Strategic Research & Innovation Agenda 2025-2027

November 2023

ETIP Wind
EUROPEAN TECHNOLOGY & INNOVATION PLATFORM ON WIND ENERGY

About ETIPWind

ETIPWind, the European Technology and Innovation Platform on Wind energy, connects Europe's wind energy community. Key stakeholders involved in the plateform include the wind energy industry, political stakeholders and research institutions.

The ETIPWind was established in 2016 to inform Research & Innovation policy at European and national level. ETIPWind provides a public platform to wind energy stakeholders to identify common Research & Innovation priorities and to foster breakthrough innovations in the sector.

Its recommendations highlight the pivotal role of wind energy in the clean energy transition. They inform policymakers on how to maintain Europe's global leadership in wind energy technology so that wind delivers on the EU's climate and energy objectives. As such, the platform is key in supporting the implementation of the SET Plan (Strategic Energy and Technology Plan).

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Foreword

Wind energy is the crown jewel of European ingenuity to use our natural resources in harmony with the environment. The way we have harnessed the power of wind has transformed our continent for centuries. Today, wind is transforming our energy system by producing clean electricity. And in the future, it has the potential to shape our society more profoundly as we electrify further our economy.

Europe is still today the technology leader in research, technology development and seamless operation of wind energy in highly integrated and complex power systems. Research and innovation are key to strengthen the EU wind energy competitiveness and resilience. Designing together a successful research and innovation pathway is essential to ensure that EU citizens have access to affordable energy with benefits for the society and low environmental impacts.

Therefore, I welcome the timely contribution made by ETIPWind in updating the innovation priorities that will sustain our leadership in research and industrial development in wind energy. As we approach the final stages of Horizon Europe, the largest EU funding programme supporting research and innovation, it is crucial for policymakers to plan, coordinate and target public investments towards those areas that will best meet our policy objectives.

Without a doubt the EU will continue to support wind energy to be made in Europe and driving the transition towards a carbon neutral economy. As we head to reaffirm our international commitments at the next COP28, I also invite us all to keep our promise that European wind energy will deliver benefits for the rest of world too. The recently published European Wind Power Package and the revamped Strategic Energy Technology Plan are sealing the long- standing commitment of the EU in setting policies that make the fight against climate change our economic model for growth, with an inclusive and strategically autonomous approach.

I count on industry, research, and the academic community to work together with policymakers and stakeholders to realise the vision that European-made wind energy will be the leading solution to deliver a resilient, affordable, and sustainable energy transition.

Designing together a successful research and innovation pathway is essential to ensure that EU citizens have access to affordable energy with benefits for the society and low environmental impacts.

Rosalinde van der Vlies

Director - Clean Planet, Directorate-General for Research & Innovation, European Commission

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Executive summary

Wind energy is at a crossroads in Europe. It faces major hurdles as it looks to **scale up, expand** its manufacturing capacity in Europe and cover the **workforce** it needs not just to deliver a significant volume of projects, but also the expectations **on sustainability** and **coexistence** from society at large.

Research & Innovation (R&I) can help to address many of these challenges. But to be effective, it needs to better prioritise its efforts and increase its funding. Without a concerted effort of private and public funding, industry won't be able to overcome its existing problems on time to meet Europe's climate and energy targets. The EU Wind Power Action Plan and the revised Strategic Energy Technology (SET) Plan are unique opportunities to boost and simplify access to wind energy R&I funding in Europe. The time to act on this couldn't come sooner.

This Strategic Research and Innovation Agenda (SRIA) updates R&I priorities, both technological and in social sciences, **for wind energy to become the leading driver of a resilient, affordable and sustainable energy transition in Europe**.

It builds on the expertise of more than 190 professionals active in industry, research, academia and civil society, coordinated under the European Technology and Innovation Platform on Wind Energy (ETIPWind). It also went through further consultation with other ETIPs and relevant stakeholder organisations.

The **23 R&I priorities** defined in this SRIA focus on the research gaps that need to be urgently addressed between 2025 to 2027. They are the short-term must-haves that we need to see from the European wind industry, research and academia to deliver the resilient, sustainable and competitive wind energy supply-chain that Europe requires.

The R&I priorities are broken into 5 interdependent areas. This means that they must all be addressed in parallel to have the desired impact on the wind energy sector. They need to be approached as part of a **programme**, as opposed to a range of options.

To address those gaps, there are four strategies the wind industry and research must carry out. The 23 R&I priorities defined in this SRIA could therefore impact more than one strategy:

Speed-up: Actions needed to sustain and fast-track the immediate future growth of wind in Europe

Scale-up: Actions needed to maintain competitiveness and deliver the volumes we need.

Expand: Actions needed to make wind viable in more places.

Enhance: Actions needed to continue improving its impact in society and the environment.

ETIPWind experts have estimated that the total public investment needed to effectively address these priorities would amount to **€1.8bn altogether for the 2025-2027 period**.


WIND ENERGY SYSTEM INTEGRATION
Definition and modelling of future system needs
Advanced grid capabilities for wind power generated units
Solutions to effectively manage curtailment
System integration of co-location, offshore hybrids, etc.
Definition and modelling of future system needs
Advanced grid capabilities for wind power
Direct Current (DC) grid solutions
Interoperability
Solutions to effectively manage curtailment
System integration of co-located renewables, offshore hybrids and wind power-to-x
Advanced grid capabilities for wind power generated units
Interoperability
€ 400 million
SUSTAINABILITY & CIRCULARITY
Biodiversity solutions
Development of material substitution
Development and demonstration of recycling methods
Lifetime extension
New decommissioning tools and methods
Biodiversity solutions
Development and demonstration of recycling methods
Biodiversity solutions
Development of material substitution
Biodiversity solutions
€ 550 million
SKILLS & COEXISTENCE
World-class education for wind energy
Skilling, re-skilling and upskilling activities
Public engagement of citizens and coexistence
Public engagement of citizens and coexistence
World-class education for wind energy
Skilling, re-skilling and upskilling activities
Skilling, re-skilling and upskilling activities
€ 121 million
OPTIMISATION AND FURTHER DIGITALISATION OF OPERATIONS & MAINTENANCE
Replacement and transport of major components
Digitalisation of maintenance and optimisation tools for operational efficiency
Autonomous Operations & Maintenance
Replacement and transport of major components
Autonomous Operations & Maintenance
Replacement and transport of major components
Digitalisation of maintenance and optimisation tools for operational efficiency
Enable digital ecosystems
€ 355 million
INDUSTRIALISATION, SCALE-UP AND COMPETITIVENESS
Design for reliable and lasting products
Improve construction and installation methods
Improve construction and installation methods
Innovative economics to scale up wind
Improve construction and installation methods
Mass production supported by automation
Design for large volume manufacturing
Design for reliable and lasting products
Mass production supported by automation
Design for large volume manufacturing
Innovative economics to scale up wind
€ 447 million
ENHANCE
EXPAND
SCALE-UP
SPEED-UP
SPEED-UP
SCALE-UP
EXPAND
ENHANCE
Wind energy
the leading solution to deliver the resilient, affordable and sustainable energy transition in Europe.
ETIP Wind
EUROPEAN TECHNOLOGY & INNOVATION PLATFORM ON WIND ENERGY

1 Wind energy today and the research and innovation challenges it faces in Europe

Wind energy is at a crossroads in Europe. It needs to expand rapidly in the face of a unique set of challenges that threaten its immediate viability. The mounting impacts of a global pandemic, a bumpy economic recovery, the energy crunch triggered by the invasion of Ukraine, and persistently high inflation in raw materials and transport prices, have all turned the otherwise bright future for wind in Europe into a precarious financial endeavour.

Structural issues have underpinned the economic challenges experienced by the wind industry today. This includes the slow project permitting regime, the patchy approach to auction design, and the lack of power grid infrastructure. Compounding this is the fact that public financial support has dwindled in recent years without any effort to tackle the underlying causes. As a result, the industry's ability to recover has run into a number of bottlenecks.

First, the supply chain is too small to deliver the huge volume of projects planned for Europe. The scale-up needed to deliver is challenging on its own, even if the political, economic and financial environment was favourable, which is not the case today. Second, while the supply chain needs to expand domestically to boost European resilience, security, and technology leadership, our auctions are not doing enough to incentivise this. Price-only auctions overlook the fact that sustaining a healthy manufacturing base in Europe is crucial to reaping the benefits that R&I and industrial investments, public and private, will bring. Third, the power system cannot cope with the surge in electricity from wind, and so curtailments are becoming more common, with financial consequences for developers and TSOs - not to mention holding up the move to decarbonise.

Aside from all this, the industry has to grapple with the expectation that wind farms should not just mitigate impacts of its operations, but that it also needs to improve the environment and communities. It needs to see decisive progress to make turbines completely recyclable, and greater cybersecurity in its digital tools as it optimises project lifecycles. And finally, it still has to address shortage of labour and skills need to tackle all these challenges.

Research & Innovation (R&I) can help Europe here. But to be effective, it needs to better prioritise delete efforts and increase its funding. Without a concerted effort in private and public funding, the industry cannot overcome these hurdles on time to meet Europe's climate and energy targets.

This Strategic Research and Innovation Agenda (SRIA) updates the R&I priorities that are needed to solve the most pressing challenges for wind energy in Europe. It also lays the groundwork for anticipating challenges in the years ahead. This Agenda builds on the expertise of more than 190 professionals active in industry, research, academia and civil society. The SRIA goes beyond technology, setting out R&I priorities for the social sciences and humanities too. These disciplines are just as essential to guaranteeing wind energy's license to operate and expand further, in harmonious coexistence with society.

1.1 Deploying wind power at scale

Europe needs to build at least 30 GW per year of wind power capacity to meet its decarbonisation and renewable energy targets by 2030. By then, wind energy should meet 34% of the EU's electricity demand, or double the figure of 17% today. While 2030 is just around the corner in the R&I timeframe, Europe must use all resources at its disposal to meet the significant volumes expected over the coming seven years as bottlenecks start appearing in the wind supply chain.

Directing significant R&I to deliver short-to-medium term objectives is a structural change needed to speed up and scale up to meet the ambitious volume of wind projects envisaged Europe. R&I has proved its historical worth in delivering a competitive, reliable, and scalable technology. It must now help to accelerate the growth of the industry. It must start by helping to design high-quality and reliable components and equipment in large volumes, manufactured with mass production in mind.

In the long-term R&I must help to sustain the growth of wind to reach a target of 1,000+ GW of capacity in Europe alone. We will need radical solutions to help install, operate and maintain wind farms in a new range of locations, in a safe and efficient manner. And we'll need to see this within the next decade to prepare for a massive deployment in the years ahead.

1.2 Manufacturing in Europe

The wind industry holds a unique position in Europe's industrial environment. It is a high-tech green and heavy manufacturing industry. Nearly all wind farms we have built until now use turbines which were made in Europe. But Europe's existing wind manufacturing and infrastructure capacity won't be able to meet the continent's ambitions going forward. There are 250+ factories in Europe making turbines and components but the supply chain is already facing a number of bottlenecks. The industry has had to purchase power cables, gearboxes and even steel towers from China. A few new local factories are being built, notable for cables, foundations and towers, but not nearly enough for the scale-up of wind to be genuinely 'made in Europe'.

1.3 Wind power in the energy system

In the process of scaling up, R&I should push for wind to transform not just the European power system but the entire energy system as well. This means prioritising solutions for better planning, operating and integrating wind energy with other generation technologies and storage. We should see a greater push for digital solutions to make wind power and the energy system safer, more reliable and more efficient. R&I should enable wind to provide the bulk of renewable power to everything that can be directly electrified, from road transport to heat pumps and industrial processes using low and medium grade heat.

