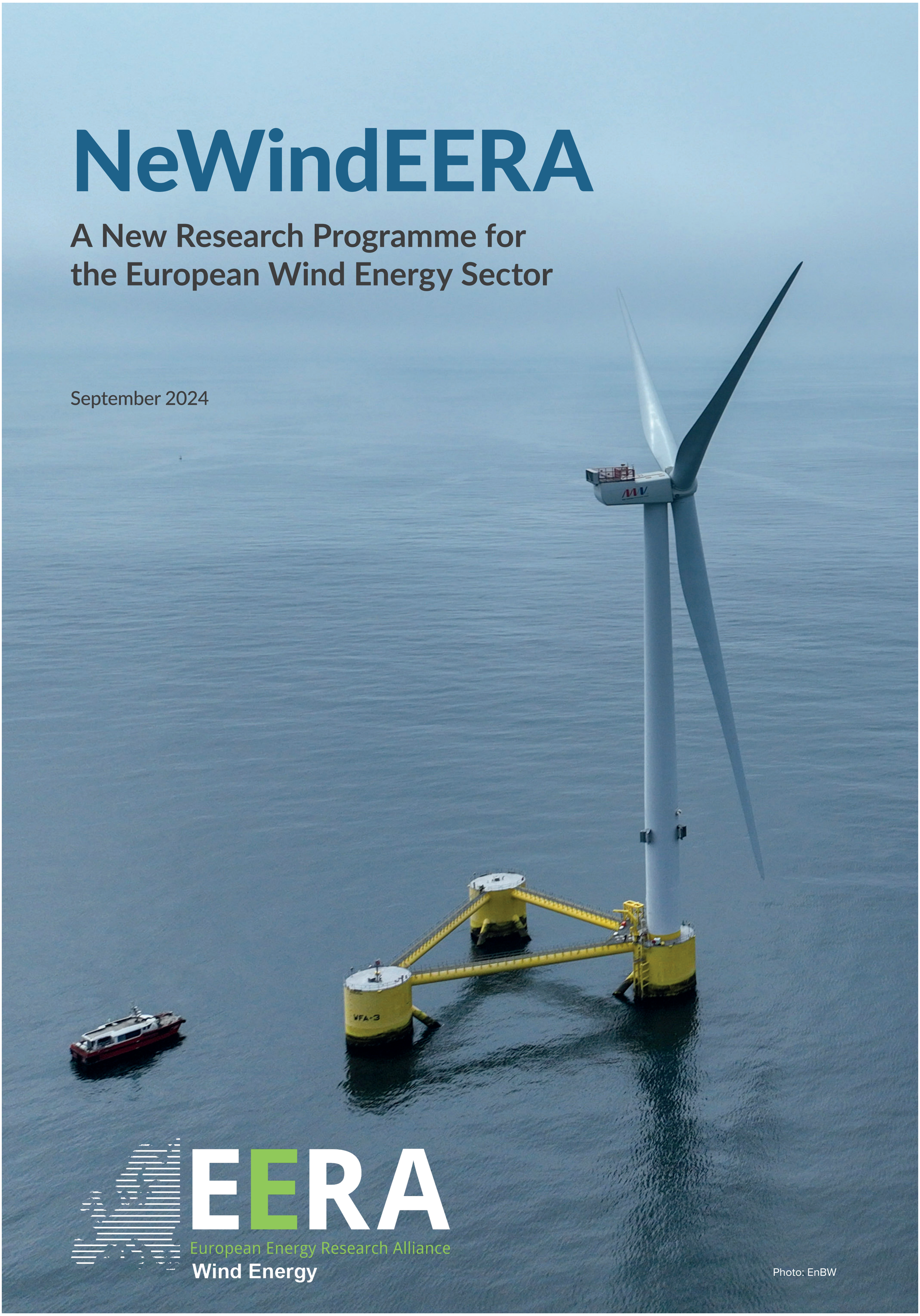
NeWindEERA

A New Research Programme for the European Wind Energy Sector

September 2024



EERA
European Energy Research Alliance
Wind Energy

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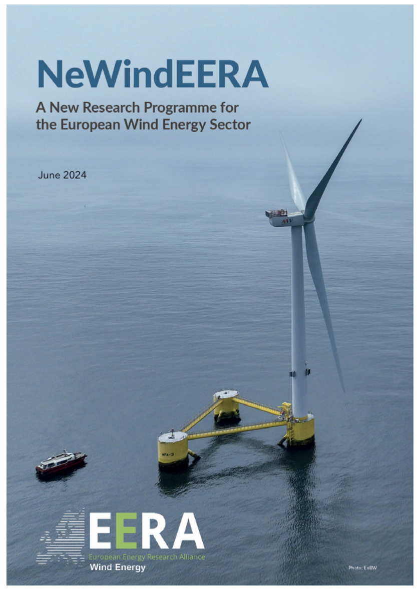
Foreword



Whilst wind energy has made huge strides over the last few decades, there is still much to do in the research and innovation arena to future-proof wind energy technology; technology that must continue to play its part as an essential contributor to key sector targets in 2035 and 2050.

To secure the 'future-proofed technology' prize, the European wind energy sector needs to execute the timely deployment of wind in Europe over the coming decades whilst developing several key supporting steps including European skills, more European led technologies, and a healthy and sustainable European market share. This requires action in both the wind energy industry and research communities.

The European Wind Power Package, launched in September 2023, highlighted several opportunities for the European wind energy industry to establish and cement itself as a world leader, and a key and sustainable cornerstone of the European energy system for decades to come. The resulting EU Wind Power Action Plan identified 15 actions to position Europe's wind energy industry to seize these opportunities, and one of the first benchmarks to address is the REPowerEU target of 420 GW by 2030. Supplementing the Wind Power Package and Action Plan was the launch of the ETIPWind Strategic Research and Innovation Agenda (SRIA) in December 2023. With 2030 in mind, the SRIA defined 23 R&I priorities that need to be urgently addressed in the 2025-2027 period. However, these priorities are short-term must-haves for industry, and we must also think and act longer-term. If you delve deeper into the SRIA content, you find several references to longer-term research topics. Welcome to the NeWindEERA project!

NeWindEERA defines a research vision for our route to 2050 and the opportunity to conduct a research programme that will position the European wind sector to seize the prize and opportunities mentioned above. The programme will also help sustain the timely deployment of wind energy and establish a foundation of skills and tools for those key supporting steps on the way to 2050. It defines a programme/roadmap for the European wind energy research community whilst staying strongly aligned with the ETIPWind SRIA industry-led priorities. The programme provides clear and simple messaging for key stakeholders and includes non-technical cross-cutting topics as well as the more traditional technical research priorities. The NeWindEERA project is funded by EERA JPWind and this report (along with a supplementary brochure providing a visual summary) presents the major findings and outcomes of the project.

In addition to cross-cutting research themes, the research programme has identified several research topics under the five themes of: Industrialisation, scale-up and competitiveness; Optimisation and further digitalisation of Operations & Maintenance; Wind energy system integration; Sustainability & Circularity; and Skills & Coexistence. This is an important feature of NeWindEERA, in that it builds upon the agreed R&I priorities of the European wind sector. Furthermore, the NeWindEERA research programme represents one of the three pillars of European wind energy research and innovation. It stands alongside the ETIPWind SRIA and the emerging European Centre of Excellence for Wind Energy (EuCoE4Wind); the vehicle that will carry us as we realise the NeWindEERA programme over the coming decades. Happy reading and looking forward to sharing the journey with you!

Paul McKeever
NeWindEERA Project Coordinator

Stephan Barth
EERA JP Wind Coordinator

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Executive Summary

When looking forward to key energy targets in 2035 and Net Zero by 2050, it is clear that wind energy has a significant role in achieving the decarbonization of our society as part of the present and future energy system.

However, some huge challenges lie ahead, and these range from material technologies to wind energy system integration, and with the extra challenge of doing this whilst establishing a strong skills base and enduring coexistence with society at large. We also need to embrace and optimise the use of digitalisation in the operation and maintenance of wind energy as well as creating a sustainable and circular economy in the way 'we do wind'. All of it while ensuring cost competitive solutions and preserving long term European leadership.

Whilst a lot of this can be done with existing technology, knowledge, expertise, and processes, it is also clear that much of it cannot be achieved without significant investment and execution in an effective research and innovation programme, that will guide us from here to 2050. Welcome to NeWindEERA!

The purpose of this report is to detail out the background, context and consensus that has been achieved in the development of the NeWindEERA research programme as well as articulating the programme itself. Whilst the bulk of the report and work behind it has been carried out by the NeWindEERA consortium (ORE Catapult, DTU, SINTEF, CWD (RWTH Aachen), and Ciemat), it is also important to note that the project has also involved significant engagement with (and input from) the wider research community (EERA JP Wind membership) and industry representatives (ETIP Wind). This includes 45 members and associated members at the time of writing the report. The collection of inputs has been achieved through a variety of means such as webinars, newsletters, and in-person workshops over the past year. Therefore, we can be confident that the results of the NeWindEERA project have strong foundations as they are based on the insights of the experts who work in wind energy.

Aligning with industry

In the early days of the NeWindEERA project, it was agreed that to define (and ultimately deliver) a successful research and innovation programme, we needed strong alignment with industry and the industrial wind agenda. A key decision was thereby taken to adopt the R&I priority themes used by industry (ETIP Wind) in the Strategic Research and Innovation Agenda (SRIA) launched in December 2023. This is a first and whether you are focusing on shorter term innovations in the SRIA or medium to long-term research priorities in this report you will see a consistent thread of five key priority areas:

1. Industrialisation, Scale-up and Competitiveness
2. Optimisation and further Digitalisation of Operations & Maintenance
3. Wind Energy System Integration
4. Sustainability and Circularity
5. Skills, Acceptability and Coexistence

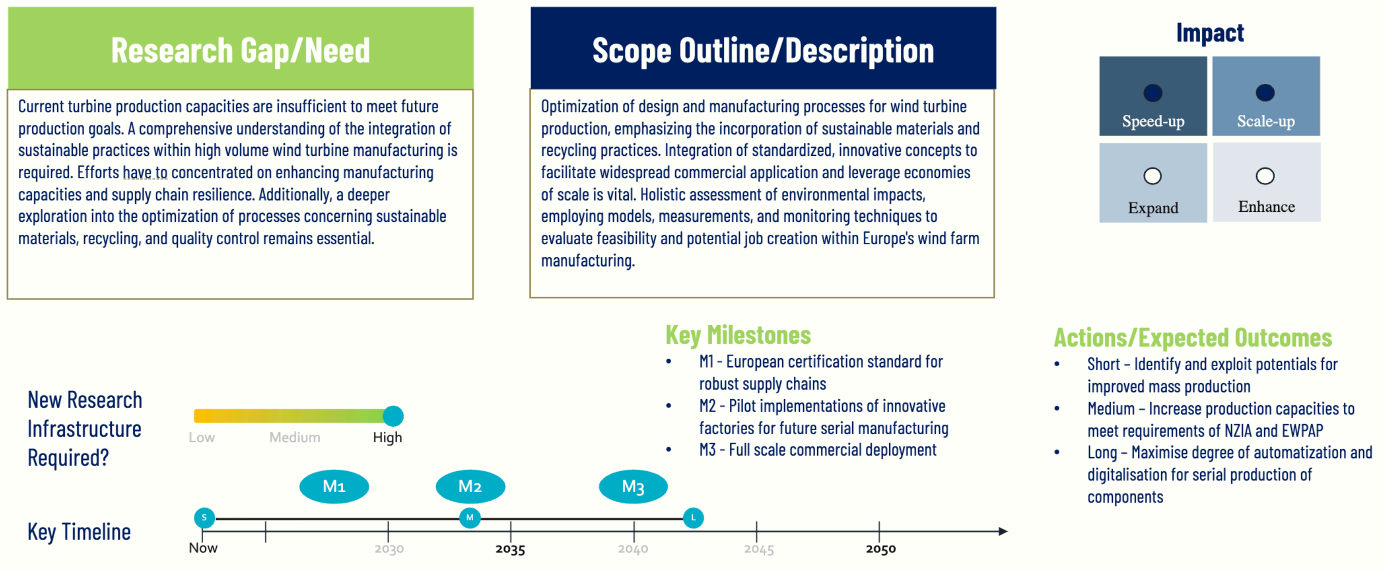
Delivering the project

The project has been conducted by executing five work packages (or chapters) that are presented in this report. Chapter 1 is all about establishing a baseline for the NeWindEERA research programme and presenting existing positions on relevant Net Zero emissions and climate change targets as well as reviewing key milestones identified in sector leading reports and strategies such as IEA Net Zero and REPowerEU Plan.

Building on the findings of Chapter 1, Chapter 2 provides an overview of the state-of-the-art research on wind energy and by doing so, also identifies the research gaps that need to be filled with the NeWindEERA research programme. It became clear in this work that each of the five priority areas would need several sub-themes and research topics that needed defining. It also became clear that the programme would introduce a sixth priority area focusing on cross-cutting research themes.

Moving onto Chapter 3, the main objective here is to build the NeWindEERA research programme and this is based around the five key priority areas mentioned earlier plus the sixth area focussing on cross-cutting issues. The programme has identified strong content in all six priority areas and for each priority area, this is framed as a series of sub-themes, each with one or more research topics identified. In total, this has resulted in six priority areas, 30 sub-themes, and almost 90 research topics. All in all, a significant research programme designed to navigate the wind sector for the next 25 years.

For each of the subthemes, an assessment is given using the following template where the research gap/need and scope outline/description are defined. Also defined are the key milestones and timeline required to address the need and the expected outcomes along the way. An assessment is also done with respect to the dependency on new research infrastructure and the anticipated impact of the research sub-theme on the wider wind sector.



In keeping with the ETIP Wind SRIA approach, impact has been assessed in terms of Speed-up, Scale-up, Expand, and Enhance where:

- **Speed-up** concerns actions needed to sustain and fast-track the immediate future growth of wind in Europe;
- **Scale-up** concerns actions needed to maintain competitiveness and deliver the required volumes;
- **Expand** concerns actions needed to make wind viable in more places; and
- **Enhance** concerns actions needed to continue improving the impact of wind energy in society and the environment.

Whilst Chapter 3 has been successful in developing a research programme with clear definition of research sub-themes and research topics, it is inevitable that the follow-on activity in delivering the programme will require further definition and granularity. Some examples are provided here:

1. **Testing floating wind:** There are several test facilities in Europe, both tank testing and real environment testing. We should consider an "Integrated European floating wind turbine testing programme"
2. **Interdisciplinary research:** The term "interdisciplinary" is addressed several times, but it is not represented as a sub-theme or research topic in its own right. For example, it would be interesting to connect "wind turbine design" to "wind energy systems integration" and "acceptability and co-existence". Essentially this could be considered a cross-cutting research theme.
3. **Aeroelastic design codes:** There are still quite large variations between the loads predicted by the different aeroelastic codes, even due to just shear and normal turbulence levels. These differences in the codes will lead to a suboptimal turbine design, so work needs to be done on better code alignment.
4. **Floating wind installation:** The successful roll-out of floating offshore wind is dependent on advance in several areas including installation and port infrastructure. This needs to be part of a new research programme, particularly when considering industrialisation and scale-up challenges.

With the NeWindEERA research programme established in Chapter 3, it is important to have a visual representation of the programme that can be shared with and understood by all stakeholders in the wind sector, not just those involved in delivering the research. This has resulted in a 12-page brochure launched in March 2024. The contents of the brochure are described in Chapter 4 and included in Appendix 1 of this report.

The final chapter of the NeWindEERA report, Chapter 5 relates to establishing a repository of existing projects, mapping the research currently addressing NeWindEERA programme. It has been recognised that a huge amount of valuable research and innovation addressing parts of the NeWindEERA research programme has already been carried out (or is ongoing). With that in mind, it is important to coordinate this work and continually track it so that it can be fully exploited and not unnecessarily repeated in the future.

What next?

With the NeWindEERA project now complete and the research programme established, attention now turns to how we deliver the programme. This is where the European Wind Energy Centre of Excellence (EuCoE4Wind) comes into play. Described as the third pillar of European wind energy research and innovation, the establishment of this centre of excellence is now perhaps the most crucial next step as it will provide a funded framework (vehicle) that will carry us on the journey in delivering the NeWindEERA programme and achieving Net Zero in 2050. Let's do it!

1. Wind Energy at the Core of a Net-Zero Strategy

This chapter was led by SINTEF with co-lead support from DTU and further contributions from Ciemat, CWD (RWTH Aachen) and ORE Catapult. The purpose of the chapter was to establish a baseline for the NeWindEERA research programme by analysing key documents and strategies relating to wind energy and the goal of Net-Zero.

Net-zero emissions have been put forward by many nations and governments worldwide to limit the climate change, making net-zero emissions a global goal. The European Green Deal[1] from 2019 aligns with this by setting the target to make Europe the first climate-neutral continent by 2050. Towards the overall goal of a climate neutrality, ambitious greenhouse gas emissions reduction targets for 2030 and 2050 were set. The associated European Climate Law[2] was adopted in 2021 to embed the targets in policies and legally binding objectives. According to the European Green Deal, climate neutrality shall be achieved while at the same time "boosting the economy, improving people's health and quality of life, caring for nature, and leaving no one behind"[3]. This requires concrete strategies supporting technological development to ensure a sufficient and reliable energy supply with net-zero emissions. Wind energy is expected to play a central role in the transition to clean energy.

This chapter identifies milestones related to wind energy in the IEA Net Zero[4] and REPowerEU Plan[5]. The IEA Net Zero scenario describes the global situation while the REPowerEU Plan focuses on the EU and associated states. The need for further development and research to reach the identified milestones is evaluated and explained.

The IEA Net Zero report is the world's first comprehensive study of how to transition to a net zero energy system by 2050 while ensuring stable and affordable energy supplies, providing universal energy access and a just transition, and enabling robust economic growth.

The REPowerEU Plan is a revised strategy to achieve the ambitions set out in the European Green Deal while phasing out the dependency on fossil fuels even faster.

1.1. OVERALL TARGETS

The key targets outlined by the European Commission in the European Green Deal1 are:

- To reach climate neutrality by 2050, i.e., to achieve net-zero greenhouse gas emissions.
- And by 2030, to reduce greenhouse gas emission by at least 55% compared to the levels of 1990.

These European targets are well aligned with the Net-Zero Emissions by 2050 Scenario (NZE) from the International Energy Agency (IEA) which demands that global energy-related and industrial process CO2-emissions fall by nearly 40% between 2020 and 2030 and to net zero in 2050. Universal access to sustainable energy is achieved by 2030. There is a 75% reduction in methane emissions from fossil fuel use by 2030 where wind and solar provide around half of emissions savings. They continue to

1 European Commission, *The European Green Deal*, COM (2019) 640 final, 11.12.2019
2 https://climate.ec.europa.eu/eu-action/european-green-deal/european-climate-law_en
3 European Commission, The European Green Deal, press release, https://ec.europa.eu/commission/presscorner/detail/en/ip_19_6691, Last access: 15 June 2023.
4 IEA, Net Zero by 2050. *A Roadmap for the Global Energy Sector*. Revised version, October 2021 (4th revision).
5 European Commission, *REPowerEU Plan*, COM (2022) 230 final, 18.05.2022.

deliver emission reductions beyond 2030, but the period to 2050 sees increasing electrification, hydrogen use and carbon-capture deployment, for which not all technologies are available on the market today, and these provide more than half of emission-savings between 2030 and 2050.

1.2. MILESTONES

The IEA Net Zero and REPowerEU strategies define several milestones providing pathways towards accomplishing the targets. These milestones are listed for each document.

1.2.1. IEA NET-ZERO EMISSIONS SCENARIO

Here, the relevant milestones among the 400+ listed to realise NZE Scenario are listed. They are broken down in accordance with the categories indicated in the original document.

Milestone 1:
Transforming low-emissions fuels

- *Low-carbon hydrogen production: 9 Mt H2 in 2020 à 150 Mt H2 in 2030 à 520 Mt H2 in 2050*
- *Electricity demand for hydrogen-related production: 1 TWh in 2020 à 3850 TWh in 2030 à 14500 TWh in 2030*

Milestone 2:
Transforming global electricity generation

- *Total electricity generation: 26800 TWh in 2020 à 37300 TWh in 2030 à 71200 TWh in 2050*
- *Wind shares in total electricity generation: 6% in 2020 à 21% in 2030 à 35% in 2050*
- *Wind to solar PV ratio in total generation: 195% in 2020 à 115% in 2030 à 105% in 2050*
- *Battery storage: 18 GW in 2020 à 590 GW in 2030 à 3100 GW in 2050*
- *Offshore wind investment (from Chapter 4) 9 billion USD between 2016-2020, 46 Billion USD between 2021-2030, 52 Billion USD between 2031-2040, 32 Billion USD between 2041-2050*

To transform the global electricity generation as defined in milestone 2, minerals and metals are critical because they are used in wind energy systems as in many other clean energy technologies. Thus, the clean energy transition and a developing (wind) energy sector require a sustainable and responsible utilisation of minerals[6].

1.2.2. REPOWEREU PLAN AND OTHER RELATED EU DOCUMENTS

Here, the relevant milestones for wind energy in the REPowerEU Plan are listed. They are broken down according to the categories indicated in the original document5. Milestones from other related EU documents are grouped to the milestones from the REPowerEU Plan.

The most prominent milestone in Europe's strategy towards climate-neutrality is the intermediary target for 2030 to have reduced greenhouse gas emission by at least 55% compared to the levels of 1990. The other milestones listed below support reaching this overall target for 2030.

From the three pillars outlined in the REPowerEU Plan, the acceleration of the clean energy transition is the most relevant for wind energy (section 3). In addition to the acceleration of the clean energy transition, the smart investment (section 4) is also relevant for wind energy research and development.

Milestone 1:
Boosting renewable energy

- *45% renewable energy generation by 2030, i.e., a total renewable energy generation capacity of 1236 GW. Wind energy, particularly offshore wind, is one of the key renewable technologies required to reach the milestone.[7]*
- *Share of renewable energy: 22% in 2021à 42.5% in 2030[8]*
- *Offshore wind capacity in Europe[9]: 12 GW in 2020 à 60 GW in 2030 à 300 GW in 2050*
- *Offshore wind capacity in North Seas (Ostend declaration)[10]: 120 GW in 2030 à 300 GW in 2050*
- *Offshore renewable energy is a core component of Europe's energy system by 2050[7]*
- *Floating offshore wind 7: 150 MW in 2024*
- *Floating offshore wind 7: reduce LCOE to less than EU 100/MWh in 2030*

[6] IEA, *The Role of Critical Minerals in Clean Energy Transitions*. World Energy Outlook Special Report. Revised version, March 2022
[7] Provisional deal (European Parliament, 30 March 2023): 42.5% share of renewable energy generation with sector-specific sub-targets (www.consilium.europa.eu/en/infographics/fit-for-55-how-the-eu-plans-to-boost-renewable-energy).
[8] European Commission, *Fit for 55 proposals, interinstitutional file 2021/0218(COD) from 19 June 2023*
[9] European Commission, An *EU strategy to harness the potential of offshore renewable energy for a climate neutral future*, COM(2020) 741 final, 19.11.2020
[10] *Ostend declaration of energy ministers on the North Seas as a green power plant of Europe*, signed by Belgium, Denmark, France, Germany, Ireland, Luxembourg, The Netherlands, Norway, and the United Kingdom 24.04.2023

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- *Long-term framework promoting co-existence and multiuse at sea[7]*
- *Competitive and resilient EU supply chain and industry[7]*
- *Long-term strategic maritime spatial planning that ensures environmental, social and economic sustainability, as well as coexistence and public acceptance[7]*

Milestone 2:
Accelerating hydrogen

- *10 million tonnes of domestic renewable hydrogen production and 10 million tonnes of renewable hydrogen imports by 2030*

Milestone 3:
Skilled people, raw materials and an improved regulatory framework

- *Predictable long-term legal framework towards a meshed offshore energy system[7]*
- *Electricity market rules considering energy islands and hybrid projects and offshore hydrogen production[7]*
- *Not more than 65% of the annual consumption of each strategic raw material at any relevant stage is from a single third country by 2030[11]*
- *Domestic capacity for mining and extraction of Strategic Raw Materials reaches at least 10% by 2030 (where sufficient reserves in the EU allow for this)*
- *Domestic capacity for processing and refining of Strategic Raw Materials reaches at least 40% by 2030*
- *Domestic capacity for recycling of Strategic Raw Materials reaches at least 15% by 2030*

Milestone 4:
European interconnection and infrastructure needs

- *Cross-border connections to build an integrated energy market*
- *Additional investments in the power grid: 5th list with Projects of Common Interest (PCI)*
- *Energy storage ensuring flexibility and security of supply in the energy system*
- *Development of crucial offshore grid*
- *Hybrid projects including energy islands and hubs, offshore energy generation and transmission in a cross-border setting, interoperability of national offshore systems*
- *Technologies to connect infrastructure in a meshed grid*
- *Common approach to grid connection requirements for high-voltage direct current (HVDC) grids: first multi-vendor multi-terminal HVDC system by 2030[7]*

1.3. KEY MILESTONES RELEVANT FOR WIND ENERGY & FURTHER RESEARCH NEEDS

The identified milestones define high-level targets whose achievement depends on a combination of political will to introduce necessary instruments and regulations, industrial commitment to invest into and deliver the required infrastructure and research efforts to advance needed knowledge and technologies. There is no distinct separation between these responsibilities, they are rather overlapping and characterised by complex interactions.

However, further research should focus on the most critical areas with the lowest technology readiness level. The remaining report follows the five thematic challenges that ETIPWind identified in 2023 when updating its Research and Innovation (R&I) priorities for 2025-2027:

1. Wind Energy System Integration
2 Operations & Maintenance and Digitalisation
3. Industrialisation, Scale-up and Competitiveness
4. Sustainability and Circularity
5. Skills & Coexistence

Moreover, a sixth overarching challenge is added to cover:

6. Cross-cutting Research

[11] European Commission, A secure and sustainable supply of critical raw materials in support of the twin transition, COM (2023) 165 final, 16.03.2023

Table 1. Matrix illustrating further research needs to achieve the identified key milestones relevant to wind energy, categorised into the thematic challenges of research and innovation priorities identified by ETIPWind.

	IEA Net Zero Milestone 1	IEA Net Zero Milestone 2	REPowerEU Plan Milestone 1	REPowerEU Plan Milestone 2	REPowerEU Plan Milestone 3	REPowerEU Plan Milestone 4
Industrialisation, Scale-up and Competitiveness	●	●	●	●		
Optimisation and further digitalisation of Operations & Maintenance		●	●			●
Wind Energy System Integration	●	●	●	●		●
Sustainability and Circularity		●	●		●	
Skills, Acceptability & Coexistence		●	●		●	
Cross-cutting Research Themes		●	●			

Table 1 provides a high-level illustration of the thematic challenges in which further research is needed to achieve the identified key milestones relevant to wind energy. A more detailed analysis of the state of the art and research gaps is provided in the next chapter.

2. Achieving a Net-Zero Society : Wind Energy Research Needs and Gaps

This chapter was led by DTU with co-lead support from CWD (RWTH Aachen) and further contributions from ORE Catapult, SINTEF and Ciemat. The purpose of the chapter is to identify the current state of the art for a wind energy research programme and establish the related research gaps that will need to be addressed by NeWindEERA to achieve wind energy and Net Zero goals by 2050.

This chapter aims to provide an overview of the state of the art (SoA) research on wind energy, building first and foremost on the outcome of Grand Challenges in the Science of Wind Energy publication series[12], and ETIPWind Strategic Research and Innovation Agenda (SRIA)[13]. It also includes the related research gaps and first indications of research priorities required to align with the IEA Net Zero and RePowerEU wind energy scenarios/targets, detailed in Chapter 1, following the themes outlined in SRIA by ETIPWind1 which is used as the framework to collocate and summarise the corresponding research topics.

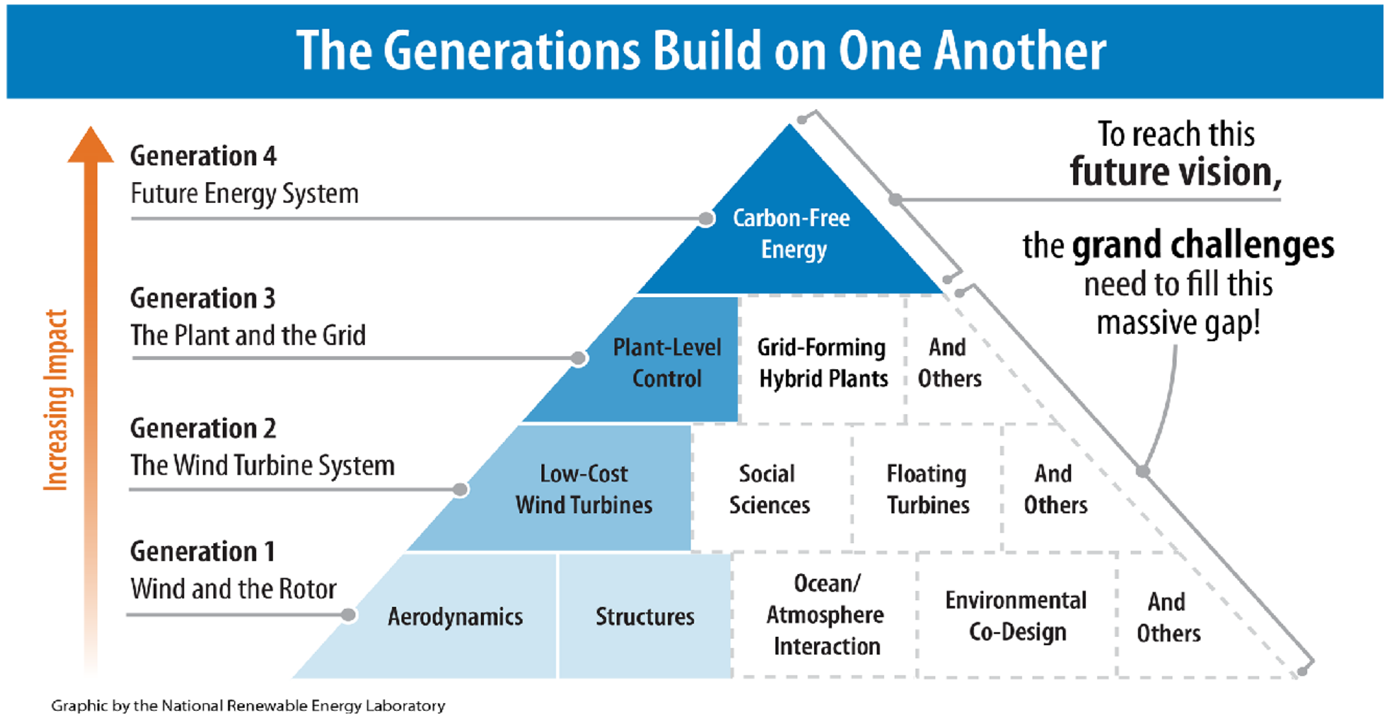
This chapter collects the relevant research needs recently identified in the context of ETIPWind and IEA, and develops each research theme with the perspective of the Net Zero and RePowerEU targets.

The energy sector must be decarbonized towards the goal of reducing greenhouse gas emissions to net zero. This requires electrification based on renewable energy sources. Wind power is considered one of the two key technologies to sufficiently increase the renewable energy production. As described in Chapter 1, the IEA estimates that the share of wind power must increase from currently 5% to 35-50% of the total electricity generation (IEA, 2021a) globally. If the additional wind power capacity was built using current design on component, plant and system level, as well as manufacturing and deployment technology, the social and environmental impact would multiply manifold. Further technology development is therefore essential to ensure that the defined goals are achieved in accordance with social and environmental requirements. As an example, today's wind turbines are neither designed to provide grid-forming and -stabilizing services. However, the provision of power system services is required to replace fossil-fuelled power plants while maintaining a reliable electricity supply.

An IEA Wind Topical Experts Meeting resulted in a review article[14] (which was later updated[15]) on the technical Grand Challenges for wind energy dividing them into three areas: the atmosphere, the turbine, and the plant. These technical challenges are expanded by the critical challenges of social[16] and environmental[17] impacts.

[12] Grand Challenges in Wind Energy Science, Grand Challenges Revisited: Wind Energy Research Needs for a Global Energy Transition (2023).
[13] European Technology and Innovation Platform on Wind Energy (ETIPWind). (2023). Strategic Research and Innovation Agenda (SRIA).
[14] Veers, P., Dykes, K., Lantz, E., Barth, S., Bottasso, C. L., Carlson, O., Clifton, A., Green, J., Green, P., Holttinen, H., Laird, D., Lehtomäki, V., Lundquist, J. K., Manwell, J., Marquis, M., Meneveau, C., Moriarty, P., Munduate, X., Muskulus, M., … Wiser, R. (2019). Grand challenges in the science of wind energy. Science.
[15] Veers, P., Dykes, K., Basu, S., Bianchini, A., Clifton, A., Green, P., Holttinen, H., Kitzing, L., Kosovic, B., Lundquist, J. K., Meyers, J., O'Malley, M., Shaw, W. J., and Straw, B. (2022). Grand Challenges: wind energy research needs for a global energy transition, Wind Energ. Sci., 7, 2491–2496
[16] Jeremy F. (2019). Wind energy: A human challenge. Science 366, 1206-1206.
[17] Katzner, T., Nelson, D., Diffendorfer, J. E. et al. (2019). Wind energy: An ecological Challenge, 366, 1206–1207. Meyers, J., O'Malley, M., Shaw, W. J., and Straw,

Figure 1. Generations of wind energy development (Veers, 2022)': Blue boxes refer to further advanced areas within each 'generation', while the white boxes indicate relatively newer research areas.



The figure illustrates the generations of wind energy and its development towards a future vision of carbon-free energy. White boxes show the main unresolved scientific issues.

A series of articles has been published in Wind Energy Science (WES) journal to summarize the state of the art and research needs, in particular:

- Grand Challenge 1: the atmosphere
  - Impact of atmospheric turbulence on performance and loads of wind turbines: knowledge gaps and research challenges
  - Mesoscale wind plant wakes
  - Scientific challenges to characterizing the wind resource in the marine atmospheric boundary layer
- Grand Challenge 2: the wind turbine
  - The design, manufacture, and operation of future wind turbine systems
  - Current status and future perspectives for small-wind-turbine technology
- Grand Challenge 3: the plant and grid
  - Wind-farm flow control: prospects and challenges
  - Grand Challenges of wind energy science – the grid
- Crosscut: digitalization
  - Grand Challenges in the digitalization of wind energy
- Beyond technical borders: environmental and social issues
  - Interdisciplinary research challenges in wind energy at the intersection of engineering and environmental science
  - Social aspects of wind energy development

Throughout 2023, ETIPWind has been collecting inputs from the wind energy community to update the Research and Innovation (R&I) priorities with the European Commission, covering 2025-2027. The challenges have been pulled into themes as detailed in Table 2.

Table 2. ETIPWind Research and Innovation (R&I) priorities with the European Commission, covering 2025-2027

1. Industrialisation, Scale-up and Competitiveness	Industrialisation of floaters for offshore wind
	Serial manufacturing of components for onshore/offshore wind and standardisation
	Automation and optimisation of manufacturing processes
	Dynamic sub-sea cables (manufacturing and repair solutions)
	Mooring and anchors for floating offshore wind
	Next generation power generators and disruptive technologies (e.g. new types of wind turbines)
	Supply chain logistics for decommissioning
	Mass-production
	Installation
	Assembly and heavy maintenance solutions for floating offshore wind
	Impacts of bigger rotors (and generators) in wind turbines
2. Optimisation and further digitalisation of Operations & Maintenance	Monitoring technologies
	Cross-border transport and transport of large components
	Ports infrastructure
	Automation for O&M and installation for offshore wind
	Integrated forecasting of power production and demand
	Digital tools for control and monitoring
	Digital solutions for smart operations
	Solutions to operate in extreme conditions
	Predicting environmental parameters
	Sensor technologies diagnostic and response
	Integrated verification of models for the balance of plant and turbine
	New installation methods or processes including low noise foundation installation technologies
	Control methods and park level control
	Cybersecurity

3. Wind Energy System Integration	Grid forming capabilities Flexibility on the transmission and generation side Renewable energy sources penetration in the energy system Long-duration energy storage, provision of ancillary services Hybridisation with other technologies (wind + solar + storage, etc) Quantification of system services and definitions Optimising transmission infrastructure Digitalisation of grids Solutions to avoid curtailment Modelling future system needs Development of new converters/systems for provision of system services
4. Sustainability and Circularity	Sustainable materials in design and recyclability by design Blade recycling, sustainability assessment and technologies to lower co2 footprint Impact on ecosystems and biodiversity Solutions for lifetime extension Development and validation of new components and materials (e.g., replacement of carbon-fibre) Reliability of secondary materials (e.g., recycled steel and copper) New recycling processes Noise reduction Material durability and protection
5. Skills & Coexistence	Education Skilling, re-skilling, and upskilling (focused on turbines but also planning Transport, etc.), solutions to improve acceptability and empowerment of citizens via socio-technical approach Coexistence with other communities (e.g., fishing) and demonstration of the benefits of windfarms for society Energy justice Higher degree specialisation for wind energy research

The rest of the chapter presents a brief outlook on the current state of the art and related research gaps, including the challenges and prospects per topic. These follow the ETIPWind R&I challenges listed above.

2.1. INDUSTRIALISATION, SCALE-UP AND COMPETITIVENESS

As the wind energy sector strives to meet the escalating demands for sustainable and clean energy solutions, it confronts grand challenges in industrialization, scale-up, and competitiveness. These challenges are intricately linked to advancements in wind turbine technology, a critical component in harnessing the power of the wind more efficiently and at a lower cost. This section delves into the pivotal role that cutting-edge turbine technology plays in addressing these challenges, where for the future wind turbine technology development, Veers et al.[18] state:

'Turbine sizes have gradually moved outside the design basis while design practice continues as though this change has a negligible effect. High safety factors have kept us safe, but … the large and flexible turbines entering the market today have pushed into territory where there are significant unknowns… Substantial opportunities for system improvement depend on resolving these issues.' Thus, further development of capabilities and further validation of modeling, methods and tools is required to enable design for other materials and operating conditions such as: connection to hydrogen plants, or operation either off-grid or as part of a wind farm where flow control technologies are applied.

Key trends in wind technology

The research gaps regarding turbine technology are divided into 7 areas (Veers et al.[19]):

- Inflow and design criteria (discussed in one of the following paragraphs)
- Control and co-design (Grid interconnect control and Wind farm control are covered in Sections 1 and 2 of this document): Challenges in control include probabilistic load control, where uncertainties in inflow as well as manufacturing variabilities are taken into account, as well as establishing fault-tolerant operational control.
- Aerodynamics and aeroelasticity: Margins to stability boundaries shrink with modern softer and more efficient designs, which means turbines operate closer to vibration phenomena that can potentially cause catastrophic structural failure. Further, existing low- and mid-fidelity models can't capture the physics well enough to predict those phenomena, such as complex instability modes or stall- and vortex-induced vibrations in standstill. The high Reynolds numbers experienced by modern wind turbine blade complicate validation of aerodynamic performance in wind tunnels, and gaps exist for predicting performance degradation due to surface erosion. Increasing rotor sizes and operation in wind farms lead to increasing variations of inflow across the rotor disc which require further validation of rotor aerodynamic models. Noise reduction techniques will be crucial, because increased blade tip speed leads to increased efficiency of the turbine, but the noise level depends on the fifth power of the blade tip speed.
- Wakes (assessed in Section 2 of this chapter)
- Offshore wind technology (discussed in one of the following paragraphs)
- Manufacturing and materials (discussed partly in Section 4 of this chapter, as well as in the following paragraphs): Improvements in inspection and structural health monitoring are needed, as is fundamental research, to define a better basis for assessing the progressive damage in components.
- High-fidelity modelling, high-performance computing and validation: High-performance computing used in high-fidelity, physics-resolving simulations offers opportunities to improve design tools, also through artificial intelligence and machine learning. However, even the high-fidelity tools are yet to be fully validated, which will require publicly available, high-fidelity experimental data.

