-specific structural and electrical design conditions for electrical infrastructure are lacking to better understand the loading and operational conditions of key electrical components like cables or power converters, enabling improvements in reliability.

Description of sub-topics

1. *Optimisation of floating wind farms* Floating wind farms are in an early stage of development. There is a need to develop tools for optimisation of design according to site conditions and to optimise performance through innovative farm design and operation. ▪ Models for integrated design optimisation of floating wind farms ▪ Cost optimisation for various design conditions (sea depth, wind, waves etc.) ▪ Assess various floating wind farm designs, including platform, mooring, turbine, and electrical system design ▪ Optimise performance of floating wind farms through innovative design and control, increasing power output and reducing loads on cables, mooring lines and anchors.	Priority: Short to medium-term TRL: Medium
2. *Grid connection, mooring and anchoring* *Grid connection, mooring and anchoring of floating wind turbines have become bottlenecks to accelerated development and cost reduction. Innovations in design must enable cost reductions in construction, deployment and maintenance. Large volumes will enable a dedicated supply chain with series production of components optimised for floating wind farms.* ▪ Optimisation of mooring system, dynamic cables and substations. This should consider the choice of materials and design for series production, installation, operation and recycling. ▪ Assess new concepts through modelling and testing.	Priority: Short-term TRL: Low
3. *Enable digital transformation in wind energy system O&M* Large-scale series manufacturing and assembly of floating wind turbines with Lean production and logistics is key to reducing the cost of energy from new large floating offshore wind farms. ▪ Standardisation of products and processes with development of cost-efficient building elements for floating offshore wind turbines, standardisation of transport methods and assembly, and more efficient mass production. ▪ Development and validation of holistic design tools	Priority: Shortm-term TRL: Medium
4. *STest methods and certification for floating wind* Test methods for floating wind are required to give developers and operators the confidence of solid investments. For floating wind power, test methods need to be developed and certification needs to be made specific.	Priority: Short-term TRL: High

4 WIND ENERGY OPERATION, MAINTENANCE & INSTALLATION

Description of the action

In order to reduce the cost of wind power, operation and maintenance must be optimised. Robotics solutions should reduce the required human intervention, and sensor systems provide the information for improved monitoring and control to increase lifetimes. The abundance of data and information should be used in big data analytics technologies to improve O&M.

Research gaps:

- Accurate reliability models of components as functions of operation and loads. Condition based maintenance or replacement of (sub)components relies on accurate reliability models that can predict remaining lifetime or probability of failure for a given load history.
- Degradation mechanisms of surfaces (wear, erosion and corrosion). Unknowns in degradation mechanisms (such as. wear in blades and drivetrain, erosion of blades and corrosion of support structures) lead to unexpected behaviour and limited options for cures.
- ▪ Lifetime extension – is an effective solution for LCOE reduction as well as impact on the environment and resources.
- ▪ Data analytics for O&M purposes and lifetime health predictions for predictive maintenance. Abundant information and data are available from wind farms, for which processing by big data analytics technology needs to be developed.
- ▪ Robotics – reduction in human presence at height on offshore platforms to improve health and safety by automated and remote inspections and to repair inside the nacelle as well as outside the turbine.

Description of sub-topics

1. *Validation of structural damage and degradation* The fundamentals concerning modelling and operational results of damage and degradation need to be developed from micro-scale to macro-scale level. Validation requires extensive testing programmes and dedicated experiments.	Priority: Medium-term TRL: Low
2. *Next generation of wind farm control (wakes, cluster layout etc.)* Advanced (including data-driven, model-free, AI etc.) and holistic multi-objective wind farm control optimising overall performance of wind farms and wind farm clusters. The optimisation relates to turbine operation improvements to reduce loads, adapting the wind farm to grid requirements and optimising energy production.	Priority: Medium-term TRL: High
3. *Enable digital transformation in wind energy system O&M* The abundance of available data requires big data analytics and the application of real-time testing and 'digital twins' to be developed, to recognise patterns and improve energy yield and to control degradation.	Priority: Medium-term TRL: Medium
4. *Sensor systems and data analytics for health monitoring* Robust, reliable, accurate and durable sensors need to be developed to monitor the condition and degradation of the most critical components and external conditions against lowest costs. Self-diagnostic systems and multi-sensor constructions may include remote sensing of external conditions and damage such as lidar, drones etc.	Priority: Short-term TRL: High
5. *Robotics* Remote and automated repair technology and strategy requires the development of sensor technology and robotic solutions. These should be tested in safe demonstration environments as well as in the dynamic wind turbine environment.	Priority: Long-term TRL: Low