Wind energy could become the leading source of power generation in Europe as soon as 2027, and could account for half of the EU's electricity demand by 2050. At this level of penetration, wind should be able to provide all the grid services that conventional thermal generators deliver today. The reliability and security of the power system depends on how soon new methods for modelling and operating with large amounts of wind become available, and how quickly they are rolled out. And demonstrating new grid technologies that would allow more efficient management of wind energy assets and the grid as a whole.

In the long-term R&I should prepare the system to expand wind power's reach to uses where direct electrification is not viable – particularly in the timeframe needed for Europe to achieve net-zero emissions. Europe should move from consuming fuels to producing electricity. From there, we would use this electricity to produce fuel via an abundant supply of renewable electricity – powering electrolysers to produce renewable hydrogen. By 2050 this indirect electrification could meet 18% of Europe's final energy demand.

1.4 The sustainability of wind energy

While wind energy is a sustainable solution which cuts down on CO2 emissions, uses negligible amounts of water and is 85-90% recyclable, deploying wind energy at the scale and pace we need will involve a number of unknown risks to environmental sustainability and resource supply.

The use of raw materials will become a pressing challenge in the near future. On the one hand access to rare earth materials for permanent magnets, used in direct drive generators of wind turbines, could become a major bottleneck for the expansion and competitiveness of industry. Substituting and recycling these materials therefore has to be looked into. On the other hand, the industry has committed to stop landfilling wind rotor blades by 2025. This puts urgent pressure on the sector to deliver new solutions for handling and recycling composite material waste at scale for both decommissioned blades and manufacturing waste of new blades.

Scaling up recycling technologies and building supply chains that use more recycled materials is critical to Europe's technology leadership and to alleviating our dependency on critical raw materials. At the same time, National Governments should harmonise their implementation of EU regulations on waste treatment to help develop a pan-European market for recycled materials. They should also bring in new incentives to use circular materials.

Meanwhile there are still a number of knowledge gaps about the impact of wind projects on biodiversity. Scientists and authorities need better methods and models to carry out environmental impact assessments, notably to monitor any impact on fauna (birds, bats, and marine ecosystems) and to ensure wind is built in harmony with nature. Secondly, the cumulative environmental impacts, positive and negative, of larger, denser wind farms on land and sea are still largely unknown. This also applies to the effects of densely built wind farms on wind, soil and the sea.

Finally as wind farms get older and approach the end of their operational lifetime, extending the durability of components will be more sought after as a way to boost profitability, avoid environmental impacts and to set the stage for repowering or decommissioning.

1.5 Workforce and skills

Wind energy employs 300,000 people in Europe. The buildout of wind would mean boosting that figure to 515,000 people by 2030. Attracting, educating, and training workers is vital to sustain Europe's place as a hub for talent in wind energy.

There is already a shortage of skilled labour for operating and maintaining (O&M) wind farms. This is because the work is specialised and requires training and experience. As the components get larger, operations also require more staff. The shortage of skilled labour is a major challenge for the industry, and is expected to worsen in the coming years.

Industry and academia must prepare future skills that reflect economies of scale, automation, and the digitalisation of a large, mature and high-tech industry. R&I should facilitate this while ensuring that environmental and social sciences and humanities are properly accounted for in curricula and skills needed for wind energy to enhance the places where it will operate. R&I should also support policymakers and academia in identifying, designing and standardising education programmes adapted for a future workforce – one that is more diverse in age, gender and professional backgrounds. There should be a special focus on expediting training, certification and reskilling workers from other industries looking to work in wind.

Lastly R&I should do its best to help wind coexist with nature and society. New methods, tools and models to enhance collaboration with stakeholders should be developed and demonstrated at scale. Once ready, these can be prepared for widespread deployment in harmony with nature and communities.

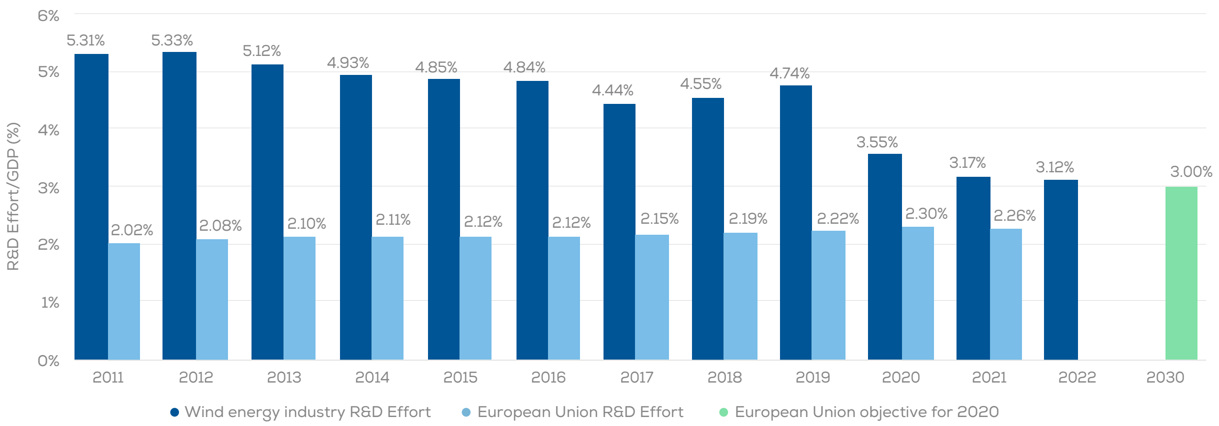
1.6 R&I investments in wind energy

Investments in R&I for wind have fallen from a historical average of 5% of the industry's contribution to EU GDP to 3.2% in the last three years (Figure 1). 2022 was the lowest year on record for R&I investments since 2011.

As with any mature industry, maintaining technology leadership and competitiveness depends on sustaining innovation to adapt to the changing circumstances of growth. Doing more of the same, faster and in new places calls for investment in innovation too. The scale, speed, expansion and new demands from society show that industry and academia must move past the tried and tested ways of developing wind technology and projects. And the expectation that wind energy should enhance the environment and communities puts pressure on the wind sector to develop more accurate indicators which measure societal costs between energy technologies.

Finally, investment in R&I will enhance the skills that researchers and industry need to solve current and future challenges.

Thus private and public investment in wind energy R&I will still be crucial going forward, not just to safeguard Europe's leadership in wind, but to guarantee the industry's survival domestically.



Source: Deloitte for ETIPWind

Figure 1. R&D efforts of wind energy industry and EU.

In particular, we need to see an urgent boost in the EU's funding for R&I. EU funding acts as a catalyst for other investments. But according to the EU Joint Research Centre, EU funding for wind energy is just now recovering from the lowest point of the last 5 years which amounted less than €30 million. In 2022 wind energy received almost €70 million (Figure 2).

The fact that the European Commission uses an open, 'challenge-based approach' for R&I funding means fewer calls for projects explicitly mentioning the wind energy sector as a potential beneficiary. These untargeted funds make it difficult to measure the real investments in wind energy innovation as they target the wider energy transition.

The same goes for R&I funding in EU Member States. However, the recently launched SET Plan Implementation Working Group (IWG) on wind energy has set a **target of earmarking 3% of the national budget to wind energy**. This is encouraging and the EU should follow suit and establish a target in line with private sector investment in R&I. A useful first step would be to increase funding for wind energy under the newly established Clean Energy Transition Partnership (CETP), launched in May 2022. This funding programme helps 70 national and regional research programme owners and managers from 32 countries to better align their priorities and implement annual joint calls from 2022-2027. CETP has a budget of €278 million or an average of €46 million/year for all clean technologies.

The upcoming financing cycles of the EU's Horizon Europe Programme should target R&I for wind more explicitly under its Pillar "Global challenges & European industrial competitiveness" inside the Cluster 5 "Climate, energy and mobility". This SRIA has identified €1.8 billion needed for R&I investment between 2025 and 2027 alone.

The European Commission should also aggregate other EU funding programmes where funding for wind is even more diluted.

We estimate that across all other EU funding programmes, wind energy receives just 1-2% of the funds available. This includes the Innovation Fund (€40bn over 10 years), ERASMUS+ (€26.2bn over 7 years), LIFE (€5.4bn), CEF (€33.7bn), EMFAF (€6.1bn).

To better address the challenges facing the wind energy sector today, the EU needs to simplify its funding programmes for clean energy technologies. This will mean faster and more efficient access to EU funding for strategic European industries. The Innovation Fund and the upcoming Strategic Technologies for Europe Platform (STEP) Fund should better target wind energy supply chain innovation and expansion.

In the medium term, public-private initiatives should be looked into. In 2021 for example, the European Commission launched the 'Green Deal Call' with a budget of €1 billion and established Joint Undertakings (JUs) as part of Horizon Europe. The EU chips into to these co-funded initiatives with €9.9 billion. The largest JUs are for clean aviation (€1.7bn), clean hydrogen (€1bn) and key digital technologies (€1.8bn).

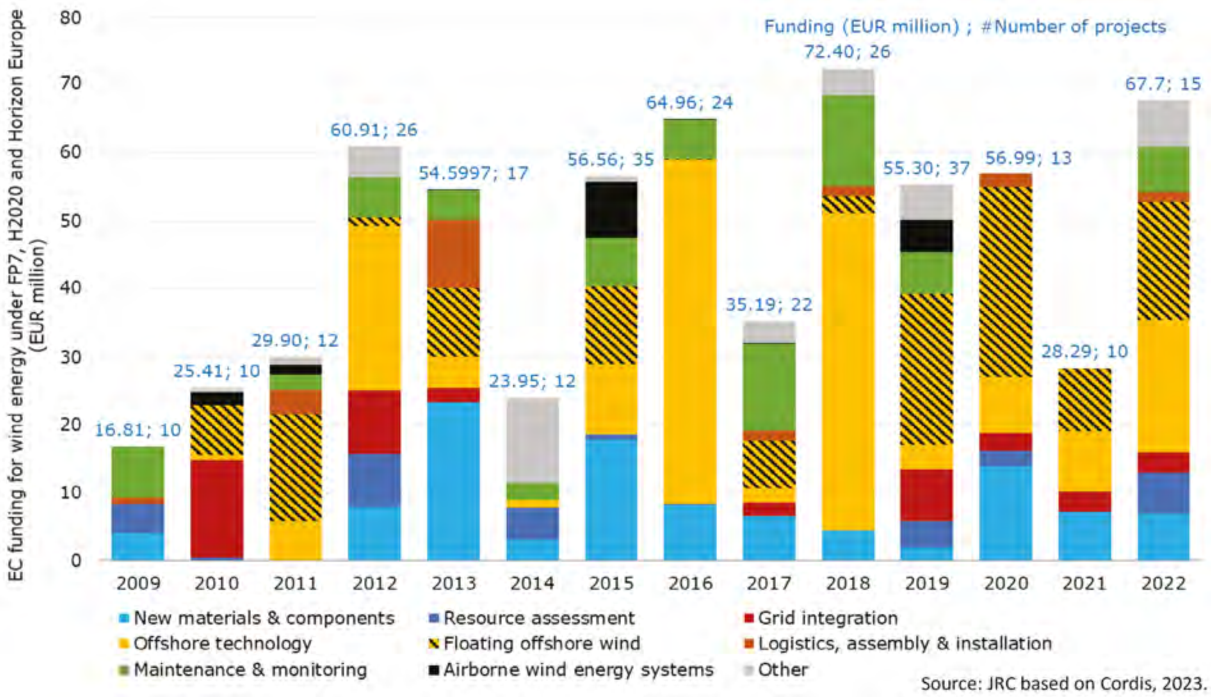


Figure 2. Public budget for wind energy R&I from 2009 to 2022.

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ETIPWind's vision for wind energy

Wind energy will be the leading solution to deliver the resilient, affordable and sustainable energy transition in Europe.