[19] Veers, P., Bottasso, C. L., Manuel, L., Naughton, J., Pao, L., Paquette, J., Robertson, A., Robinson, M., Ananthan, S., Barlas, T., Bianchini, A., Bredmose, H., Horcas, S. G., Keller, J., Madsen, H. A., Manwell, J., Moriarty, P., Nolet, S., and Rinker, J. (2023). Grand challenges in the design, manufacture, and operation of future wind turbine systems, Wind Energ. Sci., 8, 1071–1131.

In line with this, Nejad et al.[19] identify the following technology trends in wind turbine drivetrain technology:

- Lighter and more compact design concepts to improve power density and thereby reduce LCOE
- Integration of electromechanical systems together with main bearings
- Extensive research of gearbox and bearing design, aiming for:
  - Improved reliability
  - Better understanding of failure modes
  - Accurate estimation of remaining useful life
  - Development of new technologies, e.g., plain bearing applications, design, and monitoring

Drive trains

Geared drivetrains are the predominant technology for onshore applications. There is still no clear winner (geared or not) for offshore applications, but a tendency to be observed towards direct-drive systems and PMSGs with full-power converter systems rather than DFIGs with partial-power-converter systems. Superconducting generators are also seen as an attractive alternative to PMSGs because of the large quantity of rare-earth materials needed for PMSGs. Geared offshore-drivetrains are under development, ranging from medium-speed over hybrid up to even high-speed concepts. Design disruptions of mechanical components include the increased use of plain bearings to enhance power density and split bearing concepts to improve replaceability and transportability.

Atmospheric conditions

Starting from the inflow and the design process of the turbines, a better understanding of the atmospheric boundary layer needs to be highlighted. This is particularly important where interactions with atmospheric stability as well as temporal and spatial changes in the inflow profiles (including veer, shear, and local turbulence) have fundamental impacts on design loading and need to be incorporated in modelling tools and design standards. Traditionally, the representation of such physical complexities is compromised to have an adequate simulation time. However, a future wind turbine probabilistic design paradigm would expand current design standards to include inflow parameters beyond mean wind speed and turbulence and bring us to reliability-centred maintenance. In that regard, inclusion of uncertainties and integrated dynamics via more holistic systems analysis and modelling methods (from purely physics-based approaches to advanced data-driven techniques, including high-performance computing) is key. To effectively establish a reliability-centred approach to turbine maintenance, a thorough comprehension of the underlying damage mechanisms within turbine components is paramount. This involves intricately mapping these mechanisms within computational models. The acquisition of precise input data derived from turbine operations ensures the accuracy of these models.

Testing and model validation

On the other hand, the development and validation of models with the help of system or component test benches is faster and more cost-effective. The reproducibility and open critical combination of load conditions (mechanical, electrical and chemical loads) is a major advantage. This method is used world-wide and system test benches are projected for new projects up to the 30 MW class. In the long term, however, the goal must be to develop a sufficiently accurate representation of the damage-critical mechanisms for the purpose of model validation, also on scaled and virtual tests. On that regard, the automation of manufacturing the turbines as well as components, structural and fleet-level maintenance, including inspection is an important challenge.

When dealing with standardized designs of turbines and components, it is imperative to engineer these elements with targeted countermeasures against prevalent issues, such as WEC (define WEC) or current passage. Relying solely on standards that have been empirically formulated and tested on smaller scales is no longer pragmatic, given the escalating dimensions of modern wind turbines.

Foundations and floating wind

For fixed-bottom turbines, reduction of LCOE via optimized installation and maintenance costs (onshore & offshore) as well as subsurface support structures (offshore) are important research areas. Floating technology brings additional challenges and opportunities where research and innovation is focused on integrated system design, floating platform architectures, mooring and anchoring strategies, as well as multi-fidelity/multi-level controllers to manage system dynamics.

Floating wind enables access to larger sea areas and better wind conditions and has huge potential to contribute to the energy

[19] Nejad, A. R., Keller, J., Guo, Y., Sheng, S., Pollinder, H., Watson, S., Dong, J., Qin, Z., Ebrahimi, A., Schelenz, R., Guzmán, F., Cornel, D., Golafshan, R., Jacobs, G., Blockmans, B., Bosmans, J., Pluymers, B., Carroll, J., Koukoura, S., Hart, E., McDonald, A., Natarajan, A., Torsvik, J., Moghadam, F. K., Daems, P.-J., Verstraeten, T., Peeters, C., Helsen, J. (2022). Wind turbine drivetrains: state-of-the-art technologies and future development trends, Wind Energ. Sci., 7, 387-411.

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EERA European Energy Research Alliance Wind Energy

transition, with around 150 GW of installed capacity projected by 2050. However, the technology is not matured, resulting in non-competitive costs compared to bottom-fixed offshore wind. Key measures to drive the LCOE down include more standardized designs and large series production of the substructure, as well as improved offshore installation.

To overcome the barriers for large-scale deployment of floating wind energy for all European sea conditions and to drive the cost down, SETWind[20] suggested a lighthouse initiative on Floating Wind Energy[21]. The scope of the suggested research programme comprises three overarching themes: knowledge sharing, open access to data and sustainable development; as well as five technical themes: external conditions, integrated design, control, logistics, grid connection. These eight themes can be detailed as:

1. Knowledge sharing includes the creation of tools, mobility programmes and access to research infrastructure.
2. Open access to data includes the specific goal to develop a data model of a multi-GW floating wind farm and an open-air scale model of a wind farm, with data being openly accessible according to the FAIR principles.
3. Sustainable development includes solutions on circularity, eco-friendliness, and social acceptance by involving all stakeholders and devising co-existence strategies.
4. External conditions relate to the Grand Challenge 1: the atmosphere[23].
5. Integrated design relates to the Grand Challenge 2: the wind turbine[23] to tackle the complex interaction of hydro-, aero-, structural- and electrical dynamics. However, to develop new and disruptive concepts, a holistic approach considering environmental impacts, manufacturing, installation, grid connection, operation and maintenance in the system analysis and design is required. This includes the development of integrated high-fidelity multidisciplinary modelling tools and their validation. Methods for hydrodynamic laboratory testing of farm level effects must be developed.
6. Control includes the provision of dynamic stability, improved power production and avoidance of critical structural loads. Floating wind turbines with their additional degrees of freedom challenge established control solutions. Measuring and estimating wind, currents and waves can contribute here. The wake effects on floating wind turbines and intra-wind farm wake effects represent another area for development, such as reduced-order models applicable to real-time wind farm control.
7. Logistics present large opportunities for substantial cost reduction through optimised installation and operation. Optimization is needed to find the best O&M strategy, necessary vessel and port infrastructure, and overall best organisation of the supply chain. This will trade off floater type, assembly site and towing route.
8. Grid connection includes the electrical collection and transmission system within the wind farm. Developments are required regarding:
   - new dynamic power cable technology to make them lightweight, affordable, and robust,
   - development of subsea wet-mate connectors and subsea junction box technology enabling easy connect/disconnect of single turbines, and more cost-effective installation and maintenance,
   - solutions for subsea substations as an alternative to floating substations,
   - advancement in transmission technology, both AC and DC solutions.

Connecting offshore wind farms to the grid raises technical challenges related to the design and operation of an offshore grid, including also advanced ancillary services from wind farms by grid forming capabilities to prevent adverse grid and component interactions. An optimization framework should be established to coordinate these services and the power transfer according to grid needs[22], legal and market constraints[23], and energy carrier options[24].

Small wind turbines and off-grid applications

In some remote, off-grid areas with excellent renewable resources, small wind turbines experience a continuous interest and deployment. In addition to the challenges discussed above, Bianchini et al.[25] discuss the challenges regarding electrical system integration of the small wind turbines as well as fostering public engagement, social acceptance, and deployment for global distributed wind markets. The critical obstacles for the small wind turbines in particular are their higher LCOE due to a lack of an 'economy of scales', resulting in high balance-of-station cost

[21] SETWind was a Horizon 2020 project which supports the implementation of the SET-Plan Implementation Plan for Offshore Wind. The proposal has been developed in consultation with the Temporary Working group that authored the Implementation Plan and key stakeholder organisations including ETIPWIND, WindEurope, EERA JP Wind Energy, the IEA Wind TCP and the European Commission's Joint Research Centre.

[21] Tande, J., Wagenaar, J-W., Latour, M. I., Aubrun, S., van Wingerde, A., Eecen, P., Andersson, M., Barth, S., McKeever, P., Cutululis, N. (2022) Floating Wind Energy, Proposal for European Lighthouse Initiative

[22] Trötscher, T. and Korpås, M. (2011), A framework to determine optimal offshore grid structures for wind power integration and power exchange. Wind Energ., 14: 977-992.

[23] Kristiansen, M., Muñoz, F. D., Oren, S., & Korpås, M. (2018). A Mechanism for Allocating Benefits and Costs from Transmission Interconnections under Cooperation: A Case Study of the North Sea Offshore Grid. The Energy Journal, 39(6), 209–234.

[24] Bødal, E. F., Mallapragada, D., Botterud, A., & Korpås, M. (2020). Decarbonization synergies from joint planning of electricity and hydrogen production: A Texas case study. International journal of Hydrogen Energy, 45(58), 32899-32915.

[25] Bianchini, A., Bangga, G., Baring-Gould, I., Croce, A., Cruz, J. I., Damiani, R., Erfort, G., Simao Ferreira, C., Infield, D., Nayeri, C. N., Pechlivanoglou, G., Runacres, M., Schepers, G., Summerville, B., Wood, D., and Orrell, A.(2022). Current status and grand challenges for small wind turbine technology, Wind Energ. Sci., 7, 2003–2037.

(~60%), alongside social acceptability and environmental issues (noise, visual impact, vibrations, electromagnetic fields, etc.). In addressing these challenges, key enabling actions include further studies on cost and life-cycle analysis, grid compliance and integration, storage systems, and shared programmes/incentives to support small wind turbine deployment with a special focus on social acceptability.

2.2. OPTIMISATION AND FURTHER DIGITALISATION OF OPERATIONS & MAINTENANCE

To provide affordable, stable, resilient and reliable green energy, the system science that brings wind turbines, wind farms and grid operations together is of great importance, as also highlighted by Veers et al. in the Grand challenges in the science of wind energy[2]. Such holistic consideration of the turbines' collective operation within a wind farm (as well as within clusters of wind farms and larger energy systems such as hybrid power plants) connected to the grid (referred to as wind farm control, WFC or park level control) typically includes mitigation of wake effects (referred to as wind farm flow control, WFFC) as well as advanced provision of grid services and enhancement of system stability (referred to as wind power plant control, WPPC)[26]. More recently, additional objectives and constraints such as variable electricity markets and revenue as well as environmental and social aspects that are relevant for wind park operation are also gaining interest. Additionally, higher level operation management of larger assets including hybrid power plants, floating wind turbines and far offshore wind power plants in the energy mix is an increasingly important research gap towards 2050 climate targets.

Wind Farm Flow Control

For WFFC, the main challenges and current research gaps indicated in Meyers et al.[27] are categorised into:

1. **Flow control physics** for both the (quasi-)static and dynamic control; including the characterization of the (deep array) wake shape and associated dynamics for further wake mixing, optimisation-friendly representation of turbines' structural loads, and control of meso-scale effects (e.g., farm-to-farm wake control).
2. **Algorithms and Artificial Intelligence (AI)** for both open and closed loop control; including model/algorithm selection and adaptability of the controllers, advanced state estimation, synergies with AI and its associated limitations (e.g., generalizability and feasibility of the algorithms, cyber-security, explainability, etc.), digital/virtual twins, smart sensors for enhanced monitoring and control (e.g. virtual sensors), and external sensors.
3. **Validation and implementation of WFFC technologies;** including numerical challenges in high fidelity simulations for initial concept approval, scalability and representability of the wind tunnel experiments, and lack of standardisation or systematic processes for field validation as well as certification of the technology.
4. **Co-design;** including the transition from LCOE (Levelized Cost of Energy) to value-based metric(s) while exploiting the interaction between control and design towards multi-objective integrated controllers for wind and energy systems optimization.

Atmospheric conditions in wind power plants

An important part of wind power plant design and (intelligent) operation is the assessment of wind conditions and resources, as well as turbine(s) response, under complex atmospheric phenomena. Valuable progress has been made to characterise wind conditions and resources in terms of estimating wind power plant performance throughout its lifespan at various timescales. However, particularly for wind conditions and resources offshore, where the turbines are getting taller and larger in rotor diameter, major challenges remain as listed by Shaw et al.[28]

- **The marine atmospheric boundary layer** is poorly observed,
- **Air-sea interaction** is a highly complex process involving nonlinear feedback between winds and waves,
- **Current-driven Sea Surface Temperature (SST) variations** cause changes to the thermodynamic stratification and impact mean and turbulent flow at the rotor heights,
- **Effects of coastal boundary between land and sea,** such as low-level jets, need to be taken into account as these impact resources and structural loads,

[26] Eguinoa, I., Göçmen, T., Garcia-Rosa, P. B., Das, K., PetroviĆ, Vl., Kölle, K., Manjock, A., Koivisto, M. J., & Smailes, M. (2021). Wind farm flow control oriented to electricity markets and grid integration: initial perspective analysis. Advanced Control for Applications: Engineering and Industrial Systems, 3(3).
[27] Meyers, J., Bottasso, C., Dykes, K., Fleming, P., Gebraad, P., Giebel, G., Göçmen, T., & van Wingerden, J-W. (2022). Wind farm flow control: prospects and challenges. Wind Energy Science, 7(6), 2271-2306.
[28] Shaw, W. J., Berg, L. K., Debnath, M., Deskos, G., Draxl, C., Ghate, V. P., Hasager, C. B., Kotamarthi, R., Mirocha, J. D., Muradyan, P., Pringle, W. J., Turner, D. D., and Wilczak, J. M. (2022). Scientific challenges to characterizing the wind resource in the marine atmospheric boundary layer, Wind Energ. Sci., 7, 2307–2334.

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- Lack of clarity on best approaches for **ocean and the atmosphere coupled modelling and how data-driven approaches** can be applied advantageously for such applications,
- Limited ability to simulate precipitation **drop size distribution,** which is a main driver of leading-edge erosion on wind turbine blades and can be particularly important offshore.

To address these challenges, the following recommendations of actions and research needs are listed.

The role of observations

More observations are needed to improve the understanding of physics, and provide detailed validation databases to guide and quantify the model development and improvement. Such observations include:

- Large-scale, longer term (multi-season) field studies,
- Adaption of land-based measurement systems for use at sea,
  - Including remote sensing as a more cost-effective manner to obtain data, such as Doppler radar and lidar systems, multi-channel infrared profiling systems and microwave radiometer systems
- More quantities characterizing the Marine Atmospheric Boundary Layer (ABL) need to be measured, including boundary layer height, turbulence, eddy correlation measurements (fluxes), drop sizes and breaking waves.

Resources assessment modelling improvements

Model improvements are needed through research endeavours in:

- Coupling atmospheric models to microscale models, including 2-way modelling,
- Systematic investigation of model sensitivities using uncertainty quantification and implementation of data-driven approaches, also to improve practical value of wind resource modelling,
- Improvement of sub grid-scale parameterizations especially in atmospheric models,
- New data assimilation methods, in particular for ocean-atmosphere models to improve forecast of conditions,
- Adoption of the model improvements in operational modelling as the operational models are the foundation of many derived datasets created and tailored for use in the energy community.
- Combination with real-time capable digital twins for prediction of load conditions, as well as control and maintenance strategies.

Modelling large scale impacts

Further to these challenges and research needs, if the anticipated substantial deployment of offshore wind energy takes place in the form of much larger wind farms in wind farm clusters, located around energy islands, it will be of great importance to be able to model the large-scale impacts of these farms on the wind resources themselves and on the environment in general, via mesoscale models of the atmosphere. In Fischereit et al.[29] the following challenges and opportunities are stated:

- More observations (including long-term measurements) of flow close to wind farm clusters for model validation.
- Validated improvement of mesoscale modelling in general to capture the flow characteristics surrounding the wind farm clusters; for example, boundary layer height and inversion strength can have a big impact on wake behaviour.
- Improvement of the wind farm parameterizations in the mesoscale models to capture the impact on the flow of turbines, which are at sub grid-scale for these models.

When considering the challenges of mesoscale models and wind resource assessment and associated research gaps, Fischereit et al and Clifton et al[30] have identified the following challenges and opportunities:

- **Flow observation:** More observations (including long-term measurements) of flow close to wind farm clusters for model validation.
- **Mesoscale modelling validation:** Validated improvement of mesoscale modelling in general to capture the flow characteristics surrounding the wind farm clusters; for example, boundary layer height and inversion strength can have a big impact on wake behaviour.
- **Wind farm parameters:** Improvement of the wind farm parameterizations in the mesoscale models to capture the impact on the flow of turbines, which are at sub grid-scale for these models
- **Site prospecting:** At this point, the low accuracy of global or national wind data sets has to be solved, where it is necessary to search for very efficient prediction methods to obtain high accuracy of mean wind speeds. This must be resolved in combination with a scarce availability of local GIS

[29] Fischereit, J., Brown, R., Larsén, X.G. et al. (2022). Review of Mesoscale Wind-Farm Parametrizations and Their Applications. Boundary-Layer Meteorol 182, 175–224.
[30] Clifton, A., Barber, S., Stökl, A., Frank, H., and Karlsson, T. (2022). Research challenges and needs for the deployment of wind energy in hilly and mountainous regions, Wind Energ. Sci., 7, 2231–2254.

data, and a lack of local information on wind turbine icing and the evaluation of its potential risk.

- **Wind resource assessment:** With respect to wind resource assessment, the main challenges are related to the development of improved atmospheric models and reliable Measure-Correlate-Predict (MCP) processes for complex terrain. But there are also a lack of guidelines and planning tools, uncertainty and bias in the instruments need to be reduced, and the use of remote sensing and scanning wind lidar systems needs to be improved. Finally, it will be necessary to integrate the information provided by airborne measurement systems.
- **Interaction with wind farm design:** At this point it is necessary to enhance and require more information for the study of wind farm design to reduce the uncertainty of mathematical models of wind turbine performance using machine learning or multivariate analysis of parameters, where the main agents have tools to understand possible conflicts of an economic nature, noise emissions, etc.
- **Interaction with wind turbine design:** At this point it is necessary to obtain data on complex sites to better understand the operating conditions of both the rotor inflow and its mechanical characterization to improve and validate aeroelastic model tools. In this sense, standardised operating conditions for complex terrain is of high importance, as well as cheap and accurate tools to estimate operating conditions. It is also necessary to address the lack of specific standards for testing power curve and mechanical loads in complex terrain and cold climates.
- **Interaction with wind farm operation and maintenance:** It is necessary to work on writing standards for the verification of wind farm performance in complex sites using nacelle mounted lidars, as well as to improve wind prediction both at farm and turbine level by development of multi-parameter power prediction tools and to improve the forecasting of icing and its impact on the energy production of a wind farm.
- **General challenges:** It has been identified that it is necessary to work on a clear definition of what is called complex terrain, to improve the exchange of data from the range of sectors that allow us to know the physical processes occurring in complex terrain. For this purpose, it is necessary to create more test plants in mountainous terrain to obtain reliable data to address this challenge.

Legislative and regulatory issues

In addition to these technical challenges with ever-growing wind energy deployment, there exists a number of legislative and regulatory issues that are becoming increasingly important. They involve developing a new set of regulatory frameworks for even larger scale integration of wind (and other renewable and non-renewable energy resources[31] and storage, as well as P2X technologies, e.g., in energy islands), rules regarding conflict with other sea users, and wind farm densification and clustering[32], especially in North[33] and Baltic Seas. The neighbouring wind farms with different owners/operators will have an effect in terms of local wind resources for which a comprehensive and consensus-based legislation is currently lacking. The study on whether offshore bidding zones for electricity markets and agreements concerning the sale of power to avoid wind wake effects ought to be conducted[34]. Similarly, common practices for data sharing among these interacting wind farms and other energy sources are also needed for an efficient digital-green transition across Europe.

Digitalization

(Further) Digitalisation of the wind energy research, development, demonstration and deployment has great potential to increase reliability, reduce costs, generate new business models with new stakeholders, and enable efficient integration of wind energy as the primary renewable energy source. Digitalization in the product development process is also a significant advantage with regard to the multidisciplinary development of the wind turbine itself. Models and model chains must be built and linked in such a way that different questions can be answered with different model qualities in the early development phases. To this end, model-based systems engineering is being used at the cutting edge of research and in initial industrial projects. The main challenges and research gaps as listed in Clifton et. al.[35] are categorised into:

1. **Data;** including the definition, quantification and maximisation of the value of data in wind and energy systems workflows, implementation of FAIR strategies (i.e., making data Findable, Accessible, Interoperable, Reusable) for the funding organisations, data owners, end users and R&D dissemination platforms, data tenancy and cyber-security practices. A practical example of it would be the creation of open databases of technology performance to address reliability and optimization in an effective way including onshore, offshore wind power plants and hybrid power plants.
2. **Culture** towards a *digital mindset*; including digitalisation initiatives at the organisational level, digital upskilling and continuing education, increased diversity, equity, and inclusion (DEI) to maximise the potential for digital innovation.
3. **Coopetition** (a term combining parts of **Coop**eration Comp**etition**) that enables efficient collaboration and fair competition; including open-source tools and frameworks to accelerate collaboration, reproducibility of the digital applications in wind energy sector, lack of common (open) data standards and/or systematic processes for licencing, data markets and benchmarking.

2.3. WIND ENERGY SYSTEM INTEGRATION

The integration in the energy system of large-scale offshore wind energy is one of the biggest challenges facing the wind sector over the coming decades.

Different temporal and spatial scales

The main technical challenges towards 100% renewable energy generation in the European power or energy system are divided into temporal and spatial scales. For short-term applications, resilience to system level grid disturbances and external events towards further exploitation of inverter capabilities are important research gaps. For relatively longer timescales, short-term balancing via integrated and intelligent wind farm and energy market operations, are highlighted to address the demand for further flexibility in the system. For larger scales, diversification of renewable generation across a range of technologies (e.g., with low-wind technology, hybrid power plants and P2X systems) will be an important factor for long term balancing, especially with weather becoming increasingly important for regional and global energy production. On that regard, development of frameworks and testing methods for components, turbines, and performance assessment of hybrid power plants including storage is a crucial challenge to address. For system integration in general, digitalisation is seen as a crucial enabler for the transition from intelligent turbines to intelligent power plants and ultimately to intelligent operation and design of wind and energy systems.

European lighthouse initiative on grid integration

EERA JP Wind, as part of the SETWind project, looked at the challenge of wind energy system integration as part of a proposal for a European lighthouse initiative5. The report content was the result of extensive communication (including dialogue, workshops, and presentations) with key stakeholders who included representatives from industry, public bodies and the research community. The Integration of Large-Scale Offshore Wind Energy report tackled the subject of wind energy system integration from three perspectives: Excellence, Impact and Implementation. The Excellence section provides a state-of-the-art basis for a European lighthouse initiative for wind energy system integration. It recognises the significant part that European offshore wind will play in reaching 2050 climate goals (namely, offshore wind will supply 35% of electricity demand, a twentyfold increase on the current capacity status). This will require extensive research and innovation to develop offshore grid infrastructure, new solutions for the operation and design of offshore wind farms, new flexibility technologies, and offshore wind energy coupled with hydrogen production. The Excellence section also recognises the conceptual shift towards wind energy hubs (large offshore power clusters interconnected to each other) and the opportunity for economic benefits by supporting new green jobs and business across Europe; 'large scale integration of offshore wind is essential to reach climate targets, to secure the energy supply and to enhance a competitive European industry'.

New technologies, circularity

The Impact section explains the value of the proposed lighthouse initiative. It considers the challenges and ambitions of wind energy system integration recognising that the technology must be circular and ecologically friendly. It also recognises that a continued strong commitment towards deployment, industry development, and research and innovation will 'secure and maintain European leadership in offshore wind'. Regarding technology development, the report recognises this is an essential factor for a wind dominated European energy system; technologies including black start and fast frequency response capability as well as advanced control and monitoring systems for improving power production prediction and wind farm operation optimisation feeding into a stable power system.

[31] Herrera Anchustegui, I., & Glapiak, A. (2023). Wind of change: A Scandinavian perspective on energy transition and the 'greenification'of the oil and gas sector. In Regional Approaches to the Energy Transition: A Multidisciplinary Perspective (pp. 49-74). Cham: Springer International Publishing.
[32] Finseraas, E., et al. (2022) Gone with the wind? Wind farm-induced wakes and regulatory gaps. (December 6, 2022)
[33] Müller, H. K. (2015). A legal framework for a transnational offshore grid in the North Sea. PhD Thesis, University of Groningen.
[34] Kenis, M., Lanzilao, L., Bruninx, K., Meyers, J., & Delarue, E. (2023). Trading rights to consume wind in presence of farm-farm interactions. Joule.
[35] Clifton, A., Barber, S., Bray, A., Enevoldsen, P., Fields, J., Sempreviva, A. M., Williams, L., Quick, J., Purdue, M., Totaro, P., and Ding, Y. (2023). Grand challenges in the digitalisation of wind energy, Wind Energ. Sci., 8, 947–974.

Energy conversion and storage technology development will also be key to address the surge in increased capacity, the realisation of an integrated energy system and the provision of system flexibility. This may involve offshore grid infrastructure combining electricity and gas and a key technology in this space will be hydrogen. Indeed, as stated in the Offshore Renewable Energy Catapult's Solving-the-Integration -Challenge report[36] from 2020, which was supported by the Offshore Wind Industry Council, the UK alone may need 130 TWh to over 200 TWh worth of hydrogen in 2050 to help connect over 75 GW of offshore wind, and that the resulting green will be cost competitive with blue hydrogen. Europe is planning to connect around 450 GW of offshore wind by 2050[37], and the largest single national contributor will be the UK (at around 75-100 GW).

Investment needs

The Impact section also considers the extremely attractive value proposition that offshore wind offers. It is estimated that €800 billion of investment will be required to reach the EU ambitions for offshore wind development by 2050[38]. A 1% saving in this investment (€8000 million) would be about 200 times the cost of a lighthouse initiative on the integration of large-scale offshore wind energy; such an initiative would provide economic and sustainable knowledge and solutions, more reliable and efficient operation of the power system, and new green jobs in industry and goods and services to markets outside Europe.

The final perspective of the report considers Implementation. It proposes a programmatic and action-driven approach. This approach will benefit from a clear research programme, such as that under development in the NeWindEERA project. The Implementation section also scopes out the key topics of the research programme: knowledge sharing; open access to data; sustainable development; flow physics of wind farms; grid connection; integrated control of wind farms, including the interactions in wind farm clusters, and larger energy systems; market solutions; and power to X. The grid connection topic recognises the need to develop alternating current (AC), direct current (DC) and hydrogen-based technologies, including capabilities around modelling, cost reduction and failure prediction. Meanwhile, the wind farm control topic highlights the need and value of ancillary service provision and the development of solutions that recognise the offshore wind farm as a grid forming asset rather than a grid following asset. Finally, the power to X topic highlights the need to account for sector coupling. This includes several sub-topics including hydrogen conversion or other power to X options; storage options; re-purposing of existing gas infrastructure, energy islands; and energy transportation.

In summary, the Integration of Large-Scale Offshore Wind Energy report provides a vision that offshore wind will be a cornerstone of our future energy system and wind energy system integration is a key theme for the NeWindEERA research programme. The report, through its proposal for a lighthouse initiative, provides a summary of the areas where solutions need to be developed to ensure reliable and affordable power system operation in 2050 with offshore wind energy providing one third of the European electricity. The research and innovation proposed covers offshore wind farms, grid infrastructure and flexibility technologies and thus provide strong steer for the major research themes and research gaps that need to be included in an updated EERA JP Wind research programme.

2.4. SUSTAINABILITY AND CIRCULARITY

Wind turbines are still comparatively material-intensive and require the use of high-grade materials such as copper or rare earths. There is thus a need to further reduce the overall material requirements of wind turbines, especially regarding the high-grade and rare materials[39] With a significant proportion of the installed wind turbines approaching the end of their lifetime between 2020 and 2030 globally, end-of-life management, particularly for the blades, becomes increasingly important. So far, maintenance, reuse and repair/refurbishment solutions are found to be advantageous in several aspects compared to recycling or new materials[40]. There is ongoing research further developing these solutions, especially for the shorter-term end-of-life management strategies. However, new recycling technologies as well as new generation of wind turbine blade materials are steadily reaching higher technology readiness levels (TRL), though a number of technical and legislative challenges remains. Research, innovation, and implementation needs regarding the end-of-life management of wind turbine blades listed by Beauson et al.[22] are summarised below, followed by a representative value chain assessment for the end-of-life management decisions regarding turbine blades.

[36] Spyroudi, A., Wallace, D., Smart, G., Stefaniak, K., Mann, S., Kurban, Z. (2020). Offshore Wind and Hydrogen, Solving the Integration Challenge.
[37] Tande, J., Wagenaar, J-W., Vrana, T., van Wingerde, A., Eecen, P., Andersson, M., Barth, S., McKeever, P., Cutululis, N. (2022) Integration of Large-Scale Offshore Wind Energy, Proposal for European Lighthouse Initiative
[38] European Commission press release: Boosting Offshore Renewable Energy for a Climate Neutral Europe, IP/20/2096, 19 November 2020.
[39] Carrara, S., Alves Dias, P., Plazzotta, B., Pavel, C. (2020), Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system.
[40] Mishnaevsky, L. (2021). Sustainable End-of-Life Management of Wind Turbine Blades: Overview of Current and Coming Solutions. Materials 14, no. 5: 1124. .

- Assessment of the **damage state** and turbine properties, including development and validation of new methodologies to inform reuse and/or repurposing applications.
- **Alternative design solutions** for wind turbine blades, including new materials and structures taking the end-of-life processing (e.g., recycling, disassembly, etc.) into account, towards design for sustainability.
- Determination of new and existing **applications for recycled materials**.
- Holistic life cycle assessment on different turbines and recycling strategies to identify and support **environmentally preferable solutions**.
- New set of standards and guidelines on decommissioning and holistic design of wind turbines, considering the readily available and upcoming recycling solutions, towards development of sustainability certification and standardization as the end goal.
- Better estimation of the **second-hand market** for wind turbine(s) and its components, as well as the corresponding waste assessment. Generation of **new business models**.

Decisions	Economic	Technical feasibility	Legislation	Environmental impacts
Decommissioning **OR** continued operations?	Is it profitable to continue operating the turbine	What is the damage state of the wind turbine blades?	Can the turbine continue its operations where it is installed?	What are the environmental impacts of continuing the operations vs decommissioning?
Reuse **OR** end-of-life processing?	Can the blade be sold as spare parts?	What is the damage state of the wind turbine blades?	Are there legislation preventing reuse (second hand market)?	What are the potential environmental impacts of extending the lifetime of the blade by reusing it?
Recycling **OR** disposing?	What is the landfill tax? What is the value of the materials in the wind turbine blades and the recycled ones?	Is it possible to recover materials with properties and quality valuable to any applications?	Are there legislation preventing landfill? Are there legislation on the use of recycled wind turbine materials for targeted applications?	What are the potential environmental benefits and impacts of recycling the blades vs. disposing them?

Figure 2. Representative value chain assessment of the end-of-life of wind turbine blades[41]

[41] Beauson, J., Laurent, A., Rudolph, D.P. and Jensen, J.P. (2022). The complex end-of-life of wind turbine blades: A review of the European context. Renewable and Sustainable Energy Reviews, 155, p.111847.

Sustainability assessment in a more general sense, is an increasingly growing research field. Some indicators and guidelines can potentially inform the wind energy sector as well, although more investigation is required in the area. An interesting example for such a framework for defining social sustainability indicators is presented by Heide et al[42].

2.5. SKILLS, ACCEPTABILITY & COEXISTENCE

The success of the wind energy research and innovation to reach the 2050 energy goals highly depends on how society engages with the development of wind power infrastructure. Therefore, in addition to the challenges listed in technical domains earlier, there is a strong need for (further) research in social domains and how to connect them. Kirkegaard et al.[43] explore these socio-technical interactions with an interdisciplinary perspective and raise several considerations to set the scene:

- **Socio-spatial consequences** of further wind deployment, including land-use and intensified search for wind farm sites as well as site-specific socio-economic impacts and benefits;
- **Social effects of upscaling,** including the ever-growing unavailability/unfeasibility of small(er), urban-friendly wind turbine designs, increased visual impact and marginalisation of small-scale investors;
- **Human role in the system design,** including the (wind energy) consumer behaviour in smart grid concepts and adequacy of price incentives, flexibility and demand-side management, privacy and security as well as prosumers and renewable energy communities.

Corresponding socio-technical research gaps, considering the full life cycle of wind power, include:

- Energy justice and democracy in the distributional issues of project planning and development
- Co-design of the technology by engaging the societal stakeholders, and considering the social, cultural and historical context in the local operation management of wind power plants
- Addressing the concerns and expectations of the future where the wind turbines and sites have a finite lifetime.

To address these complex technical and societal challenges and support Europe's digital and green transition, interdisciplinary education programmes are needed to future-proof the careers of Science, Technology, Engineering and Math (STEM) professionals in wind and energy systems. Several higher education programmes, including the EU Marie Skłodowska-Curie Actions, aim to deliver excellence through cooperation and partnership, also boosting the geographic range, gender, and diversity for learners and educators in Master of Science (M.Sc.), Masters, PhD, Lifelong Learning and beyond. An important aspect for (re- or up-) skilling within wind energy education is (further) inclusion of digital skills, as what is today considered advanced digital skills will over time become essential digital capacities taken for granted in any technical, environmental, or social disciplines. There are several projects and programmes addressing such immediate needs and they will be further detailed in Chapter 5 of NeWindEERA.

2.6. CROSS-CUTTING RESEARCH THEME

Although partially addressed in areas of the five Research Themes elaborated in the previous sections, NeWindEERA proposes the cross-cutting topics below to identify additional challenges and explicitly convey the important research needs:

- Climate, Atmosphere, Ocean and Geophysics
- Disruptive technologies
- Policy and regulation
- Social Aspects
- Finance

2.7. SUMMARY

In this chapter, findings from recent publications and efforts to assess the state of the art and to identify challenges and research gaps have been reviewed and collectively outlined for topic areas spanning Industrialisation, scale-up and competitiveness, Optimisation and further digitalisation of Operations & Maintenance, Wind energy system integration, Sustainability and Circularity, and Skills & Coexistence. The process has collected the highest priority research needs globally. This chapter forms the basis for the next chapter in which the research themes are elaborated further and initial recommendations on the research priorities are provided. Key milestones will be determined and a timeline for obtaining these are described.

[42] Heide, M., Skrøder, N. K. P., Steffen, S. F., Hauschild, M., & Ryberg, M. (2023). Framework for selecting and setting boundaries for social sustainability indicators in a life cycle perspective. In IOP Conference Series: Earth and Environmental Science (Vol. 1196, No. 1, p. 012080). IOP Publishing.

[43] Kirkegaard, J.K., Rudolph, D.P., Nyborg, S., Solman, H., Gill, E., Cronin, T. and Hallisey, M. (2023). Tackling grand challenges in wind energy through a socio-technical perspective. Nature Energy, pp.1-10.

NeWindEERA – A New Research Programme for the European Wind Energy Sector

3. A Research Programme for Wind Energy

This chapter was led by ORE Catapult with co-lead support from SINTEF and further contributions from DTU, CWD (RWTH Aachen) and Ciemat.

Having identified the research gaps (Chapter 2), this chapter tackles the challenge of taking Chapter 2 conclusions and linking the gaps into the key research theme descriptions. The descriptions in this chapter highlight the research topics and scope needed to fill gaps and the timelines and key milestones associated with the proposed activity. For each research theme (and associated research topics/scope), the chapter highlights the suggested actions/expected outcomes to address the research gaps established in Chapter 2. In terms of methodology, the NeWindEERA project has used online workshops to garner input from the full JP Wind membership regarding their views on appropriate research themes and key milestones. The project has also strongly aligned the research themes with the ETIPWind research themes identified in their SRIA[44] document published in December 2023. This results in the following six priority themes:

- R&I Priority Theme 1 – Industrialisation, Scale-up and Competitiveness
- R&I Priority Theme 2 – Optimisation and further digitalisation of Operations & Maintenance
- R&I Priority Theme 3 – Wind Energy System Integration
- R&I Priority Theme 4 – Sustainability and Circularity
- R&I Priority Theme 5 – Skills, Acceptability & Coexistence
- R&I Priority Theme 6 – Cross-cutting Research Themes

The NeWindEERA consortium believes this alignment is very important to maximise the opportunity for industry support and co-funding as we look towards research programme implementation and the vision of a European Centre of Excellence for Wind Energy (EuCoE4Wind). The outcome of this activity is laid out in the five ETIPWind R&I challenges in the following sub-sections of this chapter as well as an important additional subsection on cross-cutting themes that will complement one or more of the five R&I challenge themes.

In other words, we add the cross-cutting themes as these concern research themes/topics that carry some of the foundational research that allows the other thematic areas 1 to 5 to be elaborated. These themes are extremely important to create the base for much of the research that is outlined in this chapter.

For example:

- Atmospheric, Ocean and Geophysics, in order to understand the natural world, both on its impact on the wind deployment but also on the wind deployment impact on nature.
- Disruptive Technologies, in order to monitor where the technologies may depart from those mapped out so far.
- Policy and regulation, in order to speed up yet enhance democratic principles.
- Social Aspects, in order to deliver better benefits to people everyday lives.
- Finance, in order to develop and explore best possible funding mechanisms for the huge volume of project needed.

Finally, when assessing the sub-themes identified for each of the six R&I priority themes, the impact of these sub-themes is assessed in terms of: Speed-up; Scale-up; Expand; and Enhance.

- 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.

Again, this allows strong alignment with the assessment provided by the ETIPWind SRIA document.

[44] European Technology and Innovation Platform on Wind Energy (ETIPWind). (2018). Strategic Research and Innovation Agenda (SRIA).