5

ECOSYSTEM, SOCIAL IMPACT & HUMAN CAPITAL AGENDA

Description of the action

Massive implementation of wind power must be done in a sustainable manner, creating maximum value for stakeholders, including investors, users and citizens with respect to the UN Sustainable Development Goals. This can be achieved by removing barriers to massive deployment and ensuring sufficient qualified human resources.

Research gaps:

- Wind can create higher value for society, both on the market side (high value energy at low cost) and on the societal side (socio-economic benefits, avoiding negative impacts), depending on the interactions between market, technological and environmental issues within the overall policy and regulatory framework.
- ▪ Contribution of wind energy to the UN Sustainable Development Goals (SDGs).
- ▪ Applying lifecycle assessment and estimating requirements of resources for the energy transition, including the availability of resources in power systems with very high shares of wind energy.
- ▪ Assessing the economic and societal impact of research and innovation projects for wind energy.
- ▪ Technologies and designs to improve recycling, re-using, decommissioning and end-of-life solutions.
- ▪ Translating understanding of mechanisms behind social acceptance into implementable approaches and demonstrating their value for project realisation.
- ▪ Identifying skills and training needs required for developing and handling future wind turbine designs and developing best practices for high quality training programmes.

Description of sub-topics

1. *Nature-inclusive wind energy (and multi-use)* Offshore wind farms offer the possibility for nature-inclusive operation. The multi-use of the platforms, vessels and area offers opportunities for the creation of artificial reefs, oyster banks, fish recovery etc. The use of the area for seaweed growth and harvesting offers important synergy advantages. ▪ Improve nature and combination with seaweed and fishery ▪ Reduce impact to marine nature and species population (such as. seabirds, marine mammals)	Priority: Short-term TRL: Medium
2. *Assessment methods to quantify/qualify the impact of research projects* Cost reduction, acceleration time to market, remove barriers Develop a method for broader socio-economic impact assessments in project proposals (including cost indicators and value creation indicators). This assessment scores the projects on their impact on socio-economic aspects and is a valuable addition to the usual impact on cost reduction and reduction of CO_2-potential.	Priority: Medium-term TRL: High
3. *Increase workforce for offshore wind by continuing education and training* Adequate human resources with the right skills and competences are key to Europe's continued global leadership in wind energy. New skills are required as the technology evolves. Continuous education, lifetime learning and massive growth of workers in offshore wind require innovations in teaching programmes that allow scalable training. (VR, augmented reality, etc.)	Priority: Short to medium-term TRL: Medium
4. *Circular economy and availability of materials* As wind power increases its share in the energy mix, it needs to address issues related to its environmental and social footprints. An environmental and community friendly design also includes the 'afterlife' of a turbine. We need to develop technologies that are easily recyclable, create designs that are good for recycling and embrace circular economy concepts in our research and development.	Priority: Medium-term TRL: Low / medium
5. *Empowering citizens and increasing public engagement* Extensive offshore wind deployment will impact citizens and the multiple users of the sea. There is a need to address how citizens can be included in investment and in the early planning stages to increase social acceptance. During recent years, we have started to understand mechanisms and solutions for effective participatory processes and how to create acceptability.	Priority: Short-term TRL: Medium

6

BASIC WIND ENERGY SCIENCES

Description of the action

Research in the fundamental wind energy sciences is required to develop research competences and the underpinning scientific knowledge. This will lead to improved standards, methods and design solutions and new wind turbine concepts. Models and experimental data are needed for complex sites and extreme climate, larger and lighter turbines with improved characteristics, more efficient wind farms and large-scale penetration in the energy system.