In the next 5-10 years the European wind industry, together with research, academia, government and society, will make wind energy the most competitive power supply source in the European economy – facilitating its decarbonisation by 2030.

To achieve this there are four strategies the wind industry must carry out:

Speed-up: Actions needed to sustain and fast-track the immediate future growth of wind in Europe

Scale-up: Actions needed to maintain competitiveness and deliver the volumes we need.

Expand: Actions needed to make wind viable in more places.

Enhance: Actions needed to continue improving its impact in society and the environment.

This vision, enabled by these four strategies, will involve a new departure from the previous policies enacted to support renewables in Europe.

A "technology-neutral" approach, ensuring the best value for money as different solutions compete to secure funding, will not help us to meet our targets on time. Europe must make critical choices to sustain the technology leadership it has built in wind energy over many decades.

Likewise, policies for the energy transition should acknowledge the needs of mature technologies with emerging industrialisation challenges. Wind energy is a proven, scalable and reliable source of power that faces the challenge of trying to significantly expand while going through financial hardship, facing the worst inflationary period seen for decades, with a tight job market, shrinking access to raw materials and expectations of improving communities and the environment in places where industry operates.

And so this SRIA goes beyond recommending cross-border, cross-sectoral collaboration fostered by public funding. It now looks to larger EU-wide needs that will deliver the industry's vision in the short to medium term, laying down the groundwork for the long-term goal of making wind the backbone of Europe's energy system and a significant driver of growth at home and abroad.

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3 Methodology

3

To update its SRIA the ETIPWind's Steering Committee first carried out a gap analysis[1] comparing the R&I priorities identified by ETIPWind's technology roadmap 2020-2027[2] against the topics addressed up to now by the Horizon Europe funding programme[3]. The outcome from this gap analysis showed that 3 R&I topics were fully addressed under Horizon Europe, 36 topics were only partially addressed, and 10 topics were not addressed at all. A key conclusion was that Horizon Europe calls for proposals are too broad and aim to cover too many R&I aspects with a very limited budget.

ETIPWind then launched a major consultation process to gather input from the European wind energy community. An online survey on the next R&I priorities was published and received 71 answers. This was followed by a public workshop, hosted by the European Commission's Directorate General on Research & Innovation, with 80 participants attending. Based on this preliminary input, ETIPWind set up 5 new Working Groups to identify short-term R&I Priorities for the sector. Four meetings per Working Group were held, a draft list of R&I priorities was put together, and a validation meeting was organised at the EERA JP Wind's Innovation Forum.

The draft list of R&I priorities was also shown to a number of WindEurope Working Groups and specific EU-funded projects (e.g. InterOPERA). Bilateral meetings with other ETIPs (e.g. ETIP SNET) were then held to look at the potential of synergies on certain R&I topics. The list of R&I priorities was finally endorsed by the national representatives from the IWG Wind (SET Plan Implementation Working Group on Wind energy) during their first joint meeting with ETIPWind.

ETIPWind's SRIA for 2025-2027 was drawn up in close collaboration with the EERA's Joint Programme on wind energy. Experts from the EERA's JP Wind were directly involved in defining the short-term priorities as part of ETIPWind's Working Groups. For each short-term priority, the EERA experts also set out research needs by 2050 , putting the wind energy sector on track to be sustainable and competitive in the long-term. These longer-term research needs are summarised in this document and will be elaborated on in the EERA JP Wind's long-term research programme[4].

1 ETIPWind Gap analysis, published in 2023.
2 ETIPWind Technology roadmap, published in 2020.
3 The analysis focused on the Horizon Europe Cluster 5's programme, including projects funded in 2021-2022 and calls for proposals launched in 2023-2024.
4 In the framework of the NeWindEERA project, the EERA JP Wind's long-term research programme will be finalised and published early 2024.

4

ETIPWind R&I agenda for 2025-2027

The 23 R&I priorities set out in this SRIA focus on the research gaps that need to be urgently addressed between 2025 to 2027. They are short-term essentials for the European wind industry, research and academia to deliver the resilient, sustainable and competitive wind energy supply-chain that Europe needs.

The R&I priorities are broken into five interdependent R&I areas. This means that the priorities must all be addressed simultaneously to have the desired impact on the wind energy sector. Experts argued strongly for these priorities to be looked at as a programme, as opposed to a menu of options.

ETIPWind experts also estimated the total public investment needed to progress each priority in technical readiness level (TRL) effectively. The total public investment includes all the different EU Funding programmes that could cover wind energy R&I (beyond Horizon Europe) as well as funding from national research and innovation programmes. And so it represents all public financial support that is needed to fast-track a technology or to develop a solution, as well as investment from the industry.

All priorities in this document will involve longer-term research too, beyond 2027. This is essential to bring the technologies and solutions up to the next level of maturity before being fully commercialised and deployed. The SRIA recognises that the technologies and solutions developed between 2025 and 2027 will inevitably benefit from further optimisation, and that the industry should be prepared for new groundbreaking technologies and solutions to emerge. The longer-term research needs have been defined by EERA JP Wind under the framework of the NeWindEERA project. EERA JP Wind's long-term research programme will complement this SRIA, laying out the scope and R&I long-term actions. It will be published early in 2024.

4.1 Industrialisation, scale-up and competitiveness

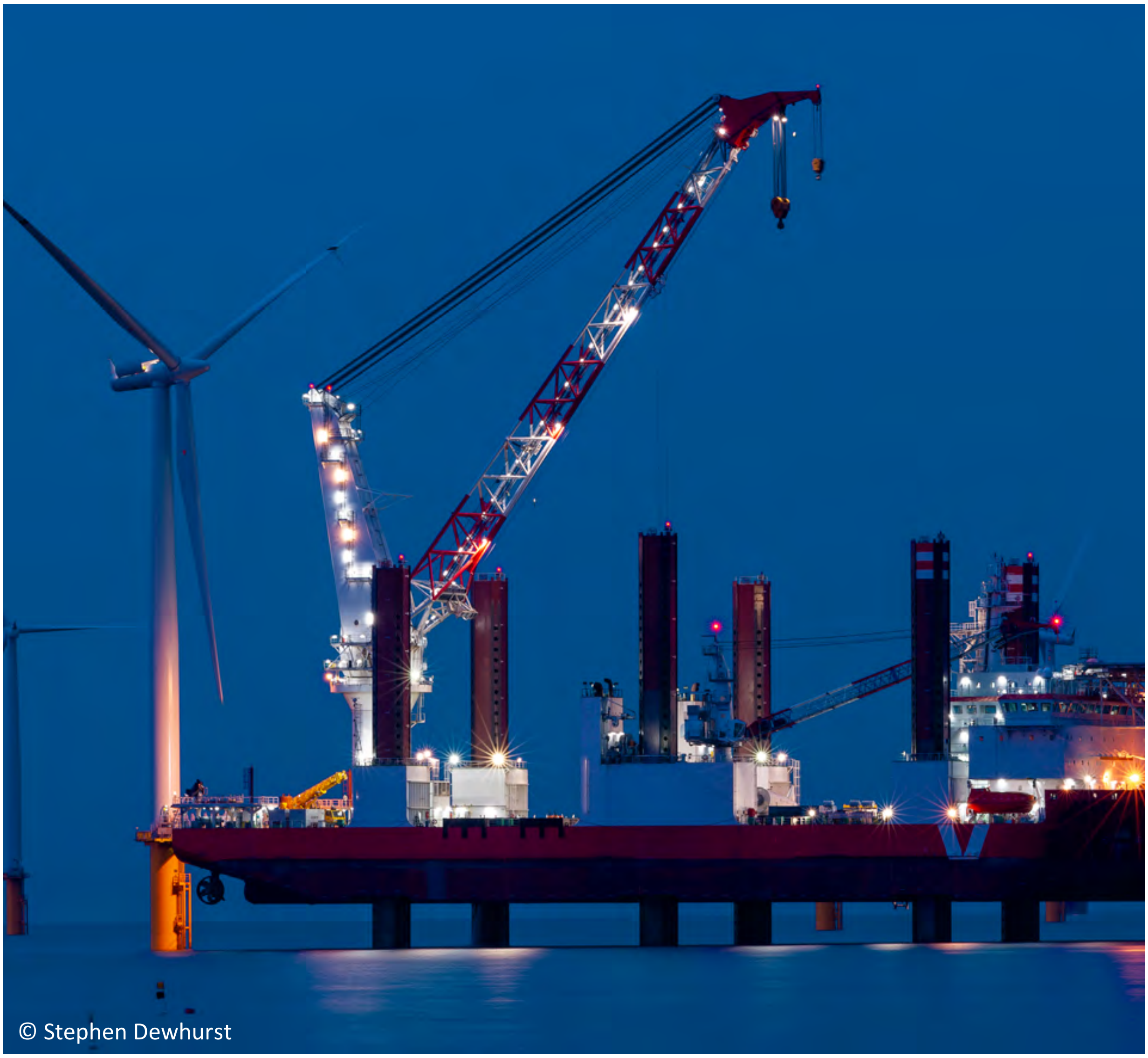
R&I can play a major role in filling the manufacturing and supply chain gaps needed for wind to scale up.

In the first place, R&I is needed at the product level to deliver new cost-competitive, quality, and reliable technologies, design tools and efficient validation of products. This includes potential new cost competitive, sustainable and reliable materials, as well as alternatives to scarce materials which help to reduce the supply chain's dependence on non-EU countries.

Second, R&I should enable mass production of wind turbine components and turbines. Gigafactories of high volume and serial production will call for a high degree of automation which R&I should contribute to developing and demonstrating for very large components. R&I is also needed to develop technologies which help operators to perform manufacturing activities and quality control.

Furthermore, new construction methods as well as innovative transport and port infrastructure adaptations will be needed to handle big components in large volumes. This has historically been a neglected area for European R&I funding. R&I should facilitate the design, assessment and optimisation of these methods and infrastructure build out, not least as society expects that the environmental and community impacts of wind farms construction are avoided or mitigated.

Finally, R&I should provide innovative economics to make the industrialisation and scale up of wind financially sound and with risk-reward ratios that allow expansion on this scale to go ahead. This is crucial to helping keep a significant portion of the wind energy supply chain domestically-based, safeguarding economic activity, sustainability and employment in the EU.



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MASS PRODUCTION SUPPORTED BY AUTOMATION AND RELIABLE SUPPLY CHAIN

IMPACT	
Speed-up	●
Scale-up	●
Expand	○
Enhance	○

4

The development of automated or semi-automated fabrication solutions with a 'lean manufacturing' approach is crucial to scaling-upin the context of a tight European job market. Such solutions should cover blades and other large components, welding for foundations, quality assurance techniques (like non-destructive testing), development of robots/cobots for a wide range of applications, as well as other operator assistance tools and large-scale additive manufacturing. R&I should also help to evaluate and implement optimised and fit-for-purpose supply-chain philosophies ("just-in-time" or "just-in-case") that complement these technological developments.

Scope of actions	
Robots/cobots developments for automated/assisted and controlled manufacturing operations.	TRL 5 to 7
Use of virtual reality, machine learning and augmented or artificial intelligence for large component manufacturing (blades, foundations, castings, towers, etc.).	TRL 4 to 6
Qualification of new automated welding and non-destructive testing processes for wind industry applications.	TRL 5 to 7
Development of digital tools to provide adequate quality control and process control of new automated process introduced.	TRL 3 to 7
Development and qualification of innovative assembly or fabrication methods and tools (additive manufacturing, new connection systems…)	TRL 3 to 7
Innovative supply-chain and production line methodologies for offshore wind components and foundations fabrication.	TRL 4 to 7

Estimated public investment needs from 2025 to 2027	
Number and types of projects	• 3 small scale prototypes • 3 medium scale demonstration projects • 3 large scale demonstration projects
Total public investment	€ 165 million

Longer-term research topics:

R&I should continue to provide solutions for scaling up manufacturing processes and strengthening supply chain resilience. In particular, it should fast-track the roll-out of digitalisation across these areas. In future more R&I will be needed on standardising and modularisation of large components, as well as advanced materials.