3.1. R&I PRIORITY THEME 1 – INDUSTRIALISATION, SCALE-UP AND COMPETITIVENESS

From the IEA's Grand challenges in the science of wind energy, we highlight:

- Design and manufacture of future wind turbines and turbine systems
- Interdisciplinary research challenges in wind energy at the intersection of engineering, social and environmental science

We have also highlighted aspects of ETIPWind's R&I priorities:

- Industrialization of floaters for offshore wind
- Serial manufacturing of components for onshore/offshore wind and standardisation
- Automation and optimization of manufacturing processes
- Dynamic sub-sea cables (manufacturing and repair solutions)
- Mooring and anchors for floating offshore wind
- Next generation gearboxes, power generators, and disruptive technologies (e.g., new types of wind turbines)
- Supply chain logistics for decommissioning
- Mass-production
- Installation
- Assembly and heavy maintenance solutions for floating offshore wind
- Impacts of bigger rotors, gearboxes, and generators in wind turbines

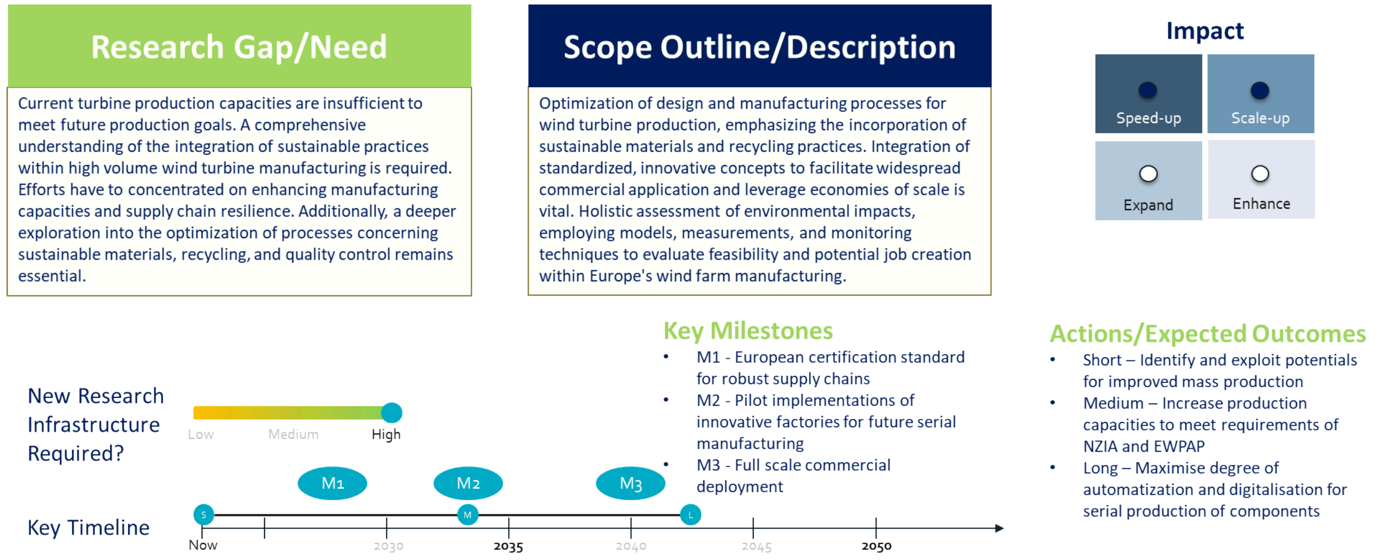
In addition to these, within this project, we have identified research topics around the State of the Art and future challenges:

- Future wind turbine technology development
  - Economic optimization for the entire lifecycle (reuse, repurposing, decommissioning, etc.)
  - Minimize the negative impacts of wind energy technology to its wider environment
  - Seamless techno-economic integration
  - Shortening the design cycle, reduced costs & faster adoption of new products
- Probabilistic design
- Small wind turbines
- Floating technology
  - Integrated system design
  - Floating platform architectures and mooring & anchoring strategies
  - Floating or subsea substations
  - Multi-fidelity/multi-level controllers to manage (additional) system dynamics
  - Logistics and optimization of O&M practices

	ST 1.1	ST 1.2	ST 1.3	ST 1.4	ST 1.5
Sub-Theme	**Mass production supported by automation and reliable supply chain**	**Design for large volume manufacturing and deployment**	**Design and testing for reliable and lasting products**	**Improve construction and installation methods**	**Adequate economic and financial conditions**
Topics	*T1.1.1 - Manufacturing for mass production* *T1.1.2 - Environmental Impacts* *T1.1.3 - Social Impacts*	*T1.2.1 - Next generation wind turbine technology and economic optimization* *T1.2.2 - Combination with other generation technologies* *T1.2.3 - Industrialisation of floating offshore wind*	*T1.3.1 – Holistic and accelerated turbine design* *T1.3.2 - Probabilistic design* *T1.3.3 - Virtual, scaled, and full-scale testing* *T1.3.4 - Small and Off-Grid Wind*	*T1.4.1 - Scaling up installation* *T1.4.2 - Assembly and heavy maintenance solutions*	*T1.5.1 - Adequate support policies* *T1.5.2 - Market design* *T1.5.3 – Impact assessment for value creation*

This multitude of challenges and applied research topics require that the underlying design and modelling tools continue to improve on various fronts. Modelling tools need to be computationally efficient, accurate and their uncertainties and validity need to be well understood and documented. This requires that research projects have a continuous focus on extensive model building, verification, and validation. In this industrialization phase of wind turbine technology development smaller efficiency gains are further obtained from integrated and holistic design and analysis process in which complex modelling approaches are coupled together in new ways.

3.1.1. R&I Priority Sub-Theme – Mass production supported by automation and reliable supply chain



3.1.1.1. Research Topic – Manufacturing for mass production

Research in wind turbine mass production and manufacturing necessitates improvements in automation and optimisation of serial manufacturing processes for components and systems. This requirement will place additional constraints on the wind turbine design and engineering process. The modelling tools used in the design process require continuous validation and alignment with the existing and newly planned automated production capabilities. A careful trade-off between turbine size and production capacity needs to be established for current and future turbine designs. Collaboration among suppliers and along the supply chain, standardization, modularization, and advanced materials are essential for efficient production. Additionally, research into recycling and quality control, along with market dynamics and policy research, will be crucial for achieving sustainable, cost-effective mass production of wind turbines. Efforts concentrate on scaling up manufacturing capacities, enhancing and testifying supply chain resilience, and embracing digitalization of production processes for both, components and turbines. Integration of sustainable, local materials together with near shoring and overall (rare) material reduction must be considered during the ramp-up of future European wind turbine production landscape. In the future, standardized innovative design and production concepts pave the way for widespread commercial application. This facilitates full-scale deployment, leveraging economies of scale through the mass production of modularized turbine components.

3.1.1.2. Research Topic – Environmental impacts of mass production

Research encompasses modelling, measurement, monitoring, and sharing of physical and biological environmental impacts of wind farm manufacturing processes to assess feasibility and sustainability within Europe. The comprehensive assessment of environmental impacts, combined with techno-economic considerations, ensures a holistic and robust approach to wind farm mass production. Key milestones are the estimation of environmental impacts of mass production for 2050 scenarios by 2025 as well as in depth assessment and mitigation approaches by 2030.

3.1.1.3. Research Topic – Social impacts of mass production

Research explores the interactions between society and manufacturing technology and infrastructure, emphasizing public benefits, participation, interaction and negative impacts. Assessment of social impacts, aligned with techno-economic considerations, contributes to evaluating feasibility, acceptance, and potential job creation and welfare within Europe. Required actions are the advancement of an energy justice frame by 2027, novel ways of informing modelling with qualitative data by 2030 and full understanding of social impacts across the entire lifecycle by 2035.

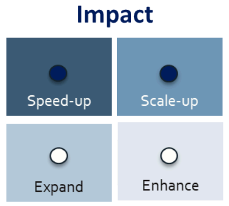
3.1.2. R&I Priority Sub-Theme – Design for large volume manufacturing and deployment

Research Gap/Need

Exploration of strategies to optimize next-generation wind turbine technology while simultaneously ensuring economic feasibility and suitability for large volume manufacturing. A deeper understanding of the trade-offs between technological advancements and economic viability is needed. There is a need to identify disruptive advancements that not only optimize power generation but also add substantial value to diverse applications of wind turbine technology. Finally, industrialization of floating offshore wind poses a impactful challenge to be solved.

Scope Outline/Description

Multifaceted approaches, including the evaluation of strategies for modularization and to integrate wind energy with other generation technologies. Emphasis should be placed on selecting and sizing technologies for seamless integration, advancing control and operation techniques, and adapting regulations for feasibility within the European context. Furthermore, the analysis extends to consider the implications of and requirements for hybrid and floating-offshore plant concepts on production and installation processes, investigating their cost-efficiency potential and market viability.

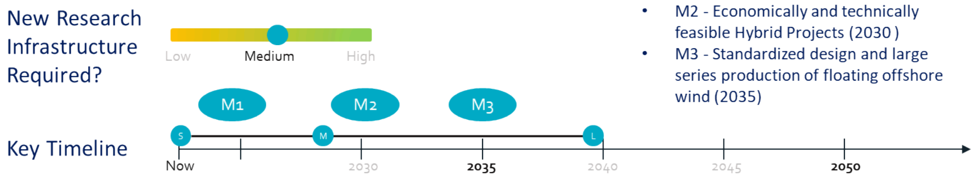


Key Milestones

- M1 - Ideal balance between turbine power and quantity (2025)
- M2 - Economically and technically feasible Hybrid Projects (2030)
- M3 - Standardized design and large series production of floating offshore wind (2035)

Actions/Expected Outcomes

- Short – assess potential of hybrid plants
- Medium – innovate holistic design approaches, focussing large volume manufacturability
- Long - Large scale validation of feasible floating solutions



3.1.2.1. Research Topic – Next generation wind turbine technology and economic optimization

This research delves into novel designs, materials, and control systems to optimize power generation, power density further reducing LCOE. By evaluating the trade-offs between technological advancements, economic feasibility, and a sustainability metric the aim is to identify strategies that maximize energy production and financial returns in future wind turbine technologies within the context of a sustainable and reliable supply chain. Disruptive advancements in this field can potentially add value to certain fields of application of wind turbine technology.

3.1.2.2. Research Topic – Combination with other generation technologies

Exploring hybridization and hydrogen projects involves assessing resource availability and market potential to identify lucrative opportunities for implementation. The crucial steps of technology selection and sizing are pivotal in ensuring the seamless integration of hybrid systems and hydrogen technologies within the existing infrastructure. The research focus is on evaluating the potential of combining wind energy with other generation technologies in Europe. Research emphasizes advancing control and operation techniques for hybrid power plants, validating their economic performance, and adapting regulations for feasibility.

Analysis of hybrid plant concepts extends beyond performance metrics to consider implications on production and installation processes. This exploration further investigates cost and efficiency potential alongside market viability. Key milestones include a European "Hybrids-potential map" by 2027, first best practice physical designs by 2030 and economically and technically feasible hybrid projects by 2035.

3.1.2.3. Research Topic – Industrialisation of floating offshore wind

A key ongoing challenge is to further drive down the lifecycle-based generating cost (LCoE) of floating wind, with industrialization of floater designs. The corresponding research involves the development, validation, and implementation of standardized simulation models for sustainable and economic design of different floaters, considering various dynamics, controllers, and loads. Additionally, integrated design of floater, mooring, grid infrastructure and WTs is required. A comprehensive understanding of the new load situation regarding strong coupling between mooring, cables and hydrodynamics is needed. Design adaptations for turbine components and drive trains like blades, blade bearings or main bearings may be required. New technology is further needed to connect floating wind farms to the grid, i.e., further development of dynamic electrical cables and floating or subsea substations. Transport and installation methods need verification. Finally, there is also a need for manufacturing and repair solutions for mooring, anchors and dynamic sub-sea cables. Key milestones are a significant cost reduction by 2030 and standardised design procedures for large serial production by 2035. The corresponding actions include the creation of an open-access data model of a multi-GW floating wind farm by 2027, an integrated design approach for floaters and turbines by 2030 and finally the large-scale validation of industrially feasible floating solutions by 2035.

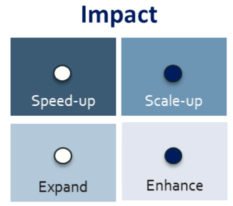
3.1.3. R&I Priority Sub-Theme – Design and testing for reliable and lasting products

Research Gap/Need

Achieving a holistic and accelerated turbine design process. There is a challenge in integrating components into a comprehensive, efficient design that considers uncertainties across the entire design chain and economic optimization. Further exploration into new technologies and methodologies is essential to improve design processes, emphasizing advancements in specific components to enhance overall system performance and cost-effectiveness. Integrating validated design and analysis tools into a multi-fidelity, multi-physics design process is crucial to showcase their utility in modern reference designs.

Scope Outline/Description

Developing and validating innovative design and testing principles to understand and mitigate modelling uncertainties, focusing on virtual, scaled and full scale testing and model validation as well as probabilistic analysis methods for failure mechanisms. Optimization strategies aimed at reducing material usage while ensuring reliability are imperative. Implementing these principles in new technologies fosters ongoing reliability and a holistic approach to system analysis and design. Outcomes encompass enhanced turbine performance, increased efficiency, improved reliability and safety, and reduced environmental impact.

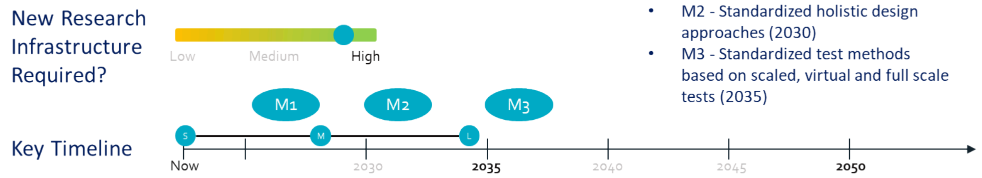


Key Milestones

- M1 - Scaling method for complete components (2027)
- M2 - Standardized holistic design approaches (2030)
- M3 - Standardized test methods based on scaled, virtual and full scale tests (2035)

Actions/Expected Outcomes

- Short - Collaborative projects to derive transferable scaling method
- Medium – Combine virtual and scaled testing to develop a standardized test method for wind turbine components
- Long – Application of the method to different design options on different power levels



3.1.3.1. Research Topic – Holistic and accelerated turbine design

Existing design frameworks have been focusing on various sub-problems (rotor, floater, mooring lines, generator, storage, etc.), but a fully integrated procedure is still challenging and time consuming to perform, including uncertainties in the entire design chain as well as economic optimization. Research explores and develops new technologies and design methods for both,the turbine and its support structure, e.g. model based systems engineering. These design methodologies can be improved to design for certain purposes. Advancements in specific components lead to system-wide improvements and more effective configurations in terms of cost and performance. Integration of validated design and analysis tools into a multi-fidelity multi-physics design process will demonstrate their utility on state-of-the-art reference designs and shorten the design cycle. Extension of modelling capabilities to model all load cases accurately, including the off-design conditions (such as installation, standstill/idling, transportation, etc), is crucial to accelerate the time to market of new designs and potentially reduce the need for prototype tests in the long term..

3.1.3.2. Research Topic – Probabilistic design

This research involves full-scale model validation based on measurements to understand and reduce modelling uncertainties. Probabilistic analysis method development for known and unknown failure mechanisms is integral, along with design optimization to exploit potential material reduction. The application of probabilistic design principles to new technologies post-2027 ensures ongoing reliability, fostering an integrated approach to system analysis and design.

3.1.3.3. Research Topic – Virtual, scaled and full-scale testing

In order to rely on a virtual testing environment a well validated modelling chain is required. With increasing turbine size, and significant changes across different design generations, there is a continuous need to validate new designs, at a wide range of conditions (both on- and off-design), by a detailed comparison between full-scale testing and its virtual modelling counterpart. Anyhow, full-scaled nacelle tests are already very costly; with further growth in size, nacelle tests in particular will become more challenging and may be replaced or accompanied by scaled tests. The design tools used to validate and certify turbines require further benchmarking and validation efforts before it can serve as a robust and reliable virtual testing method. The requirements and loads on wind turbine components (drivetrains, blades, floaters, ...) grow steadily with the rated power and the design margins are under pressure to further reduce costs. Full scale system test facilities for large future Offshore wind turbines (20MW+) do currently not exist due to the enormous necessary budget. One alternative is scaled and virtual tests. There is no standardized method for such tests yet. Research focuses on developing standardized methods for scaled, decentralized, and virtual testing to validate new wind turbine designs cost-effectively. Application and adaptation of these testing methods to new and disruptive concepts post-2027 ensure ongoing reliability and this application/adaptation could include the potential to test in off-design conditions such as large yaw errors or standstill (some of which has been investigated already in research projects such as TotalControl (TotalControl (totalcontrolproject.eu)). Probabilistic design principles enhance overall system reliability based on subcomponent reliabilities. Key milestones are scaling methods for complete components by 2027 and standardised test methods based on scaled and virtual tests as well as practical application to various designs by 2035.

3.1.3.4. Research Topic – Small and Off-Grid Wind

Research focuses on creating openly accessible models and metrics for assessing loads, flow, and site characteristics for small and off-grid wind applications. The aim is to standardize certification and testing for small manufacturers. The translation of design experience and modelling from large turbines to small wind applications enhances the efficiency and viability of small-scale wind energy.

3.1.4. R&I Priority Sub-Theme – Improve construction and installation methods

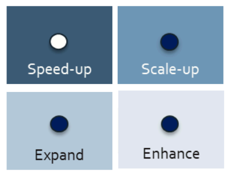
Research Gap/Need

Optimizing logistical chains and installation processes to accommodate larger wind turbine units and facilitate more substantial annual deployments. Efforts focused on technological advancements need to prioritize infrastructure upgrades, like durable roads, to support transporting oversized turbine components efficiently. Additionally, exploring innovative assembly techniques, such as pre-assembly hubs and advanced engineering solutions for offshore environments, is crucial.

Scope Outline/Description

Integrating predictive maintenance tech and robust logistical strategies are key for efficient maintenance and the longevity of both onshore and offshore wind systems. Closing this gap involves enhancing logistics, infrastructure, and assembly methods to ensure efficient deployment and long-term operational effectiveness in the wind energy sector.

Impact

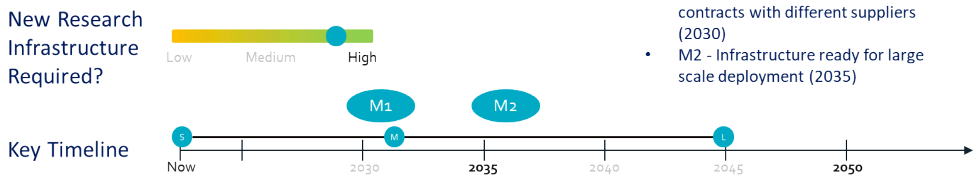


Key Milestones

- M1 - implementation of new construction strategies and contracts with different suppliers (2030)
- M2 - Infrastructure ready for large scale deployment (2035)

Actions/Expected Outcomes

- Short – develop and innovate approaches for the installation and logistics of wind farms
- Medium - expansion of the offshore wind supply chain
- Long - continued development of installation methods, infrastructure, and regulatory frameworks



3.1.4.1. Research Topic – Scaling up installation

Efforts concentrate on efficiency improvements and technological advances in the logistical chain and installation processes to enable larger annual deployments and accommodate bigger individual wind turbine units. Continued focus on logistical chain development and installation technology for very large wind turbines ensures sustained growth in the wind energy sector. As onshore and offshore wind farms expand, optimizing infrastructure like roads and ports becomes paramount to facilitate the transportation of large turbine components and ensure smooth and cost-effective wind turbine construction and installation. Future requirements will focus on port capacities and supply chain for logistics' operations as well as road durability and upgrades to support heavy and frequent transportation. This will help to reduce logistical challenges and costs associated with wind turbine assembly and maintenance, both onshore and offshore, fixed and floating. Innovations in construction techniques, such as pre-assembly hubs nearer to sites, could mitigate road congestion and minimize disruptions to local communities, aligning with the evolving needs of onshore wind turbine assembly and upkeep.

3.1.4.2. Research Topic – Assembly and heavy maintenance solutions

In the future, assembly and heavy maintenance of floating offshore wind turbines will demand advanced engineering solutions that accommodate the complexities of offshore environments, including harsh weather conditions and remote locations. Modelling tools and virtual testing methods should be developed further to support investigating novel assembly techniques involving modular designs and autonomous assembly systems as well as extending installation windows through knowledge of safe wind speeds and wind directions for the installation of blades and towers. Those could streamline the construction process and reduce time (renting installation vessels is very expensive) and manpower required. Solutions might also integrate predictive maintenance technologies, enabling real-time monitoring and pre-emptive repairs to minimize downtime and operational disruptions. Robust logistical strategies, possibly involving dedicated service vessels and specialized equipment, will be pivotal in facilitating efficient maintenance and ensuring the longevity of these offshore wind systems.

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3.1.5. R&I Priority Sub-Theme – Adequate economic and financial conditions

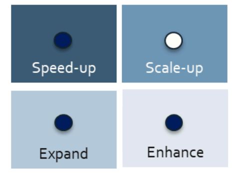
Research Gap/Need

Creating a robust policy framework supporting a resilient European energy market, emphasizing job creation and energy security amidst evolving landscapes. While progress has been made, a critical evaluation of changing energy markets and political dynamics is essential to develop legal and financial tools that continuously strengthen Europe's energy market.

Scope Outline/Description

Integrating environmental costs into wind energy assessments using multidisciplinary approaches like life cycle assessments. This integration into financial models is crucial for informed decision-making, striking a balance between renewable energy expansion and environmental preservation for long-term sustainability in wind energy projects. Refining policy frameworks, adapting to evolving energy landscapes, and integrating environmental costs into financial models to support sustainable decision-making in the wind energy sector.

Impact

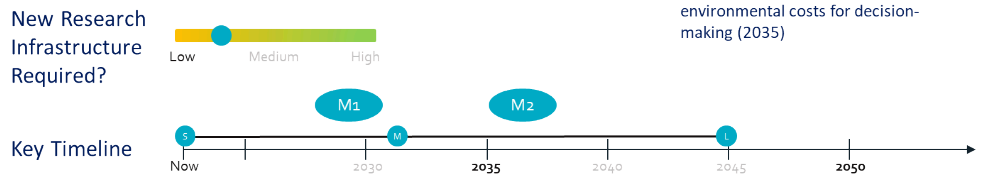


Key Milestones

- M1 - Robust policy framework (2028)
- M2 - Full integration of environmental costs for decision-making (2035)

Actions/Expected Outcomes

- Short – Identify wind policy vulnerabilities and evaluate effective support policies
- Medium - define future market roles and formulate stability instruments
- Long - implement standardized quantification of sustainability cost



3.1.5.1. Research Topic – Adequate support policies

While financial support payment needs are currently declining for deployment of wind energy on European markets, as wind projects become cost-competitive with fossil alternatives (in terms of lifetime cost), it is far from certain that this will remain the development in the future. Research will identify on how to future-proof wind support policies, integrate with financial safeguarding and create resilient long-term investment environments.

Further, European industry policy to support OEMs is coming into focus, and research will identify which policies are most effective in which areas to support a resilient European wind supply chain.

Recent policy developments in European countries around seabed lease payment structures may need to be revised and need research to align with incentives to significantly ramp up European offshore deployment within few years.

3.1.5.2. Research Topic – Market design

The goal is to create electricity markets that can provide the long-term future products and risk hedging options needed to encourage and manage sufficiently high levels of investments in wind energy. The future roles and interactions of power purchase agreements, contracts-for-difference, hedging and insurance products must be defined and developed.

New market areas, such as in meshed offshore grids, must be set up and regulated. The new design of the markets should also more adequately consider sector integration between energy carriers and along different levels of the value chains.

Critical consideration of changing energy markets and political landscapes results in the formulation of legal and financial instruments that strengthen the European energy market over time.

3.1.5.3. suResearch Topic – Impact assessment for value creation

To inform policy making and investment decisions, methods need to be developed that allow more detailed and thorough impact assessment of policies and regulatory decisions, including a range of factors, including social, environmental and socio-economic.

Methods and data will consider land use, wildlife preservation, manufacturing, operations, and decommissioning, job creation and energy security, resiliency. The goal is to create standardized methodologies that quantify these costs, enabling their integration into financial models. This integration will inform sustainable decision-making in wind energy projects, ensuring a balance between renewable energy expansion and environmental preservation for long-term viability.

3.2. R&I PRIORITY THEME 2 – OPTIMISATION AND FURTHER DIGITALISATION OF OPERATIONS & MAINTENANCE

Sub-Theme / Topics

Digitalisation of maintenance and optimisation tools for operational efficiency
- Innovative training for technicians using AR, VR, and/or AI
- AI-driven predictive maintenance for key components & report analysis
- AI-driven resource assessment and forecasting tools

Autonomous Operations & Maintenance
- Enhanced robotics for blade servicing & semi-automated inspection
- Advanced offshore repair methodologies and autonomous vehicles for marine operations
- Autonomous wind installation, O&M and decommissioning

Digital Ecosystem(s)
- Data exchange across sub-systems
- Sensor technologies
- Industrial IoT, cloud analytics, cybersecurity
- Optimisation & Decision-making
- Holistic understanding of natural systems (physical, social, biological)

Replacement and transport of major components
- Component replacement solutions onshore & offshore
- Quick connect/ disconnect systems for mooring lines & inter-array cables
- In-situ repairs and craneless exchange
- Autonomy & digitalization for port operations
- Novel fuel alternatives in ports(e.g., hydrogen fuelling)

3.2.1. R&I Priority Sub-Theme – Digitalisation of maintenance and optimisation tools for operational efficiency

Research Gap/Need

Research and innovation opportunities in wind farm maintenance include enhancing digital tools like digital twins and AI algorithms as well as virtual and augmented reality. There is a need to facilitate the integration of these tools for improved resource and yield assessment, wind farm operation and forecasting. Advanced AI algorithms should be developed to support efficient asset operation. Additionally, R&I efforts should focus on validating and certifying these software and methods.

Scope Outline/Description

Innovative training for technicians using AR, VR, and/or AI solutions as well as leveraging the digital capabilities for report analysis. Development and validation of AI -driven predictive maintenance tools for key components. Utilisation of advanced digital tools for climate prediction to assess wind resources and yield quantification to be used for smartwind farm operation strategies.

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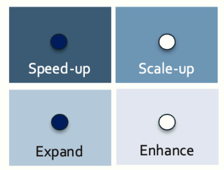
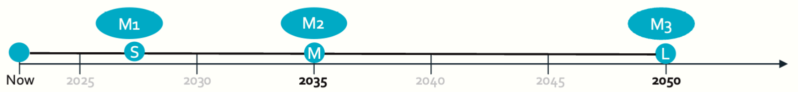


New Research Infrastructure Required?

Key Milestones
- M1 – Advanced AR/VR and AI tools are developed & validated for several aspects of O&M (2028)
- M2 – Advanced digital tools are fully implemented into O&M workflow for better performance overall (2035)
- M3 – Climate (Change) resilience and advanced energy control systems are validated (2050+)

Actions/Expected Outcomes
- Short, S - Deliver collaborative projects to (further) introduce digital processes into O&M (2027)
- Medium, M – Develop and validate advanced digital models for the entire O&M workflow, including smart controls for optimum efficiency (2035)
- Long, L – Climate (change) resilient model development and validation for operation & design (2050+)

Key Timeline



3.2.1.1. Research Topic - Innovative training for technicians using AR, VR, and/or AI

The field of digitalization and its relevant capabilities for servicing, maintenance, optimisation as well as tool development are growing rapidly. One key area is the development of new solutions to train and assist service technicians in the field. Utilizing augmented or virtual reality, along with AI-driven tools, can revolutionize the way maintenance protocols are read and produced, offering real-time guidance and support. There is a strong need for further initiatives towards implementing digitalization practices aimed at accelerating internal processes at the organisational level and enhancing collaboration between several stakeholders of wind energy operation. These initiatives should involve the digital upskilling of personnel to better leverage modern technologies and improve the application of various models within and across organisations by 2030.

3.2.1.2. Research Topic - AI-driven predictive maintenance for key components & report analysis

The role of AI is also expanding into monitoring and predictive maintenance activities, particularly for critical components such as gearboxes, electronic parts, and generators. The application of AI tools extends to analysing service reports, where large language models can extract patterns, offering insights into maintenance needs and efficiency improvements. Another critical area is the development of reliability prognosis models for very long-term operations, potentially up to 40 years. This requires a combination of experimental methods and simulation-oriented and/or theoretical approaches to predict and plan for long-term maintenance needs.

3.2.1.3. Research Topic - AI-driven resource assessment and forecasting tools

Advanced forecasting methods for wind resources and yield quantification including wake effects are essential for integrating into wind farm control strategies, enabling more effective and efficient energy production. There is also an increasing focus on the utilisation of open-source tools and frameworks within wind energy O&M, will need to be continuously updated and validated against (ideally standardized) data, frameworks and benchmarks, and should also include resilience testing protocols. Such efforts will greatly benefit from enhanced international cooperation and consistent updates along the way towards the realisation of the climate targets. In fact, heading towards 2050, the emphasis shifts to Climate Resilience and Advanced Energy Control Systems. This includes developing an in-depth understanding of extreme natural events through climate prediction and impact analysis, continuously enhancing forecasts of climate change impacts, and how wind energy infrastructure can adapt to changing climate conditions, such as increased frequency of extreme weather events or rising sea levels, especially for installations and O&M offshore. Developing adaptive and resilient controllers with multi-level and multi-objective functionalities is crucial in that regard, especially for next-generation turbines and plants.

3.2.2. R&I Priority Sub-Theme – Autonomous Operations & Maintenance (Tools, Robots, Vehicles)

Research Gap/Need

To advance wind farm automation, R&I efforts should concentrate on deploying robots for maintenance, including airborne, on-structure, and underwater robots. Research should cover robot development and AI-based control systems. Autonomous wind farm operation R&I is essential, encompassing market-aware electricity selling, maintenance scheduling, and performance monitoring. These initiatives will enhance wind farm efficiency, effectiveness, and reliability, onshore and offshore.

New Research Infrastructure Required?

Scope Outline/Description

Enhanced robotics for blade servicing and semi-automated inspections. Development of advanced offshore repair methodologies and autonomous vehicles for marine operations. Facilitation of autonomous wind installation, O&M and decommissioning as the overall target towards 2050 and beyond.

Key Milestones

- M1 – Enhanced robotics for blade servicing and semi-automated inspections are in use (2030)
- M2 – Offshore repair methodologies and autonomous vehicles for marine operations are advanced (2035)
- M3 – Autonomous wind installation, O&M and decommissioning (2050+)

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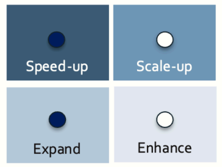
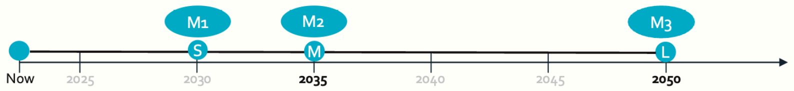


Actions/Expected Outcomes

- Short, S – Research and implementation projects for O&M robotics, including inspections(2027)
- Medium, M – Develop, validate and test advanced digital methods for offshore repairs and autonomous vehicles for marine operations(2035)
- Long, L – Wind turbines/farms that build, operate and decommission themselves (2050+)

Key Timeline



3.2.2.1. Research Topic – Enhanced robotics for blade servicing & semi-automated inspection

This topic focuses on advancing the technology and methods for servicing wind farms, e.g., enhancing the efficiency and efficacy of robotic blade services, particularly in the areas of deep-layer damage repair and inspection. This includes developing semi-automated methods for inspecting wind turbine blades using advanced detection technologies that go beyond conventional cameras, allowing for a more thorough assessment of conditions beneath the blade surface. Additionally, there is a need for improved monitoring methods for gearboxes, converters, offshore foundations, and cables.

3.2.2.2. Research Topic – Advanced offshore repair methodologies and autonomous vehicles for marine operations

Advanced repair techniques for both bottom-fixed and floating offshore foundations and cables are also a priority. The integration of autonomous vessels and Unmanned Underwater Vehicles (UUVs) is crucial for optimizing marine operations by 2030.

3.2.2.3. Research Topic – Autonomous wind installation, O&M and decommissioning

Looking further ahead, long-term research needs encompass the autonomous installation of wind farms, which involves leveraging Unmanned Aerial Vehicles (UAVs) and UUVs. This extends to the complete operation and maintenance cycle, as well as decommissioning processes, particularly for offshore installations. Key aspects include controlled payload distribution among drones, enhanced communication capabilities for UUVs, and sophisticated operational mechanisms for UAVs, such as automated landing, take-off, and efficient loading systems, as well as implementation of a digital backbone to facilitate such a large-scale data transfer. The ultimate goal is to achieve comprehensive, autonomous wind farm installation, maintenance, and decommissioning by 2050, in line with the objectives set out in the Strategic Research and Innovation Agenda (SRIA).

3.2.3. R&I Priority Sub-Theme – Digital ecosystems

Research Gap/Need

Due to the complexity of O&M practices, selecting and connecting the right sub-models is challenging. Digitalization, AI, and data science can help establish effective communication between O&M sub-systems and external factors, using correlations, databases, and advanced technologies like sensors and cloud analytics. These systems should prioritize cybersecurity and standardized data sharing, ultimately supporting data-driven decision-making and optimizing value across the lifecycle.

New Research Infrastructure Required?

Scope Outline/Description

Smooth data exchange across different sub-systems of within O&M workflows. Advanced sensor technologies. Industrial IoT, cloud analytics, cybersecurity, optimisation and decision-making. Holistic understanding and digitalization of natural systems (physical, social, biological).

Key Milestones

- M1 – Integration of Industrial IoT, cloud analytics, advanced communication technologies, and cybersecurity measures into safe operation (2030)
- M2 – Holistic analysis of natural systems through advanced sensors and digitalization, and environmental data-driven spatial planning for human and ecological needs (2050)

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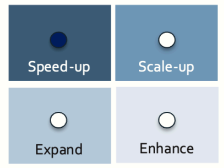
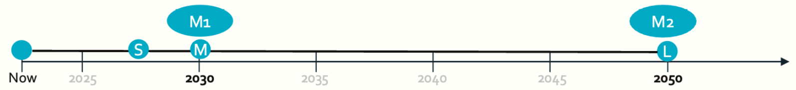


Actions/Expected Outcomes

- Short, S – Best practices for data standardisation and exchange(2027)
- Medium, M – Further develop and integrate advanced digital technologies (Industrial IoT, cloud analytics, etc.) into wind farm O&M(2030)
- Long, L – Advanced sensors and digitalization for holistic natural system analysis and data-driven spatial planning that harmonizes human needs with ecological conservation. (2050+)

Key Timeline



3.2.3.1. Research Topic – Data exchange across sub-systems

Efficient data exchange among various wind farm sub-systems is essential for optimizing energy production, enhancing safety, and minimizing operational costs. It enables real-time monitoring, predictive maintenance, and grid integration, contributing to operational efficiency and grid stability. Moreover, effective data exchange facilitates compliance with regulatory standards, reduces environmental impact, and supports the sustainable growth of wind energy.

3.2.3.2. Research Topic – Sensor technologies

The advancement of existing and development of new sensor technologies, especially for diagnostics and Structural Health Monitoring/Assessment (SHM/A), is of utmost importance. These sensors play a pivotal role in assessing the structural integrity of wind turbines and identifying potential issues, enabling proactive maintenance, and ensuring the safe and efficient operation of wind farms. Improved sensor technologies enhance the reliability and lifetime of wind energy systems while minimizing downtime and maintenance costs.

3.2.3.3. Research Topic – Industrial IoT, cloud analytics, cybersecurity

In addition to sensor technology, the integration of Industrial IoT, cloud analytics, and advanced communication technologies, including robust cybersecurity measures, is crucial as wind power plants are safety critical structures. This integration ensures the smooth interoperability of digital tools within the wind energy systems. It supports real-time data sharing, predictive analytics, and efficient wind farm operation, safeguarding the sensitive infrastructure against cyber threats and enhancing the overall reliability and effectiveness of wind energy O&M.

3.2.3.4. Research Topic – Optimisation & Decision-making

Optimization and decision-making support are essential in developing digital ecosystems for efficiently optimizing system-level processes, notably in the context of O&M and lifetime optimization. They are the foundation for the digital ecosystems that enable data-driven decision-making, predictive maintenance, and holistic lifecycle management of wind energy systems.

3.2.3.5. Research Topic – Holistic understanding of natural systems (physical, social, biological)

A holistic understanding of natural systems, which encompasses physical and biological dimensions, is essential. Furthermore, innovations in spatial planning, driven by data-driven approaches, are vital for achieving a delicate balance between human needs and ecological conservation. These approaches support sustainable development by considering the complex interplay of environmental and societal factors, ensuring the preservation of ecosystems while meeting human requirements.

3.2.4. R&I Priority Sub-Theme – Replacement and transport of large components

Research Gap/Need

Cost-effective alternatives for replacing larger components should be available to minimize operational expenses, especially in challenging locations like mountains or deep offshore sites. This is crucial for offshore floating wind turbines, where such operations can be costly due to long vessel mobilization times. Simplifying and expediting these operations can reduce financial impact and eliminate the need for towing foundations to port, allowing on-site major component replacements.

Scope Outline/Description

Development of advanced component replacement solutions onshore & offshore as well as solutions for quick connect/ disconnect systems for mooring lines & inter -array cables. Enabling in-situ repairs and craneless exchange. Autonomous and digitalized port operations. Provision of novel fuel alternatives in ports (e.g., hydrogen fuelling).

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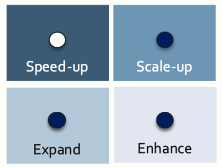


New Research Infrastructure Required?

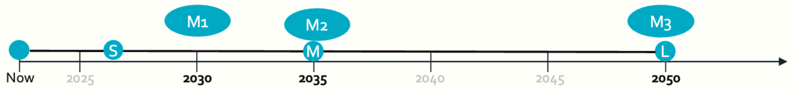
Key Milestones

- M1 – Demonstration and qualification of major component replacement solutions onshore and offshore, including floating wind (2030)
- M2 – Quick connect/disconnect systems for mooring lines and inter-array cables are in place (2035)
- M3 - Autonomous and digitalized port operations with novel fuel alternatives (2050)

Actions/Expected Outcomes

- Short, S – Develop demonstration projects for major component replacement solutions(2026)
- Medium, M – Build quick connect/disconnect systems for mooring lines and inter-array cables (2035)
- Long, L – Integration of technologies for automation and digitalization in ports, including novel fuel alternatives(2050+)

Key Timeline



3.2.4.1. Research Topic – Component replacement solutions onshore & offshore

In an effort to reduce operational expenses (OPEX) for wind farms, particularly in challenging terrains such as mountains and deep offshore locations, it is imperative to explore cost-effective solutions for replacing increasingly larger and heavier components. Instead of relying on the expensive and logistically complex task of mobilizing large cranes, there is a growing need for accessible alternatives in the market.