Research gaps:

- Climate change and extreme climate affect design, performance and operation. The development in critical geophysical condition in the future needs to be modelled and assessed.
- ▪ Atmospheric multi-scale flow from meso-scale to wind farm flows i.e. accurate and validated models predicting properties of flow in complex terrain regions down to wind farm flow affected by wakes and turbine control.
- ▪ Physics of large rotor aerodynamics and high-fidelity fluid structure interaction (FSI): inflow, blade and wake aerodynamic characterisation i.e. accurate model development for the flow around large blades including add-ons and active flow devices and wake models.
- ▪ High-performance computing and digitalisation call for extensive research and testing to be fully applied and to enable accurate and reliable solutions.
- ▪ Materials, including better knowledge of properties, new and improved materials and their degradation and failure mechanisms, provide new opportunities for weight and cost reductions, new concepts and higher reliability and improved manufacture of wind energy systems.
- ▪ System engineering models, including detailed fluid-structure, soil-structure and electromechanical interaction, needs development in order to allow optimal design and operation for reduced LCOE and system compliance.

Description of sub-topics

Modelling and measurement of offshore conditions including multi-scale flow modelling Multi-scale modelling using high-fidelity and high-performance computing to provide accurate estimates for siting, control, performance and operation of wind farms as well as predictions of effects from climate change and extreme climates.	Priority: Medium-term TRL: Low
1. *Efficient multi-disciplinary optimisation and system engineering* Optimisation of wind farm design requires a multi-disciplinary, system engineering approach including rotor, nacelle, tower, support structure, electrical infrastructure, soil, environment, markets and regulations and includes public acceptance as well as societal costs and benefits. Tools need to be developed and matured, taking into account the complete lifecycle. Global high-fidelity system models provide insights into critical interactions between system components, i.e. for the drivetrain components, and engineering tools offer total system optimisation of wind energy plants, while being essential for the development of reduced order engineering design tools for technology and plant design.	Priority: Long-term TRL: Low
2. *Digital turbine and data analytics* New sensors, data processing, machine learning, data analytics and methods for implementation in data-driven design, digital twins, and control and monitoring for O&M need development for increased reliability and reduced costs in wind energy.	Priority: Medium-term TRL: Low/ medium
3. *Material science for sustainability* Better and more accurate knowledge of properties, behaviour, degradation and damage mechanisms of materials as well as development of new materials or treatments to offer less conservative and more reliable designs needed for upscaling, cost reduction, circularity and lifetime extension. Material science is required with a focus on fracture mechanics, composite blades with structural couplings, structural elements, corrosive and erosive environments, mechanical and electrical components such as generators and magnets and subsea cables.	Priority: Short to medium-term TRL: Low
4. *Open access database for research validation (FAIR data)* Remote and automated repair technology and strategy require the development of sensor technology and robotic solutions. These should be tested in safe demonstration environments as well as in the dynamic wind turbine environment. Relevant experiments need to be developed and implemented to create open access databases involving industry.	Priority: Short-term TRL: N/A

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The SET Plan Implementation Working Group for Offshore Wind

setwind.eu

The SET Plan Implementation Working Group for Offshore Wind (IWG Offshore WInd) is composed of representatives from relevant European countries and stakeholders, representing both industry and academia with interests in offshore wind.

Since the first version of the SET Plan Implementation Plan for Offshore Wind was published in 2018, the IWG has continued its work in collaboration with the EU-funded project SETWind. This collaboration has led to this updated version of the SET Plan Implementation Plan for Offshore Wind.

The updated Implementation Plan sets new strategic cost targets, enlarges the scope of offshore wind energy R&I to cover all European sea basins, includes the contribution of social sciences and humanities and updates the priority actions for research and innovation to achieve the EU’s ambition of +300GW offshore wind by 2050.

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