The industrialisation of floating substructures for offshore wind will continue to be a key focus area for research. R&I will be needed to further develop, validate and implement standard simulation models for these components, sustainably and economically. New modelling and simulation tools should better represent mooring, grid infrastructure interactions with the floater dynamics as well as with the wind turbine controller and its loads. And new modelling for transport and installation will be needed too.

DESIGN FOR LARGE VOLUME MANUFACTURING / DEPLOYMENT

IMPACT	
Speed-up	●
Scale-up	●
Expand	○
Enhance	○

Manufacturing of wind turbine components still requires a large amount of manual labour, especially for components such as blades, drivetrains, castings and offshore foundations. The potential of automating manufacturing processes has not been fully exploited at this stage. But it will be vital as we seek to develop and implement cost-effective automated processes, with innovative design methods that focus on manufacturability. R&I should accelerate modularisation, local assembly and in situ repair solutions to speed up the deployment of wind energy while cutting down on operating costs. It should also focus on innovate materials that enable large scale manufacturing.

Enabling more effective designs for wind turbine manufacturing and balance of plant will mean testing methods, updated design tools and demonstration projects, with focus on low CAPEX automation methods. Key components such as blades and offshore foundations have great potential for further industrialisation, but this potential should be developed across the entire supply chain.

4

Scope of actions	
Innovative design, testing and certification methods for modular blades, offshore foundations, drive trains and drive train components.	TRL 6 to 8
Innovative design concepts and materials for modularisation of wind turbines, testing and certification.	TRL 3 to 5
Demonstration of modularising wind turbine technology (manufacturing and assembly).	TRL 5 to 7

Estimated public investment needs from 2025 to 2027	
Number and types of projects	• 3 small scale prototypes • 3 large scale demonstration projects
Total public investment	€ 90 million

DESIGN FOR RELIABLE AND LASTING PRODUCTS

IMPACT	
Speed-up	○
Scale-up	●
Expand	○
Enhance	●

4

Improved reliability in wind farm designs and production should be a key focus area for future R&I. Strengthening reliability in wind turbine design allows material consumption to be optimised, cuts down on investment costs and saves valuable resources. At the same time, it allows estimating more accurately the operational cost and downtimes than we can at present (see priorities in "Optimisation and further digitalisation of O&M").

Up to now the wind industry has not fully implemented methods for analysing/predicting reliability – such as DFR (design for reliability) and probabilistic design - of components and assemblies under development, especially when new technologies or materials are involved. Furthermore, statistical validation tests for product samples – common in other industries – are almost impossible due to the size of components and assemblies and unpredictable load cycles. Thus, other innovative methods badly need to be developed to show reliability of wind turbine components during their development phase. Alternatively, new methods for condition/health monitoring need to be developed for critical components and assemblies where reliability cannot be fully demonstrated during design. With that in mind, these components and assemblies need to be carefully tracked during operation to ensure the wind turbine's structural integrity or operational safety.

Scope of actions	
Development and validation of reliability prediction tools for large components.	TRL 3 to 7
Investigating possible standardisation of wind-related load cycles while also accounting for ambient operating conditions (I.e. climate, pollution, air density, humidity, etc.) to simplify reliability testing.	TRL 1 to 6
Development of realistic validated test methods based on knowledge and data using combinations of analytical techniques/coupon tests and statistics to reduce large-scale tests.	TRL 3 to 7
Development of innovative health monitoring systems for structural and functional relevant components with undemonstrated reliability.	TRL 3 to 7
Development of components to cope with growing wind turbines sizes (e.g. bearings, etc).	TRL 7 to 9
Adaptation of design quality methodologies from other sectors to wind energy.	TRL 5 to 8

Estimated public investment needs from 2025 to 2027	
Number and types of projects	• 3 small scale prototypes • 2 medium scale demonstrations projects • 2 large-scale demonstration projects
Total public investment	€ 51 million (for all R&I actions)

Longer-term research topics:

R&I should continue to work on standardised methods for scaled, decentralised and virtual testing for new designs to allow for cost efficient validation. It should also support the emergence of probabilistic design to speed the optimisation of materials use. It should use full-scale model validation based on measurements to reduce modelling uncertainties in design, together with new probabilistic analyses to detect failure mechanisms based on physics and field data.

R&I should enable the holistic design of wind turbines. Advances on specific components can bring about system-wide improvements or other more effective configurations. We will need to integrate validated design and analysis tools into multi-fidelity multi-physics design procedures and demonstrate them on state-of-the-art reference designs.

IMPROVE CONSTRUCTION AND INSTALLATION METHODS INCLUDING PORTS INFRASTRUCTURE

IMPACT	
Speed-up	○
Scale-up	●
Expand	●
Enhance	●

The upscaling and acceleration of on- and offshore wind calls for new logistical and installation solutions to boost efficiency while ensuring safety and reducing environmental impact. R&I should help to improve assembly and loading processes in ports to maximise limited quay space. It should also develop and demonstrate innovative installation and low noise piling methods for offshore substructures, effective underwater noise mitigation technology and robotics and motion control for working at heights in rough sea conditions. All these will also be beneficial in O&M to efficiently replace large components.

For floating offshore wind innovative installation methods for floaters, large substations and cable systems are needed.

For onshore wind it is required improvements to better cope with transportation restrictions on land (road & rail), as larger turbine components need to be moved around. This is even more pressing when site logistics are taken into account. Paved roads, hard stands for big crawler cranes and logistics areas all occupy a significant amount of land. Also innovative methods to limit the space needed for civil works (i.e. costs) and to avoid or mitigate any environmental impact should be investigated. This is especially true for mountainous terrain where excavations and removal of trees are needed to create the necessary logistical areas.

Scope of actions	
Cost-efficient installation methods that reduce environmental impact; demonstration projects for low noise foundation installation methods and underwater noise mitigation.	TRL 4 to 8
Optimisation of logistics (inc. Transport) making use of robotics to enable faster and safer lifting operations through improved motion control when working at heights under difficult environmental conditions.	TRL 4 to 8
Optimisation of wind turbine design for easier transport and installation, including concepts for separable rotors, frames, nacelles, housing.	TRL 5 to 8
Optimisation of port logistics enabling faster load-out, efficient use of port space, design of waterways specifically for very wide offshore wind component transport.	TRL 3 to 8
Innovative methods to enable inland transport and installation methods with reduced environmental impact.	TRL5 to 8

Estimated public investment needs from 2025 to 2027	
Number and types of projects	• 3 small-scale prototypes to investigate new concepts • 3 demonstration projects
Total public investment	€ 135 million

Longer-term research topics:

R&I should continue work on developing new installation methods and logistical solutions for very large components as projects continue to scale-up significantly in the future.

RESEARCH ON INNOVATIVE ECONOMICS TO SCALE UP WIND

IMPACT	
Speed-up	●
Scale-up	○
Expand	●
Enhance	○

Industrialising wind power means big investments in wind power assets, as well as in the industrial ecosystem needed to deliver them. This is only achievable if wind farms and power grids can be efficiently and heavily financed as critical infrastructure, such as roads or railways. But patchy legal and social frameworks, which in some cases distort competition, have hampered the availability of this effective financing.

Pure market mechanisms, driven by demand, cannot deliver efficient funding for this essential infrastructure because of their volatility. This is clearly highlighted by the recent slowdown in renewable power investment. The USA has responded with Inflation Reduction Act, a far-reaching financial instruments to fast-track its energy transition, while Europe has been toying with policies that try to imitate this.

R&I should also focus on the legal, financial, and economic sciences needed to develop market-related, financial, and regulatory instruments. These in turn would be used to deliver fast, cost-effective, and lean funding of wind power assets – and the industrial infrastructure and innovation associated with it.

4

Scope of actions
Development of market-related, financial and regulatory solutions to support the deployment of wind energy in Europe.
Innovative financing instruments to de-risk wind energy technologies (e.g. risk assessment tools, etc.)
Development of financial mechanisms to support and accelerate the industrialisation (e.g. of recycling plants).

Estimated public investment needs from 2025 to 2027	
Number and types of projects	• 2 desk-research projects to investigate new solutions • 2 development projects for the tools
Total public investment	€ 6 million

Longer-term research topics:

R&I will be needed to put forward changes in the market design – given the rapid transition to renewables. It should help to define a general policy framework focusing on supporting a sustainable and resilient value chain and should set out new legal and financial instruments to strengthen the case for wind and other renewables in Europe.

4.2 Optimisation and further digitalisation of Operations & Maintenance

The wind industry has heavily invested in improving technologies and methods to strengthen the operations and maintenance (O&M) of its assets. But the rapid development of digital technologies calls for continued R&I to keep up , and to adapt them to the wind sector. At the same time, the growth in wind turbine components has made O&M more of a challenge. Even with the trend towards standardisation and modularisation, new technologies and methods for transport and replacement will be needed.

Further digitalisation of wind energy O&M would help to tackle future challenges. These would include maintaining a much larger fleet of aging assets thanks to better predictive techniques, assisting maintenance workers with virtual or augmented reality, or even automating these activities in inaccessible areas. Digital tools for O&M would also help to improve operations over a longer lifetime, reducing costs and maximising value for the system. And R&I should enable digital ecosystems to communicate, coordinate, and take decisions on wind farms O&M.

To make this happen, R&I should focus on data, autonomous technologies and optimisation tools.

Operators would need to connect and gather real time data from wind turbines and all their subsystems, working closely with wind turbine manufacturers. This will mean developing platforms, cybersecurity solutions, and standardising data, protocols and interoperability. Then new big data analytic techniques (for example with artificial intelligence and interconnected digital twins) could lead to optimal wind park O&M with maximum autonomy. Finally, with more data and better data analytics, effective performance management could be achieved with improved algorithms for O&M and lifetime extension.

DIGITALISATION OF MAINTENANCE AND OPTIMISATION TOOLS FOR OPERATIONAL EFFICIENCY

IMPACT	
Speed-up	●
Scale-up	○
Expand	●
Enhance	○

There is major scope for R&I to improve digital tools needed to facilitate wind farm maintenance. Digital twins, artificial intelligence- (AI) based algorithms, virtual and augmented reality, and cloud computing are seeing greater use across many industries and there is no reason why the wind industry should be left out.

R&I should also fast-track the real-time interconnection and communication of digital tools that allow for more effective control and wind farm operation thanks to better forecasting methods. As well as this, R&I should look to improve advanced AI algorithms. These would then be used to support tasks ranging from optimising real-time energy generation to life extension with little or no human intervention, allowing autonomous operation of assets. A lot of this software and these methods will require validation and certification, and R&I should help to support these processes too.

4

Scope of actions	
New solutions to train and assist service technicians in the field, for example by using augmented or virtual reality or AI to read and produce maintenance protocols.	TRL 4 to 8
New AI tools for monitoring and predictive maintenance activities. Especially for gearboxes, electronic components and generators.	TRL 5 to 8
New AI tools to read service reports and extract patterns by large language models	TRL 3 to 7
Reliability prognosis models and data for very long operations (up to 40 years) including experimental methods and/or simulative theoretical methods.	TRL 2 to 5
Advanced forecasting methods for wind resources and yield quantification to be used in windfarm control strategies.	TRL 5 to 8

Estimated public investment needs from 2025 to 2027	
Number and types of projects	• 4 demonstration projects • 4 small or large-scale prototypes
Total public investment	€ 60 million

Longer-term research topics:

R&I should continue to accelerate digitalisation and upskilling of personnel as well as developing improved digital O&M applications for the years ahead. This will call for more open-source tools, standards, licensing, data markets and benchmarking. The R&I actions in this SRIA will greatly benefit from enhanced international cooperation and consistent updates.