3.2.4.2. Research Topic – Quick connect/ disconnect systems for mooring lines & inter-array cables

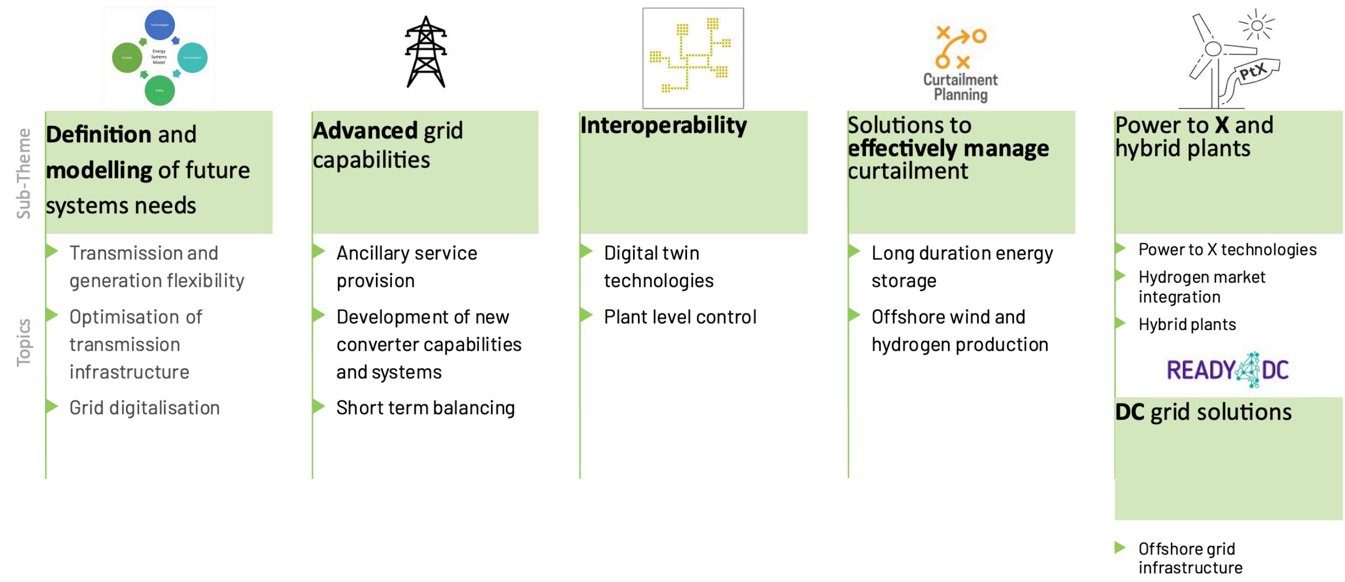
The quick connect/ disconnect systems address the critical operational challenges associated with complex and costly procedures required for major component replacements for floating offshore wind. By streamlining and optimizing these procedures, downtime, operational costs, and reliance on weather-dependent constraints can be significantly reduced. Additionally, these innovations eliminate the need for towing foundations to port, enabling on-site major component replacements, positively contributing to the affordability and reliability of offshore wind energy operations.

3.2.4.3. Research Topic – Autonomy & digitalization for port operations with novel fuel alternatives

The integration of automation and digitalization technologies within ports include the development of smart port infrastructure, which can enhance the efficiency of logistics and transportation related to offshore wind energy components. Furthermore, R&I efforts should focus on the incorporation of alternative fuel solutions in ports. This involves studying and implementing technologies like battery charging systems and hydrogen fuelling facilities, which are essential for supporting the transition towards more sustainable and eco-friendly energy solutions in the maritime sector.

3.3. R&I PRIORITY THEME 3 – WIND ENERGY SYSTEM INTEGRATION

Integrating wind energy systems into the energy systems is a fundamental requirement to enable the large-scale deployment of massive amounts of wind power. The sustainable integration requires collaboration and communication across sectors and interest groups including wind farm operators, TSOs and DSOs as system operators, consumers, and researchers.



Following the six R&I Priority Sub-Themes for wind energy integration defined in ETIPWind's SRIA, the graphic above highlights topics with medium to long-term research needs. Two research topics were added from the IEA's Grand challenges in Wind Energy Science[45]:

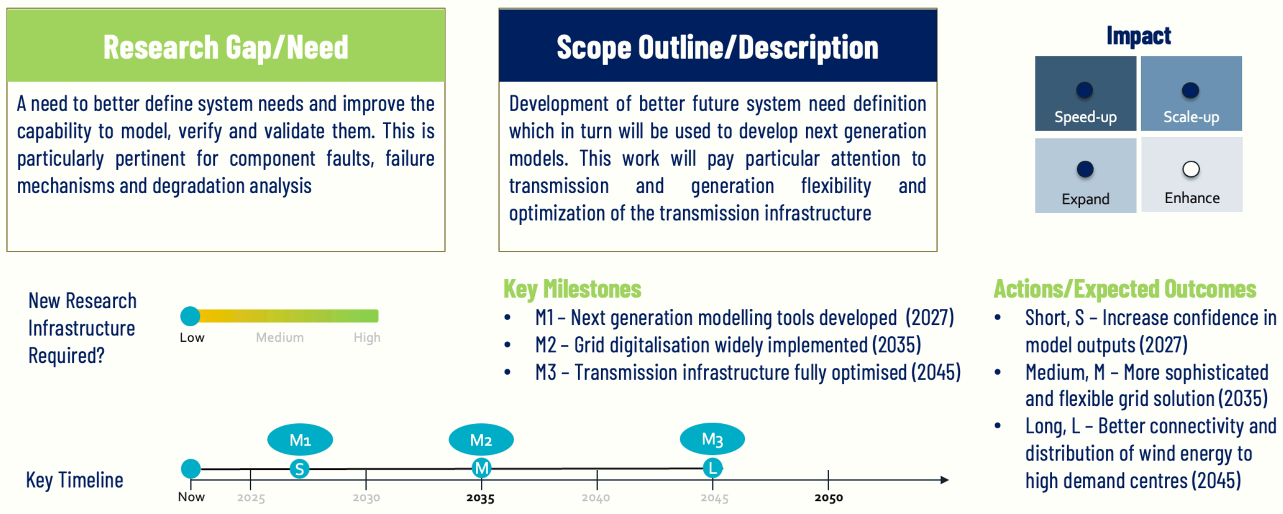
- Plant level control
- Grid forming hybrid plants

Additionally, reference is made to the European lighthouse initiative: Integration of large-scale offshore wind energy[46].
In addition to these, within this project, we have identified research topics around the State of the Art and future challenges:

[45] GRAND CHALLENGES IN WIND ENERGY SCIENCE | IEA Wind TCP (iea-wind.org)
[46] Proposal for European lighthouse initiative: Integration of large-scale offshore wind energy, SETWind, https://blogg.sintef.no/wp-content/uploads/2022/05/Lighthouse_SetWind_II.pdf (Last accessed: 08/02/2024).

3.3.1. R&I Priority Sub-Theme – Definition and modelling of future system needs

Faults in offshore grid components such as cables, transformers and high-voltage direct current (HVDC) converters can be significant and bring substantial loss in revenue. There are big potential gains to be achieved by being able to predict component failure through better definition and modelling. Therefore, we suggest investigating the degradation and failure mechanisms of cables, transformers and HVDC converters to enable reliable grid solutions (as part of grid digitalisation, 3.3.1.3). This will include the use of digital twin technology and AI to give a real-time estimate of the time to failure of key components (as part of 3.3.3.1).



3.3.1.1. Research Topic – Transmission and generation flexibility

Solutions for managing power grid stability and flexibility must be further developed and demonstrated to ensure transmission and generation flexibility. Updating modelling tools is a prerequisite to assess system needs. These tools will accelerate the development and demonstration of new technologies for grid stability and flexibility. Important aspects to be considered in the investigations are potential designs of future energy markets and sector coupling. It provides an opportunity to revisit the definition and modelling of future systems needs and incorporate new technologies. High-fidelity models of the power system enable to investigate in simulations the impact of large amounts of offshore wind power on system stability and flexibility. This should also include modelling electrical components in order to analyse harmonic interactions and stability.

3.3.1.2. Research Topic – Optimisation of transmission infrastructure

There is a need to further investigate ways to transmit the vast offshore wind power to where it is needed, notably by refining the planning and optimisation of power grid infrastructure, including the combination with hydrogen. This addresses also the refinement of offshore transmission infrastructure that accommodates the existing onshore transmission infrastructure. The dynamics of wind turbines and the behaviour of their components must be included in an appropriate level of detail.

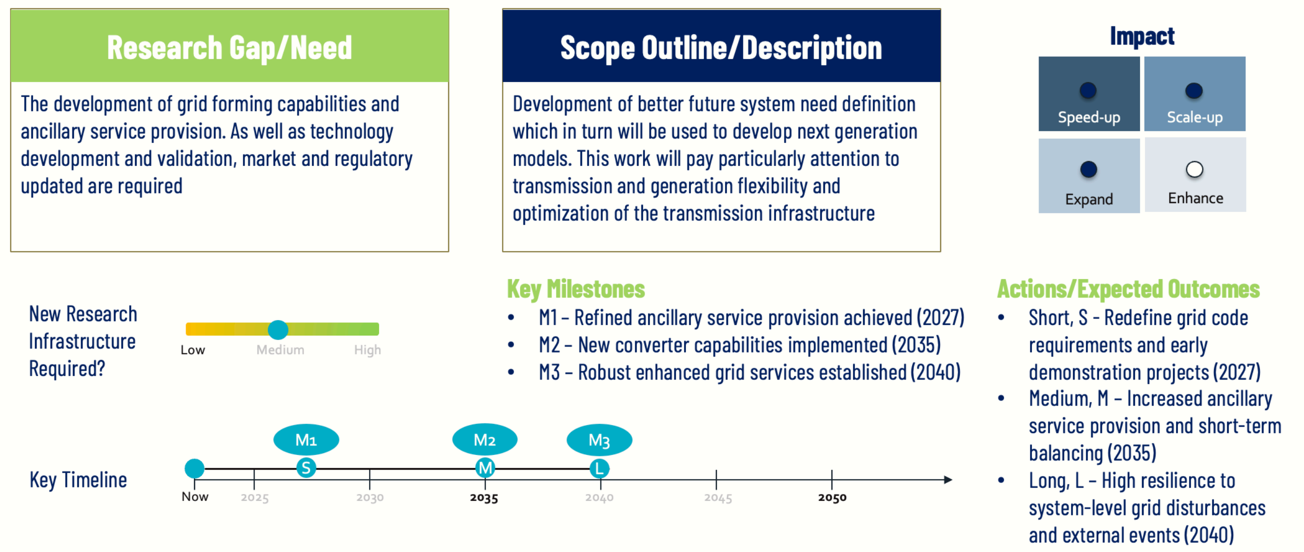
As the coupling of power and hydrogen is emerging, models are needed that represent the whole system accounting for power transmission and hydrogen transport but also the conversion technologies (linking this research to 3.3.5 R&I Priority Sub-Theme – Power to X and hybrid plants). Optimization models are needed that provide guidance to incrementally develop offshore grids. It is crucial to model and investigate both offshore energy hubs and combined AC/DC networks, as well as analysing the impact of uncertainties related to the installed wind power capacity, fluctuating power market prices and the hydrogen demand.

3.3.1.3. Research Topic – Grid digitalisation

There is a need to generate new digital tools for managing the power grid and to serve other R&I priorities. This requires an assessment and further refinement of the first wave of grid digitalisation technologies and implementation. There will be an opportunity to implement second generation technologies and optimise digitalisation across other R&I priorities.

3.3.2. R&I Priority Sub-Theme – Advanced grid capabilities

Medium and longer term R&I should provide new technical solutions to meet grid code requirements, notably the provision of grid-forming capabilities and ancillary services. The validation and demonstration of technologies will evolve towards 2050 and R&I will be needed to refine them. Short-term demonstration projects on ancillary services provision will unveil new areas for improvement beyond 2030. Markets and regulations will continue to adapt to larger penetration of wind and other renewables, particularly in the area of short-term balancing of the power system.



3.3.2.1. Research Topic – Ancillary service provision

Further refinement of grid code requirements will be required as well as the optimization of wind farm capabilities to support the grid stability. Research should address grid forming, black start, fast frequency response, damping of power oscillations, etc. The validation and demonstration activities identified in the ETIP Wind SRIA will utilize first generation technologies that will benefit from further research and innovation activities to refine and optimize future solutions for longer term targets in 2050. This includes to study the impact of enhanced ancillary service provision on the lifetime of the turbine components.

3.3.2.2. Research Topic – Development of new converter capabilities and systems

The control of the wider power grid requires further integration of inverter capabilities and other systems for provision of ancillary services. This includes the resilience to system-level grid disturbances and resilience to external events. It is anticipated that the demonstration projects identified for 2025-2027 will highlight areas for improvement for implementation in 2035/2050.

3.3.2.3. Research Topic – Short term balancing

Assessment and further development of integrated and intelligent operations related to short term balancing are recommended. It is expected that market operations (and regulations) will evolve beyond 2027 requiring further technology optimisation and integration.

3.3.3. R&I Priority Sub-Theme – Interoperability

Research Gap/Need

The ability for wind energy system integration to be increasingly interoperable including across different OEM technologies, wind power plants and the wider electrical network, and in the implementation of digital technologies

Scope Outline/Description

The development and demonstration of plant level control and new transmission infrastructure coupled with the increased integration of digital twin technology and AI-based solutions.

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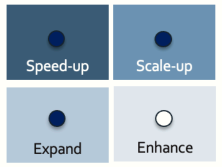

New Research Infrastructure Required?

Key Timeline

Key Milestones

- M1 – Plant level control demonstrated (2030)
- M2 – Digital twin technologies fully established (2035)

Actions/Expected Outcomes

- Short, S – Early advanced control system for plan level control (2030)
- Medium, M – Compatibility across different OEM technologies with digital twins in operation (2035)

As mentioned earlier, faults in offshore grid components such as cables, transformers and high-voltage direct current (HVDC) converters can be significant and bring substantial loss in revenue. There are big potential gains to be achieved by being able to predict component failure through better definition and modelling. In addition to the earlier suggested work (as part of grid digitalisation, 3.3.1.3), this will include the use of digital twin technology and AI to give a real-time estimate of the time to failure of key components (see 3.3.3.1).

3.3.3.1. Research Topic – Digital twin technologies

Digital twins are key enablers to develop and test the interoperability of different components, models, data exchange protocols and communication interfaces in a cost-effective way. Research is needed to develop techniques for efficient modelling, computation and hardware-in-the-loop testing that combines simulations with physical systems parts. It is crucial to model the wind power plant, the turbines, their single components as well as the impact from/on the environment and interlinked systems with an appropriate level of fidelity depending on the application. This will help to understand the behaviour of the integrated sub-systems as well as the holistic system. Besides specific use cases such as studying a future power-electronic converter-based grid, there should be broad investigations of new application areas to fully exploit the potential benefits of digital twin technologies in wind energy system integration. Last, the required digital developments outlined in 3.2.3 R&I Priority Sub-Theme – Digital ecosystem for Theme 2 – Optimisation and further digitalisation of Operations & Maintenance will also be essential for digital twin technologies that can successfully support the system interoperability.

3.3.3.2. Research Topic – Plant level control

Advanced control systems are essential to operate wind farms in a smart way while maintaining a reliable and efficient operation of the power system. The plant level control must provide operational flexibility beyond power maximisation and the fulfilment of grid code requirements. Research should focus on integrated wind farm control combining the requirements of wind power plant control with the benefits of wind farm flow control. Wind power plant control (WPPC) summarizes here the compliance with grid codes and provision of ancillary services, whereas wind farm flow control (WFFC) refers to the mitigation of wake losses. Prerequisites for implementing WFFC is to better understand the flow physics, atmospheric conditions, wind-wave interactions and to model the wakes. In addition, there is a need for control strategies that reduce and/or distribute the accumulation of structural fatigue at key components and single wind turbines require further development. This requires also to exploit sensor and digital twin technologies to accurately estimate structural loads and accumulated fatigue to inform the control system in real time. Another area to be addressed by future research is market-driven plant-level control that adjusts the operation depending on the fluctuating power market prices. Moreover, novel control functionalities could enhance the sustainability of wind power. This includes to alter the propagation of acoustic noise, reduce the acoustic emissions, and avoid collisions with birds and bats.

3.3.4. R&I Priority Sub-Theme – Solutions to effectively manage curtailment

R&I activities should further develop emerging technologies and their optimisation to effectively manage curtailments at different spatial scales and larger regions (long-term balancing). Also, medium to longer term R&I should incorporate the use of hydrogen and storage to manage curtailments beyond 2030.

Research Gap/Need

Effective curtailment management at different spatial scale and larger regions with the adoption of emerging storage technologies including hydrogen

Scope Outline/Description

Develop emerging technologies including hydrogen particularly in energy storage, to address curtailment management. This will tackle different spatial scales and larger regions (establishing long-term balancing capability).

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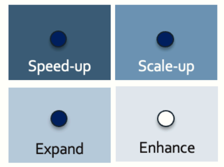

New Research Infrastructure Required?

Key Timeline

Key Milestones

- M1 – Offshore wind/hydrogen production demonstrated (2030)
- M2 – Long duration energy storage implemented (2035)

Actions/Expected Outcomes

- Short, S - Deliver collaborative project to define grid code requirements (2027)
- Medium, M - Model/simulate wind energy grid forming provision (2030)
- Long, L - Design/demonstrate wind energy grid forming provision (2035)

3.3.4.1. Research Topic – Long duration energy storage

Further development of emerging technologies and spatial scales relating to larger regions and long-term balancing are expected. Emerging technology will need to be fully incorporated and optimised across larger network regions to address effective curtailment management.

3.3.4.2. Research Topic – Offshore wind and hydrogen production

This will involve optimisation of emerging hydrogen technology for energy vector and storage applications. The development of hydrogen technology will continue beyond 2027 and towards 2035 and 2050 targets.

3.3.5. R&I Priority Sub-Theme – Power to X and hybrid plants

R&I will be needed to develop integrated and intelligent operations for hybrid and co-located projects to maximise renewables in the energy system. The evolution of renewable energy hybrid technologies will require further optimisation opportunities in the long-term.

Research Gap/Need

The development of integrated and intelligent operations for hybrid and co-located projects including the development of power to X technologies

Scope Outline/Description

The modeling, simulation and control of power to X technologies in combination with wind power plants. Integration of the hydrogen market and the development of hybrid plants and offshore energy hubs.

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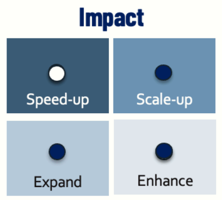
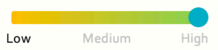


New Research Infrastructure Required?



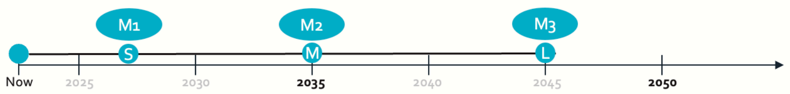
Key Milestones

- M1 – Early power to X technologies demonstrated (2027)
- M2 – Hydrogen market integration established (2035)
- M3 – Hybrid plants fully realised (2045)

Actions/Expected Outcomes

- Short, S – Effective management of curtailment (2027)
- Medium, M – Early hydrogen adoption and better market understanding (2035)
- Long, L – Offshore energy hub operation and integration (2055)

Key Timeline



3.3.5.1. Research Topic – Power-to-x technologies

Power-to-x technologies can be a valuable solution to effectively manage curtailment from an industrial perspective. The potential benefits of different power-to-x options depending on the operational state of the wind power plant and power market situation should be investigated. This includes modelling, simulation and control of batteries, hydrogen conversion, pumped hydro subsea storage or compressed air in combination with the wind power plant.

3.3.5.2. Research Topic – Hydrogen market integration

The conversion to hydrogen is currently the most promising power-to-x technology for large scale deployment. Besides the solution of technological challenges of hydrogen conversion and transport, a better understanding of the hydrogen market and its interactions with the power market is needed.

3.3.5.3. Research Topic – Hybrid plants

Expected activities include development of integrated and intelligent operations for the hybridisation with other technologies (wind + solar + storage…) and maximisation of renewable energy sources penetration in the energy system. Evolution and diversification of renewable energy hybrid technologies will continue to evolve beyond 2027 providing further optimisation opportunities. Special emphasis should be placed on the operation of offshore energy hubs and their integration in the energy system, and their effect on the power market and other relevant markets such as hydrogen.

3.3.6. R&I Priority Sub-Theme – DC grid solutions

R&I should investigate new solutions for the operation and design of offshore wind farms, including floating wind with an emphasis on further development of DC grid technology. DC grid technology will range from component development (such as DC circuit breakers) to system-level development (such as multi-terminal DC-based solutions).

Research Gap/Need

The availability of cost-effective and reliable DC grid solutions to enable longer distance transmission, floating offshore wind and flexible and optimized offshore grid networks.

Scope Outline/Description

The development of offshore grid infrastructure incorporating DC technology-based solutions and forming part of a network of offshore energy hubs and energy islands, potentially combining with other energy vectors such as hydrogen

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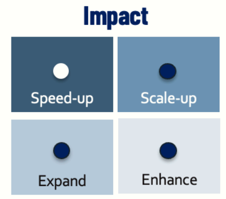


New Research Infrastructure Required?

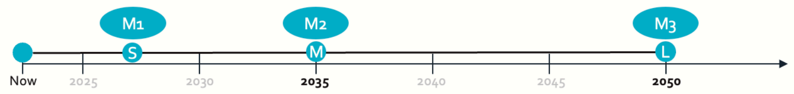
Key Milestones

- M1 – Planning & optimisation tools developed (2027)
- M2 – Energy hub/island demonstrators established (2035)
- M3 – DC grid network fully implemented (2050)

Actions/Expected Outcomes

- Short, S – Optimised electrical (and hydrogen) network designs (2027)
- Medium, M – Operational knowledge of early offshore energy hubs/islands (2035)
- Long, L – Optimised offshore networks incorporating mature DC technology (2050)

Key Timeline



3.3.6.1. Research Topic – Offshore grid infrastructure

New solutions for the operation and design of offshore wind farms will be required, including floating wind, with an emphasis on further development of dc grid technology. The development of energy hubs and energy islands will continue beyond 2027 and towards 2035 and 2050 targets. The future offshore grid may include a combination of an electricity and hydrogen transmission system. Planning and optimization tools should be developed to assess such combined electricity and hydrogen networks.

3.4. R&I PRIORITY THEME 4 – SUSTAINABILITY AND CIRCULARITY

Wind capacity installed is increasing exponentially which calls stronger than ever for advanced circularity strategies to be developed and accelerated to mitigate potentially negative impacts on the environment.

Relevant research tasks from two sources have been identified.

An IEA Wind Topical Experts Meeting resulted in a review article on the technical Grand Challenges for wind energy dividing them into three areas: the atmosphere, the turbine, and the plant. These technical challenges are expanded by the critical challenges of social and environmental impacts. Beyond technical borders, environmental and social issues, we highlight:

- Environmental co-design. Interdisciplinary research challenges in wind energy at the intersection of engineering and environmental science
- Social aspects of wind energy development

Throughout 2023, ETIPWind has been collecting inputs from the wind energy community to update the Research and Innovation (R&I) priorities with the European Commission, covering 2025-2027. The challenges pulled for this theme "Sustainability and Circularity" are:

- sustainable materials in design and recyclability by design
- blade recycling, sustainability assessment and technologies to lower CO2 footprint
- impact on ecosystems and biodiversity
- solutions for lifetime extension
- development and validation of new components and materials (e.g., replacement of carbon-fibre)
- reliability of secondary materials (e.g., recycled steel and copper)
- new recycling processes
- noise reduction
- material durability and protection

In addition to these, within this project, we have identified research topics around the State of the Art and future challenges:

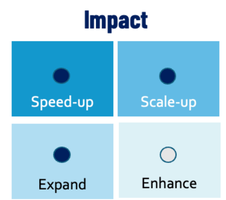
- End-of-life management
- Assessment of the damage state and turbine properties
- Alternative design solutions
- Holistic life cycle assessment
- New business models (Second hand markets)

	Sub-Theme	Topics
	Material substitution for decarbonisation	Sustainable materials in design and recyclability by design; New components and materials; Material durability and protection; Alternative design solutions
	Recycling methods	Sustainable blade recycling.; New recycling process; Reliability of secondary materials; Holistic life cycle assessment; New business models
	Lifetime extension	Solutions for lifetime extension; End of life management; Assessment of damage state of turbine properties
	Decommissioning tools and methods	Methods and tools for offshore wind.; Technologies for environmentally friendly decommissioning; Processes and components to ease, reuse and recycling; Economic model for full decommissioning project cycle
	Biodiversity solutions	Environmental co-design; Impact on ecosystems and biodiversity; Noise reduction

3.4.1. R&I Priority Sub-Theme – Development of material substitution enabling decarbonisation and reducing the use of rare-earth materials

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

Research Gap/Need	Scope Outline/Description
Consolidation of knowledge on current materials and research into new materials for blades, generators, power converters, and cables. In the field of large-scale wind turbines, research is being conducted on new bearings for those larger than 12 MW.	Use nanomaterials and more sustainable options for permanent magnets. Development of biofibers and new bearings and generators. Work on new materials and coatings for the blades. Power converter designs with improved topologies. Resource efficiency through higher conversion power ratings.

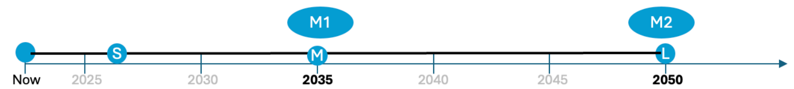


New Research Infrastructure Required?

Key Milestones

- M1 - Validation of blades with new materials and more circular coatings (2035)
- M2 - Validation of new concept of WT with new materials (2050)

Key Timeline



Actions/Expected Outcomes

- Short, S - Development and demonstration of new materials for bearings, blades and generators (2027)
- Medium, M - Validation of this new advances in materials and power converters in WT offshore and onshore (2035)
- Long, L - dynamic high-temperature superconductors (2050)

3.4.1.1. Research Topic - Sustainable materials in design and recyclability by design

In the future R&I should support the consolidation of today's knowledge on materials and investigate the possible use new ones such as nano-materials, self-healing materials, and other more sustainable alternatives to manufacture permanent magnets.

3.4.1.2. Research Topic - New components and materials

For components, R&I should evolve new designs for bearings, converters, gearboxes, and generators for larger turbines. It should investigate and validate the use of bio-fibres instead of carbon fibres, as well as other new more resistant blade materials and coatings for anti-erosion and cold climates, new generators with new permanent magnets, new converter designs. etc.

3.4.1.3. Research Topic – Material durability and protection

It should investigate new power converter topologies to reduce maintenance needs in places with difficult access and logistics. Development of new blade materials and coatings (anti-erosion, cold climate). New power converter topology design to increase redundancy to reduce maintenance needs for less logistics resource use. Transmission cables (e.g. materials for dynamic HV subsea cable), Development of new HTS materials for superconductive generators. Development of new bearings for large wind turbines (+12 MW).

3.4.1.4. Research Topic – Alternative design solutions

The next generation of wind turbines with lighter and less volume of materials is an area for continued research. The resource efficiency of wind energy will need further optimisation and R&I should play an important role in achieving this. R&I should assist to optimise upfront design and enhance turbine lifetime thanks to more accurate data cluster analysis too. Last, R&I should contribute to establish an industrialised design process that satisfies confidentiality restrictions between the designers and manufacturers of wind turbines, substructures and mooring systems for floating offshore wind.

3.4.2. R&I Priority Sub-Theme – Development and demonstration of recycling methods for wind turbine materials, manufacturing waste and components

Incentivisation is needed to ensure recycling facilities construction and operation and to find cost-effective solutions as well as the creation of a cross sectorial waste stream to support the recycling business. Additional investments are needed to diversify, scale up and optimisation recycling technologies (such as chemical recycling) are needed, including design processes.

Research Gap/Need

Development and demonstration of sustainable recycling of wind turbine composite components, development of processes to re-use materials and components to get a 100% wind turbine recyclability or reusing.

Scope Outline/Description

Development of sustainable low-CO2-footprint procedures for blades recycling.
New procedures to obtain a better recycling of neodymium and composites have to be developed as well as 0% landfill disposal in wind applications.

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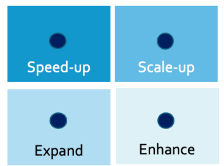
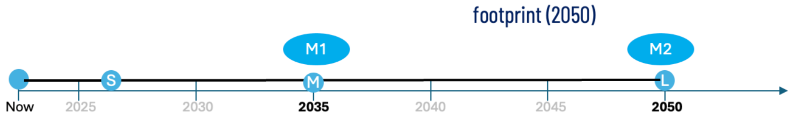


New Research Infrastructure Required?

Key Timeline



Key Milestones

- M1 - Maximize the benefits of material at the end of life (2035)
- M2 - 100% wind turbine recyclability with the lowest CO2 footprint (2050)

Actions/Expected Outcomes

- Short, S - New procedures to obtain the recyclability of actual blades (2027)
- Medium, M - Better recycling of neodymium (2035)
- Long, L - 100% recyclability of wind turbine materials (2050)

Research Topic – Blade recycling, sustainability assessment and technologies to lower CO2 footprint

Development of sustainable procedures for recycling wind turbines blades with the lowest CO2 footprint. Disruptive blade design may be achieved by using recyclable blade materials. This will go in hand with more adequate LCA methodologies that should validate the sustainability of such processes.

3.4.2.1. Research Topic – Reliability of secondary materials

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

3.4.2.2. Research Topic – New recycling process

In the future R&I is needed to develop processes and methods to recycle 100% wind turbines with the lowest possible CO2 footprint. This should include composite materials and neodymium from permanent magnets.

3.4.2.3. Research Topic – Holistic life cycle assessment

A holistic LCA tool for the different types of wind energy systems considering materials and components manufacturing, assembly, transport, installation, operation, maintenance, decommissioning and End-of-Life stages

3.4.2.4. Research Topic – New business models

R&I should assist continuously the regulation requirements for the recycling wind turbine blades and other materials in all EU countries. But crucially it should provide solutions to use recycled materials in wind blades and to explore whether closed loop approach could be possible.

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

3.4.3. R&I Priority Sub-Theme – Lifetime extension via re-using, refurbishing, re-purposing

The primary objective of this R&I priority sub-theme is to further develop the operating lifetime of wind turbine components to prolong the windfarm life and therefore minimise the quantity of decommissioned wind turbine waste to landfill. In addition, environmental assessments of lifetime extension strategies achieved by reuse or refurbishment should be performed in comparison to alternative methodologies e.g. the use and direct replacement of non-recyclable or bio-sourced wind turbine components, to determine the optimum strategy in terms of material utilisation for each wind turbine component.

Finally, Life-Time Extension covers all kind of material and components waste coming out from wind turbines, then the strategies for achieving LTE of wind turbines includes the re-purposing of components, defining repurpose as the reuse of part of the wind turbine blade for different applications, usually of lower value than the original one. E.g. construction of poles, bridges, outdoor urban installations, furniture etc. In this sense, the development of a blade material database digital platform is a highly recommended topic to facilitate the re-purposing strategy.

Research Gap/Need

New economically viable solutions for wind turbines lifetime extension can drop the LCoE of wind power significantly. More precise tools for prediction of the remaining lifetime and management strategies are required, as well as the environmental assessments of lifetime extension strategies.

Scope Outline/Description

Development of a holistic approach to lifetime extension that includes engineering solutions, digital solutions and human resources for diagnostics, structural health monitoring and system level lifetime optimization.

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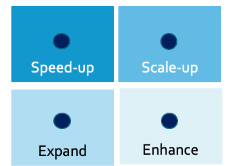
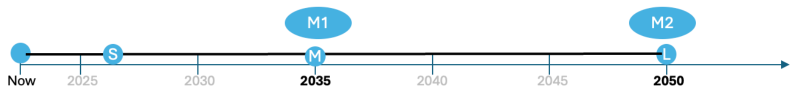


New Research Infrastructure Required?

Key Timeline



Key Milestones

- M1 - LCA methodology (2035)
- M2 - Digital twinning and use of AI (2050)

Actions/Expected Outcomes

- Short, S - Development of supply-chain infrastructure and prototype processes for refurbishment (2027)
- Medium, M - Development of lifecycle assessment of strategies (2035)
- Long, L - Assessment of most prominent wind turbine component failure modes (2050)

3.4.3.1. Research Topic – Solutions for lifetime extension

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

3.4.3.2. Research Topic – End-of-life management

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

3.4.3.3. Research Topic – Assessment of the damage state of turbine properties

R&I should also develop and validate 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 optimization.

3.4.4. R&I Priority Sub-Theme – New decommissioning tools and methods

Managing a decommissioning project requires involvement at an early state of the project and the existence of a regulatory framework establishing the requirements for the procedures. 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.

Research Gap/Need

Decommissioning procedures are quite standardized 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.

Scope Outline/Description

The decommissioning procedures should be planned within the design phase of a project and should therefore be improved to allow easier reuse and recycling of components and materials.

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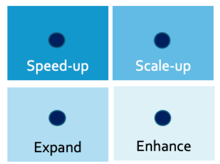
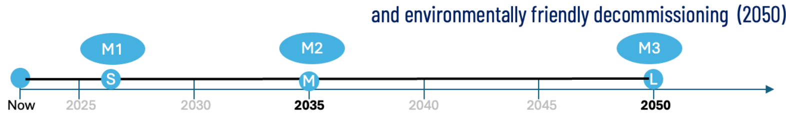


New Research Infrastructure Required?

Key Timeline



Key Milestones

- M1 - New methods and tools for offshore wind (2027)
- M2 - Economic model for full decommissioning project (2035)
- M3 - New technologies for effective and environmentally friendly decommissioning (2050)

Actions/Expected Outcomes

- Short, S - Development of supply-chain infrastructure and processes, based on oil & gas (2027)
- Medium, M - Development of off-shore wind-specific supply-chain infrastructure and processes (2035)
- Long, L - Reduced cost and environmental footprint decommissioning processes (2050)

3.4.4.1. Research Topic – Decommissioning methods and tools for offshore wind

Whereas offshore wind decommissioning is not mature enough (only a few offshore wind turbines have been decommissioned, based on reversed installation), the oil & gas industry has long experience with decommissioning. So, a first approach is based on the synergies encountered with oil & gas and consists in the use of the experience from the oil & gas industry to develop tools/methods for decommissioning of offshore wind turbines to reduce the decommissioning cost and the environmental footprint. A second phase will be to develop specific methods and tools for offshore wind applications, whenever the proposal for the oil & gas industry will not apply to offshore wind.

3.4.4.2. Research Topic – Technologies for environmentally friendly decommissioning

The considerations of environmental requirements are equally as important as the cost and time consumption. Thus, potential risks related to offshore decommissioning projects must be understood and addressed. Indeed, addressing these matters can help to make the project more cost efficient, reducing at the same time the environmental impact, considering and exploiting all the relevant alternatives avoiding landfills and non-sustainable actions.

3.4.4.3. Research Topic – Processes and components to ease reuse and recycling

Decommissioning of WTGs is becoming ever more important with the first wind plants reaching their end-of-life. The limited experience makes the decommissioning procedure challenging. The decommissioning procedures should be planned within the design phase of a project and should therefore be improved to allow easier reuse and recycling of components and materials. These improvements will bring new developments in processes and components, such as the development of decommissioning vessels specifically suited to offshore wind, building either on experiences from the oil & gas sector or specifically designed for offshore wind.

3.4.4.4. Research Topic – Economic model for full decommissioning project cycle

It is of course the case that inadequate knowledge on the subject and equally inadequate or insufficient data, obviously will result in results of equally poor quality. So, it is necessary the development of the 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.

3.4.5. R&I Priority Sub-Theme – Biodiversity solutions

Assessment of environmental effects and biodiversity is an integrated part of planning for new wind farms. Still, it is important to understand impacts on biodiversity during construction and operation. The lack of knowledge on the impact from wind power installations on biodiversity leaves the developers and authorities without scientific facts and arguments in the debate. The impact from wind energy installation and operation on biodiversity needs closer studies and development of models that can be used in the assessment including negative and positive impacts such as formation of artificial reefs, fishing restricted areas, etc Also, birds, bats strike, whales orientation and communication affection require of mitigation technologies which need to be further developed, assessed, and documented in a more systematic way.

Research Gap/Need

The overall impacts of OWF on marine ecosystems and biodiversity is unknown, and largest uncertainty is related to potential impacts of noise and electromagnetic fields (EMF) on fish, marine mammals and benthic environments.

Scope Outline/Description

Improvement of the environmental co-design in the definition of new wind turbines and wind farms, to mitigate their negative influence in environmental processes (Siting & behavioral interactions, aeroecology, marine ecology, etc.), including nature-inclusive design / nature-positive solutions.

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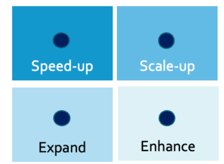
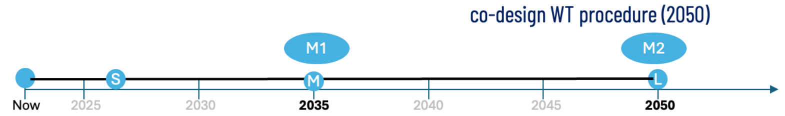


New Research Infrastructure Required?

Key Timeline



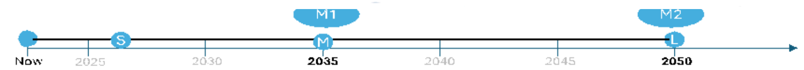
Key Milestones

- M1 - LCA of all the influences among WT and environmental processes (2035)
- M2 - Quasi-Zero environmental co-design WT procedure (2050)

Actions/Expected Outcomes

- Short, S - Development and demonstration of nature positive strategies and technologies for wind farms. (2027)
- Medium, M - Collaborative program to mitigate the effect of wind turbine in marine ecology (2035)
- Long, L - Wind farms with Quasi-Zero or even positive interaction in environmental processes (2050)

Key Timeline



wind turbine in marine
ecology (2035)
- Long, L - Wind farms with Quasi-Zero or even positive interaction in environmental

3.4.5.1. Research Topic – Environmental co-design

R&I should also enable collaborative programmes to quantify and mitigate the effect of wind turbine in marine ecology. 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 quasi-zero impacts in environmental processes. The most appropriate mitigation solutions will be proposed, deployed and verified.

3.4.5.2. Research Topic – Impact on ecosystems and biodiversity

R&I should investigate the most appropriate mitigation solutions for noise emissions. It should determine relevant exposure levels to noise and EMF in situ and validate solutions to further mitigate negative impacts on wildlife, including nature-inclusive design / nature-positive solutions.

3.4.5.3. Research Topic – Noise reduction

R&I should support advances in noise emission reduction from wind turbines, notably by contributing to future guidance and regulation in order to mitigate or acceptance the noise by exploring new technical solutions. To ensure sufficient control of the exposure to wind turbine noise (WTN), with new developments of wind power farms closer to residential areas, R&I should investigate the generation and propagation of wind turbine noise (WTN) and impact on humans and wildlife, under all relevant atmospheric and environmental conditions.

3.5. R&I PRIORITY THEME 5 – SKILLS, ACCEPTABILITY & COEXISTENCE

The large-scale expansion of wind energy demands a skilled workforce, cultivating both inter- and transdisciplinary collaboration, and nurturing a holistic understanding. Coexistence with individuals, diverse industries, and the environment is crucial. We underscore the imperative for an expanded workforce and increased educational opportunities, specifically tailored to wind technologies. Universities face the challenge to educate the future workforce with a long-term perspective of societal needs/challenges while at the same time serving short-term requirements of the industries to align education with current market needs. Scaling up wind energy introduces spatial challenges that impact individuals, industries, and the environment. Therefore, inclusiveness, active involvement, as well as the establishment of clear assessment criteria and a holistic evaluation framework for wind projects are essential. These measures ensure a positive coexistence, facilitating the realization of both renewable energy objectives and environmental sustainability goals.

The "Dreiebok"4, a practical guide outlining principles for coexistence between offshore wind and fisheries, serves as a valuable example. It demonstrates effective methods for collaborative coexistence, offering insights applicable to Priority Theme 5, ensuring the success of renewable energy objectives, environmental sustainability, and co-existence with fisheries (in this case).

Another source of information aimed at the general public is the UK-based "Guide to a floating offshore wind farm" web site.5 It encompasses elements that contribute to skill development, efficient project execution, and the overall coexistence of wind energy projects, making it a valuable resource in the broader context of R&I Priority Theme 5.