As well as this, new tools to support wind power operational decision-making, including comprehensive mapping of options for maintenance, operation and expansion of power plants by leveraging predictive analytics and modelling should be developed in the future.

Also, Climate Resilience and Advanced Energy Control Systems will be key areas to focus on between now and 2050. This includes climate prediction and impact analysis with in-depth understanding of extreme natural events, with continuous enhancements in forecasting the impacts of climate change. With that in mind, developing adaptive and resilient controllers with an emphasis on multi-level and multi-objective functionalities is also critical. These aspects require a specialised focus on next-generation turbines and plants.

AUTONOMOUS OPERATIONS & MAINTENANCE (TOOLS, ROBOTS, VEHICLES)

IMPACT	
Speed-up	○
Scale-up	●
Expand	●
Enhance	○

4

Wind farms building and maintaining themselves. It might sound like a thing of the future but given the expected shortage of skilled labour and the fact that humans must stop doing the three D's: dangerous, dirty and dull, we will have to start channelling our R&I efforts towards making this a reality. The first obvious goal on this journey is deploying robots to carry our maintenance activities on wind farms, both offshore as well as onshore. Airborne robots, on the structures and under-water will all be needed. R&I in this area should focus on the robots themselves, but also on the AI-based systems that control and operate them. When it comes to the wind farm as a whole, R&I in the area of autonomous operation will also be needed. Subjects like the market-aware selling of electricity, scheduling of maintenance, and overall performance monitoring of the wind farm will be areas of special focus. This R&I action will lead to a major boost in wind farm efficiency, effectiveness and reliability, both on and offshore.

Scope of actions	
Improve robotic blade service especially regarding damage reparations in deeper layers.	TRL 5 to 7
Semi-automated inspection methods before repairs with advanced detection methods (i.e. beyond cameras) to evaluate conditions below surface for blades. And methods for improved condition monitoring for gearboxes and converters, offshore foundations, and cables.	TRL 5 to 7
Advanced repair methods for offshore foundations and cables, bottom fixed and floating.	TRL 5 to 8
Autonomous vessels, Unmanned Underwater Vehicles (UUVs) and optimisation of marine operations.	TRL 3 to 7

Estimated public investment needs from 2025 to 2027	
Number and types of projects	• 3 small scale projects • 2 big demonstration projects
Total public investment	€ 110 million

Longer-term research topics:

Longer-term research needs to look at autonomous installation of the wind farms, as well as the partially covered aspects of the O&M actions covered in SRIA. With additional scope especially on the Unmanned Underwater Vehicle (UUVs) and Unmanned Aerial Vehicles (UAVs), autonomous wind installation, O&M and decommissioning (particularly for offshore) should become a reality by 2050.

R&I should develop controlled payload distribution among multiple drones. And it should enhance data and signal transmission capabilities for improved UUV Communication. It also needs to develop advanced operational Mechanisms for UAVs, including automated landing and take-off protocols and development of efficient loading and unloading as well as implementation of a digital backbone to facilitate such a large-scale data transfer.

ENABLE DIGITAL ECOSYSTEMS

IMPACT	
Speed-up	●
Scale-up	○
Expand	○
Enhance	○

Due to the multi-fidelity, multi-disciplinary, and multi-parameterised nature of O&M practices, it is not a straightforward decision to 'select' and 'connect' the right sub-models and the corresponding scales, constraints, and limitations of the potential solutions. Digitalisation and advances in applied data science and AI can facilitate a stable communication between different O&M sub-systems and relevant external processes (e.g., environmental conditions) by building the right correlation between the disciplines and their performance targets, as well as the corresponding databases, scales, sensitivities, and uncertainties.

These digital ecosystems should be built on advances in sensor technologies, industrial IoT (Internet of Things) and cloud analytics, considering the interoperability of digital tools from sensor to cloud which should include cybersecurity concerns as well as standardised and systematic data sharing and tenancy practices. They ultimately would provide support in decision-making via heuristics and data-driven optimisation strategies, providing holistic solutions for increased value across the entire lifecycle.

4

Scope of actions	
Definition and implementation of best practices for exchange of data across different sub-systems of wind farms.	TRL 2 to 5
Sensor technologies: Advancement of the existing and development of new sensor technologies particularly for diagnostics, Structural Health Monitoring / Structural Health Assessment	TRL 2 to 5
Industrial IoT, cloud analytics, interoperability of digital tools and advanced communication technologies for wind energy, including Cybersecurity	TRL 2 to 5
Optimisation and Decision-making support: Development of digital ecosystems for efficient optimisation of system level processes, particularly for O&M and lifetime optimisation	TRL 3 to 7

Estimated public investment needs from 2025 to 2027	
Number and types of projects	• 3 small to large scale prototypes • 1 demonstration project
Total public investment	€ 50 million

Longer-term research topics:

R&I should boost the holistic analysis of natural systems, aided by new sensor technologies and greater digitalisation in wind energy. It should also improve spatial planning using gathered data from the environment to develop comprehensive spatial plans that cater to both human needs and ecological preservation.

R&I should also boost operational enhancements by infusing the latest monitoring techniques to improve the efficiency and operational safety within natural environments. This includes advanced forecasting models (for wind-related environmental parameters, production, and demand) to predict changes, challenges, and opportunities in natural systems. Today's models are not sufficiently equipped to anticipate the multifaceted changes, challenges, and potential opportunities arising from evolving natural systems.

REPLACEMENT AND TRANSPORT OF MAJOR COMPONENTS

IMPACT	
Speed-up	○
Scale-up	●
Expand	●
Enhance	●

During the life of an average turbine, major components will need to be replaced at least once. Cost-effective approaches to replacing ever larger/heavier components should be available on the market to minimise the OPEX of commercial farms, as an alternative to mobilising large cranes, especially in hard-to-access areas (mountains, deep offshore). This is particularly critical for offshore floating wind turbines where these operations can have a big financial impact due to the long mobilisation of different vessels to disconnect and reconnect mooring lines and inter-array cables and to tow the foundation to port. Simplifying, speeding up and relaxing weather window limitations for these operations would have a positive impact. It would also help to avoid the tow-to-port operations and to perform the major components replacement on-site.

4

Scope of actions	
Major component replacement solutions onshore qualification & demonstration	TRL 5 to 7
Major component replacement solutions for floating wind qualification & demonstration	TRL 5 to 7
Quick connect/disconnect systems for mooring lines	TRL 4 to 7
Quick connect/disconnect systems for Inter-Array Cables	TRL 4 to 7
Develop improved large component repairs for in situ repair and/or craneless exchange	TRL 3 to 5

Estimated public investment needs from 2025 to 2027	
Number and types of projects	• 3 small to large scale prototypes • 3 big demonstration projects
Total public investment	€ 135 million

Longer-term research topics:

In the future, R&I should focus on improving transport for large components and port infrastructure. It should develop automated tools to aid industry stakeholders in streamlining the routing and permitting processes for transport. Beyond this, R&I should help to harmonise regulations across Europe to ensure standardised transport practices, taking into account different transport modes with their various regulatory constraints, which often add extra layers of decision making complexity.

Additionally, R&I should bring forward the integration of technologies for automation and digitalisation in ports. And it should study and work on solutions to incorporate new fuel alternatives, such as battery charging systems and hydrogen fuelling facilities in ports.

Finally R&I for transport and wind turbines logistics could contribute to road planning, by indicating future trends and challenges associated with the transport of very large components.

4.3 Wind energy system integration

The rapid integration of large amounts of wind power into the energy system will require a new class of technologies and solutions for system planners and operators alongside a functional market design. R&I is needed to develop this technological suite, which will make the energy system more flexible and resilient. Research actions outlined in this section overlap with some actions coming from the ETIP on smart networks for the energy transition (ETIPSNET) and should be addressed jointly (Annex 1).

First, R&I is needed to make the most out of existing grid infrastructure while modelling and demonstrating future system needs. It should also help us to find solutions to manage wind curtailment, fast track new grid technologies such as Flexible AC Transmission Systems (FACTS), and short- and long-term storage. And it should demonstrate the needs for and solutions to provide ancillary services, such as the dynamic control of active and reactive power compensation, grid islanding[5] and black start[6] and advanced grid-forming capabilities by wind power generators.

Second, R&I is needed to facilitate the harmonisation and standardisation of major hardware components, electric and data interfaces, software control and protection functions to facilitate a smooth operation of complex, multi-vendor systems. Third, large-scale demonstrations of different types of hybrid projects, virtual power plants, and sector coupling projects should be implemented across Europe by 2030. And lastly R&I should communication and work closely with plant operators, system operators (TSOs/DSOs), consumers, and different energy and grid services markets. As digital communication expands, data management, privacy and cybersecurity will be essential.

5 Islanding operation is the condition in which a generator continues to power a location even though the external electric grid power is no longer present.

6 Black start capability refers to the process of restoring an electric power station of a part of an electric grid following a total or partial shutdown without relying on the external power transmission network.

DEFINITION AND MODELLING OF FUTURE SYSTEM NEEDS

IMPACT	
Speed-up	●
Scale-up	●
Expand	○
Enhance	○

Wind power is expected to provide more flexibility services and stability support to the grid in the near future. But these services must be redefined to reflect specific characteristics of converters as service providers (OPEX, losses, degradation, possible revenues etc.). It should also consider the impact on other wind turbine components, such as the drive train. Given all this, real-life piloting will be needed ahead of widespread mandatory requirements as well as the deployment of such services and capabilities in order to assess suitable market mechanisms.

As well as this, wind farm developers and manufacturers should have better digital tools and models to design and adjust control systems to reduce risks and ensure adequate mitigation procedures and stable operation of new phenomena and interactions arising from more wind in the grid. This includes resonance and power oscillations, controls and protections interactions, islanding operation, and harmonic instabilities.

Beyond this, we need to see new software tools for planning and to carry out stability analyses at all system levels (wind turbine/plant/cluster and the entire power grid) in control centres. And for advanced solutions to monitor and control the grid. This would deploy wind power plant capabilities in a more cost-effective way.

4

Scope of actions	
Analysis of interdependencies between grid developments and increased system services requirements from wind turbines, comprising, among others, grid forming capabilities, energy storage and grid optimisation solutions.	TRL 7 to 9
Design impacts on wind turbine components (converters, drive train, controllers, protections, etc.) from increased system service requirements.	TRL 7 to 9
New methodologies/digital benchmarks for assessing the impact of resonances/oscillations, control and protection interactions.	TRL 3 to 7
Analyse conditions for islanded operation of grid-forming wind power plants after system splits and move to an interconnected state.	TRL 3 to 4/5
Digital benchmarks to verify/adjust advanced capabilities (emulation of inertia, oscillation damping, etc.) of new renewable generators.	TRL 3 to 7
Operational tools for predicting and real-time monitoring system stability (e.g., system inertia and strength).	TRL 3 to 7
Pilot projects to trial potential system services and market mechanisms to handle new, advanced capabilities from renewable generators and storage. > *Assess impact on OPEX, energy losses, equipment degradation related to relevant functionalities*	TRL 4/5 to 7

Estimated public investment needs from 2025 to 2027	
Number and types of projects	• 1 small scale prototype • 1 demonstration project
Total public investment	€ 20 million

Longer-term research topics:

R&I beyond 2027 should continue to develop and demonstrate solutions to manage power grid stability and flexibility, particularly by updating modelling tools to assess system needs. Also, R&I will continue to look into ways of transmitting the vast amount of offshore wind power to where it is needed, notably by refining the planning and optimisation of onshore and offshore power grid infrastructure. Lastly, industry will need to further develop the first wave of grid digitalisation technologies and their implementation to managing the power grid and to serve other R&I priorities.