	Education and skilling		Inclusiveness and co-existence		
Sub-Theme	**Education**	**Skilling, re-skilling and upskilling**	**Increase public engagement of citizens**	**Fair transition, inclusiveness and stakeholder interests**	**Interdisciplinary & Transdisciplinary relations with coexistence**
Topics	▶ Continue examine gaps in wind energy education ▶ Assess measures/tools to increase number of study places and increase recruitment (e.g long-term campaigns)	▶ Programmes to skill, re-skill and upskill experts in related professions (e.g O&G sector). (Seamless transition and leveraging transferable skills) ▶ Designing comprehensive programs covering entire value chain	▶ Provide guidelines for continuous community involvement throughout the whole project period, and implement in regulations ▶ Demonstrate the benefits of wind energy for society as a whole and local communities.	▶ Develop tools to identify stakeholders, improve the understanding and map stakeholder concerns ▶ Develop novel governance and ownership models of wind farms	▶ Planning for positive co-existence: Identification and definition of relevant societal and environmental assessment criteria of site-specific impacts ▶ Evaluation of the consequences of intensified wind energy production and upscaling.

▶ Emphasizing geographic, gender, and diversity considerations

▶ Socio-economic analyses of potential needs in terms of number of jobs, divided by industry, education level, geography for wind energy upscaling

▶ Cross-cutting: Interdisciplinarity of technical, upscaling, societal, economic, environmental skills.

3.5.1. R&I Priority Sub-Theme -Education

Research Gap/Need

Effective teaching methods, interdisciplinary competence, and innovative tools for diverse skill development. Long-term recruitment campaigns, gender empowerment initiatives, and sustained interest in wind energy programs also need be looked into. A comprehensive analysis is needed to enhance educational initiatives for a skilled workforce meeting evolving sector demands. Increased work force for wind energy needed on vocational/technical, BSc, MSc and higher educational level.

Scope Outline/Description

Examine gaps in wind energy education, focusing on effective teaching methods, interdisciplinary competence, and innovative skill development tools. Evaluate long-term campaign effectiveness, gender empowerment initiatives, and sustained interest in wind energy programs. Assess efforts preparing a skilled, diverse workforce for evolving sector demands to enhance educational initiatives. Increase number of students in relevant education programs.

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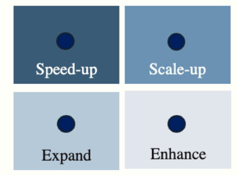


Actions/Expected Outcomes

- Medium - Ensure continuous professional development programs for the majority of industry experts. (2030)
- Long – Attain a highly adaptive wind energy workforce through ongoing skilling initiatives. (2035)

Key Milestones

- Establish a robust interdisciplinary wind energy education framework (2030)
- Achieve industry-wide continuous learning, fostering adaptability and sustainable expertise (2050)

Key Timeline

3.5.1.1. Research Topic - Education and strategic workforce expansion for the wind energy sector

Increasing students in relevant programs aims to lead to a cultivation of a highly skilled and diverse workforce, ensuring sustained innovation and addressing the escalating demands of the rapidly expanding wind energy sector by 2035 and 2050. There is a need for people on vocational/technical training, BSc, MSc and higher education. This includes educating teachers that are engaged in skilling, re-skilling and upskilling the activities. Boosting the number of PhD students in wind energy is essential by 2035 and 2050 to foster cutting-edge research, drive technological innovation, and address the evolving challenges of a rapidly advancing and expanding wind energy landscape.

3.5.1.2. Research Topic – Innovative Pedagogy for Wind Energy Excellence

Effective teaching methods, interdisciplinary competence, and innovative tools are crucial for advancing wind energy education. This research topic emphasizes the development and implementation of cutting-edge pedagogical approaches, ensuring that education in the wind energy sector and related sectors goes beyond traditional methods. It involves exploring new ways to impart interdisciplinary skills, incorporating industry partnerships, and utilizing innovative tools such as numerical simulations and e.g. project games to grow a diverse and highly skilled workforce for the evolving demands of the wind energy industry.

3.5.1.3. Research Topic – Cultivating Diversity and Sustained Interest in Wind Energy

This research topic involves the development and assessment of long-term recruitment strategies, gender empowerment initiatives, and programs to sustain interest in wind energy. Gender empowerment is crucial to rectify historical imbalances, ensuring an inclusive and diverse workforce. By actively engaging women and non-binary persons, the industry benefits from a larger workforce with more skilled people, diverse perspectives, innovative solutions, and increased resilience. This research aims to create comprehensive strategies fostering an inclusive workforce and sustaining enthusiasm for wind energy, thereby securing a vibrant and skilled talent pool for the sector's future.

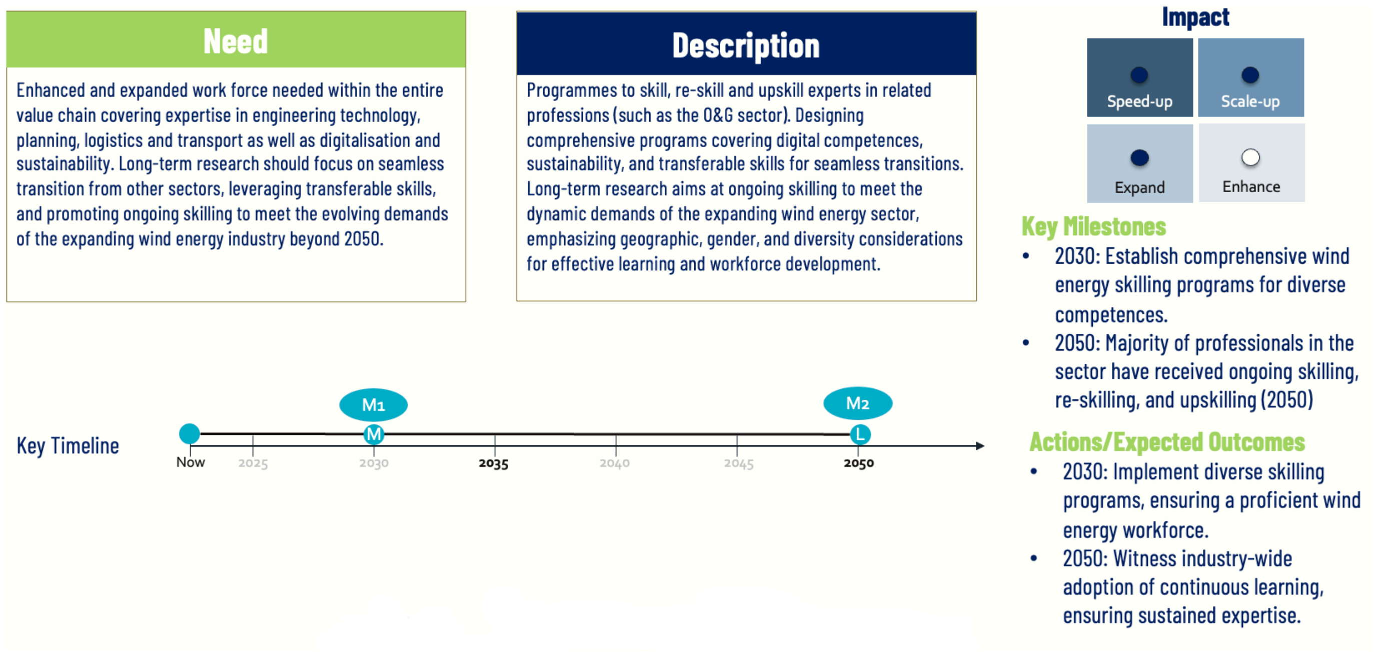
Long term recruitment strategies could include e.g.:

- Targeted Campaigns: Develop campaigns reaching diverse demographics, promoting wind energy as an inclusive and exciting career option.
- Educational Partnerships: Collaborate with educational institutions to establish clear pathways for students interested in wind energy careers.
- Industry Collaboration: Engage with industry partners to showcase career opportunities, internships, and mentorship programs.
- Public Awareness: Increase public awareness of the long-term benefits and opportunities within the wind energy sector through media campaigns and community outreach.

- Continuous Engagement: Implement ongoing initiatives to keep prospective talents informed and engaged throughout their academic and professional journeys.

It will be of importance to thoroughly examine and understand the current state of educational programs in the wind energy sector. A detailed analysis should assess the effectiveness of existing initiatives, identify gaps in skill development, and evaluate how well the current education system aligns with the dynamic requirements of the evolving wind energy industry. The aim is to inform strategic improvements, ensuring that educational programs are tailored to equip students with the diverse and specialized skills necessary to thrive in a rapidly advancing sector.

3.5.2. R&I Priority Sub-Theme- Skilling, re-skilling and upskilling activities



This sub-theme addresses the need of cultivating an enhanced and expanded workforce within the wind energy sector.

As assumed here, "skill" generally refers to acquiring new capabilities, "re-skill" emphasizes acquiring new skills in a different domain, and "upskill" emphasizes enhancing and advancing existing skills within the same domain. These terms are often used in the context of workforce development and lifelong learning to ensure professionals remain adaptable and relevant in their careers.

Recognizing the diverse expertise required, this initiative focuses on engineering technology, planning, logistics, digitalization, and sustainability. Programs are needed to skill, re-skill and upskill people into the wind energy sector. They should cover digital competences, sustainability competences (natural and social science) in addition to technological competences.

The research aims to drive seamless transitions from other sectors, leveraging transferable skills. The main goal is to meet the dynamic demands of the expanding wind energy industry beyond 2050.

3.5.2.1. Research Topic – Strategic workforce development across the wind energy value chain

Skilling, re-skilling, and upskilling initiatives cater to individuals with varied educational and professional backgrounds outside the wind sector. Recognizing the value of transferable skills, these programs aim to seamlessly integrate professionals from diverse sectors into the wind energy workforce. To meet the demands of a rapidly evolving wind energy landscape, there is a pressing need for an enhanced and expanded workforce spanning the entire value chain. This includes cultivating expertise in engineering technology, planning, logistics, transport, digitalization, and sustainability. The aim is to establish a skilled workforce that can contribute to every facet of the wind energy sector, ensuring its sustained growth, innovation, and environmental responsibility. This involves targeted education, training, and recruitment initiatives aligned with the diverse demands of the industry.

3.5.2.2. Research Topic – Optimizing cross-sector talent integration for wind energy sustainability.

This research focuses on the strategic and long-term aspects of facilitating a seamless transition for professionals from diverse sectors into the wind energy industry. The goal is to leverage transferable skills effectively, ensuring a harmonious integration of individuals with backgrounds outside the wind sector. By exploring innovative skilling programs and ongoing training initiatives, the research aims to develop a sustainable model that addresses the evolving demands of the wind energy industry beyond 2050. The emphasis is on creating a skilled, adaptive workforce capable of driving continued growth and innovation in the sector.

This research envisions a comprehensive strategy to facilitate the transition of professionals from e.g. declining fossil industries into a (hopefully) thriving wind energy sector. Tailored transition programs will be crafted to acknowledge the unique skills of individuals and ease their shift into wind energy roles. Leveraging Recognition of Prior Learning (RPL), this initiative will formally recognize and utilize the valuable experience of individuals navigating the evolving energy landscape.

Internship and mentorship initiatives within the wind energy sector will provide practical exposure, bridging the knowledge gap and instilling a firsthand understanding of the industry's dynamics. Digital skill enhancement programs will be integral, equipping the workforce with the technological acumen demanded by the evolving wind energy landscape.

Collaborations between wind energy and declining fossil industries (as an example) will be forged to facilitate knowledge exchange and collaborative training programs. Career guidance will map out clear pathways and qualifications for various roles, while government incentives will support individuals and companies navigating this transition. Skill recognition platforms will endorse acquired skills, boosting the credibility of transitioning professionals. Adaptive training modules will ensure ongoing learning, aligning the workforce with the evolving demands of the wind energy sector. Community engagement forums will provide spaces for networking and mutual support, fostering a collaborative environment. This research aims to build a sustainable and inclusive talent pool, ensuring a successful transition for professionals navigating the shift from industries in decline to the promising future of wind energy.

3.5.3. R&I Priority Sub-Theme- Increase public engagement of citizens.

Research Gap/Need

Socio-economical-technical approach for wind project development and execution to improve engagement and empowerment of citizens, considering societal energy needs.

Scope Outline/Description

Provide guidelines for continuous community involvement throughout the whole project period as good practices for project developers.
Demonstrate the benefits of wind energy for society as a whole and local communities.

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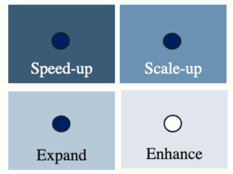
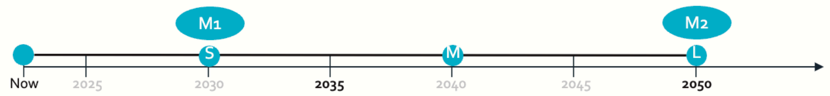


Key Milestones

- Pilot projects with enhanced community involvement established (2030)
- All European wind project developments follow good practices of community involvement (2050)

Key Timeline



Actions/Expected Outcomes

- Short – Awareness of participatory approaches (2030)
- Medium – Consensus on good practices for empowering citizens (2040)
- Long – Good practices implemented in regulations (2050)

Existing models for citizen involvement lack inclusivity, prompting the need for community-tailored initiatives such as innovative citizen science projects and tools that foster diverse community engagement in wind energy projects. In addition, there is a recognized gap in tools for meaningful stakeholder dialogue, hindering transparent communication in wind energy projects. To address this, the focus should be on designing and implementing practices and platforms that facilitate inclusive communication and involvement ensuring a more transparent decision-making process.

The inadequacy of tools for comprehensive stakeholder concern, mapping sectors like fishing, aquaculture, energy, military, tourism, and transport, present critical gaps. Developing mapping tools to address concerns during the project planning phase will become important for effective stakeholder engagement. Another challenge lies in the limited interdisciplinary collaboration in developing models for stakeholder interaction. Encouraging collaboration among researchers from different fields of research is essential to create holistic models that consider local conditions and societal impacts, thereby enriching project design.

Among longer-term research topics, there's a need to enhance the evaluation of site-specific socio-economic impacts, recognizing current inadequacies in evaluation methods. The focus should be on improving techniques and defining criteria for responsible wind energy expansion. Lastly, the documentation of energy justice practices is currently limited, highlighting the critical need for ethical evaluation including documenting and sharing best practices. This comprises addressing concerns related to the finite lifespan of wind turbines and sites and the long-term effects of the activities on the local communities. Simultaneously, the absence of guidelines for sustained community involvement emerges as a significant gap. Establishing comprehensive guidelines for developers is imperative to ensure ongoing community engagement throughout the entire project period. This approach not only fosters transparency, trust, and sustainable partnerships but also contributes to addressing energy justice concerns in the context of wind energy projects.

3.5.4. R&I Priority Sub-Theme- Fair transition, inclusiveness and stakeholder interests

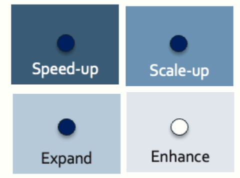
Research Gap/Need

Develop tools and methods to identify all relevant stakeholders, improve the understanding and map stakeholder concerns, as key elements to ensure a fair and inclusive energy transition.

Scope Outline/Description

Develop novel governance and ownership models of wind farms that consider societal needs and interests, include diverse stakeholders and ensure energy justice. Establish and document good practices for considering affected parties and generations (including e.g local stakeholders as well as marginalised groups outside Europe.)

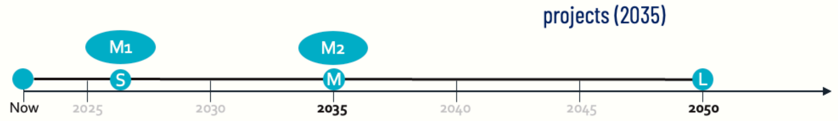
Impact



Key Milestones

- Governance models developed (2027)
- Implementation and assessment of governance models in wind energy projects (2035)

Key Timeline



Actions/Expected Outcomes

- Short - Awareness of the challenges related to energy justice (2027)
- Medium - Good practices to ensure energy justice for marginalized groups in the value chain (2035)
- Long – Good practices to ensure energy justice for future generations (2050)

3.5.4.1. Research Topic - The good process

Local resistance to wind farm developments is more and more common. This phenomenon still tends to be simplified and labelled as selfish (not-in-my-backyard) NIMBY-behaviour. However, Kirkegaard et al. (2023a) clarify that local resistance and annoyance has now been rethought as representing responses to disruptions related to place identity, place attachment, spatial-visual perceptions, as well as reactions towards issues of spatial justice. Research will help to better understand the human experience with wind energy in people's everyday lives and develop solutions to improve it. Much more data on impacts and human responses will need to be collected, also across projects, i.e. going beyond project-by-project case studies.

3.5.4.2. Research Topic - Tools to map stakeholder concerns

Within the realm of wind energy project planning and development, this sub-theme dives into the profound aspects of energy justice and democracy, extending its view to encompass the whole of the project life cycle and the global value chain, reaching far beyond European borders. The imperative task at hand involves crafting and institutionalizing good practices by 2050, a strategic move designed to methodically consider and address the concerns and expectations that arise throughout the finite lifetime of wind turbines and sites.

At its core, this sub-theme is dedicated to stimulating the principles of energy justice and democracy, ensuring a balanced and inclusive approach to distributional aspects, transparent and fair procedural issues and recognition fairness. The emphasis lies not only on the immediate planning and development phases but extends seamlessly across the entire life cycle and value chain of wind energy projects. The overarching goal is to lay the foundation for robust practices that consider the multifaceted considerations of affected parties, fostering a sense of global inclusivity and championing responsible stewardship in the evolution of the wind energy sector.

This sub-theme also harmonizes with the broader narrative of energy justice and democracy, aligning with the imperative need to establish practices that surpass geographical boundaries and temporal constraints. As we progress towards 2050, the focus remains committed on creating an equitable and responsible framework for wind energy transition, ensuring a sustainable and inclusive global energy landscape.

3.5.4.3. Research Topic – Technology-people-relations and public perception

We experience a change in the interactions between people and wind energy technology. Contestations are arising on grounds of a commodification and marketisation of wind energy.

Research may also have to look 'inwards' into the wind energy sector to understand the perception and reactions of the sector toward their changed relations with the public. It is not an easy task to master the transition from 'welcome saviour' who was perceived as green ally in preventing climate change to (in some places) 'suspicious intruder' who is expected to make an effort to win people's acceptance, prove sustainability, minimise environmental impacts and to create additional societal value in multiple dimensions (Kirkegaard et al., 2023a).

Research must map and understand the attitude and valuations toward and opinions regarding wind energy technology itself as well as of its use of materials and space.

3.5.5. R&I Priority Sub-Theme- Interdisciplinary/ Transdisciplinary relations with coexistence

This sub-theme addresses the intricate web of interdisciplinary and transdisciplinary relations crucial for fostering harmonious coexistence in the wind energy landscape. Rooted in the principles outlined in the ETIPwind report, it drives the concept of co-design into the forefront. By engaging stakeholders, this sub-theme champions a collaborative approach that considers the social, ethical, cultural, and historical context in local operation management of wind power plants.

At its core, the focus extends to understanding the socio-spatial consequences of continued wind deployment, particularly digging into the social effects of upscaling. In the planning phase, the emphasis is on the co-creation of technology by involving stakeholders, ensuring a holistic understanding of the local context. Furthermore, this sub-theme advocates for an in-depth evaluation of the consequences stemming from intensified wind energy production. It calls for the identification and definition of relevant assessment criteria, specifically tailored for site-specific socio-economic and environmental impacts and benefits. This careful planning during the early phases becomes the bedrock for responsible wind energy expansion and paves the way for inclusive, beneficial integration into diverse communities by 2050.

Guided by a commitment to interdisciplinary collaboration, the sub-theme acknowledges that assessing land and sea use impacts and defining socio-economic and justice criteria are paramount. These actions are not just technical necessities; they are essential components of a vision that imagines wind energy expansion as a responsible and integral part of diverse communities, contributing to a sustainable and inclusive future.

Research Gap/Need

Co-design of the technology by engaging the stakeholders, and considering the social, cultural and historical context in the local operation management of wind power plants. Understanding of socio-spatial consequences of further wind deployment and the social effects of upscaling.

Scope Outline/Description

Evaluation of the consequences of intensified wind energy production.
Identification and definition of relevant assessment criteria of site-specific socio-economic and environmental impacts and benefits. (Planning phase)

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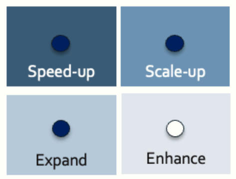


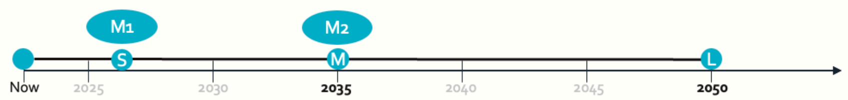
Key Milestones

- Systematic method to identify relevant stakeholders and their (competing) interests in specific projects (2027)
- Assessment criteria of balanced coexistence (2035)

Actions/Expected Outcomes

- Short – Method for stakeholder identification (2027)
- Medium – Propose roadmap to coexistence (2035)
- Long – Propose criteria to balance co-existence in spatial planning (2050)

Key Timeline



3.6. CROSS-CUTTING RESEARCH THEMES

Although partially addressed in areas of the five Research Themes elaborated in the previous sections, NeWindEERA has introduced the cross-cutting topics below to address additional challenges and explicitly convey the important research needs. The cross-cutting topics have been grouped into five sub-themes:

- Climate, Atmosphere, Ocean and Geophysics
- Disruptive technologies
- Policy and regulation
- Social aspects
- Finance

It is recognised that aspects of these sub-themes also appear (to a greater or lesser degree) in the earlier five R&I priority themes, but they were deemed significant enough to have their own place under the cross-cutting research themes too.

3.6.1. Climate, Atmosphere, Ocean and Geophysics

Research Gap/Need

Advances in measuring and modelling the geophysical characteristics of air, sea, and seabed is a fundament requirement for several of the priority areas. Greater accuracy in assessment and greater understanding of the physical processes in nature and wind energies feedback on nature is essential.

Scope Outline/Description

Climate change impacts on all physical conditions relevant for wind energy. Description, assessment and prediction (including forecasting) of physical conditions needed to accurately estimate distribution of conditions and assess variations that impact operations and integration of wind energy.

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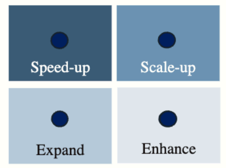

New Research Infrastructure Required?

Key Milestones

- M1 – Accurate validated models of wind farm cluster wake effects (2028)
- M2 – Comprehensive operational collaboration with weather and climate centres (2035)

Actions/Expected Outcomes

- Short, S – Common shared measurement database for for validation of physical models (2025)
- Medium, M – Improved and shared model set-ups for geophysical modelling (2030)
- Long, L – Infrastructure for measurement and modelling supporting research and operations (2035)

Key Timeline

3.6.1.1. Research Topic – Geophysical characteristics measuring and modelling advancement

Understanding of wakes and blockage effects will be essential for future larges cale deployment of wind. Estimation of wind climate of large wind parks and wind farm clusters is subject of ongoing research due to interaction with larger scale processes than heretheto addressed in current engineering practices. The subject is active research that spans several of the research themes outlined in this document.

It is important for resource and yield assessment as well as wind conditions in and around wind power plants impacting integration (wind variability etc) and operations (weather windows etc).

3.6.1.2. Research Topic – Wake effect model development

Understanding of the impacts of massive scale wind energy deployment is of also important because uncertainty on this subject can be highlighed as a risk factor also influencing social engagement and citizen suppport of wind energy projects. To what extent massive scale wind energy deployment influences other meteorological fields is also important and can broaden the size of stakeholders impacted by large scale wind energy.

3.6.1.3. Research Topic – Climate change physical conditions impact analysis

The interaction between the reduced wind speeds inside a park and the horizontal water transport remains as a potential factor that may significantly change the conditions important, for example, for primary production, and affect the stratification depth and arrival time. Literature seems very uncertain about the effects and consequences of these effects. This will be important for wide range of stakeholders in the area – including the ecosystems – thus also for public acceptance.

Interaction between ocean currents and protrusion of offshore wind structures through the thermocline may also offer significant effects to several stakeholders.

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3.6.2. Emerging technologies

In this section, a small number of emerging technology examples is mentioned, but it must be emphasised that this list is not exhaustive. For example, other concepts could be introduced in the future that have the potential to disrupt the advancement of wind turbine technology and this applies to components of the turbine as well as the entire machine.

The important point to note is that there is a place in the NeWindEERA research programme to consider and develop such technologies and this is an important part of the ongoing evolution of wind turbine technology.

Research Gap/Need

New concept for harvesting wind energy need to be explored and assessed for their potential to expand the exploitation of wind in new ways, and to enhance the performance and efficiency of new technologies and reduce costs.

Scope Outline/Description

Emerging technologies are unforeseeable but examples may be airborne wind, building mounted units, multirotor concepts, and concepts working in directly in other sectors, such as ship propulsion, hydrolysis, pumping, etc

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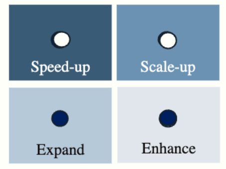
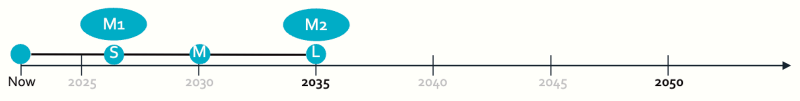


New Research Infrastructure Required?

Key Timeline



Key Milestones

- M1 – "Watch-list" established on most promising disruptive technologies (2028)
- M2 – Innovation (2035)

Actions/Expected Outcomes

- Short, S – In depth conference session of disruptive technologies (2025)
- Medium, M – Several largescale demonstration projects underway exploring most promising technologies (2030)
- Long, L – One or two new technologies in full operation (2035)

3.6.2.1. Research Topic – New concept assessment and development

The following list of disruptive technologies are provided as examples of where we expect disruptive technology development to take place. It is recognised that time and funding in the NeWindEERA research programme should be set aside to develop these technologies and provide an opportunity for them to flourish. Inevitably, some of these technologies will progress more successfully than others as the wind sector moves forward towards its 2050 Net Zero targets.

- Multirotor concepts
- Airborne wind
- Small wind turbines
- Tip rotor designs
- Ducted turbines

3.6.2.2. Research Topic – Turbine component performance and efficiency

The following list of disruptive technologies are provided as examples of where we expect disruptive technology development to take place at component level, particularly when considering performance and efficiency improvements. As with section 3.6.2.1, it is recognised that time and funding should be set aside to develop these technologies and provide an opportunity for the most promising developments to flourish. Inevitably, some of these technologies will progress more successfully than others as the wind sector moves forward towards 2050 Net Zero targets.

- Trailing edge flaps
- Slats
- Two-bladed rotors and downwind/lee rotors
  - E.g., Aerodyn SCD technology or similar
- Scaled model components/tests
  - E.g., Aerodyn Nezzy technology or similar
  - Nezzy: rotor downwind/lee, two-bladed rotor, no yaw drive – floater is combined with the turbine and is yawing too
  - Nezzy2: a multirotor concept combined with Nezzy

3.6.3. Policy and regulation

There is a need to accelerate the permitting process without jeopardising democratic principles of planning and stakeholder involvement. This requires new approaches to planning renewable energy infrastructures, including regulations for engagement, decision-making and community benefits.

Research Gap/Need

There is an urgent needs to speed up and streamline the permitting process without jeopardizing democratic principles and ignoring local particularities. This necessitates an improvement of current engagement and assessment methods, design and planning procedures and regulations to incorporate new areas and technologies

Scope Outline/Description

Approaches and tools for enhancing public involvement beyond 'invited participation" within design phase of energy projects, strategic special planning and for end-of-life decision-making. Advance environmental and social impact assessment to incorporate PtX/hybrid infrastructures, cumulative impacts, co-location, and co-existence in streamlined process. Assessment of transfer insight to Global South.

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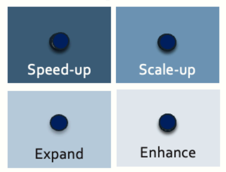


New Research Infrastructure Required?

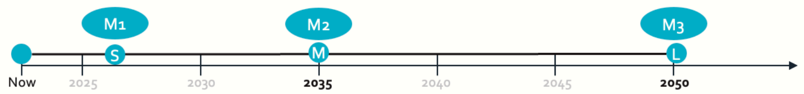
Key Milestones

- M1 – Experimental assessment to novel approaches (2030)
- M2 – New engagement and assessment methods verified in different contexts (2035)
- M3 – Implementation in regulation (2050)

Actions/Expected Outcomes

- Short– Enhance approaches for public involvement (2028)
- Medium– Revision in good practices in engagement and impact assessment (2035)
- Long – Regulatory implementation across countries and development of approaches for the Global South (2035)

Key Timeline



3.6.3.1. Research Topic – Spatial planning

Given the required scale of expanding wind energy landscapes, there should be greater attention to spatial planning, in particular on strategic and sectoral planning (i.e. before particular projects are considered, while priority areas or zones are designated). This also necessitates the involvement of affected stakeholders, the wider public and potential host communities in strategic planning with the aim to facilitate and ease the subsequent development of specific projects. This also encompasses the consideration of hybrid projects, beyond the deployment of wind turbines, that play an increasingly important role in energy plans.

3.6.3.2. Research Topic – Evolution of environmental impact assessments

Current standards and approaches to planning are not well suited to respond to and cope with novel technologies, such as hybrid projects, Power-to-X solutions, hydrogen projects. This particularly relates to environmental impact assessments that are not entirely appropriate to adequately deal with hybrid infrastructures, cumulative impacts, co-existence and re-powering as well as the pace of the necessary expansion.

3.6.3.3. Research Topic – Wind farm life cycle public/ community engagement

Possibilities for engaging the public and host communities during the whole life-cycle of wind farm projects, i.e. beyond the planning and development stage. This includes the design phase, operational phase and decisions concerning the end-of-life and repowering.

3.6.3.4. Research Topic – Best practice transfer to the Global South

The transfer and export of experiences, approaches, policies and regulations to the Global South should be considered and assessed carefully. What works in one place, may not work in another place. Hence, regulations and approaches would need to be adapted to the contexts and requirements for the expanding wind energy in developing countries to avoid reproducing extractivist practices that have been experienced from other sectors.

3.6.4. Social Aspects

Research Gap/Need

It is no longer viable to avoid conflicts with communities as more and more people are exposed to expanding wind energy landscapes, given the required upscaling and rollout. Instead it is necessary to identify and develop new solutions for reconciling wind farm projects with in order for them to benefit from and attach wind turbines to their everyday lives, and ensure a just transition.

Scope Outline/Description

Enhance public participation and co-creation across all development phases. Develop novel approaches for socializing wind rights by identifying possibilities for communities to co-create and co-own onshore and offshore wind turbines and creating tangible benefits. Investigate socio-technical implications, temporalities of acceptance, people-technology-place relations, and social impacts of supply chain.

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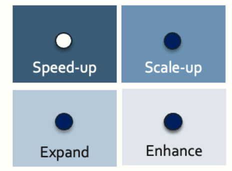


New Research Infrastructure Required?

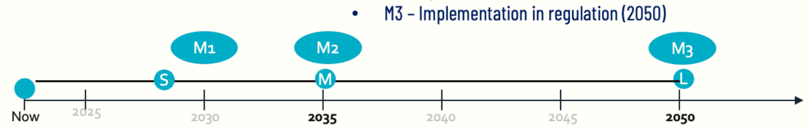
Key Milestones

- M1 – Approaches for creating tangible benefits identified (2030)
- M2 –New governance models assessed and developed (2035)
- M3 – Implementation in regulation (2050)

Actions/Expected Outcomes

- Short – Meta-analysis of local contestations and advancement of energy justice frame (2027)
- Medium – New participation (co-design) and ownership solutions (2035)
- Long – Implementation in regulation in all wind energy projects (2050)

Key Timeline



3.6.4.1. Research Topic – Communication streamlining and host community benefit creation

There is a need to simplify and streamline the communication of research outcomes to relevant audiences. This involves both technical and social aspects of research on wind energy.In light of the massive rollout of wind farm projects, it seems no longer viable to only focus on solutions for evading conflicts with communities. Instead, it is necessary to find new solutions to reconcile wind farms with the interests of neighbours and co-design new approaches for creating tangible benefits for host communities. This requires a better understanding and awareness of potential wind energy benefits.

3.6.4.2. Research Topic – Development of practical approach to lifecycle public participation

Develop practical terms of public participation in the process outlined in the policy and regulation section, particularly regarding participation along the lifecycle. This involves the process co-creation in order to co-create solutions and outcomes. Moreover, for the planning processes, it also includes experiments with different approach to the decision-making (e.g. co-creation workshops, citizen assemblies and citizen juries)

3.6.4.3. Research Topic – Socialising wind rights

There is a need to explore new ways and possibilities for socialising wind rights, i.e. allowing community groups to initiate the planning process, financially benefit from wind farms and invest in or (co-) own onshore and offshore wind farms in order to generate a revenue flow creating shared value with local communities. This will inform issues of procedural and distributional justice that have been repeatedly identified as central constituents underlying contestations over wind farm projects.

3.6.4.4. Research Topic – Relationship between people, technology and places for all relevant social issues

There should be a greater research focus on dynamics and temporalities of acceptance beyond the planning phase in order to understand how the relationship between people, technology and places may be variously affected (or altered or enhanced) over time, and to inform future approaches of deploying and expanding wind farms.

Social issues do not only refer to the siting of wind turbines, but the sustainability of the wind industry, including the supply chain of sourcing of materials, manufacturing and constructing wind turbines that have impacts on local communities and environments.

3.6.5. Finance

3.6.5.1. Research Topic – Upgrade to finance and cost models to incorporate environmental/external costs

This upgrade needs to include environmental (external) costs and compare across energy sectors to maximise its effectiveness and impact.

3.6.5.2. Research Topic – Risk factors impacting financing costs

Risk: a (very) important parameter in the LCOE, is the discount rate. What affects the discount rate is a range of factors, most of them currently outside the realm or understanding from the engineering side. However, risk is a central piece of the puzzle.

Risk as understood and seen from the insurance and thus financial side (high risk mean high capital costs and insurance premiums) seem rather disconnected from how risk is understood from the engineering side, as the former is seen more from the "top-down" while from the latter a more "bottom-up" view is common. A common understanding here is likely to benefit more effectively towards lower LCOE.

3.7. SUMMARY

In this chapter, we have introduced six R&I priority themes that closely align with the five themes from the ETIPWind SRIA document and added an equally important six theme covering cross-cutting research. The chapter has developed these six priority themes by summarising the key research and innovation issues faced by the wind energy sector, the expected timelines involved and the potential impact of addressing the identified issues.

The issues have been grouped into sub-themes and research topics for each of the six priority themes and this then forms the basis for the NeWindEERA research programme (priority themes, sub-themes, research topics, expected impact and outcomes, milestones, and timelines) which is visually represented in Chapter 4 and Appendix 1 of this report.

4. A Roadmap for Future Wind Energy Research

This chapter was led by ORE Catapult with co-lead support from Ciemat and further contributions from DTU, SINTEF and CWD (RWTH Aachen).

The purpose of the chapter was to provide a visual representation of the NeWindEERA research programme complete with timeline. This was published as a 12-page brochure, most of which can be found in Appendix 1 of this report.

The five R&I priority themes of Industrialisation, Operations & Maintenance, Wind Energy System Integration, Sustainability & Circularity, and Skills & Coexistence along with the Cross-cutting research themes are illustrated in this brochure across six pages along with the associated research programme timelines in the centrefold. The timelines provide a forecast for the expected duration and milestones of the key research activities across the six research themes identified. These are included in Appendix 1 of this report.

The penultimate page of the brochure highlights another important feature of NeWindEERA, in that it builds upon the well-founded research activity of the EERA JP Wind research community; previously summarised in the 2020 EERA JP Wind R&I Strategy publication. This is represented via a table (see overleaf) to indicate how the ongoing research activities map against the newly established NeWindEERA research programme. Finally, the back cover of the brochure (and the back cover of this report) illustrates how the NeWindEERA research programme represents one of the three pillars of European wind energy research and innovation. It stands alongside the ETIPWind SRIA and the emerging European Wind Energy Centre of Excellence (EuCoE4Wind).

MAPPING THE EERA JP WIND RESEARCH DISCIPLINES

The NeWindEERA project builds on the EERA JP Wind R&I Strategy released in 2020 and recognises the strong heritage of research disciplines and technical excellence currently in existence amongst the EERA JP Wind membership.

The table below maps how this existing capability and activity will continue to be utilised and developed in the six R&I priority themes identified in this brochure.

EERA JP Wind R&I Strategy Topic	NeWindEERA R&I Priority Theme					
	Theme 1	Theme 2	Theme 3	Theme 4	Theme 5	Theme 6
Next generation wind turbine technology & disruptive concepts						
Implementation of 6000GW wind power worldwide	x		x	x		x
Unknowns in degradation mechanisms	x	x		x		
Interpretation and extrapolation of testing	x		x	x		
Multi-purpose platforms	x		x			x
Degradation and damage mechanisms	x	x		x		
Access to data	x	x	x	x		
Upscaling of wind	x	x	x	x	x	
Development of larger and larger turbines	x	x	x		x	x
Grid integration & energy systems						
Validated energy systems models			x			
System friendly wind power			x		x	x
Behaviour and control of large HVDC connected clusters			x		x	x
Dynamic performance of very large wind power clusters			x		x	
Failure mechanisms of cables, transformers, converters	x	x	x			
Advanced system services from wind power		x	x		x	
Sustainability, social acceptance & human resources						
Identifying higher societal value from wind energy				x	x	x
Assessing wind energy contribution to sustainable goals				x	x	x
Developing sustainable technologies and designs	x	x		x		x
Identifying skills and training needs					x	
Assessing R&I project economic and societal impact	x	x	x	x	x	x
Applying life cycle assessment		x		x	x	x
Social acceptance mechanism understanding	x			x	x	x
Offshore wind (bottom fixed + floating)						
Validation of integrated design models for floating wind	x	x				
Offshore physics (soil, waves, air, sea)	x	x				x
Efficient multi-disciplinary optimisation	x	x			x	x
Site specific conditions for electrical infrastructure		x	x			
Operation & Maintenance	x	x	x			
Accurate component reliability models	x	x	x	x		
Lifetime extension		x		x		x
Robotics	x	x				x
Degradation mechanisms of surfaces (wear, erosion..)	x	x		x		
Data analytics for O&M and condition monitoring	x	x	x	x	x	x
Fundamental wind energy science						
Climate change and extreme climate impact	x			x		x
Physics of large rotor aerodynamics (inflow, blade, wake)	x	x		x	x	
Better knowledge of materials (properties, degradation..)	x			x		x
Atmospheric multi-scale flow (mesoscale to wind farm)	x	x				x
High performance computing and digitalisation	x	x	x		x	
System engineering models (fluid, soil, electro-mech.)	x		x	x	x	x

5. Navigating Existing European Wind Energy Research – An Analysis of Key Projects

This chapter was led by Ciemat with co-lead support from CWD (RWTH Aachen) and further contributions from DTU, ORE Catapult and SINTEF.

5.1. SUMMARY

Having identified the research gaps (Chapter 2) and once those gaps have been linked into the key research theme descriptions (Chapter 3), the consortium has identified and analysed the most relevant ongoing EU R&D projects with activity related to the different key research themes and associated research topics/scope, with the aim to identify R&D topics partially or not addressed yet.