ADVANCED GRID CAPABILITIES FOR WIND POWER GENERATED UNITS

IMPACT	
Speed-up	●
Scale-up	○
Expand	●
Enhance	●

R&I is needed to bring forward the demonstration of the provision of grid forming, black start and other ancillary services via wind farms. This needs to build on the UK CT black start and integrator workstreams and on the Carbon Trust SIF-BLADE[7], Integrator ancillary services/synthetic inertia and other black start evaluation activities. The R&I agenda should also look into setting up an inventory of black start requirements broken down by country and suggested revisions of technical requirements to allow wind farms to take part in its provision. Finally, R&I should investigate the historic availability for black start capability from wind power. Similar R&I actions would be proposed for other ancillary services.

4

Scope of actions	
Black start demonstration across multiple markets, involving wind turbine manufacturers and developers.	TRL 7 to 8
Grid synthetic inertia development including effects on wind turbine components (e.g. drive train, converters, etc) and analysis of availability and requirements, through cooperation between wind turbine manufacturers, developers, and TSOs.	TRL 3-4 to 4-5
Black-start scenarios modelling. Including gap analysis of grid codes against equipment capabilities and future capacity installed with geographic and time resolution of wind energy resources.	TRL 3 to 4
Grid ancillary service development involving wind turbine manufacturers, developers and TSOs to test the ability to send ancillary service deployment signals to the WTG/windfarm.	TRL 7 to 8+

Estimated public investment needs from 2025 to 2027	
Number and types of projects	• 1 big demonstration project for black-start • 3 big demonstrations projects for grid synthetic inertia • 1 big demonstration project for grid ancillary services in different locations
Total public investment	€ 130 million

Longer-term research topics:

Looking ahead, R&I should help to clearly define grid forming and the different capabilities to meet grid code requirements. This would allow us to standardise and developing tests protocols to ensure proper behaviour in wind farms of each capability in a stable manner. Future R&I should further refine and provide wind energy with new technical solutions to meet grid code requirements, especially a better provision of grid forming capabilities and ancillary services. The validation and demonstration of technologies in this SRIA will evolve up until 2050 – R&I will be needed to optimise them. Also, short-term demonstration projects on ancillary services provision will lead to new areas for improvement beyond 2030 and allow further integration of inverter capabilities and more resilient solutions. Markets and regulations will continue to adapt to larger penetration of wind and other renewables, including in the area of integrated/ intelligent operations for the short-term balancing of the power system.

7 More info: https://www.ofgem.gov.uk/sites/default/files/2023-04/SIF%20Funding%20Decision%20-%20Discovery%20Round%2021680291703515.pdf

INTEROPERABILITY - STANDARDISATION OF DATA STRUCTURE AND COMMUNICATIONS

IMPACT	
Speed-up	●
Scale-up	●
Expand	○
Enhance	○

Large scale offshore renewable energy hubs, such as those in development like the North Sea Wind Power Hub, will need to have interoperability of multi-vendor offshore wind power plants, together with meshed, multi-terminal DC grids. This calls for infrastructure interoperability and robustness, both for cyber and physical, to ensure security, reliability, and controllability. It will require high fidelity and interoperable models from different vendors, online and offline validation techniques, to be developed for wind power plants that can be used for system level studies, overcoming the barriers from various version and software. It will also involve new technologies that can efficiently speed up the electromagnetic transient simulation for large-scale systems, as well as interoperable, efficient real time simulation and a testing environment that can be used to test various critical control and coordination functions involved in system operation.

There will need to be development in wind power plant digital twin technologies, where various component models, system level controls, and communication can be simulated and calibrated by various data and measurements though online or offline studies. This would then be used to enhance design and operational studies to de-risk large scale renewable projects.

Scope of actions	
Digital twin for wind and hybrid power plants	TRL 7 to 8
Online tools for monitoring and coordinated control of wind power plants	TRL 7 to 9
Cyber resilience and cybersecurity of offshore and onshore wind power plants	TRL 7 to 9
Multi-vendor wind power plants combined with batteries, PVs, etc.	TRL 7 to 9
Interoperability of models and testing platforms	TRL 6 to 8

Estimated public investment needs from 2025 to 2027	
Number and types of projects	• 2 demonstration projects to test several concepts
Total public investment	€ 60 million

Longer-term research topics:

Greater understanding of wider grid development, the holistic energy system solution and the full prospects and challenges of wind farm flow control are all essential. This will go far beyond the planned demonstration projects of discrete wind farms and energy system technology. R&I should consider the interoperability needs of wind power-to-x projects and infrastructure.

SOLUTIONS TO EFFECTIVELY MANAGE CURTAILMENT

IMPACT	
Speed-up	●
Scale-up	○
Expand	●
Enhance	○

Despite many European countries doing major work to manage large amounts of wind power in their grid, those with wind penetration levels over 30% have increased their curtailment in recent years. If curtailment continues to increase, the energy transition could be delayed with significant financial implications for wind farm operators. Recent projects such as EU-SysFlex[8] have shown the challenges for congestion management in the continental and Nordic power systems for the year 2030 – due to the combined rapid penetration of variable renewables and lack of grid infrastructure build-out.

Existing and upcoming technologies for grid optimisation and flexibility (e.g. storage, FACTS, demand-side management) used at local/zonal level to solve local congestions together with adequate operational methodologies will require large-scale demonstration through pilot exercises. These pilots will also help to specify and trial possible congestion management services, including potential market design for large-scale Virtual Power Plants.

4

Scope of actions	
Assessment of interdependencies between the share of wind generation and curtailments including wider impacts on the grid, generation mix, operational procedures for grid management, interconnection and storage.	TRL 7 to 9
New tools/simulation models/digital benchmarks for assessing the impact of grid developments, new grid operating methods, grid optimisation and storage solutions to avoid curtailments	TRL 7 to 9
Pilot projects to trial congestion management technologies (DLR, FACTs, Storage, RAS,...) and their potential service and market mechanisms	TRL 7/8 to 9
Adoption of virtual power plants concepts and their automated controls (for loads and distributed generators) as flexibility resources	TRL 3/4 to 7

Estimated public investment needs from 2025 to 2027	
Number and types of projects	• 2 demonstration projects to test different technologies including validation of models and tools
Total public investment	€ 60 million

Longer-term research topics:

Future R&I activity will continue to develop emerging technologies to effectively manage curtailments at different spatial scales and across larger regions (thus providing more effective long-term balancing).

R&I activity will also foster and embrace the use of hydrogen and storage technology as part of the multi-energy vector solutions to manage curtailments beyond 2030.

8 EU-SysFlex is a Horizon 2020 project which finished in February 2022. More information at https://cordis.europa.eu/project/id/773505

SYSTEM INTEGRATION OF CO-LOCATED RENEWABLES, OFFSHORE HYBRIDS AND WIND POWER-TO-X

IMPACT	
Speed-up	○
Scale-up	●
Expand	○
Enhance	●

Alternative energy vectors will be key if Europe is to connect around 450 GW of offshore wind by 2050. We will need to see new projects which combine wind energy with other assets such as energy storage, hydrogen production, or the co-location with other renewables to demonstrate the provision of grid support services and the development of offshore hybrid projects, which connect offshore wind farms to two or more power systems. Investment decisions in hybrid, co-located, wind power-to-X and energy islands projects are very complex and need R&I to focus on de-risking the technical, economic and regulatory aspects – including the re-use/repurposing of existing infrastructure. Nonetheless, the R&I priority in this SRIA is on the system integration aspects of these wind-based solutions (co-located projects, offshore hybrids, and wind-to-x).

4

Scope of actions	
Analysis of system integration needs (technical, economic, regulatory) to support the development of wind energy co-located projects with other technologies, offshore hybrids and wind-to-x	TRL 4/5 to 6
Modelling and optimisation of hybrid projects including ancillary service provision	TRL 5/6 to 7
Development of system integration solutions for wind power projects coupled with hydrogen production and energy storage technologies.	TRL 5/6 to 7
Demonstration of offshore hybrid project solutions and wind-to-x projects involving repurposed and new infrastructure	TRL 6/7 to 8/9

Estimated public investment needs from 2025 to 2027	
Number and types of projects	• 2 small scale prototypes • 2 large scale prototypes • 1 big demonstration project
Total public investment	€ 70 million

Longer-term research topics:

R&I will be needed to develop integrated and intelligent operations for hybrid and co-located projects to get the most out of renewables in the energy system. The evolution and diversification of renewable energy hybrid technologies will continue beyond 2027 and will need further opportunities for optimisation. The ongoing development of energy islands in particular is seen as a key driver for this research topic.

DIRECT CURRENT (DC) GRID SOLUTIONS FOR WIND POWER

IMPACT	
Speed-up	○
Scale-up	○
Expand	●
Enhance	○

The roll-out of DC grid solutions to connect wind farms over long distances must first be shown to support supply chain competitiveness and the scale-up of wind power in Europe. R&I should look at network topology options (e.g. meshed HVDC, multi-terminal DC, etc.), assess technology equipment (converters, DC breakers, etc.) and carry out large-scale demonstration projects with these solutions – in some cases incorporated into energy islands. The expected impact of these R&I actions is to demonstrate DC grid solutions deployment in key locations such as the North Sea, which aims to connect wind to multiple countries.

4

Scope of actions	
Grid topology option assessment and development	TRL 4-5 to 5-6
Technology development and validation (at component and system level)	TRL 4-5 to 6
Large scale demonstrations (some incorporating offshore demonstration and energy island operation)	TRL 6-7 to 8-9

Estimated public investment needs from 2025 to 2027	
Number and types of projects	• 2 small or large scale prototypes • 1 big demonstration project
Total public investment	€ 60 million

Longer-term research topics:

R&I should fast-track solutions to help operate and design offshore wind farms installed very far offshore (including floating wind), with an emphasis on further development of DC grid technology best suited for long-distance electricity transmission. The ongoing development of offshore energy hubs and energy islands will play a key part in EERA JP Wind's long-term research programme.

4.4 Sustainability and Circularity

Wind energy is a sustainable solution to help tackle global climate change, the destruction of ecosystem and biodiversity loss. But more R&I is needed for wind energy to get on top of resource efficiency and circularity. A 3 megawatt (MW) wind turbine using permanent magnets consumes two tonnes of rare earth materials, which are scarce, and processing these leads to pollution. And while 85-90% of a wind turbine can be recycled, the rotor blades, made from fiber reinforced plastics, still pose a challenge. The industry has called for a Europe-wide landfill ban on decommissioned wind turbine blades by 2025[9]. It should now work on all waste streams of composites including manufacturing waste for blade production.

To achieve this, the EU should prioritise R&I funding to diversify and scale-up demonstration projects for new sustainable and circular materials. These new materials should be lighter, more durable and more recyclable to help boost circularity, turbine performance and lifetime. The EU should also consider alternatives to rare earths, and make more use of non-virgin material in cables.

There is also a need to see a scale-up of existing recycling technologies, establish viable value chains, and adopt emerging solutions, such as chemical recycling for composite materials or recycling permanent magnets.

And R&I should help to develop positive nature-based solutions to install, operate and decommission wind farms in line with EU's biodiversity strategy. New decommissioning tools and techniques are especially needed to reuse and recycle, as well as to reduce the environmental impacts of these activities.

Life extension is also one of the key levers to a sustainable wind farm. The lifetime estimate for wind farms has already risen from 20-25 years to 30-35 years. Monitoring and ensuring all components of a wind farm can meet and potentially exceed current design parameters is vital if we want to build up that advantage.


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9 More info: https://windeurope.org/newsroom/press-releases/wind-industry-calls-for-europe-wide-ban-on-landfilling-turbine-blades/.