For this purpose, the consortium has collected most of the national and EU-funded R&D projects considered relevant for the analysis, applying these general criteria to include the most representative projects: not to include projects that finished before 2017; and not to include projects with a budget under 2 M€. However, some exceptions have been included for projects that, without meeting these criteria, were considered due to their relevance.

A specific template has been designed to integrate the most relevant project data including some brief analysis of results and gaps. And a master spreadsheet list has been also established with the most relevant data from the R&D projects collected, to friendly classify all this information.

The consortium has decided to develop a high-level analysis of the project templates collated for each research theme. This analysis will be provided by each Research Theme Leader.

Finally, some conclusions will be defined at the end of the Chapter 5 document with valuable comments for the Mid and Long-Term R&D needs analysis.

5.2. A DESCRIPTION OF THE PROJECT TEMPLATE

The R&D projects template target is to offer a friendly recipient for the most relevant information collated from the R&D projects. The main information required from all the projects collected are the Research Themes addressed by the project. Then the main research sub-topic and research topic addressed according to the Chapter 3 definitions are also included. A bunch of administrative data are also included but there are three specific points with a more elaborate information as the brief description of the main activities developed in the project, the results / highlights obtained, and the research gaps partially or not addressed in the project.

5.2.1. Template explanation

A template has been established to harmonize the collection of information of the different projects among the partners of the NeWindEERA project. The template is shown in the following Figure.

Fig : Template of projects

NeWindEERA
R&I PROJECTS List

R&I PRIORITY THEME 1	R&I PRIORITY THEME 2	R&I PRIORITY THEME 3	R&I PRIORITY THEME 4	R&I PRIORITY THEME 5	R&I PRIORITY THEME 6
Industrialization, Scale up and Competitiveness	O&M Digitalization	Wind Energy System Integration	Sustainability and Circularity	Skill and Co-existence	Cross-cutting

MAIN RESEARCH SUB-THEMES:

- TITLE:
- FUNDING SOURCE: PROJECT SIZE/TOTAL BUDGET(M€):
- COORDINATOR:
- NUMBER OF PARTNERS AND TYPE: RESEARCH-ACADEMY: INDUSTRY: OTHERS:
- MAIN OBJECTIVE:.
- WEB PAGE:
- START DATE/END DATE:
- BRIEF DESCRIPTION:
- RESULTS ASSESSMENT/HIGHLIGHTS:
- RESEARCH GAPS:

RESEARCH TOPICS ADDRESSED:

A brief description on how to navigate the project templates is given in this section, aiming to explain how to interpret them. The NeWindEERA R&I project list template includes in the upper part six checkboxes with the different Research Themes identified in Chapter two. The different RTs are represented with different colours:

- Yellow colour for RT 1: Industrialization, Scaler Up and Competitiveness
- Blue colour for RT 2: Operation and Maintenance and digitalisation
- Orange colour for RT 3: Wind Energy System Integration
- Green colour for RT 4: Sustainability and circularity
- Red colour for RT 5: Skills and coexistence
- Grey colour for RT 6: Cross cutting themes

Depending on the number of RT addressed in the projects, more than one checkbox can be ticked.

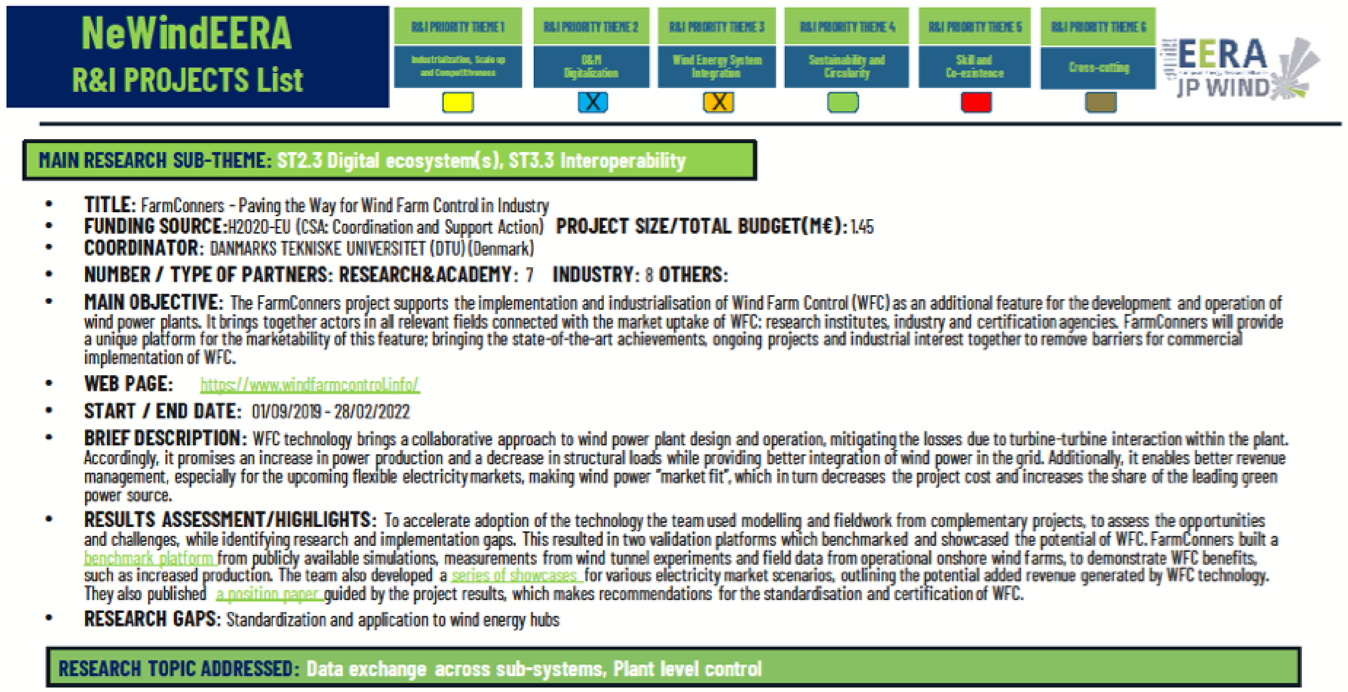
Then several test boxes must be fulfilled:

- Two of them with green background include:
  - the main research sub-themes and
  - the research topics addressed

- Then general information of the project included in template as:
  - **Title:** Complete project title and acronym
  - **Funding source:** EU Commission funding programs or national & regional funding programs. In this case the funding agency must be included in the template.
  - **Project size/Total budget:** (in M€)
  - **Name of coordinator:** Entity and country.
  - **Number of partners:** sorted by Research/Academic, Industry and Others
  - **Main objective of the project:** Very brief description.
  - **Web page:** checked address
  - **Start Date/End Date:** Formal dates
  - **Brief description:** The main activities developed in the project can be described here.
  - **Results assessment/Highlights:** Brief description of all kinds of results obtained in the project execution.
  - **Research gaps.** According to Chapter 2, topics fully, partially or non-addressed in the project

An example of a populated project template is given in the following Figure, as a reference of the available information available for each project.

Fig: Example of project



NeWindEERA
R&I PROJECTS List

R&I PRIORITY THEME 1	R&I PRIORITY THEME 2	R&I PRIORITY THEME 3	R&I PRIORITY THEME 4	R&I PRIORITY THEME 5	R&I PRIORITY THEME 6
Industrialisation, Scale up and Competitiveness	O&M Digitalization	Wind Energy System Integration	Sustainability and Circularity	Skill and Co-existence	Cross-cutting
	X	X			

MAIN RESEARCH SUB-THEME: ST2.3 Digital ecosystem(s), ST3.3 Interoperability

- TITLE: FarmConners - Paving the Way for Wind Farm Control in Industry
- FUNDING SOURCE:H2020-EU (CSA: Coordination and Support Action) PROJECT SIZE/TOTAL BUDGET(M€): 1.45
- COORDINATOR: DANMARKS TEKNISKE UNIVERSITET (DTU) (Denmark)
- NUMBER / TYPE OF PARTNERS: RESEARCH&ACADEMY: 7 INDUSTRY: 8 OTHERS:
- MAIN OBJECTIVE: The FarmConners project supports the implementation and industrialisation of Wind Farm Control (WFC) as an additional feature for the development and operation of wind power plants. It brings together actors in all relevant fields connected with the market uptake of WFC: research institutes, industry and certification agencies. FarmConners will provide a unique platform for the marketability of this feature; bringing the state-of-the-art achievements, ongoing projects and industrial interest together to remove barriers for commercial implementation of WFC.
- WEB PAGE: https://www.windfarmcontrol.info/
- START / END DATE: 01/09/2019 - 28/02/2022
- BRIEF DESCRIPTION: WFC technology brings a collaborative approach to wind power plant design and operation, mitigating the losses due to turbine-turbine interaction within the plant. Accordingly, it promises an increase in power production and a decrease in structural loads while providing better integration of wind power in the grid. Additionally, it enables better revenue management, especially for the upcoming flexible electricity markets, making wind power "market fit", which in turn decreases the project cost and increases the share of the leading green power source.
- RESULTS ASSESSMENT/HIGHLIGHTS: To accelerate adoption of the technology the team used modelling and fieldwork from complementary projects, to assess the opportunities and challenges, while identifying research and implementation gaps. This resulted in two validation platforms which benchmarked and showcased the potential of WFC. FarmConners built a benchmark platform from publicly available simulations, measurements from wind tunnel experiments and field data from operational onshore wind farms, to demonstrate WFC benefits, such as increased production. The team also developed a series of showcases for various electricity market scenarios, outlining the potential added revenue generated by WFC technology. They also published a position paper guided by the project results, which makes recommendations for the standardisation and certification of WFC.
- RESEARCH GAPS: Standardization and application to wind energy hubs

RESEARCH TOPIC ADDRESSED: Data exchange across sub-systems, Plant level control

5.2.2. Spreadsheet with essential templates information

A master spreadsheet list showing all projects collated has been carried out, to organize all the information included in the templates. This master spreadsheet list include eleven columns with the basic data of the projects collected as the name of the project, Research Themes including the same background colour code applied in the template, Sub-themes with numeric code using the sub-themes list from the R&I Priority Theme schemes included in Chapter three, funding source, budget (in Euros), Coordinator, Country, Start date/End date with green or red background colour if the project is already in progress (green) or closed (red) and research topic addressed using the topics from the R&I Priority Themes schemes included in Chapter three. In the following Figure, a capture of the first few rows of the spreadsheet is shown as an example.

5.2.3. EERA Database

All the projects templates can be found here on EERA JP Wind website.

Name of the project	Research Theme	Research Theme	Research Theme
X-ROTOR	Industrialization, Scale-up and Competitiveness	Cross-cutting	
PivotBuoy	Industrialization, Scale-up and Competitiveness		
Aquada-GO	Operation & Maintenance, Digitalization		
DATA DRIVEN OFFSHORE	Industrialization, Scale-up and Competitiveness	Operation & Maintenance, Digitalization	
MooringSense	Operation & Maintenance, Digitalization		
SUDOCO	Wind Energy System Integration	Cross-cutting	
MERIDIONAL	Industrialization, Scale-up and Competitiveness		
Green Island	Wind Energy System Integration		
TWAIN	Wind Energy System Integration	Operation & Maintenance, Digitalization	Sustainability and circularity
FarmConners	Operation & Maintenance, Digitalization	Wind Energy System Integration	
DigiWind	Skills and co-existence		
LIFE Wind farms and Wildlife	Sustainability and circularity	Skills and co-existence	
FLOATECH	Industrialization, Scale-up and Competitiveness		
STRETCH	Industrialization, Scale-up and Competitiveness		
Innotip & Tiade	Industrialization, Scale-up and Competitiveness		
Bolt & Beautiful	Industrialization, Scale-up and Competitiveness	Operation & Maintenance, Digitalization	
Pile driving and pile extraction	Industrialization, Scale-up and Competitiveness	Sustainability and circularity	
Demonstrator GE Haliade X	Industrialization, Scale-up and Competitiveness		
SJOR	Industrialization, Scale-up and Competitiveness		
DOT	Wind Energy System Integration	Cross-cutting	
Cable JP project 1&2	Industrialization, Scale-up and Competitiveness	Operation & Maintenance, Digitalization	Cross-cutting
SAWOP	Operation & Maintenance, Digitalization		
WINDCORE, PROWESS	Operation & Maintenance, Digitalization		
AIRTUB 1 & AIRTUB-ROMI	Operation & Maintenance, Digitalization		
Dutch Offshore Wind Atlas	Operation & Maintenance, Digitalization	Cross-cutting	
SENSE Hub	Wind Energy System Integration		
North Sea Energy Programme	Wind Energy System Integration		
MARINEWIND	Cross-cutting	Industrialization, Scale-up and Competitiveness	Wind Energy System Integration
AIRE	Operation & Maintenance, Digitalization	Wind Energy System Integration	Sustainability and circularity
CL Windcon	Operation & Maintenance, Digitalization	Wind Energy System Integration	
ELOGOW	Wind Energy System Integration	Operation & Maintenance, Digitalization	
WiSAbigdata	Operation & Maintenance, Digitalization		
WindRamp	Wind Energy System Integration		
X-Wakes	Cross-cutting		
FLOAWER	Industrialization, Scale-up and Competitiveness	Skills and co-existence	
Active Yaw Control	Industrialization, Scale-up and Competitiveness		
PLATOON	Operation & Maintenance, Digitalization		
SuperSized 4.0	Operation & Maintenance, Digitalization		
RAINBOW	Operation & Maintenance, Digitalization		
Cloud4Wake	Operation & Maintenance, Digitalization		
MaSiWEC	Operation & Maintenance, Digitalization		
POSEIDON	Operation & Maintenance, Digitalization		

Sub-Themes	Funding Source	Budget (M€)	Coordinator	Country	Start Date	End Date	Research Topics addressed
ST1.2;ST6.2	Horizon 2020	3,9	University of Strathclyde	United Kingd	1/01/21	30/04/24	Aerodynamics, structural loads, drive train, turbine design
ST1.2	Horizon 2020	3,96	Exponential Renewables SL	Spain	1/01/19	31/12/23	Industrialization of floating offshore wind
ST2.2, ST2.3	Danish EUDP	3,4	DTU Wind	Denmark	1/01/23	TotalControl	Autonomous wind turbine operation, O&M and digitalization; Sensor technologies
ST1.3, ST2.3	European Research Council	2	University of Bergen	Norway	1/01/23	31/03/28	Holistic accelerated turbine design, Data exchange across subsystems
ST2.1, ST2.2, ST2.3	Horizon 2020	4,7	CTC	Spain	1/11/19	31/10/22	Digital Twin, Failure risk mitigation, O&M's costs reduction; Sensor technologies
ST3.3, ST6.1	Horizon Europe	5,8	TU Delft	Netherlands	1/10/23	30/09/27	Aerodynamics, wakes, control, AI, cybersecurity
ST1.3	Horizon Europe	6	TU Delft	Netherlands	1/10/22	30/09/26	Resource assessment, wake models, turbulence models, load models, CFD, aerodynamics
ST3.2, ST3.4, ST3.5	ERDF, Greek State	8,5	CRES	Greece	30/03/17	31/12/24	Grid operation at high RES penetration, ancillary services, long term storage
ST2.3, ST3.3, ST4.3	Horizon Europe	6	DTU Wind	Denmark	1/11/23	31/10/27	Data exchange across sub-systems, Optimisation & Decision making, Plant level control, Environmental c
ST2.3, ST3.3	Horizon 2020	1,45	DTU Wind	Denmark	1/09/19	28/02/22	Data exchange across sub-systems, Plant level control
ST5.1, ST5.2	Digital Europe Programme (DEP)	19,2	DTU Wind	Denmark	1/01/24	31/12/27	Education and strategic workforce expansion for the wind energy sector, Innovative Pedagogy for Wind E
ST4.?, ST5.2	LIFE, Greek State	0,9	CRES	Greece	1/10/13	31/12/18	Grid Environmental impact mitigation, coexistence
ST2.2	Horizon 2020	4,3	Technische Universitat Berlin	Germany	1/01/21	31/12/23	FOWT Simulation Tools, FOWT Control Techniques, LCOE Analysis
ST1.2, ST1.3	NL HER+	15	LM Wind Power	Denmark	1/01/18	1/01/22	Next generation WT technology, O&M, Sensor technologies, turbine design, virtual and full-scale testing
ST1.2, ST1.3	NL HER+	20	TNO, LM Wind Power	Netherlands	1/01/18	1/01/23	Next generation WT technology, Sensor technologies, turbine design, virtual and full-scale testing
ST1.2,ST1.3;ST2.3	NL HER+	4	TNO	Netherlands	1/01/22	1/01/26	Next generation WT technology, Sensor technologies, full-scale and scaled testing
ST1.4, ST4.4	NL HER+	15+	IHC Hydrohammer, Innogy, Va	Netherlands	1/01/13	1/01/22	Next generation support structures, Sensor technologies, Full-scale testing
ST1.2, ST1.3	NL HER+	20	GE Renewable Holding BV	Netherlands	1/01/18	1/01/22	Next generation WT technology, Sensor technologies, Full-scale testing
ST1.4, ST1.1	NL HER+	6	Delft Offshore Turbine BV	Netherlands	1/01/18	1/01/22	Next generation WT technology, Sensor technologies, virtual and scaled testing
ST3.5, ST6.2	NL HER+	15+	Delft Offshore Turbine BV	Netherlands	1/01/17	1/01/22	Disruptive WT technology, System integration potential, scaled and full-scale testing
ST2.2, ST2.3, ST6.2	NL HER+	3	MARIN, TNO	Netherlands	1/01/18	1/01/23	Sensor technologies, virtual and scaled testing, disruptive design
ST2.1, ST2.3	NL HER+	5	TNO	Netherlands	1/01/21	1/01/23	Sensor technologies, virtual and full-scale testing, AI driven forcasting tools
ST2.1, ST2.3	NL HER+	5	TNO	Netherlands	1/01/18	1/01/23	Sensor technologies, virtual and scaled testing
ST2.1, ST2.3	NL HER+	8	Zephyros	Netherlands	1/01/18	1/01/26	Sensor technologies, virtual, scaled and full-scale testing
ST2.3, ST6.1	NL HER+	3	TNO	Netherlands	1/01/17	1/01/21	AI driven forcasting tools, virtual testing
ST3.5	NL MOOI	6	TNO	Netherlands	1/01/17	1/01/21	Hybrid plants, Floating solar
ST3.1, ST3.2, ST3.3, ST3.4, ST3.5	NL MOOI	15+	TNO	Netherlands	1/01/17	1/01/21	Hybrid plants, operations, offshore energy infrastructure, energy islands, electrolysers, CCS, modelling
ST6.3, ST1.5, ST3,5	Horizon Europe	1,38	APRE	Italy	1/01/22	31/10/25	Renewable Energy Sources, Floating Offshore Wind
ST2.2, ST2.3, ST3.3, ST4.3	Horizon Europe	5,4	CENER	Spain	1/01/23	31/12/26	Autonomous wind installation, O&M and decommissioning; Optimisation & Decision-making; Plant level
ST2.2, ST3.3	Horizon 2020	4,9	CENER	Spain	1/11/16	31/10/19	Autonomous wind installation, O&M and decommissioning; Plant level control
ST 2.1, ST3.1, ST 3.3	Research Council of Norway	1,4	IFE	Norway	1/01/20	1/01/23	AI-driven resource assessment and forecasting tools, Transmission and generation flexibility, Hybrid plan
ST2.3	BMWK - 7th Energy Research	2,5	ForWind	Germany	1/12/19	30/11/23	Data Exchange across sub-systems; Optimisation & Decision making;
ST3.2, ST3.3	BMWK - 7th Energy Research	2,75	ForWind	Germany	1/07/20	31/12/23	Short term balancing; Plant level control; Forecasting
ST6.1, ST6.3	BMWK - 7th Energy Research	4,3	Fraunhofer IWES	Germany	1/11/19	30/04/23	Large wind farm and wind farm cluster flow; Impacts of massive scale wind energy deployment; Spatial
ST1.2, ST5.1, ST2.3	Horizon 2020	3,5	Ecole Centrale de Nantes	France	1/11/19	31/01/24	Industrialisation of floating offshore wind; Education and strategic workforce expansion;
ST1.2	Swedish Energy Agency	0,2	RISE	Sweden	3/01/22	1/05/24	Next generation wind turbine technology and economic optimization
ST2.1, ST2.3	Horizon 2020	11,5	ENGIE	Belgium	1/01/20	31/12/22	Big data, Energy management, real time data analytics, Software architecture, Energy grid
ST2.1	Flanders Innovation	1,3	VUB-AVRG	Belgium	1/01/20	31/12/23	Turbines, Life Performance
ST2.1	Flanders Innovation	0,55	VUB-AVRG	Belgium	4/01/21	30/09/24	Offshore wind farms, erosion, turbine blades
ST2.1	Flanders Innovation	0,77	VUB-AVRG	Belgium	1/04/23	1/03/26	Big data, wind farm wake
ST2.1	SIM&IWT	0,77	VUB-AVRG	Belgium	1/07/18	31/08/22	Rolling contact fatigue, Crack initiation, inclusions, finite element analysis, WEC
ST2.1, ST2.3	FOD EnergieTransitie	1,11	VUB-AVRG	Belgium	1/10/21	30/09/25	Digital Methodologies, Wind Assets, Digital Platform

5.3. ANALYSIS OF THE COLLATED PROJECTS

Based on the information available in the collated project templates, a brief analysis has been elaborated on a Theme bases, i.e., one analysis for each of the six identified Priority Themes (PT). The analysis includes a table with the list of the projects related to that PT (prepared from the master spreadsheet), with some basic information for each project, including the sub-theme and topic(s) addressed by the project, the budget, the number of partners and the funding source. The table also includes the total budget invested in each sub-theme.

In relation to the budget, a clarification is required: some projects address different sub-themes, sometimes even in different themes. To take this into account, while maintaining consistency in the figures, the amount that appears in the "Budget" cell is the total budget of the project, but the amount considered for each sub-theme has been calculated dividing the total amount by the number of subthemes. In this case, an asterisk has been added in the "Budget" cell as an indication that the project appears in different sub-themes. So, for example, if a project covers 2 sub-themes, each sub-theme includes ½ of the budget.
Finally, the analysis includes a statistical graph showing the number of identified projects that address each Topic.

5.3.1. Analysis of projects of Priority Theme 1 – Industrialisation, Scale-up and Competitiveness

The analysis of submitted projects reveals a significant concentration of research projects within Theme 1. A total of 66 (4+35+19+6+1) projects were submitted, amounting to a combined budget of 472 million euros. Notably, there is a predominant focus on the industrialisation of Floating Offshore Wind Turbines (FOWT), with 26 projects dedicated to this aspect, representing 39% of the total submissions and 35.5% of the budget allocated to this theme.

However, it is observed that there is a lack of emphasis on addressing the ramp-up of manufacturing capacities within Europe, particularly in view of the NZIA and EWPAP. Additionally, there is a noticeable underrepresentation of onshore wind projects, despite its anticipated dominance in future wind capacity installations and the accompanying unresolved issues and conflicts.

Generally, there is a notable and positive trend of collaboration between industry and research across the projects. Almost all consortiums in this Theme consist of at least one industrial partner. However, it is noteworthy that the aspect of ST1.5 (Adequate economic and finance conditions) is not predominantly addressed within this theme, which raises questions about its coherence with Theme 5 (Skills, Acceptability and Coexistence).

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Table: List of Projects for Priority Theme 1 – Industrialisation, Scale-up and Competitiveness

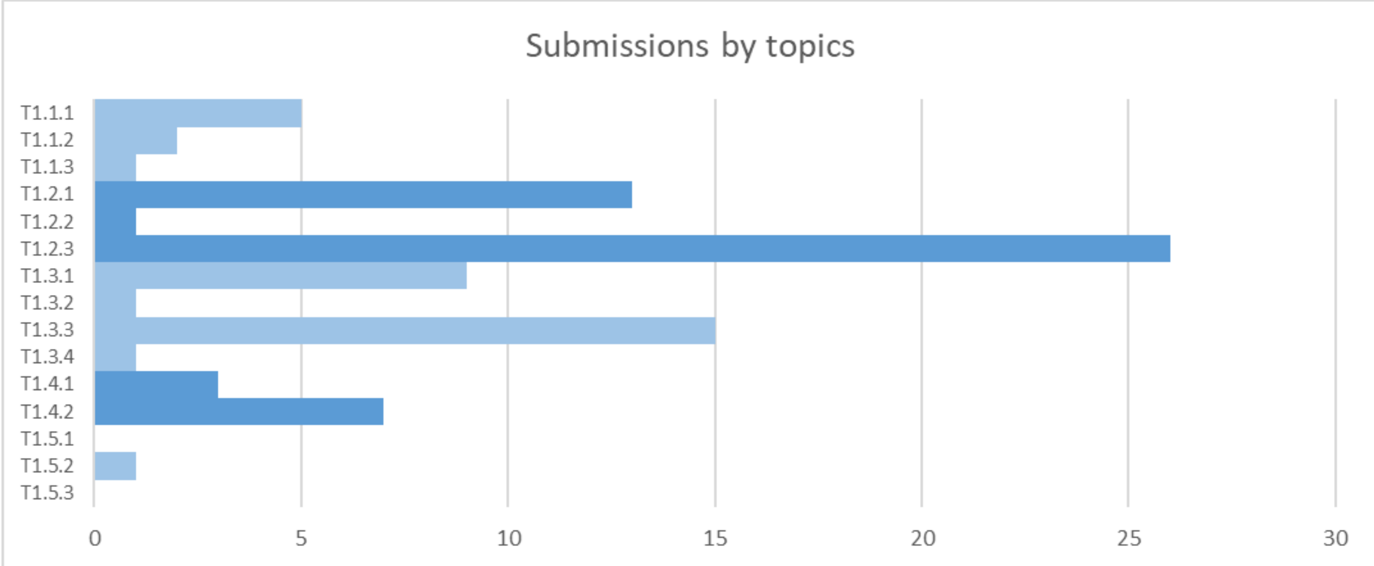
Sub-theme	Project Acronym	Coord. Country	Start year	End year	Budget (M€)	Partners RES/ IND/OT	Funding Topic EU	Funding Topic Nat	Topic
ST1.1 49.2M€	Joule Challenge Phase 1	United Kingdom	2019	2020	0.5*	2/0/0		x	T1.1.1
	LEADFLOAT	France	2018	2020	3.6*	0/1/0	x		T1.1.1
	LEAF	Spain	2020	2022	32.5*	2/7/0	x		T1.1.1
	marTech	Germany	2017	2022	35*	1/2/0		x	T1.1.2
	NorthWind	Norway	2021	2029	30.6*	8/45/0	x		T1.1.2
	WINDRISE	Norway	2023	2025	9.5*	4/7/0	x		T1.1.3
	X-ROTOR	United Kingdom	2021	2024	3.9*	4/1/0	x		T1.1.1
ST1.2 248.8M€	Active Yaw Control	Sweden	2022	2024	0.2	1/1/0	x		T1.1.1
	ARCHIME3	Spain	2021	2022	3.5	0/2/0		x	T1.2.1
	BLOW	Spain	2023	2027	21.2	6/7/1		x	T1.2.3
	Carbo4Power	Greece	2020	2024	7.9*	10/8/0		x	T1.2.3
	Connect-FOW	Norway	2022	2025	2.1	2/4/0	x		T1.2.3
	COREWIND	Spain	2019	2023	5	7/11/0		x	T1.2.3
	Demonstrator GE Haliade X	Netherlands	2018	2022	20*	1/2/0	x		T1.2.1
	DFWind (I & II)	Germany	2016	2024	31*	3/0/0		x	T1.2.3
	FLOATECH	Germany	2021	2023	4.3	5/4/0		x	T1.2.1
	FloatLab	Denmark	2023	2026	3*	1/5/0		x	T1.2.1
	FloatMastBlue	Greece	2017	2021	2.9	0/3/0		x	T1.2.3
	FLOAWER	France	2019	2024	3.5*	13/11/1	x		T1.2.3
	FLOTANT	Spain	2019	2021	4.9	6/11/0	x		T1.2.3
	FRONTIERS	Netherlands	2022	2026	2.5*	4/4/0		x	T1.2.3
	i4Offshore	Denmark	2018	2023	27.1*	3/12/0	x		T1.2.3
	ICONIC	Belgium	2023	2027	3.9	5/6/0	x		T1.2.1
	INFINITE	Spain	2022	2026	22.3*	2/7/0	x		T1.2.1
	Innotip & Tiade	Netherlands	2018	2023	20*	1/2/0	x		T1.2.1
	INSPIRE	Norway	2024	2028	0	4/1/0	x		T1.2.3
	Joule Challenge Phase 1	United Kingdom	2019	2020	0.5*	2/0/0			T1.2.1
	Joule Challenge Phase 2	United Kingdom	2021	2023	5.9*	2/0/0	x		T1.2.1
	LEADFLOAT	France	2018	2020	3.6*	0/1/0	x		T1.2.3
	LEAF	Spain	2020	2022	32.5*	2/7/0	x		T1.2.3
	Made4Wind	Norway	1900	1900	6	3/8/0		x	T1.2.3

	NEOHIRE	Spain	2017	2022	4.5*	7/3/0	x		T1.2.3
	NEXTFLOAT	Netherlands	2022	2027	22.1	2/17/0		x	T1.2.3
	NYMOOR	Norway	2023	2027	1.6	3/7/0		x	T1.2.1
	PivotBuoy	Spain	2019	2023	4*	3/5/0		x	T1.2.3
	RealCOE	Denmark	2018	2026	32.3*	6/3/0		x	T1.2.3
	SATH	Spain	2019	2021	2.7	0/1/0		x	T1.2.3
	SeaTwirl	Sweden	2019	2022	3.5	0/1/0	x		T1.2.1
	SFI Blues	Norway	2020	2028	16	4/11/0		x	T1.2.3
	Space@Sea	Netherlands	2017	2020	7.6	8/13/0	x		T1.2.3
	STEP4WIND	Netherlands	2020	2024	2.8	4/5/0	x		T1.2.3
	TRIBLADE	Sweden	2017	2020	3	0/2/0		x	T1.2.2
	WELD CAST	Denmark	2021	2024	4	1/4/1	x		T1.2.3
	WHEEL	Spain	2023	2027	25.3	10/1/1	x		T1.2.1
	X1 ACCELERATOR	Spain	2021	2023	3.5	0/1/0	x		T1.2.1
	X-ROTOR	United Kingdom	2021	2024	3.9*	4/1/0	x		T1.2.3
ST1.3 129.4M€	BearTEC	Germany	2023	2024	2	2/9/0	x		T1.2.3
	Bolt & Beautiful	Netherlands	2022	2026	4*	2/6/0	x		T1.2.3
	B-WAVEs	Norway	2023	2027	1.5	2/5/0		x	T1.3.3
	Demonstrator GE Haliade X	Netherlands	2018	2022	20*	1/2/0	x		T1.3.3
	DFWind (I & II)	Germany	2016	2024	31*	3/0/0		x	T1.3.1
	DynaGET	Germany	2019	2022	1	5/2/0	x		T1.3.3
	FASTAP	Denmark	2021	2024	3.9	1/6/1		x	T1.3.1
	FloatLab	Denmark	2023	2026	3*	1/5/0		x	T1.3.3
	FRONTIERS	Netherlands	2022	2026	2.5*	4/4/0		x	T1.3.1
	Innotip & Tiade	Netherlands	2018	2023	20*	1/2/0	x		T1.3.3
	INNTERESTING	Spain	2020	2022	4.7	4/3/1		x	T1.3.1
	JB4WT	Germany	2022	2025	2*	1/4/0	x		T1.3.3
	MERIDIONAL	Netherlands	2022	2026	6	6/4/2	x		T1.3.3
	MISSION	Norway	2024	2027	10.4*	3/7/0	x		T1.3.3
	Njord	Iceland	2018	2020	2.5*	0/1/0		x	T1.3.3
	Pile driving and pile extraction	Netherlands	2013	2022	15*	3/8/0	x		T1.3.1
	PRESTIGE	Denmark	2020	2023	1.8	2/3/0	x		T1.3.4
	RealCOE	Denmark	2018	2026	32.3*	6/3/0		x	T1.3.3
	SCARLET	Norway	2022	2027	19.6*	7/8/0		x	T1.3.3
	SeaConnect	Norway	2022	2026	1.5*	3/13/0	x		T1.3.1

	STRETCH	Denmark	2018	2022	15	1/2/0	x		T1.3.1
	TWEET-IE	Greece	2022	2025	1.5	5/0/0		x	T1.3.1
	UPWARDS	Norway	2018	2022	4*	5/8/0	x		T1.3.3
	Zukunftskonzept2	Germany	2019	2024	23	1/0/0	x		T1.3.3
ST1.4 43.1M€	4SWIND	Norway	2023	2027	1.1*	6/2/0	x		T1.3.1
	Cable JP project 1&2	Netherlands	2018	2023	3*	2/8/0		x	T1.3.3
	i4Offshore	Denmark	2018	2023	27.1*	3/12/0	x		T1.3.3
	INFINITE	Spain	2022	2026	22.3*	2/7/0	x		T1.4.2
	NBTECH	Spain	2019	2023	2.4*	1/1/0	x		T1.4.2
	OPTIWISE	Netherlands	2022	2025	4.7*	4/5/0		x	T1.4.1
	Pile driving and pile extraction	Netherlands	2013	2022	15*	3/8/0	x		T1.4.2
	PivotBuoy	Spain	2019	2023	4*	3/5/0		x	T1.4.1
	SJOR	Netherlands	2018	2022	6	2/4/0	x		T1.4.2
	WINDRISE	Norway	2023	2025	9.5*	4/7/0	x		T1.4.2
ST1.5 0.5M€	MARINEWIND	Italy	2022	2025	1.4*	7/1/1		x	T1.4.2

*This project contains parts of more than one Theme or sub-theme, an equal amount is accordingly included in the budget for each relevant the sub-themes. Example: project covers 2 sub-themes, each sub-theme includes ½ of the budget.

Figure: Submissions by Topics for Priority Theme 1 – Industrialisation, Scale-up and Competitiveness



X axis label : Number of Topics
Y axis label : Topics Reference
T1.1.1 = Manufacturing for mass production – T1.1.2 = Environmental impact for mass production – T1.1.3 = Social impacts for mass production – T1.2.1 = Next generation wind turbine technology and economic optimization – T1.2.2 = Combination with other generation technology – T1.2.3 = Industrialization of floating offshore wind – T1.3.1 = Holistic and accelerated turbine design – T1.3.2 = Probabilistic design – T1.3.3 = Virtual, scaled and full scale testing – T1.3.4 = Small and Off Grid Wind – T1.4.1 = Scaling up installation – T1.4.2 = Assembly and maintenance heavy solutions – T1.5.1 = Adequate support policies – T1.5.2 = Market design – T1.5.3 = Impact assessment for value creation

5.3.2. Analysis of projects of Priority Theme 2 – Optimisation and further digitalisation of Operations & Maintenance

After Theme 1 (Industrialisation, Scale-up and Competitiveness), Theme 2 (Optimisation and further digitalisation of Operations & Maintenance) has the second highest number of projects submitted. A total of 38 projects are collected with a distribution of (16+13+19+1) across its 4 sub-themes, amounting to a combined budget of 153 million euros. Please note that some of the projects collected under this theme covers more than one sub-topic listed. The main focus areas within the research team seem to be the Digital ecosystems with 19 projects and 52% of the budget. It is followed by Autonomous Operations & Maintenance topics addressed by 13 projects and 24% share of the budget allocated in this theme, and Digitalisation of maintenance and optimisation tools for operational efficiency focus across 16 projects and 21% of the budget. However, the Replacement and transport of large components is significantly underrepresented with only a single project addressing the topics for 3% of the budget of Theme 2.