DEVELOPMENT OF MATERIAL SUBSTITUTION ENABLING DECARBONISATION AND REDUCING THE USE OF RARE-EARTH MATERIALS

IMPACT	
Speed-up	●
Scale-up	○
Expand	○
Enhance	●

The objectives are to increase recycled content, to minimise environmental impacts and to allow recycling of waste streams within a circular economy framework. Other drivers are material scarcity and supply chain constraints.

The development of alternative materials is crucial to reduce the environmental footprint of products and solutions that the market needs. With the foreseen volume and size of future wind turbines and wind farms, testing and validation new or existing materials and components will be key, as will improvements to the overall manufacturing environmental impact. Additionally, critical raw materials are economically vital for the European wind sector, while also being highly vulnerable to supply disruptions. Material challenges include resource scarcity, a lack of capacity for circularity, sustainability by design, and hazardous properties, while manufacturing challenges cover resource consumption and footprint. Looking into alternatives to enable sustainable development will mean searching for alternatives to scarce materials (bottlenecks), adapting to the growing size of future wind turbines, e.g. through numerical methods for digital twins, finding alternatives for circular material flows, and reducing hazardous properties in materials.

In the short-term, the priority should be to focus on the materials that have the most impact on the lifecycle of wind energy (e.g. carbon-fibres in blades, concrete or steel in foundations and towers, etc.). However, alternative materials for grid components also need to be tackled (e.g. PFAS in electrical wires of cables).

4

Scope of actions	
Development and demonstration of reinforcement materials (glass and carbon fibre) for wind turbine blades with increased recycled content and reduced carbon footprint.	TRL 4/5 to 7/8
Development and demonstration of substitution of hard to recycle or critical raw materials in key components:	
> *For wind turbine blades: recyclable polymers, bio-based and artificial materials, recyclable composite materials, etc.)*	TRL 5/6 to 8/9
> *For generators: alternatives to permanent magnets with no or lower rare earth content*	TRL 6 to 9
> *For electrical and grid components: thermoset polymers with thermoplastics, alternative materials for valves, conductors and power conversion applications, replacement of lead and PFAS, alternatives for gas-insulated equipment like switchgear.*	TRL 7 to 8/9

Estimated public investment needs from 2025 to 2027	
Number and types of projects	• 3 applied research/prototype project • 3 demonstration projects
Total public investment	€ 105 million

Longer-term research topics:

In future R&I should help to consolidate today's knowledge on materials and look into the possible use of new ones such as nano-materials, self-healing materials, and other more sustainable alternatives to manufacturing permanent magnets. It should test the use of alternative fibres to carbon fibres, as well as other new more resistant blade materials and coatings for anti-erosion and cold climates.

For components, R&I should bring forward new designs for bearings, converters, and generators for larger turbines. It should investigate new power converter topologies to cut down maintenance needs in places with difficult access and logistics. The same goes for subsea cables which will need new materials adapted to dynamic High Voltage cables, and for new high-temperature superconducting (HTS) materials.

The next generation of wind turbines, with lighter materials and less volume, should continue to be researched The resource efficiency of wind energy will need more optimisation and R&I should play an important role in achieving this. It would include, for example, a reduced converter volume for the same power rating.

DEVELOPMENT AND DEMONSTRATION OF RECYCLING METHODS FOR WIND TURBINE MATERIALS, MANUFACTURING WASTE AND COMPONENTS

IMPACT	
Speed-up	○
Scale-up	●
Expand	○
Enhance	●

R&I is needed to allow the wind sector to reach up to 100% recyclability. Recycling should include manufacturing waste as well as end-of-life waste, particularly for composite materials which represent a large volume of waste stream.

Actions are needed not just on recycling, but also on re-using recycled materials in a number of industrial sectors, guaranteeing the creation of a well-established value chain and exploring the closed-loop circularity approach as well.

Collaboration in the R&I actions below may be possible together with the European Boating Association (for composite recycling) and the European Composites Industry Association (EuCia).

4

Scope of actions	
Development and demonstration of recycling of wind turbine composite components (like wind turbine blades and nacelle covers) as well as manufacturing waste from blade manufacturing providing a separation of reinforcement fibres, thermoplastics, metals and resins into a state, where such materials can be circled back and used to manufacture new components and products.	TRL 4/5 to 8/9
Development of recycling processes for permanent magnets and other components (like lubricants and greases)	TRL 3 to 6
New solutions to use recycled content in the design of wind components ("circularity by design") looking into whether a closed loop approach is possible.	TRL 3 to 5

Estimated public investment needs from 2025 to 2027	
Number and types of projects	• 2 small or large scale prototypes • 3 demonstration projects
Total public investment	€ 110 million

Longer-term research topics:

In future R&I will be needed to hone processes and methods to recycle of a wind turbine with the lowest possible CO2 footprint. This should include composite materials and neodymium from permanent magnets. This will go hand in hand with more adequate LCA methodologies that should test the sustainability of these processes. R&I should continuously help to regulate requirements for recycling wind turbine blades and other materials across all EU countries. But crucially it should come up with solutions to use recycled materials in wind blades and to explore whether a closed loop approach could be possible.

In addition, R&I should help to create an EU value chain for the use of recycled materials coming from wind farms across other industrial sectors. To this end it should put forward validation and certification procedures for secondary materials use.

The development and demonstration activities identified in the SRIA will develop new business models that will benefit from further research and innovation activities to refine and build on future solutions for longer term targets in 2050.

LIFETIME EXTENSION VIA RE-USING, REFURBISHING, RE-PURPOSING

IMPACT	
Speed-up	○
Scale-up	○
Expand	○
Enhance	●

It is better to prevent material and component waste of wind turbines by extending the material durability of components, as well as reusing and refurbishing materials, according to the waste hierarchy[10]. Strategies for achieving lifetime extension of wind turbines are crucial, as waste prevention strategies, including the repurposing and recycling of components, are not fully integrated and adopted at an industrial scale. R&I should develop the operating lifetime of wind turbine components to prolong wind farm life to minimise the amount of waste to landfill. In addition, environmental assessments of lifetime extension strategies achieved by reuse or refurbishment should be performed and compared with alternative methodologies e.g. the use and direct replacement of non-recyclable or bio-sourced turbine components, to determine the optimum strategy in terms of material utilisation for each turbine component.

4

Scope of actions	
Development of supply-chain infrastructure and prototype processes for refurbishment of wind turbine components and associated grid equipment.	TRL 7 to 9
Assessment of most prominent wind turbine component failure modes that require further technology development to achieve lifetime extension e.g. blades (fatigue, LEE), gearbox (wear), generator (bearing failure)	TRL 3 to 7
Development of holistic lifecycle assessment of R-strategies (recycle, re-use, re-purpose, refurbish, etc.) that will support decision-making to extend lifetime of key materials and components.	TRL 4 to 8
Digital twinning and use of AI for lifetime extension of wind turbine components (e.g. gearboxes, blades, bearings) hotspot detection and health monitoring.	TRL 5 to 8
Explore methods to extend operation of structural relevant components beyond the current limits (based on fatigue load calculations) using e.g. probabilistic approaches	TRL 1 to 5

Estimated public investment needs from 2025 to 2027	
Number and types of projects	• 1 basic/applied research project • 3 demonstration projects
Total public investment	€ 80 million

Longer-term research topics:

In the future R&I will be needed to extend the durability of materials and components in wind farms. This is particularly true for new solutions which would prevent material and component waste, including grid equipment. For example, solutions based on advanced digital monitoring and artificial intelligence to detect early degrading of key materials and electrical equipment (semiconductors, converters, grid equipment, etc.), remote and/or condition-based service, inspection, and predictive maintenance.

R&I should also test and develop and new methodologies to inform, reuse and/or repurpose components. For example, advanced sensor technologies and AI decision-making support tools for diagnostics, structural health monitoring and system level lifetime optimisation.

Finally, future R&I should develop new decommissioning tools and methods to facilitate reuse and repair components, particularly in blades.

10 Article 4 of directive 2008/98/EC.

NEW DECOMMISSIONING TOOLS AND METHODS

IMPACT	
Speed-up	○
Scale-up	○
Expand	○
Enhance	●

Decommissioning procedures are quite standardised for onshore wind farms. At the same time, innovative solutions for O&M and decommissioning are needed especially for offshore applications to contribute to broader knowledge, influencing the sustainable and functional expansion of offshore wind. Research activities are needed to bring down installation costs, supply chain costs and the environmental impact.

Decommissioning of WTGs is becoming ever more important with the first wind plants reaching their end-of-life. The current decommissioning process should therefore be improved to allow easier reuse and recycling of components and materials, reduction of environmental impact and creating new supply chains, considering and exploiting all the relevant alternatives avoiding landfills and non-sustainable actions.

4

Scope of actions	
Development of decommissioning methods and tools for offshore wind, including monopile extraction and new cutting tools for subsea bed cutting.	TRL 4 to 7
Development of new technologies for effective and environmentally friendly decommissioning of offshore wind energy systems.	TRL 4 to 7
Development of decommissioning processes to ease reuse and recycling of wind components for both onshore and offshore.	TRL 4 to 7
Development of new technologies for effective and environmentally friendly decommissioning of onshore wind energy systems.	TRL 6 to 8
Development of decommissioning vessels specifically suited to offshore wind, building on experiences from the oil & gas sector.	TRL 4 to 7
Development of economic model for full decommissioning project cycle, including a cost/benefit analysis, to evaluate and find cost-effective solutions for the decommissioning of offshore wind farm.	TRL 3 to 7

Estimated public investment needs from 2025 to 2027	
Number and types of projects	• 3-4 small demonstration projects • 2 demonstration projects
Total public investment	€ 120 million

BIODIVERSITY SOLUTIONS

IMPACT	
Speed-up	●
Scale-up	●
Expand	●
Enhance	●

EU ambitions to increase the share of renewable energy will lead to more wind turbines being built on- and offshore in the future. Assessment of environmental effects and biodiversity is a key stage in planning for new wind farms. Still, it is important to understand the impact on biodiversity during construction and operation. Certain knowledge gaps on the impact from wind power installations on biodiversity leaves the developers and authorities without scientific facts to improve sitting and operations of future projects avoid, mitigate, or compensate impacts, and to enhance biodiversity. The impact from wind energy installation and operation on biodiversity needs to be studied more closely, with new models developed that can be used in the assessment. Also, technologies to mitigate bird and bat strike need to be worked on, assessed, and documented in a more systematic way.

4

Scope of actions	
Development and demonstration of nature-positive strategies and technologies for onshore wind farms during construction, operation, maintenance, and decommissioning. This includes the impact on birds and bats as well as other wildlife living close to wind farms.	TRL 3 to 7
Development and demonstration of nature positive strategies and technologies for offshore wind farms during construction, operation, maintenance, and decommissioning. This includes marine wildlife with special focus on underwater noise, electromagnetic radiation, underwater structures as foundations and mooring lines.	TRL 3 to 7
Development and demonstration of use of offshore wind installations as artificial reefs in a nature positive perspective.	TRL 6 to 9
Development and demonstration of collision mitigation and deterrent technologies preventing collision of birds and bats with the wind turbine rotor (single wind turbine or multiple in wind farm).	TRL 4 to 7
Development and improvement of modelling of wind farms impacts and cumulative environmental impacts on ecosystems based on typical species behaviour to decide on future development areas and minimise the impact.	TRL 4 to 6

Estimated public investment needs from 2025 to 2027	
Number and types of projects	• 6 small or large scale prototypes • 3 demonstration projects
Total public investment	€ 135 million

Longer-term research topics:

R&I should support progress to reduce noise emission from wind turbines, by contributing to future guidance and regulation. R&I should look into the most appropriate mitigation solutions for noise emissions. It should determine relevant exposure levels to noise and EMF (Electromagnetic Interference) in situ and consider solutions that might further mitigate impacts on wildlife.

R&I should also encourage collaborative programmes to mitigate the effect of wind turbine in marine ecology. The gradual reduction in the environmental effect should be considered in the design of the overall life of the wind assets, with a final goal of next to no impact on the environment.