For the Optimisation and further digitalisation of Operations & Maintenance theme, the trend suggests a strong industrial engagement in the projects, where the number of industry partners is more than double the number of academic partners on average. That is surely positive in the context of applied research and development and can lead to practical, real-world applications for the generated technologies. While a high number of industrial partners can provide practical insights, market orientation, and potential for commercialisation, academic partners contribute with fundamental research, theoretical frameworks, and innovative methodologies – which would be the key in realising environmental targets towards 2050

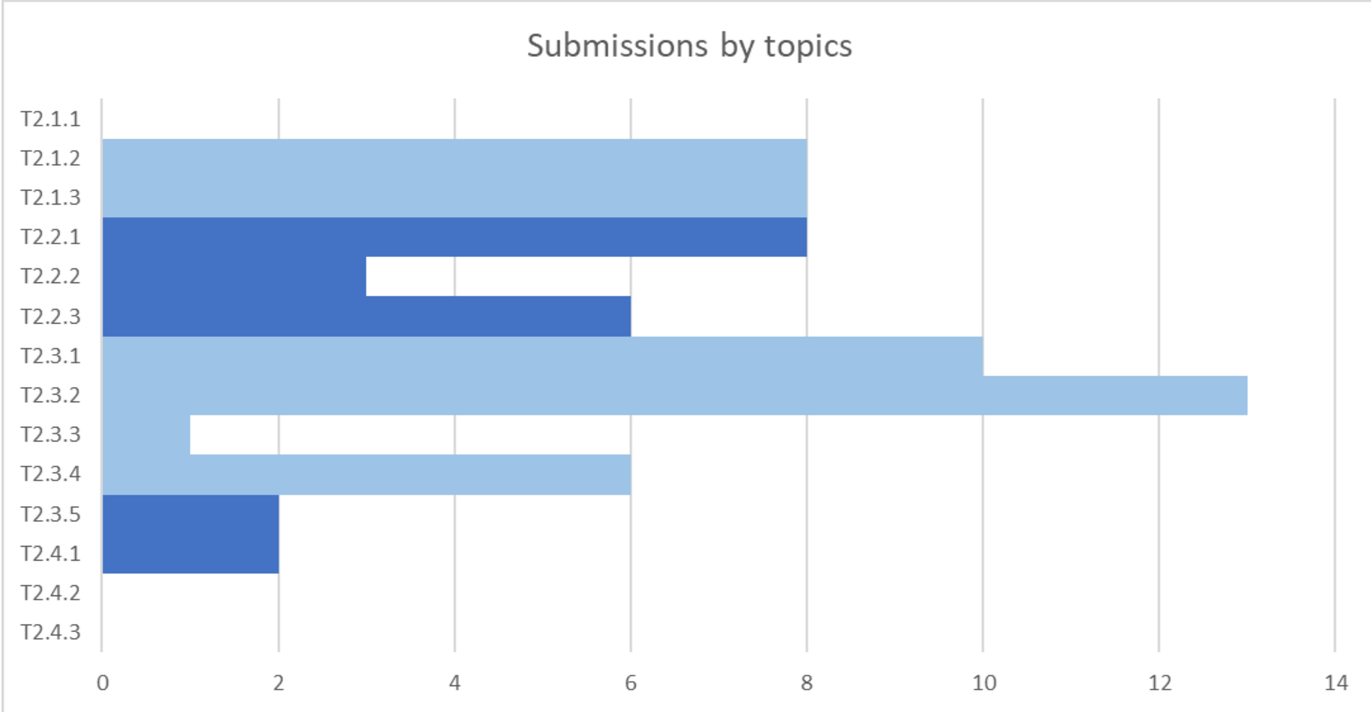
Table: List of Projects for Priority Theme 2 – Optimisation and further digitalisation of Operations & Maintenance

Sub-theme	Project Acronym	Coord. Country	Start year	End year	Budget (M€)	Partners RES/ IND/OT	Funding Topic		Topic
							EU	Nat	
ST2.1 30,44 M€	AIRTUB 1 & AIRTUB-ROMI	Netherlands	2018	2026	8*	8/12/0		x	T2.1.2
	BeFORECAST	Belgium	2022	2025	0.52*	3/3/0		x	T2.1.3
	Cloud4Wake	Belgium	2023	2026	0.88	3/1/0		x	T2.1.3
	ELOGOW	Norway	2020	2023	1.4*	2/3/1		x	T2.1.3
	FuturePowerFlow	Germany	2020	2022	2.4	0/2/0	x		T2.1.3
	Global Wind Atlas	Denmark	2012	on-going	1.5*	1/1/1	x		T2.1.3
	JB4WT	Germany	2022	2025	2*	1/4/0	x		T2.1.2
	MaSiWEC	Belgium	2018	2022	0.77	3/1/2		x	T2.1.2
	MooringSense	Spain	2019	2022	4.7*	0/6/0	x		T2.1.2
	NEWA	Denmark	2015	2019	1.8*	20/9/1	x		T2.1.3
	Platoon	France	2020	2022	11.5*	7/8/5	x		T2.1.3
	POSEIDON	Belgium	2018	2022	1.1*	3/1/2		x	T2.1.2
	RAINBOW	Belgium	2021	2024	0.55	2/5/0		x	T2.1.2
	S2S4E	Spain	2017	2020	4.7	4/7/1	*		T2.1.3
	SAWOP	Netherlands	2021	2023	5*	2/6/0		x	T2.1.3
	Supersized 4.0	Belgium	2020	2023	1.3	1/5/0		x	T2.1.2
	WINDCORE, PROWESS	Netherlands	2018	2023	5*	2/6/0		x	T2.1.2
ST2.2 39M€	AIRE	Spain	2023	2026	5,4*	5/4/0	x		T2.2.3
	AQUADA-GO	Denmark	2023	2025	3,4*	1/4/1		x	T2.2.1
	ATLANTIS	Portugal	2020	2023	8,5	3/12/0	x		T2.2.2
	AVIMo	Germany	2019	2022	2,1	2/1/0		x	T2.2.2
	CABLE JIP 1 & 2	Netherlands	2018	2023	1,5*	2/8/0		x	T2.2.1
	CL-Windcon	Spain	2016	2019	4,9	8/10/1	x		T2.2.3
	Hiperwind	Denmark	2020	2024	2*	5/2/0	x		T2.2.3
	Koalalifter	Spain	2020	2023	2	0/0/0	x		T2.2.3
	MooringSense	Spain	2019	2022	4,7*	4/6/0	x		T2.2.3
	OPTIWISE	Netherlands	2022	2025	4.7*	4/5/0		x	T2.2.2
	ReliaBlade	Denmark	2018	2023	11,1*	2/9/0		x	T2.2.1
	ReLife	Denmark	2020	2024	2,5*	1/5/2		x	T2.2.1
	ROMAIN	Portugal	2022	2025	2,7	1/3/0	x		T2.2.1
	SENTRY	United Kingdom	2017	2019	2	0/1/0	x		T2.2.1

	SheaRIOS	United Kingdom	2022	2025	3,2	2/9/0	x		T2.2.1
	WATEREYE	Spain	2019	2022	4,7*	6/3/0	x		T2.2.1 T2.2.3
ST2.3 75,15M€	2D4D	Italy	2020	2025	1,5	3/0/0	x		T2.3.5
	AIRE	Spain	2023	2026	5,4*	5/4/0	x		T2.3.4
	AIRTUB 1 & AIRTUB-ROMI*	Netherlands	2018	2026	4	8/12/0		x	T2.3.2
	AQUADA-GO*	Denmark	2023	2025	1,7	1/4/1		x	T2.3.2
	BladeSave	UK	2017	2020	2,54	0/5/0	x		T2.3.2
	Bolt & Beautiful	Netherlands	2022	2026	4*	2/6/0	x		T2.3.2
	CABLE JIP 1 & 2*	Netherlands	2018	2023	1,5	2/8/0		x	T2.3.2
	CRC1463 Offshore Megastructure	Netherlands	2021	2024	10,5*	6/0/0		x	T2.3.2
	DATA DRIVEN OFFSHORE	Sweden	2020	2025	1,5	1/0/0	x		T2.3.1
	Dutch Offshore Wind Atlas	Netherlands	2017	2021	3	2/2/0		x	T2.3.1
	FarmConners	Spain	2019	2022	1,45*	7/8/0	x		T2.3.4
	Hiperwind	Denmark	2020	2024	2*	5/2/0	x		T2.3.1
	MooringSense	Spain	2019	2022	4.7*	4/6/0	x		T2.3.4
	OpenRAVE	Germany	2020	2025	9,3	2/0/1		x	T2.3.2
	Platoon	France	2020	2022	11,5*	7/8/5	x		T2.3.2
	POSEIDON	Belgium	2018	2022	1.11*	3/1/2		x	T2.3.1
	ReliaBlade	Denmark	2018	2023	11,1*	2/9/0		x	T2.3.3 T2.3.4
	ReLife	Denmark	2020	2024	2,5*	1/5/2		x	T2.3.1
	ROMEO	Spain	2017	2022	16,3*	2/20/0	x		T2.3.1 T2.3.2
	SAWOP	Netherlands	2021	2023	5*	2/6/0		x	T2.3.2
	SMARTLIFE	Denmark	2023	2025	0,43*	1/0/0		x	T2.3.1
	TWAIN	Denmark	2023	2027	6*	0/0/0	x		T2.3.1 T2.3.4 T2.3.5
	WATEREYE	Spain	2019	2022	2,35*	6/3/0	x		T2.3.2
	WILLOW	Denmark	2023	2026	9.3*	2/10/0	x		T2.3.1
	WINDCORE, PROWESS	Netherlands	2018	2023	5*	2/6/0		x	T2.3.2
	WINSENT	Denmark	2016	2024	13*	6/0/0		x	T2.3.1
	WiSAbigdata	Germany	2019	2023	2,5	4/6/0		x	T2.3.1 T2.3.4
ST2.4 9 M€	NEXUS	France	2017	2021	4,25	2/6/0	x		T2.4.1
	WINDRISE	Norway	2023	2025	9,5*	4/7/0	x		T2.4.1

*This project contains parts of more than one Theme or sub-theme, an equal amount is accordingly included in the budget for each relevant the sub-themes. Example: project covers 2 sub-themes, each sub-theme includes ½ of the budget.

Figure: Submissions by Topics for Priority Theme 1 – Industrialisation, Scale-up and Competitiveness



X axis label : Number of Topics
Y avis label : Topics Reference
T2.1.1 = Innovative training for technicians using AR, VR, and/or AI – T2.1.2 = AI-driven predictive maintenance for key components & report analysis – T2.1.3 = AI-driven resource assessment and forecasting tools – T2.2.1 = Enhanced robotics for blade servicing & semi-automated inspection – T2.2.2 = Advanced offshore repair methodologies and autonomous vehicles for marine operations – T2.2.3 = Autonomous wind installation, O&M and decommissioning – T2.3.1 = Data exchange across sub-systems – T2.3.2 = Sensor technologies – T2.3.3 = Industrial IoT, cloud analytics, cybersecurity – T2.3.4 = Optimization & Decision-making – T2.3.5 = Holistic understanding of natural systems (physical, social, biological) – T2.4.1 = Component replacement solutions onshore & offshore – T2.4.2 = Quick connect/ disconnect systems for mooring lines & inter-array cables – T2.4.3 = Autonomy & digitalization for port operations with novel fuel alternatives

5.3.3. Analysis of projects of Priority Theme 3 - Wind Energy System Integration

A total of 40 projects were collected under Theme 3 Wind Energy System Integration. The total budget of the included projects spent on Wind Energy System Integration is approximately 262 MEUR. The ratio among academia and industries are quite compensated in the 6sub-themes, but the biggest projects are dominated by companies, like i.e. EU-SCORES or North Sea Energy Programme.

Some large projects have been identified within ST3.1 (Definition and Modelling of futures systems needs), most of them EU funded and most of them covering different themes and subthemes. The focus in this subtheme is the optimization of transmission infrastructure.

It is remarkable the National funding predominance within ST3.2 (Advanced grid capabilities) projects (being some of them large in budget), Advanced grid capabilities. These projects are in general dominated by industrial partners.

The subtheme with more identified projects is ST3.3 (Interoperability), where the Plant level control topic is by far the most addressed topic in this Theme. Projects in this subtheme are not as large as in previous subthemes, and there is a dominant presence of research partners, balanced with the participation of industrial partners. Funding is evenly distributed between EU and national.

Whereas in the previous subthemes most of the projects are finished or about to finish, in the remaining ones (ST3.4 to ST 3.6), there are not so many identified projects and there is predominance of ongoing projects. Within ST3.4 (Solution to effectively manage curtailment), it is remarkable the interest in Denmark, in particular with the North Sea Energy Programme, which also tackles all other subthemes within this Theme 3. On the other hand, projects in ST3.6 (DC Grid Solutions) are mainly EU funded, being the Promotion Project the largest of them all.

Finally, 12 projects are related with ST3.5 (Power to X and hybrid plants), being most of them nationally funded, with an increasing activity, according to the starting year of the projects. Projects within this subtheme are not large in size, in general; however, the off-shore hybridization project EU-SCORES, is the largest project in budget within this whole Theme, is included in the subtheme.

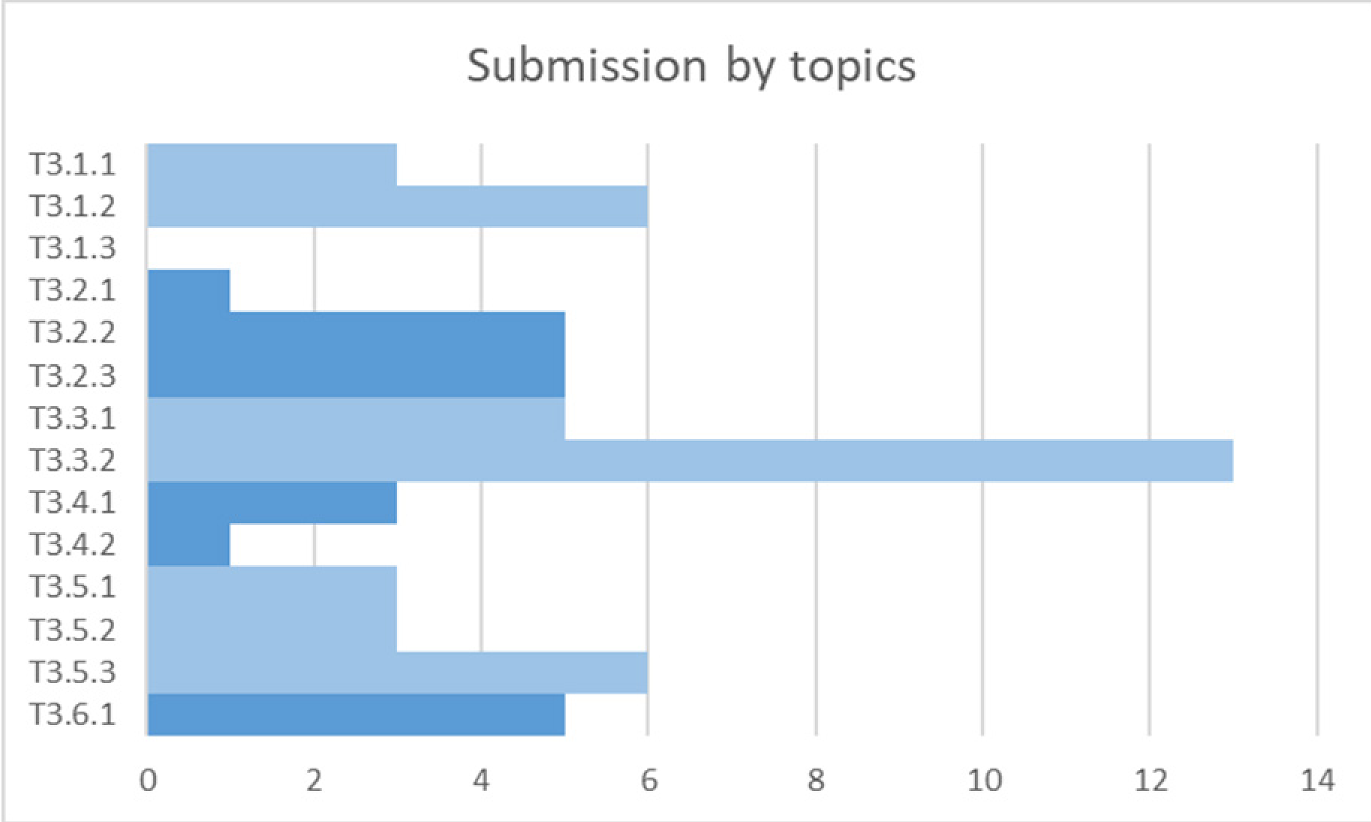
Table: List of Projects for Priority Theme 3 – Wind Energy System Integration

Sub-theme	Project Acronym	Coord. Country	Start year	End year	Budget (M€)	Partners RES/ IND/OT	Funding Topic		Topic
							EU	Nat	
ST3.1 37.72M€	ADOreD	Greece	2022	2026	2	5/9/1	x		T3.1.1
	EdgeFLEX	Netherlands	2020	2023	5	4/6/1	x		T3.1.2
	ELOGOW	Spain	2020	2023	1,4*	2/3/1		x	T3.1.1
	iTESLA	United Kingdom	2012	2016	20*	6/10/5	x		T3.1.1 T3.1.2
	Marinet II	Norway	2017	2021	10,6*	39/30/0	x		T3.1.2
	North Sea Energy Programme	Denmark	2017	2021	15*	4/40/0		x	T3.1.2
	Ocean Grid Research	France	2021	2024	11,37*	3/14/0		x	T3.1.2
	SCARLET	Norway	2022	2027	19,6*	7/8/0	x		T3.1.2
ST3.2 68,05M€	ENGEL	Belgium	2023	2026	20	1/2/0		x	T3.2.2
	Green Island	Denmark	2017	2024	8,5*	1/0/1		x	T3.2.3
	iTESLA	United Kingdom	2012	2016	20*	6/10/5	x		T3.2.1 T3.2.2 T3.2.3
	North Sea Energy Programme	Denmark	2017	2021	15*	4/40/0		x	T3.2.2
	Ocean Grid Research	France	2021	2024	11,37*	3/14/0		x	T3.2.2
	PHOENIX	Netherlands	2017	2022	24	2/2/0		x	T3.2.3
	SCAPP	Portugal	2014	2018	2,44	1/1/0		x	T3.2.3
	SeaConnect	Netherlands	2022	2026	1,5*	2/13/0		x	T3.2.2
	WindRamp	United Kingdom	2020	2023	2,75*	2/6/0		x	T3.2.3
ST3.3 44,86M€	AIRE	Spain	2023	2026	5,4*	5/4/0	x		T3.3.2
	BeFORECAST	Norway	2022	2025	0,52*	3/3/0		x	T3.3.2
	CL Windcon	Denmark	2016	2019	4,9*	8/10/1	x		T3.3.2
	CRC1463 Offshore Megastructure	Netherlands	2021	2024	10,5*	6/0/0		x	T3.3.1
	DynaWEA	Norway	2018	2022	1,4	2/1/0		x	T3.3.2
	ELOGOW	Spain	2020	2023	1,4*	2/3/1		x	T3.3.1
	FarmConners	Spain	2019	2022	1,45*	7/8/0	x		T3.3.2
	North Sea Energy Programme	Denmark	2017	2021	15*	4/40/0		x	T3.3.2
	NorthWind	Denmark	2021	2029	30,6*	8/45/1		x	T3.3.1
	Ocean Grid Research	France	2021	2024	11,37*	3/14/0		x	T3.3.2
	SMARTLIFE	Denmark	2023	2025	0,43*	1/0/0		x	T3.3.2
	SUDOCO	Netherlands	2023	2027	5,8*	3/3/1	x		T3.3.1 T3.3.2

	TotalControl	Netherlands	2018	2022	4,88	4/1/0	x		T3.3.2
	TWAIN	Denmark	2023	2027	6*	4/8/0	x		T3.3.1
	WATEREYE	Spain	2022	2025	4,7*	6/3/0	x		T3.3.2
	WindRamp	United Kingdom	2020	2023	2,75*	2/6/0		x	T3.3.2
	WinGrid	Sweden	2019	2024	4,29*	7/1/0	x		T3.3.2
ST3.4 11,13M€	Green Island	Denmark	2017	2024	8,5*	1/0/1		x	T3.4.1
	North Sea Energy Programme	Denmark	2017	2021	15*	4/40/0		x	T3.4.1
	OYSTER	Spain	2021	2025	5.4	0/7/0	x		T3.4.2
	WILLOW	Denmark	2023	2026	5,8*	2/10/0	x		T3.4.1
ST3.5 69,54M€	DOT	United Kingdom	2017	2022	15*	2/8/0		x	T3.5.3
	EU-SCORES	Republic of Ireland	2021	2025	45,7	5/17/2	x		T3.5.3
	Green Island	Denmark	2017	2024	8,5*	1/0/1		x	T3.5.3
	HOMEY	United Kingdom	2022	2024	1,3	1/1/0	x		T3.5.1 T3.5.2 T3.5.3
	INSPIRE	Denmark	2024	2028	0*	3/1/0		x	T3.5.2
	MARINEWIND	United Kingdom	2022	2025	1,38*	7/1/1	x		T3.5.1
	MP Multi-Use	Belgium	2023	2025	0,47	1/0/0		x	T3.5.1 T3.5.3
	North Sea Energy Programme	Denmark	2017	2021	15*	4/40/0		x	T3.5.1 T3.5.2
	Ocean Grid Research	France	2021	2024	11,37*	3/14/0		x	T3.5.3
	SENSE Hub	Spain	2017	2021	6	3/4/0		x	T3.5.3
	COOLWIND	Belgium	2019	2023	3,58	1/0/0	x		T3.6.1
ST3.6 53,0M€	MISSION	Greece	2024	2027	10,39*	3/7/0	x		T3.6.1
	Ocean Grid Research*	France	2021	2024	11,37	3/14/0		x	T3.6.1
	PROMOTioN	Greece	2017	2020	42,69	11/21/5	x		T3.6.1
	READY4DC	Germany	2022	2023	0,99	2/2/3	x		T3.6.1

*This project contains parts of more than one Theme or sub-theme, an equal amount is accordingly included in the budget for each relevant the sub-themes. Example: project covers 2 sub-themes, each sub-theme includes ½ of the budget.

Figure: Submissions by Topics for Priority Theme 3 – Wind Energy System Integration



X axis label : Number of Topics
Y axis label : Topics Reference
T3.1.1 = Transmission and generation flexibility – T3.1.2 = Optimization of transmission infrastructure – T3.1.3 = Grid digitalization – T3.2.1 = Ancillary service provision – T3.2.2 = Development of new converter capabilities and systems – T3.2.3 = Short term balancing – T3.3.1 = Digital twin technologies – T3.3.2 = Plant level control – T3 4.1 = Long duration energy storage – T3 4.2 = Offshore wind and hydrogen production – T3 5.1 = Power to X technologies – T3 5.2 = Hydrogen market integration – T3 5.3 = Hybrid plants – T3 6.1 = Offshore grid infrastructure

5.3.4. Analysis of projects of Priority Theme 4 – Sustainability and Circularity

A total of 27 projects were collected under Theme 4 Sustainability and Circularity. The total budget of the included projects spent on Sustainability and Circularity is approximately 130 MEUR. The ratio among academia and industries are quite compensated in the 5 sub-themes.

There are 9 projects under ST4.1 (Material substitution for decarbonisation), where most of them are related with the development of new materials, for example the use of nanomaterials for blades manufacturing in the project Carbo4Power. New designs using alternative materials are also developed in the collated project such us MODVION where wood is used to manufacture some parts of the wind turbine tower. There is a lack of projects detected in T4.1.3 (Sustainable materials in design and recyclability by design). The projects to reduce the rare-earth materials have carried out important results as well.

ST4.2 (Recycling methods) has the biggest budget with 67.8 MEUR. The recycling and reuse processes of composites and rare-earth materials have been addressed in SecREEts, NEOHIRE and BLADES2BUILD.

The last three sub-themes projects are mainly in progress, so the results are not already published but the most relevant topic is Impact on ecosystems and biodiversity with three projects selected. The total budgets are respectively 18 MEU, 13.1 MEUR and 13.5 MEUR. The only topic without any projected collated is T4.4.4 (Economic model for full decommissioning project cycle) although this issue is implicitly addressed in some of the projects, but not so explicitly that it was detected in the results of the search. Main advances about the study in LCA in offshore wind farms in ROMEO project is one of the principal results in those Topics. It's important to notice that the projects related with biodiversity are starting to gain importance in the EU framework programme.

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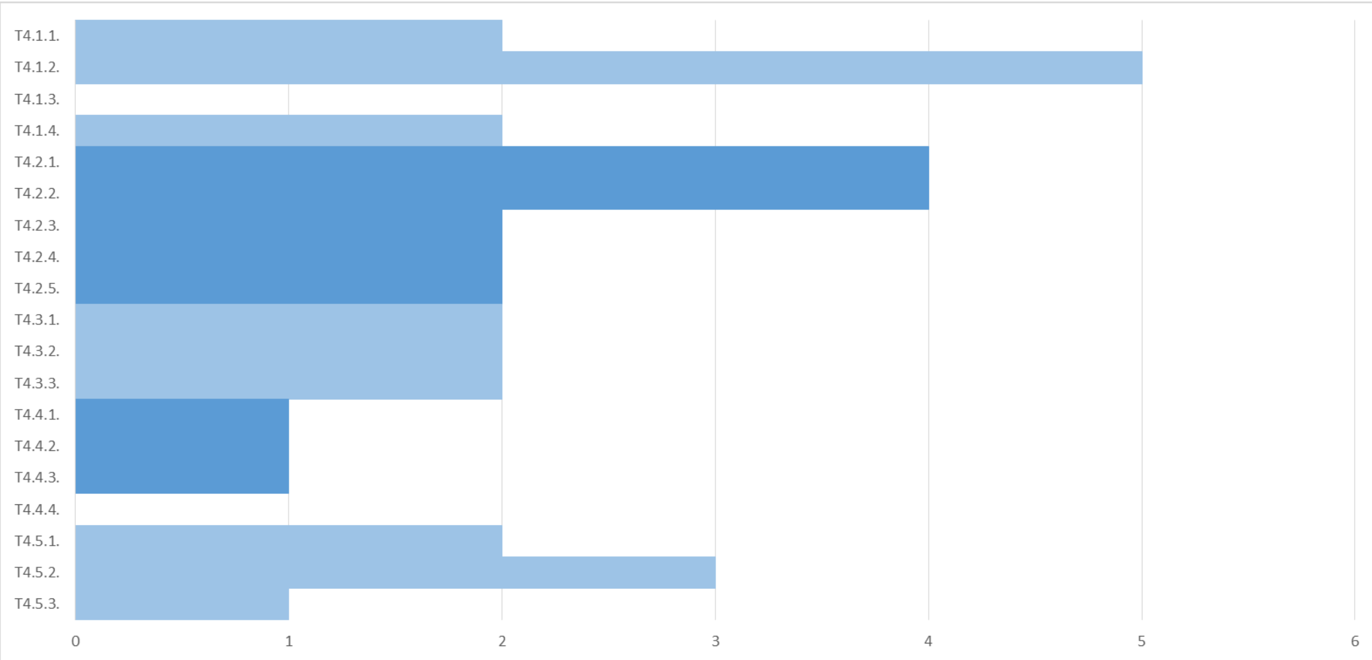
Table: List of Projects for Priority Theme 4 – Sustainability and Circularity

Sub-theme	Project Acronym	Coord. Country	Start year	End year	Budget (M€)	Partners RES/IND/OT	Funding Topic		Topic
							EU	Nat	
ST4.1 17.6M€	WISEWIND	Denmark	2023	2026	1,7	1/1/0		x	T4.1.1
	Modvion	Sweden	2020	2023	3,4	0/1/0	x		T4.1.4
	Carbo4Power	Greece	2020	2024	3,9	10/8/0	x		T4.1.2
	INSPIRE	Norway	2024	2028	0	3/1/0		x	T4.1.2
	NEOHIRE	Spain	2017	2022	0,75	7/3/0	x		T4.1.1
	NBTECH	Spain	2019	2023	1,7	0/1/0	x		T4.1.4
	Joule Challenge Phase 1	United Kingdom	2019	2020	0,2	2/0/0		x	T4.1.2
	Joule Challenge Phase 2	UK	2021	2023	2,9	2/0/0		x	T4.1.2
	MISSION	Norway	2024	2027	3,5	3/7/0	x		T4.1.2
ST4.2 67.8M€	NEOHIRE	Spain	2017	2022	0,75	7/3/0	x		T4.2.2
	BLADES2BUILD	Denmark	2023	2025	15,5	4/10/0	x		T4.2.1, T4.2.3, T4.2.4
	SUSMAGPRO	Germany	2019	2023	14,7	8/15/0	x		T4.2.2
	REFRESH	Italy	2023	2026	15,5	3/7/1	x		T4.2.1 T4.2.3 T4.2.4 T4.2.5
	SecREEts	Norway	2018	2022	17,2	8/15/0	x		T4.2.2
	EoLo-HUBs	Spain	2023	2026	4,03	8/8/2	x		T4.2.1 T4.2.2 T4.2.5
	REKOVIND	Sweden	2022	2023	0,1	2/0/0		x	T4.2.1
ST4.3 18.0M€	EoLo-HUBs	Spain	2023	2026	4,03	8/8/2	x		T4.3.1 T4.3.2
	CIRCUBLADE	Sweden	2021	2024	0,4	2/7/0		x	T4.3.2
	AIRE	Spain	2023	2026	5,4	5/4/2	x		T4.3.1, T4.3.3
	ROMEO	Spain	2017	2022	8,2	2/20/0	x		T4.3.3
ST4.4 13.1M€	EoLo-HUBs	Spain	2023	2026	4,03	8/8/2	x		T4.4.2
	Pile driving and pile extraction	Netherlands	2013	2022	7,5	3/8/0	x		T4.4.1
	OPTIWISE	Netherlands	2022	2025	1,6	4/5/0	x		T4.4.3

ST4.5 13.5M€	WENDY	Spain	2022	2025	1,5	3/5/1	x		T4.5.2
	TWAIN	Denmark	2023	2027	2,0	4/8/0	x		T4.5.1 T4.5.2 T4.5.3
	CoastalFutures	Germany	2021	2024	5,5	15/10/5		x	T4.5.2
	OLAMUR	France	2022	2024	9,1	12/11/2	x		T4.5.1

*This project contains parts of more than one Theme or sub-theme, an equal amount is accordingly included in the budget for each relevant the sub-themes. Example: project covers 2 sub-themes, each sub-theme includes ½ of the budget.

Figure: Submissions by Topics for Priority Theme 4 – Sustainability and Circularity



X axis label : Number of Topics
Y axis label : Topics Reference
T4.1.1 = Sustainable materials in design and recyclability by design – T4.1.2 = New components and materials – T4.1.3 = Material durability and protection – T4.1.4 = Alternative design solutions – T4.2.1 = Blade recycling, sustainability assessment and technologies to lower CO2 footprint – T4.2.2 = Reliability of secondary materials – T4.2.3 = New recycling process – T4.2.4 = Holistic life cycle assessment – T4.2.5 = New business model – T4.3.1 = Solutions for lifetime extension – T4.3.2 = End-of-life management – T4.3.3 = Assessment of the damage state of turbine properties – T4.4.1 = Decommissioning methods and tools for offshore wind – T4.4.2 = Technologies for environmentally friendly decommissioning – T4.4.3 = Processes and components to ease reuse and recycling – T4.4.4 = Economic model for full decommissioning project cycle – T4.5.1 = Environmental co-desing – T4.5.3 = Impact on ecosystems and biodiversity – T4.5.3 = Noise reduction

5.3.5. Analysis of projects of Priority Theme 5 – Skills, Acceptability and Coexistence

A total of 17 projects were submitted under Theme 5 Skills & Coexistence. The total budget of the included projects spent on Skills & Coexistence is approximately 77,2 MEUR.

Thereof, 9 projects under the sub-themes on ST5.1 (Education) and ST5.2 (Skilling, re-skilling and upskilling activities). All of these 10 projects with educational focus have received European funding. They provide professional networks, develop training programs, improve education and skilling by novel learning methods. It should be noted that most research projects include education by providing doctoral or post-doctoral positions. This applies, for example, to Marie Skłodowska-Curie Actions. Strategic workforce development included in the current list is mainly provided in projects building doctoral networks with focus on specific thematic areas, these include the projects zEPHYR, FLOAWER, WinGrid, FRONTIERS, TWIND, Train2Wind, ADOreD. The reason for a lack of national projects under sub-themes ST5.1 and ST5.2 may be that national educational initiatives are directly implemented in the curriculum of study programmes at single institutions rather than project based.

Acceptability and coexistence are often addressed in projects that conduct also significant research in other research themes. Only one larger national research centre (NorthWind) has been included in the list that deals with coexistence. No other national projects are included in the project list. The reason could be that the budget of national projects on acceptability and coexistence has typically been lower than 1 M€.

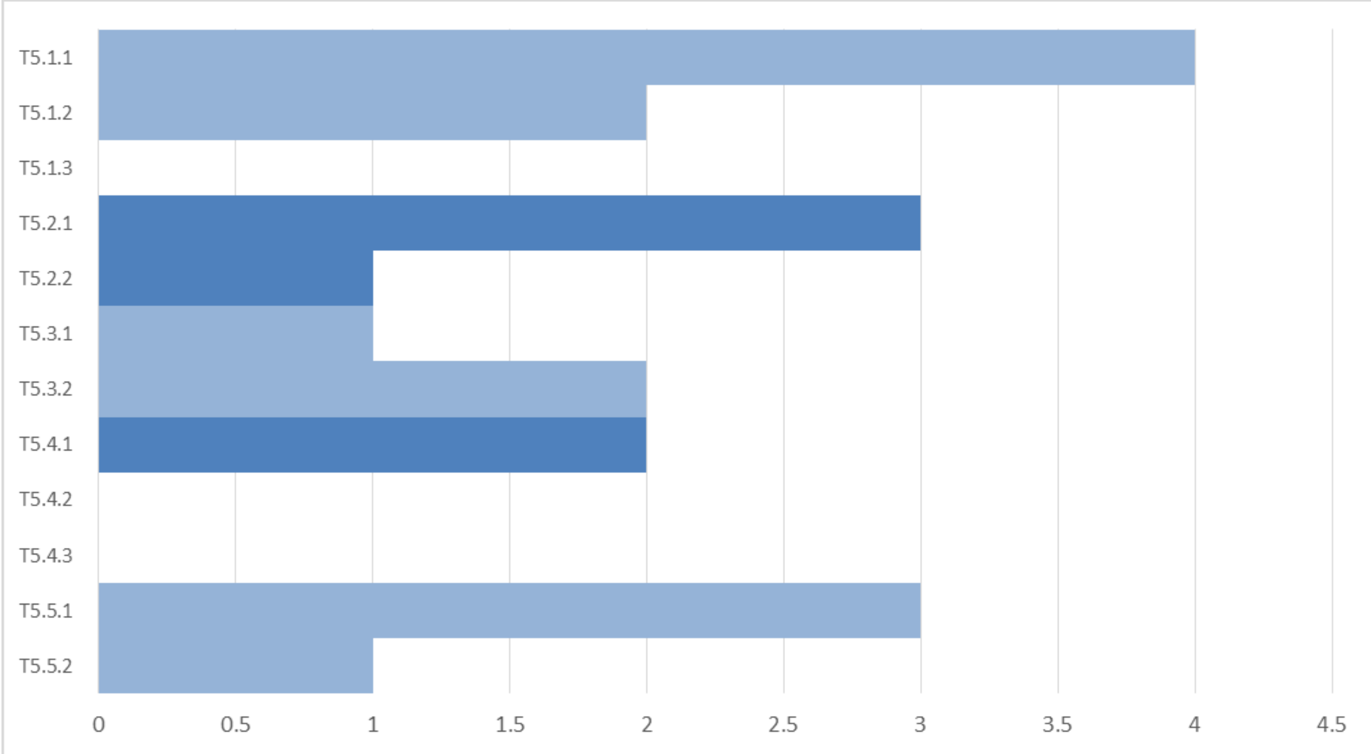
The research gaps/topics identified that need to be addressed belong particularly to ST5.4 (Fair transition, inclusiveness and stakeholder interests) like the just transition. Collecting projects on coexistence, even those with a smaller budget, could provide a more extensive list. However, it is likely that there are fewer projects because the main stakeholders in wind energy development have only recently started to focus on these topics.

Table: List of Projects for Priority Theme 5 – Skills, Acceptability and Coexistence

Sub-theme	Project Acronym	Coord. Country	Start year	End year	Budget (M€)	Partners RES/ IND/OT	Funding Topic		Topic
							EU	Nat	
ST5.1 21,6 M€	NEWA	Denmark	2015	2019	1,8	20/9/1	x	x	T5.1.2
	zEPHYR	Belgium	2019	2023	3,8	10/2/0	x		T5.1.2
	FLOAWER	France	2019	2024	3,5*	13/11/1	x		T5.1.1
	WinGrid	United Kingdom	2019	2024	4,3*	7/1/0	x		T5.1.1
	FRONTIERS	Netherlands	2022	2026	2,5	4/4/0	x		T5.1.1
	DigiWind	Denmark	2024	2027	19,2*	6/4/0	x		T5.1.1
	TWIND	Portugal	2019	2022	0,8	4/0/0	x		T5.2.1
	Train2Wind	Denmark	2020	2024	4,2	5/0/0	x		T5.2.1
	ADOreD	Denmark	2022	2026	4,0*	5/9/0	x		T5.2.1
	DigiWind	Denmark	2024	2027	19,2*	6/4/0	x		T5.2.2
ST5.3 3,6 M€	WinWind	Germany	2017	2020	2,1	4/4/4	x		T5.3.2
	WENDY	Spain	2022	2025	2,9*	3/5/1	x		T5.3.1 T5.3.2
ST5.4 3,1 M€	JustWind4All	Netherlands	2022	2025	2,8*	7/2/3	x		T5.4.1
	WIMBY	Belgium	2023	2025	3,4*	9/3/1	x		T5.3.1
ST5.5 32,3 M€	UNITED	Netherlands	2020	2023	11,3	7/19/3	x		T5.5.1
	NorthWind	Norway	2021	2029	30,6*	8/45/0		x	T5.5.1
	OLAMUR	Norway	2022	2026	9,1	12/11/2	x		T5.5.2
	WIMBY	Belgium	2023	2025	3,4*	9/3/1	x		T5.5.1

*This project contains parts of more than one Theme or sub-theme, an equal amount is accordingly included in the budget for each relevant the sub-themes. Example: project covers 2 sub-themes, each sub-theme includes ½ of the budget.

Figure: Submissions by Topics for Priority Theme 5



X axis label : Number of Topics
Y axis label : Topics Reference
T5.1.1 = Education and strategic workforce expansion for the wind energy sector – T5.1.2 = Innovative pedagogy for wind energy excellence – T5.1.3 = Cultivating diversity and sustained interest in wind energy – T5.2.1 = Strategic workforce development across the wind energy value chain – T5.2.2 = Optimizing cross-sector talent integration for wind energy sustainability – T5.3.1 = Community involvement modelling/tool development – T5.4.1 = The good process – T5.4.2 = Tools to map stakeholder concerns – T5.4.3 = Technology-people-relations and public perception – T5.5.1 = Planning for positive coexistence – T5.5.2 = Evaluation of the consequences of intensified wind energy production and upscaling

5.3.6. Analysis of projects of Priority Theme 6 – Cross-cutting Research Themes

A total of 20 projects were selected under Theme 6 Cross-cutting. The total budget of the included projects spent on Cross-cutting is approximately 64.1 MEUR. This research theme is different to the other ones, which are more wind technology specific.

The 12 projects under the sub-theme on ST6.1 Climate, Atmosphere, Ocean and Geophysics show an increasing interest in the knowledge of these topics. They include the outstanding European and Global Wind Atlas, with both national and EU funding. For the remaining projects, 4 of them received national funding (two from Germany, one from Belgium and one for the Netherlands), whereas the other 4 projects received funding from the EU (two of the coordinators were from the Netherlands, one from Norway and one from the UK). Research institutions are predominant among the partners in these projects.

On the other hand, industrial partners are predominant in the 6 projects that were found under the sub-theme ST6.2 Disruptive technologies. In fact, three of them were carried out only by one industrial partner (two airbornes, one small wind turbine). Airborne technology is proposed in three out of the six projects, whereas disruptive components are proposed in the three other projects. Half of the six projects received EU funding and half national funding.

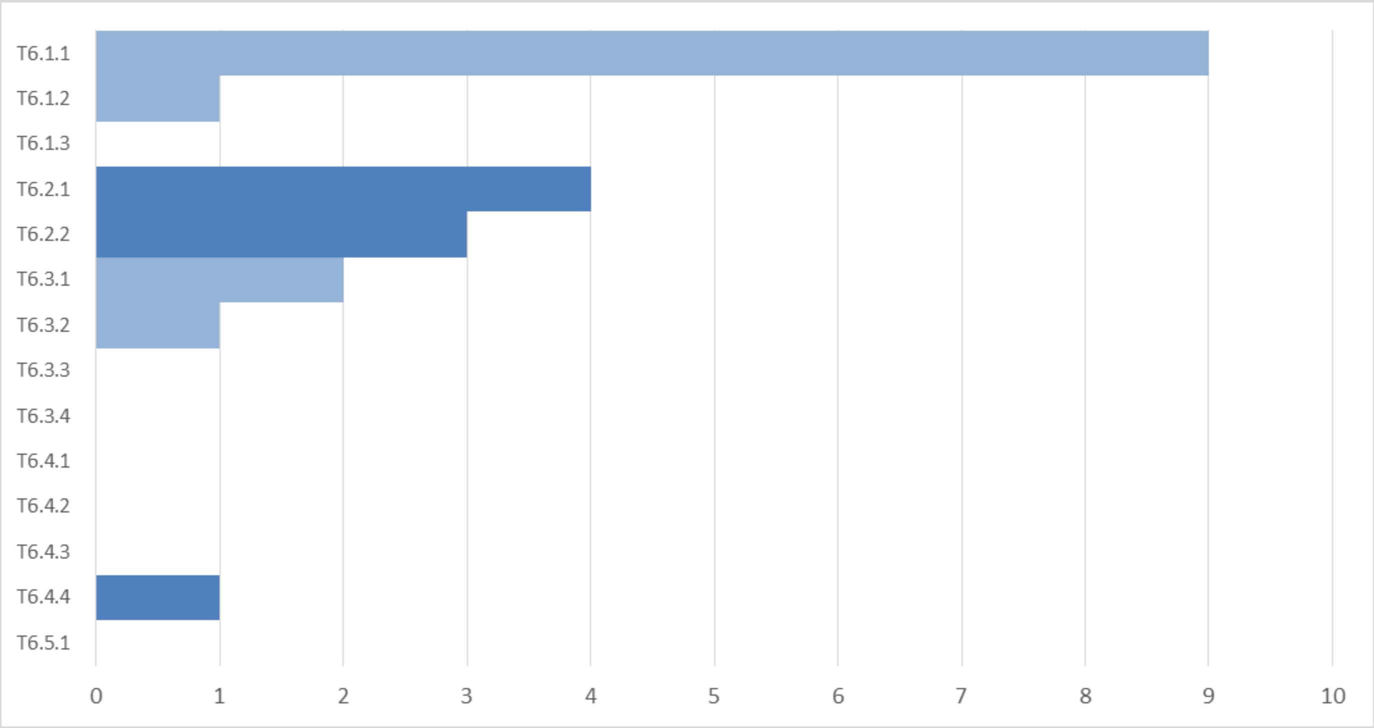
The 5 Projects addressing Policy and regulation (6.3) and Social aspects (6.4), three for sub-theme 6.3 and two for 6.4, conduct also significant research in other research themes. And only one of them (X-Wakes) has received national funding (Germany); the other three ones received EU funding. This project, X-Wakes, is focused only on this research theme, but covers two sub-themes: it was one of the above mentioned on ST6.1 and addresses the Policy and regulation sub-theme as well.