4.5 Skills and Coexistence

Europe should maintain a highly skilled and educated workforce with comprehensive knowledge of specific wind areas, but also focusing on interdisciplinary and interconnected expertise, including the domain of IT. It should continue to be a hub of talent for wind energy. And to put in place reskilling programmes for the existing workforce and lifelong learning for future workers. R&I should also help to bridge skills and equity, diversity and inclusion gaps in the wind workforce. Teachers (at all levels of education) should be trained to support this massive undertaking.

As the share of wind energy grows rapidly, new challenges are emerging, particularly with concerning the coexistence of wind with the natural environment.

The coexistence of wind energy with society is equally important and complex. Depending on the location and scale, wind energy projects might impact local communities and raise concerns as well as create needs for collaboration with different stakeholder groups. On the other hand, it can also have positive impacts. R&I is key to offer evidence on all these aspects. It should reflect the dialogue between stakeholders of wind energy. And it could help developing assessment criteria for selecting projects.

R&I should facilitate a harmonious coexistence between society and wind energy, where sustainably managed and implemented wind power plays a pivotal role in the energy transition. R&I will be needed to foster citizens' financial participation, social innovation, and public engagement, so that industry, academia, and Governments can continuously address societal concerns about wind energy, enhance societal awareness about the benefits of wind, and nurture practical support for wind energy deployment across its Member States.

Finally, it is needed research on coexistence through Holistic Research. This is a form of interdisciplinary research to better understand societal concerns related to wind energy. It would consider factors such as visual impact, noise pollution, ecological effects, and meaningful forms of citizen engagement. The purpose should be to move from doing research for society to doing research with society.


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ENSURE A WORLD-CLASS EDUCATION FOR WIND ENERGY AND EXPAND IT

IMPACT	
Speed-up	○
Scale-up	●
Expand	○
Enhance	●

The scale as well as the value of planned projects in the wind energy sector shows how important a well-prepared education process, especially with regard to digital competences, will be in the whole process of preparing the entities to carry out the tasks within the planned supply and service chains. The key to implementing the planned investments is a highly qualified workforce. A well-planned education and training process, in cooperation with industry, covering all levels: professional, technical, higher, and the organisation of an appropriate qualification and competence enhancement system will ensure that the intended investment goals can be achieved.

At present, the educational areas mainly concern engineering and technical aspects, but wind energy is not just a technical, engineering and onshore/offshore competence. It is a very broad spectrum, ranging from legal, environment, finance, purchasing, logistics, human resources, training, certification, preparation and development of documentation, tenders, approvals, stakeholder cooperation, etc.

Scope of actions
Creation of dedicated interdisciplinary programmes in technology-industry partnerships. This includes systemic cooperation activities between educational institutions and business, empowerment of women in the wind sector.
Development of new educational tools for teachers (business games, computer simulations, project games) adapted to each stage of education. Creation of an educational platform for teachers to exchange experience, knowledge and to cooperate with business practitioners.
Development of centres of competence at schools, integrating science with industry and business, supporting schools in cooperation with universities, carry out innovation and development activities to disseminate knowledge and new technologies, in particular digital technologies. To develop and implement a path of support and development involving the engagement of students, both doctoral and graduate, as well as school students, with particular emphasis on career guidance.
Promotion of educational programmes in wind energy.
Development and preparation of multi-level educational campaigns, practical workshops (based on a real analysis of the target audience's needs).

Estimated public investment needs from 2025 to 2027	
Number and types of projects	• 3 projects on interdisciplinary programmes • 1 project for educational tools • 1 project focusing on educational campaigns
Total public investment	€ 20 million

Longer-term research topics:

Future R&I actions should maintain and expand the number of students in relevant Bachelors of Science, Masters of Science and programmes of higher education. This is key to sustaining a skilled and diverse workforce for future demands in the sector beyond 2030. R&I actions should also draw more PhD students into wind energy. This will be vital to fostering cutting-edge research, driving technological innovation, and addressing the evolving challenges of a rapidly advancing wind energy landscape.

SKILLING, RE-SKILLING AND UPSKILLING ACTIVITIES

IMPACT	
Speed-up	●
Scale-up	●
Expand	○
Enhance	●

To address the complex technical, financial, societal, environmental and regulatory challenges facing the growth of wind energy R&I up to 2050 and beyond, skilling, re-skilling and upskilling activities are central to future-proofing the career of Science, Technology, Engineering and Math (STEM) professionals in wind energy. In these activities, covering the entire value chain including digital competences (machine learning, big data analytics, high performance computing, robotics and automation, cybersecurity etc.) as well as sustainability and circularity (development and design of new materials, structural evaluations and tool chain development, system-level life cycle analysis and optimisation, circular procurement, strategies to mitigate or even promote biodiversity etc.), socio-economic and environmental cross-disciplinary aspects including legal/regulatory frameworks, governance and business are key. With that in mind, there is a strong need for ongoing skilling/re-skilling and upskilling programmes, especially as interdisciplinary lifelong learning activities focusing on these key capacity areas, boosting the geographic range, gender, and diversity of learners and educators, and also providing opportunities to lightweight transition from non-renewable energy sectors. These activities are also major drivers for attracting the human resources we need to speed up wind deployment to meet our 2030 and 2050 climate targets, supporting Europe's green and digital transformation.

4

Scope of actions
Interdisciplinary programmes for (re- /up-) skilling covering the entire value chain, including digital competences, system-level sustainability and circularity as a whole, socio-economic and environmental aspects, regulatory frameworks, governance and business.
Easy-to-access lifelong learning activities, also boosting the geographic range, gender, and diversity for learners and educators.
Mapping transferable resources (e.g. oil and gas sector).
R&I that helps people to enter into the workforce faster (e.g. augmented reality technologies, etc.)
Training programmes for local authorities to accelerate permitting process (use of digitalised procedures, etc.)

Estimated public investment needs from 2025 to 2027	
Number and types of projects	• 1 coordination project • 4 projects to address the skill shortages
Total public investment	€ 81 million

Longer-term research topics:

R&I actions would mean providing programmes to skill, re-skill and up-skill experts from other sectors, notably from oil and gas. This is key to enabling a seamlessly transition between sectors and to leverage transferable skills, ensuring a qualified workforce for the evolving demands of an expanding wind energy industry.

INCREASE PUBLIC ENGAGEMENT OF CITIZENS AND COEXISTENCE WITH OTHER STAKEHOLDERS

IMPACT	
Speed-up	○
Scale-up	○
Expand	●
Enhance	●

4

With large-scale deployment of wind energy across Europe, questions of energy justice and citizen's participation will become more and more important. Local communities need to profit from the energy transition taking place in their direct proximity. To tackle the societal challenges of something as ambitious as the energy transition, large-scale interdisciplinary research including elements of co-design will be needed, particularly in the social sciences and humanities. Research is needed to develop fair, inclusive and innovative tools for public engagement both offline as well as in digital formats. Tools and platforms should bring together all parties affected by infrastructure projects, including those usually not engaged because of their socio-economic background, education and because of timing.

Understanding the effects of wind energy's coexistence with other activities (e.g. ecosystem; agricultural use; fishery; industries; airborne wind energy) will involve data-collection and models to simulate the interactions between these activities.

Also the coexistence with military and defense activities is essential. Researching an effective military and other security systems to minimise the risk of both digital and physical sabotage of renewable energy infrastructure is important.

Interdisciplinary (involving different kinds of wind energy expertise as well as social and environmental sciences) and transdisciplinary (involving also broader public and wind energy stakeholders) research and innovation will be key. Wind energy's successful integration into society requires a holistic understanding that cuts across many different fields of knowledge. Such an approach to R&I will help to address the range of complex challenges that cannot be effectively addressed through a single discipline. In turn this will facilitate innovation which often arises at the intersection of different fields and collaborations between researchers, engineers, social scientists, policymakers, and community representatives.

Scope of actions
Citizen science projects that focus on answering questions from society
New ways and practices for increasing public dialogue in wind energy projects
Tools to map stakeholder concerns and facilitate the interactions between stakeholders. (including fishing, aquaculture, energy, military, tourism, and transport).
Development of models and data sets specifically for interaction between stakeholders in the planning phase and demonstration of these models in (existing) digital interaction tools suitable for interactive stakeholder involvement in the project design phase. Model and tool development should be interdisciplinary involving technical, ecological and economical researchers and should address local physical and societal conditions.

Estimated public investment needs from 2025 to 2027	
Number and types of projects	• 5 citizen science projects • 1 large-scale prototype to develop mapping tools
Total public investment	€ 20 million

Longer-term research topics:

R&I should continue to improve the evaluation of impacts of using land and sea areas for wind farms, including identifying and defining relevant criteria for site-specific socio-economic impacts and benefits. This is essential for a responsible wind energy expansion and to ensure inclusive, beneficial integration into communities.

R&I should inform and foster future energy justice by documenting good practices for considering affected parties, including marginalised groups outside Europe. It should also address concerns and expectations surrounding the finite lifetime of wind turbines and sites.

Empowering citizens and acceptability by society will be needed more extensively in the future. R&I should lay out guidelines for continuous community involvement throughout the whole project period as good practices for project developers. This should help to foster transparency, trust, and sustainable partnerships to ensure the successful coexistence of wind energy within diverse communities.

Annex

Annex 1. Summary of the overlaps between ETIPWind and ETIP SNET R&I priorities.

ETIP SNET R&I priorities (R&I Roadmap 2022-2031)	R&I Actions linked to the ETIPWind Strategic R&I Agenda	Possible synergies with ETIPWind R&I priorities 2025-2027
1 Optimal Cross-sector Integration and Grid-Scale Storage	• Integrating hydrogen and CO2-neutral gases	• Wind power-to-X (Integration of wind with hydrogen and energy storage technologies)
2 Market-driven TSO–DSO–System User Inter-actions	• Control and operation • Develop a Digital Twin of the European Electricity Grid	• Definition and modelling of future system needs: Operational tools for predicting and real-time monitoring system stability. • Interoperability: Digital twin for wind and hybrid power plants. • Solutions to manage curtailment: Online tools for monitoring and coordinated control of wind power plants .
3 Pan-European Wholesale Markets, Regional and Local Markets	• Regulatory framework and strategic investments	• Definition and modelling of future system needs: Analysis of interdependencies between grid developments and increased system services requirements.
4 Massive Penetration of RES into the transmis-sion and distribution grid	• Well-functioning markets for a RES-based energy system • Policies and governance for a RES-based energy system	• Advanced grid capabilities: Grid synthetic inertia development involving OEM, developer and TSO. • Interoperability: Online tools for monitoring and coordinated control of wind power plants. • Interoperability: Multi-vendor wind power plants combined with batteries, PVs etc. • Solutions to manage curtailment: Online tools for monitoring and coordinated control of wind power plants, Multi-vendor wind power plants combined with batteries, PVs etc. • DC Grid solutions: Grid topology option assessment and development. • DC Grid solutions: Technology development and validation (at component and system level).
5 One stop shop and Digital Technologies for market participation of consumers (citizens) at the centre	• Service management and operations	• Definition and modelling of future system needs: Pilot projects to trial system services and market mechanisms to handle new capabilities.
6 Secure operation of widespread use of power electronics at all system levels	• Simulation methods and digital twins • HVDC interoperability, multi-terminal configurations, meshed grids • Large-Scale Demonstration activities	• Interoperability: Digital twin for wind and hybrid power plants. • DC grid solutions (Grid Topology option assessment and development). • DC grid solutions (large-scale demonstration).
7 Enhance System Supervision and Control including Cyber-Security	• Cybersecurity of Energy Networks	• Solutions to manage curtailment: Cyber Resilience and Cyber-Security of offshore and onshore wind power plants.

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