Table: List of Projects for Priority Theme 6 – Cross cutting Research Themes

Sub-theme	Project Acronym	Coord. Country	Start year	2024	Budget (M€)	Partners RES/IND/OT	Funding Topic		Topic
							EU	Nat	
ST6.1 34.7M€	DFWind (I & II)	Germany	2016	On-going	31.0*	3/0/0		x	T6.1.1
	Dutch Offshore Wind Atlas	Netherlands	2017	2019	3.0*	2/2/0		x	T6.1.1
	Global Wind Atlas	Denmark	2012	2019	1.5*	1/1/1	x	x	T6.1.1
	NEWA	Denmark	2015	2024	1.8*	20/9/1	x	x	T6.1.1
	OffshorePlan	Portugal	2017	2027	0.6*	1/0/1	x		T6.1.1
	SeaFD	Belgium	2020	2022	0.7	3/1/1		x	T6.1.1
	SUDOCO	Netherlands	2023	2024	5.8*	3/3/1	x		T6.1.1
	UPWARDS	Norway	2018	2023	4.0*	5/8/0	x		T6.1.1
	WINSENT	Germany	2016	2023	13*	6/0/0		x	T6.1.1
	X-Wakes	Germany	2019	2022	4.3*	6/8/1		x	T6.1.2
ST6.2 18.4M€	AWE	Norway	2019	2025	3.4	0/1/0	x		T6.2.1
	AWESOME	Germany	2019	2023	3.3	0/1/0	x		T6.2.1
	BeFORECAST	Belgium	2022	2022	0.5*	3/3/0		x	T6.2.1
	Cable JP project 1&2	Netherlands	2018	2020	3.0*	2/8/0		x	T6.2.2
	DOT	Netherlands	2017	2024	15*	2/8/0		x	T6.2.2
	Njord	Iceland	2018	2019	2.5*	0/1/0	x		T6.2.1
	X-ROTOR	United Kingdom	2021	2024	3.9*	4/1/0	x		T6.2.2
ST6.3 2.9M€	OffshorePlan	Portugal	2017	2023	0.6*	1/0/1	x		T6.3.1
	MARINEWIND	Italy	2021	2025	1.4*	7/1/1	x		T6.3.2
	X-Wakes	Germany	2019	2025	4.3*	6/8/1		x	T6.3.1
ST6.4 2.5M€	JustWind4All	Netherlands	2022	2026	2.8*	7/2/3	x		T6.4.4
	Wimby	Belgium	2023	2022	3.4*	9/3/1	x		T6.4.3

*This project contains parts of more than one Theme or sub-theme, an equal amount is accordingly included in the budget for each relevant the sub-themes. Example: project covers 2 sub-themes, each sub-theme includes ½ of the budget.

Figure: Submissions by Topics for Priority Theme 6



X axis label : Number of Topics
Y axis label : Topics Reference
T6.1.1 = Geophysical characteristic measuring and modelling advancement – T6.1.2 = Wake effect model development – T6.1.3 = Climate change physical conditions impact analysis – T6.2.1 = New concept assessment and development – T6.2.2 = Turbine component performance and efficiency – T6.3.1 = Spatial planning – T6.3.2 = Evolution of environmental impact assesments – T6.3.3 = Wind farm life cycle public/community engagement – T6.3.4 = Best practice transfer to the Global South – T6.4.1 = Communication streamlining and host community benefic creation – T6.4.2 = Development of practical approach to lifecycle public participation – T6.4.3 = Socialising wind rights – T6.4.4 = Relationship between people, technology and places for all relevant social issues – T6.5.1 = Upgrade to finance and cost models to incorporate environmental/external costs – T6.5.2 = Risk factors financing costs

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5.4. CONCLUSION

Finally, some conclusions will be defined with comments for the Mid and Long-Term R&D needs analysis. We would like to remark that a significant number of relevant national R&D projects are missing in this collection because of the lack of available information about the results obtained.

5.4.1. Conclusions of Research Theme 1- Industrialisation, Scale-up and Competitiveness

A reasonable number of R&D projects devoted to manufacturing capacities for mass production has been collected but in order to ramp-up of manufacturing capacities and the competitiveness in the wind sector in Europe, it would be recommended to increase of the research in automation and optimisation of serial manufacturing processes for components and systems. In this sense collaboration among suppliers and along the supply chain, standardization, modularization, and advanced materials are essential for efficient production.

The industrialization process of wind energy systems also requires evolved modelling approaches in order to integrate holistic, modular and accelerated design with new analysis processes. The modelling tools used in the design process require continuous validation and alignment with the existing and newly planned automated production capabilities. The research on scaled and virtual tests are crucial for large future wind turbines development.

In spite of the big number of R&D projects focused in the industrialization of floating wind turbines, most of these projects are in the prototyping phase, then efforts to concentrate on scaling-up manufacturing capacities, enhancing and testifying supply chain resilience, and embracing digitalization of production processes for both components and turbines are strongly recommended to further drive down the lifecycle-based generating cost (LCoE) of floating wind, with standardization and industrialization of floater designs. The development and manufacturing of new tools and solutions to assembly and maintain heavy structures are also needed. Research on manufacturing synergies with other generation technologies is also recommended. Regarding small wind research is required on creating openly accessible models and metrics for assessing loads, flow, and site characteristics for small and off-grid wind applications. The translation of design and standardization experience from large turbines to small wind can facilitate the competitive industrialization of small-scale wind energy.

Research into energy efficiency, recycling and quality control, along with market dynamics, policy research and interactions between society and manufacturing technology are considered crucial for achieving sustainable, cost-effective mass production and social acceptation of wind turbines. The integration of sustainable, local materials together with near shoring and overall (rare) material reduction must be considered during the ramp-up of future European wind turbine production landscape.

5.4.2. Conclusions of Research Theme 2- Optimisation and further digitalisation of Operations & Maintenance

The reality of research into the O&M of onshore and offshore wind farms is that significant progress has been made in terms of the use of artificial intelligence and the digitalisation of O&M, however there is still a need for more training of workers in the use of artificial intelligence tools, augmented reality and the development of better tools that allow operation and maintenance to take into account the effects of waves or climate change to do so in a more holistic way.

The use of robots to perform some inspection and maintenance tasks is already a fact in many wind farms, however, there is a need for greater implementation of robots that are capable of performing underwater and aerial tasks (drones or airbornes) in an autonomous and safe way. In addition, further research is needed in automatic installation and dismantling tasks, as well as semi-automatic repairs, especially of the blades.

The decision-making part of O&M is a critical part of efficient and safe operation and maintenance and is where the most money and projects have been made. Numerous advances have been made in data exchange and decision-making algorithms, but the complexity of the systems and the multitude of variables to be taken into account, (for instance, energy, economic, environmental, regulatory, impact on biodiversity, etc.) makes the problem extremely complex and efforts must be made to improve these algorithms, also taking into account the study of the life cycle from a holistic point of view. Cybersecurity aspects of IoT data collection and transmissions is another aspect that needs to be pushed further in the coming years. In addition, new sensors with other characteristics (artificial intelligence, artificial vision, deep learning, etc..) are bound to appear and will need to be integrated into decision systems.

In the area of transport and replacement of large components, it is undoubtedly where the least effort has been found in the review of the NEWINDEERA project and is therefore a key point for the realisation of more and better R&D projects. Efforts in more and better connection and disconnection of mooring lines and cables will be necessary in the near future. The tasks of moving different equipment from the ports is another important point for enhancing, as it is an important cost in terms of improving the efficiency of assembly and disassembly as well as maintenance, needing to be as autonomous or semi-autonomous as possible.

5.4.3. Conclusions of Research Theme 3- Wind Energy System Integration

The NEWINDEERA project has established a number of gaps and needs in the integration of current and future wind farms into existing and new grids. Different solutions supported by digital twins and artificial intelligence have been identified to obtain better control plant and interoperability with existing grids and other generation sources. To this end, there is a need to implement new electricity transmission and distribution grids, both onshore and offshore, in conjunction with hybrid AC and DC grids, as well as an urgent need to find solutions for curtailment. All of this in conjunction with the integration of the new wind farms characteristics must have to provide a solution to the produced energy, where they will also be hybridised with other types of generation and storage technologies.

Several projects have been carried out to study models that identify the special needs of the new transmission grids to provide security, flexibility and efficiency, in order to be able to integrate the vast amount of energy that needs to be generated from wind power to achieve the decarbonisation plans proposed by the EU. In addition, new studies are needed to optimise how to transport electricity on its own or in combination with hydrogen and/or other forms of energy to where it will be consumed in an effective and safe mode.

These grids will also have the handicap of integrating new converters and systems that allow a secure and economically profitable short-term balance in order to optimise consumption, as well as taking responsibility for managing the ancillary services that guarantee the supply of available wind energy at all periods. It will therefore be necessary to develop new grid codes which, based on previous models and studies, guarantee the stability of the system. Significant progress has already been made in this area in a number of important projects such as the North Sea Energy Programme or Ocean Grid Research, but improvements still need to be made and implemented in the future grid.

Regarding the interoperability of these systems, different efforts still need to be made in terms of wind farm control to optimise generation, while being respectful of the different bio-systems that live around them. This will imply to mitigate noise emissions and the impact on birds and fishing, and also taking into account that they should be used to reduce losses due to the effects of waves on the wind farms. The widespread use of digital twins of park control level systems may be a viable solution to these problems. In fact, some projects are already underway to establish control algorithms based on AI and digital twins that will optimise the lifetime of plant components. One of the best examples of this is probably the TWAIN project, which will achieve a major breakthrough in the integrated multibody control of wind farms. However, new approaches are needed for all types of wind generation, including hybrid projects with other technologies.

Regarding the solution to curtailment, some projects have been carried out, although not too many, and the spotlight will have to be placed on them in the coming years. The key will be how to store massively all the wind energy that can be produced and that due to the fact it cannot be sold or because there is no capacity, can be stored in technologies such as hydrogen or other types of storage systems, for instance compressed air, pumping or batteries. It's important for this type of storage systems that use materials that are not critical for the EU and whose performance was significant.

Last but not least, it is necessary to work on the hybridisation of generation and storage technologies, from modelling to demonstration plants and the creation of regulatory standards that allow the advancement of wind technologies to guarantee energy supply without having to produce energy at high costs. This solution includes, as already mentioned, the integration of mass storage and its possible evacuation in ocean transmission grids that could transmit in HVDC. This will require modelling, studying the different grid configurations, their advantages and disadvantages compared to AC, and establishing modelling and optimisation tools for the use of both hybrid grids and the wind energy conversion systems.

5.4.4. Conclusions of Research Theme 4- Sustainability and Circularity

Given the ageing wind fleet and the substantial share of wind turbines reaching their end of life in Europe, recycling and the transition to a circular economy will become key. Moreover, the wind industry called for a Europe-wide landfill ban on decommissioned wind turbine blades by 2025. Within the wind energy industry several companies and original equipment manufacturers have announced ambitious targets with respect to recycling and circularity approaches.

Although 80-95% of the total mass of a wind turbine can be recycled some components, such as blades, pose a challenge. Within the development of material substitution enabling decarbonisation and reducing the use of rare-earth materials, an effort has been made during the last years, mainly focused on the research of new components and materials, and to a less extent in including recyclability in the design solutions. No projects have been identified in other activities in this field, such as investigation on material durability and protection.

An important effort has been identified in the development and demonstration of recycling methods for wind turbine materials, manufacturing waste and components. Many focus on circularity approaches with respect to the blade component, but several initiatives extend this approach to other parts of the wind energy supply chain (e.g. new tower concepts, moorings in floating offshore wind applications reducing the weight of conventional approaches, drivetrains, nacelle cover and novel grid integration methods). Yet the processes applied and technology readiness level (TRL) of these innovations varies.

The latest research on circular economy strategies for offshore wind stresses that current practice in the end-of-life treatment of offshore wind focuses mainly on recycling, energy recovery and landfill and less as a starting point for system regeneration. As the end-of-life of many wind farms in Europe arose the lifetime extension solution in order to delay the decommissioning that allows circularity, and it will become a massive option once the age of wind generation plants in Europe is reaching their planned end-of-life, via re-using, refurbishing, re-purposing.

In this sense, research activities are needed to bring down installation costs, supply chain costs and the environmental impact of new decommissioning tools and methods. Some projects have been identified within this area.

Some of the newest projects include biodiversity as an integrated part of planning for new wind farms. Still, it is important to understand impacts on biodiversity during construction and operation.

5.4.5. Conclusions of Research Theme 5 -Skills, Acceptability & Coexistence

The shortage of skills required to achieve the goals of the clean energy transition is one of the main bottlenecks of accelerated clean energy transitions. In 2020, the Commission launched the Pact for Skills initiative to support public and private organisations with upskilling and reskilling, so they can thrive through the green and digital transitions. Some projects have been identified on these activities, mainly starting during the last years and being some of them Marie Sklodowska - Curie actions. However, more efforts will be needed in the upcoming years to cope with the foreseen increase: in 2022, the European Union's wind energy industry employed approximately 300,000 people; by 2030, wind energy jobs in the EU are forecasted to reach between 760,000 and 940,000.

Social acceptance is an important factor that may have an impact on the length of time it takes for the process of establishing an installation. Coexistence with individuals, diverse industries, and the environment is crucial. Although a few projects have been found showing the increasing importance of these issues in the last calls, the projection for the near future is an even more important presence of these topics for the energy transition, as it is a complex socio-technical process involving changes not only to energy technologies but also to the broader social and economic aspects of energy production and consumption. A just energy transition strives for a more equitable distribution of benefits and burdens and ensuring that vulnerable groups are not disproportionately harmed is increasingly seen as a crucial success factor for a just transition. For example, one of the conclusions the report Offshore renewable energy in the EU is that the social implications of offshore renewable energy development have not yet been comprehensively considered.

5.4.6. Conclusions of Research Theme 6- Cross-cutting Research Themes

NeWindEERA has assessed some cross-cutting topics to address additional challenges and explicitly convey the important research needs not fitting in the previous research themes.

For example, the improvement in the understanding of climate, atmosphere, ocean, and geophysics arises as a need derived from the upscale of wind generation. Some new wind maps have been developed in projects during the last years, but new challenges appear for resource and yield assessment as well as wind conditions in and around wind power plants impacting integration (wind variability, etc.) and operations (weather windows, etc.), or for the interaction in offshore wind, for example.

The door to disruptive technologies remains open as well, both for new concepts and/or new components. Airborne wind is the main proposed concept in the identified projects, but they are still far from the commercial readiness level, and new concepts may appear in the future. The disruptive opportunities are even larger for components, where new materials or new technologies may bring relevant improvements at the component level, such as those identified in past projects.

Some projects have been identified in relation to the policy and regulation of the permitting process without jeopardising democratic principles of planning and stakeholder involvement, but there is still work to be done in this area, as derived from one of the commitments of the recently signed European Wind Charter (December 2023): "Improve, simplify and provide consistency in the design of auctions for wind energy ...".

Finally, as mentioned before, a special interest has arisen during the last years in the social implications of the upscale of wind power: involvement (in the benefits, in the planning ...), communication, acceptance, justice, sufficiency, etc. Some identified projects start to tackle some of these topics, but future developments will be necessary to cope with this important new European approach.

6. Appendix 1

NeWindEERA Research Programme Timeline

Appendix 1 contains the NeWindEERA Research Programme Themes & Timeline that have been developed as a central part of the NeWindEERA project.

Research Themes

The six Research Themes are visually represented on the following pages and broken down into their identified sub-themes and research topics.

Timeline

The timeline is presented across two pages at the end of Appendix 1 and identifies the key milestones that must be achieved between now and 2050 as part of the NeWindEERA research programme delivery. Milestones are presented for each of the six Research Themes and identified at sub-theme level.

R&I PRIORITY THEME 1

Industrialisation, Scale-up and Competitiveness

This R&I priority theme is guided by the IEA's Grand Challenges in Wind Energy Science and the R&I priorities from ETIPWind's Strategic Research and Innovation Agenda. Research topics take note of the current State of the Art and future challenges and also recognise the need to continuously improve the underlying design and modelling tools.

Mass Production supported by automation and reliable supply chain

- Manufacturing capacities for mass production
- Serial manufacturing of components
- Automation and optimisation of manufacturing processes
- Environmental Impacts
- Social Impacts

3.1.1.1 Research Topic – Manufacturing for mass production

3.1.1.2 Research Topic – Environmental impacts of mass production

3.1.1.3 Research Topic – Social impacts of mass production

Design for large volume manufacturing and deployment

- Next generation wind turbine technology and economic optimization
- Combination with other generation technologies
- Industrialisation of floating offshore wind

3.1.2.1 Research Topic – Next generation wind turbine technology and economic optimization

3.1.2.2 Research Topic – Combination with other generation technologies

3.1.2.3 Research Topic – Industrialisation of floating offshore wind

Design for reliable and lasting products

- Holistic, accelerated turbine design
- Probabilistic design
- Virtual and scaled testing
- Small and Off-Grid Wind

3.1.3.1 Research Topic – Holistic and accelerated turbine design

3.1.3.2 Research Topic – Probabilistic design

3.1.3.3 Research Topic – Virtual, scaled and full-scale testing

3.1.3.4 Research Topic – Small and Off-Grid Wind

Improve construction and installation methods

- Scaling up installation
- Assembly and heavy maintenance solutions

3.1.4.1 Research Topic – Scaling up installation

3.1.4.2 Research Topic – Assembly and heavy maintenance solutions

Adequate economic and financial conditions

- Market design
- Accounting for environmental cost

3.1.5.1 Research Topic – Adequate support policies

3.1.5.2 Research Topic – Market design

3.1.5.3 Research Topic – Impact assessment for value creation

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R&I PRIORITY THEME 2

Optimisation and further digitalisation of Operations & Maintenance

R&I Priority Theme 2 creates four sub-themes focusing on improving operational efficiency through digitalisation; the need to automate a significant amount of O&M; the opportunity to embrace a digital ecosystem; and the need to cater for the replacement and transport of major components as the size of offshore wind turbines continues to grow.

Digitalisation of maintenance and optimisation tools for operational effficiency

- Innovative training for technicians using AR, VR and/or AI
- AI-driven predictive maintenance for key components & report analysis
- AI-driven resource assessment and forecasting tools

3.2.1.1 Research Topic – Innovative training for technicians using AR, VR, and/or AI

3.2.1.2 Research Topic – AI-driven predictive maintenance for key components & report analysis

3.2.1.3 Research Topic – AI-driven resource assessment and forecasting tools

Autonomous Operations and Maintenance

- Enhanced robotics for blade servicing & semi-automated inspection
- Advanced offshore repair methodologies and autonomous vehicles for maine operations
- Autonomous wind installation, O&M and decommissioning

3.2.2.1 Research Topic – Enhanced robotics for blade servicing & semi-automated inspection

3.2.2.2 Research Topic – Advanced offshore repair methodologies and autonomous vehicles for marine operations

3.2.2.3 Research Topic – Autonomous wind installation, O&M and decommissioning

Digital Ecosystem(s)

- Data exchange across sub-systems
- Sensor technologies
- Industrial IoT, cloud analytics, cybersecurity
- Optimisation & Decision-making
- Hollistic understanding of natural systems (physical, social, biological)

3.2.3.1 Research Topic – Data exchange across sub-systems

3.2.3.2 Research Topic – Sensor technologies

3.2.3.3 Research Topic – Industrial IoT, cloud analytics, cybersecurity

3.2.3.4 Research Topic – Optimisation & Decision-making

3.2.3.5 Research Topic – Holistic understanding of natural systems (physical, social, biological)

Replacement and transport of major components

- Component replacement solutions onshore & offshore
- Quick connect/disconnect systems for mooring lines & inter-array cables
- In-situ repairs and craneless exchange
- Autonomy & digitalization for port operations
- Novel fuel alternatives in ports (e.g. hydrogen fuelling)

3.2.4.1 Research Topic – Component replacement solutions onshore & offshore

3.2.4.2 Research Topic – Quick connect/ disconnect systems for mooring lines & inter-array cables

3.2.4.3 Research Topic – Autonomy & digitalization for port operations with novel fuel alternatives

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R&I PRIORITY THEME 3

Wind Energy System Integration

The integration of large scale wind energy remains one of the biggest challenges facing the sector. This priority theme identifies six sub-themes including plant level control and grid forming hybrid plants that were highlighted in the IEA's Grand Challenges in Wind Energy Science.

Definition and Modelling of future system needs

- Transmission and generation flexibility
- Optimisation of transmission infrastructure
- Grid digitalisation

3.3.1.1 Research Topic: Transmission and generation flexibility

3.3.1.2 Research Topic: Optimisation of transmission infrastructure

3.3.1.3 Research Topic: Grid digitalisation

Advanced grid capabilities

- Ancillary service provision
- Development of new converter capabilities and systems
- Short term balancing

3.3.2.1 Research Topic: Ancillary service provision

3.3.2.2 Research Topic: Development of new converter capabilities and systems

3.3.2.3 Research Topic: Short term balancing

Interoperability

- Digital twin technologies
- Plant level control

3.3.3.1 Research Topic: Digital twin technologies

3.3.3.2 Research Topic: Plant level control

Solutions to effectively manage curtailment

- Long duration energy storage
- Offshore wind and hydrogen production

3.3.4.1 Research Topic: Long duration energy storage

3.3.4.2 Research Topic: Offshore wind and hydrogen production

Power to X and hybrid plants

- Power to X technologies
- Hydrogen market integration
- Hybrid plants

3.3.5.1 Research Topic: Power to X technologies

3.3.5.2 Research Topic: Hydrogen market integration

3.3.5.3 Research Topic: Hybrid plants

DC grid solutions

- Offshore grid infrastructure

3.3.6.1 Research Topic: Offshore grid infrastructure

R&I PRIORITY THEME 4

Sustainability and Circularity

Inspired by IEA Wind and ETIPWind activity, this R&I priority theme focuses on several topics including environmental co-design, social aspects of wind energy development, sustainable materials, and reuse and recycling. It also identifies the need to research end-of-life management, life cycle assessment, and new business models for reusing materials.

Material substitution for decarbonisation

- Sustainable materials in design and recyclability by design
- New components and materials
- Material durability and protection
- Alternative design solutions

3.4.1.1 Research Topic: Sustainable materials in design and recyclability by design

3.4.1.2 Research Topic: New components and materials

3.4.1.3 Research Topic: Material durability and protection

3.4.1.4 Research Topic: Alternative design solutions

Recycling methods

- Sustainable blade recycling
- New recycling process
- Reliability of secondary materials
- Holistic life cycle assessment
- New business models

3.4.2.1 Research Topic: Blade recycling, sustainability assessment and technologies to lower CO2 footprint

3.4.2.2 Research Topic: Reliability of secondary materials

3.4.2.3 Research Topic: New recycling process

3.4.2.4 Research Topic: Holistic life cycle assessment

3.4.2.5 Research Topic: New business models

Lifetime extension via re-using, refurbishing and re-purposing

- Solutions for lifetime extension
- End-of-life management
- Assessment of the damage state of turbine properties

3.4.3.1 Research Topic: Solutions for lifetime extension

3.4.3.2 Research Topic: End-of-life management

3.4.3.3 Research Topic: Assessment of the damage state of turbine properties

New decommissioning tools and methods

- Methods and tools for offshore wind
- Technologies for environmentally friendly decommissioning
- Processes and components to ease reuse and recycling
- Economic model for full decommissioning project cycle

3.4.4.1 Research Topic: Decommissioning methods and tools for offshore wind

3.4.4.2 Research Topic: Technologies for environmentally friendly decommissioning

3.4.4.3 Research Topic: Processes and components to ease reuse and recycling

3.4.4.4 Research Topic: Economic model for full decommissioning project cycle

Biodiversity solutions

- Environmental co-design
- Impact on ecosystems and biodiversity
- Noise reduction

3.4.5.1 Research Topic: Environmental co-design

3.4.5.2 Research Topic: Impact on ecosystems and biodiversity

3.4.5.3 Research Topic: Noise reduction

R&I PRIORITY THEME 5

Skills, Acceptability & Coexistence

The large-scale expansion of wind energy demands a skilled workforce, cultivating both inter- and transdisciplinary collaboration, and nurturing a holistic understanding and acceptance. Coexistence with individuals, diverse industries, and the environment is crucial.

Education

Continue examine gaps in wind energy education

Assess measures/tools to increase number of study places and increase recruitment (e.g. long term campaigns)

- 3.5.1.1 Research Topic: Education and strategic workforce expansion for the wind energy sector
- 3.5.1.2 Research Topic: Innovative pedagogy for wind energy excellence
- 3.5.1.3 Research Topic: Cultivating diversity and sustained interest in wind energy

Skilling, re-skilling and upskilling activities

Programmes to skill, re-skill and upskill experts in related professions

Designing comprehensive programs covering entire value chain

- 3.5.2.1 Research Topic: Strategic workforce development across the wind energy value chain
- 3.5.2.2 Research Topic: Optimising cross-sector talent integration for wind energy sustainability

Increase public engagement of citizens

Provide guidelines for continuous community involvement throughout the whole project period, and implement in regulations

Demonstrate the benefits of wind energy for society as a whole and local communities

- 3.5.3.1 Research Topic: Community involvement modelling/ tool development
- 3.5.3.2 Research Topic: Wind energy societal benefits and impacts analysis

Fair transition, inclusiveness and stakeholder interests

Develop tools to identify stakeholders, improve the understanding and map stakeholder concerns

Develop novel governance and ownership models of wind farms

- 3.5.4.1 Research Topic: The good process
- 3.5.4.2 Research Topic: Tools to map stakeholder concerns
- 3.5.4.3 Research Topic: Technology-people-relations and public perception

Interdisciplinary and transdisciplinary relations with coexistence

Planning for positive co-existence: Identification and definition of relevant societal and environmental assessment criteria of site specific impacts

Evaluation of the consequences of intensified wind energy production and upscaling

R&I PRIORITY THEME 6

Cross-cutting Research Themes

Although partially addressed in the earlier R&I priority themes, the NeWindEERA programme proposes a number of critical cross-cutting topics. They will address additional challenges and explicitly convey important research needs in the areas of climate, atmosphere, ocean and geophysics; disruptive technologies; policy and regulation; social aspects; and finance.

Climate, Atmosphere, Ocean and Geophysics

Understanding wakes, blockage effects, wind resource, and yield

Large wind effects on meteorological fields

Reduced wind speed and horizontal water transport interaction

Ocean current and offshore wind structure interaction through the thermocline

- 3.6.1.1 Research Topic: Geophysical characteristic measuring and modelling advancement
- 3.6.1.2 Research Topic: Wake effect model development
- 3.6.1.3 Research Topic: Climate change physical conditions impact analysis

Disruptive technologies

Multirotor concepts

Airborne wind

Small wind turbines

- 3.6.2.1 Research Topic: New concept assessment and development
- 3.6.2.2 Research Topic: Turbine component performance and efficiency

Policy and regulation

Acceleration permitting processes (decision and regulation)

Spatial planning

- 3.6.3.1 Research Topic: Spatial planning
- 3.6.3.2 Research Topic: Evolution of environmental impact assessments
- 3.6.3.3 Research Topic: Wind farm life cycle public/community engagement
- 3.6.3.4 Research Topic: Best practice transfer to the Global South

Social Aspects

Better understanding and awareness of wind energy benefits

Ease of communication

Improved communication of research outcomes

- 3.6.4.1 Research Topic: Communication streamlining and host community benefit creation
- 3.6.4.2 Research Topic: Development of practical approach to lifecycle public participation
- 3.6.4.3 Research Topic: Socialising wind rights
- 3.6.4.4 Research Topic: Relationship between people, technology and places for all relevant social issues

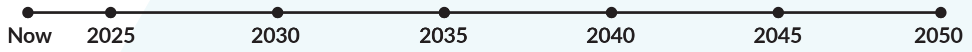
Finance

Include environmental (external) costs and compare cross energy sectors

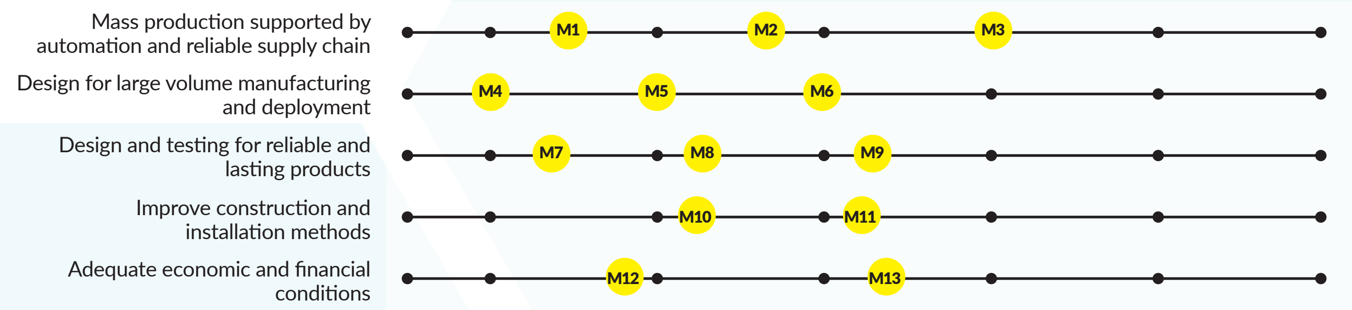
Risk: consider the LCOE discount rate, a (very) important parameter

- 3.6.5.1 Research Topic: Upgrade to finance and cost models to incorporate environmental/external costs
- 3.6.5.2 Research Topic: Risk factors impacting financing costs

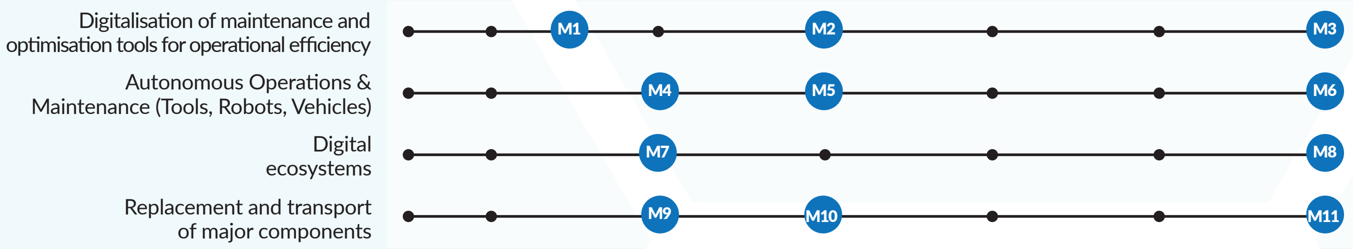
TIMELINE



Theme 1 – Industrialisation, Scale-up and Competitiveness

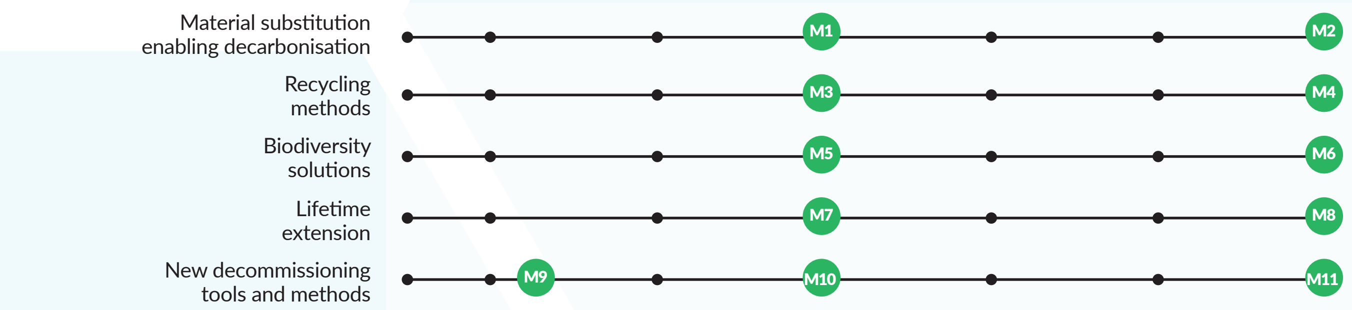


Theme 2 – Optimisation and further digitalisation of Operations & Maintenance

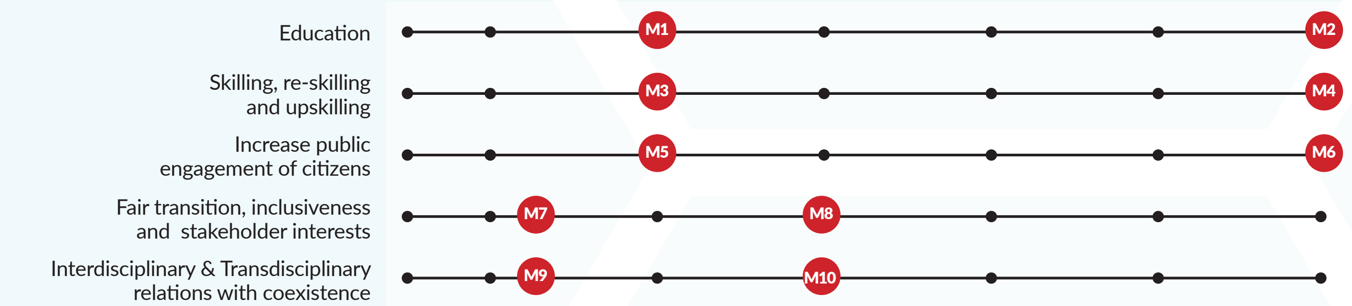


Theme 3 – Wind Energy System Integration

Theme 4 – Sustainability and Circularity



Theme 5 – Skills, Acceptability & Coexistence



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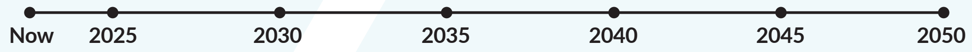
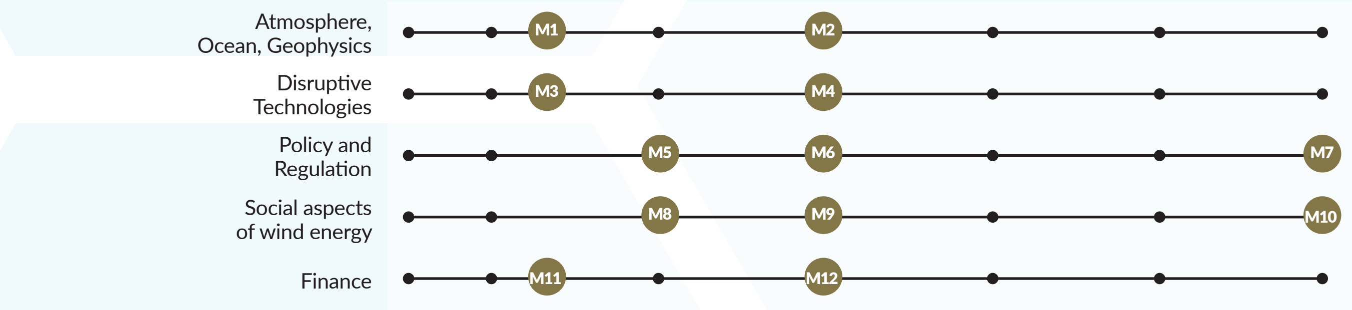


Theme 6 – Cross-cutting Research Themes



MILESTONES – KEY

Theme 1 – Industrialisation, Scale-up and Competitiveness

M1 European certification standard for robust supply chains
M2 Pilot implementations of innovative factories for future serial manufacturing
M3 Full scale commercial deployment
M4 Ideal balance between turbine power and quantity
M5 Economically and technically feasible Hybrid Projects
M6 Standardized design and large series production of floating offshore wind
M7 Scaling method for complete components
M8 Standardized holistic design approaches
M9 Standardized test methods based on scaled, virtual and full scale tests
M10 Implementation of new construction strategies and contracts with different suppliers
M11 Infrastructure ready for large scale deployment
M12 Robust policy framework
M13 Full integration of environmental costs for decision-making

Theme 2 – Optimisation and further digitalisation of Operations & Maintenance

M1 Advanced AR/VR and AI tools are developed & validated for several aspects of O&M
M2 Advanced digital tools are fully implemented into O&M workflow for better performance overall
M3 Climate (Change) resilience and advanced energy control systems are validated
M4 Enhanced robotics for blade servicing and semi-automated inspections are in use
M5 Offshore repair methodologies and autonomous vehicles for marine operations are advanced
M6 Autonomous wind installation, O&M and decommissioning
M7 Integration of Industrial IoT, cloud analytics, advanced communication technologies, and cybersecurity measures into safe operation
M8 Holistic analysis of natural systems through advanced sensors and digitalization, and environmental data-driven spatial planning for human and ecological needs
M9 Demonstration and qualification of major component replacement solutions onshore and offshore, including floating wind
M10 Quick connect/disconnect systems for mooring lines and inter-array cables are in place
M11 Autonomous and digitalized port operations with novel fuel alternatives

Theme 3 – Wind Energy System Integration

M1 Next generation modelling tools developed
M2 Grid digitalisation widely implemented
M3 Transmission infrastructure fully optimised
M4 Refined ancillary service provision achieved
M5 New converter capabilities implemented
M6 Robust enhanced grid services established
M7 Plant level control demonstrated
M8 Digital twin technologies fully established
M9 Offshore wind/hydrogen production demonstrated
M10 Long duration energy storage implemented
M11 Early power to X technologies demonstrated
M12 Hydrogen market integration established
M13 Hybrid plants fully realised
M14 Planning & optimisation tools developed
M15 Energy hub/island demonstrators established
M16 DC grid network fully implemented

Theme 4 – Sustainability and Circularity

M1 Validation of blades with new materials and more circular coatings
M2 Validation of new concept of WT with new materials
M3 Maximize the benefits of material at the end of life
M4 100% wind turbine recyclability with the lowest CO2 footprint
M5 LCA of all the influences among WT and environmental processes
M6 Quasi-Zero environmental co-design WT procedure
M7 LCA methodology
M8 Digital twinning and use of AI fully established
M9 New methods and tools for offshore wind
M10 Economic model for full decommissioning project
M11 New technologies for effective and environmentally friendly decommissioning

Theme 5 – Skills, Acceptability & Coexistence

M1 Establish a robust interdisciplinary wind energy education framework
M2 Achieve industry-wide continuous learning, fostering adaptability and sustainable expertise
M3 Establish comprehensive wind energy skilling programs for diverse competences.
M4 Majority of professionals in the sector have received ongoing skilling, re-skilling, and upskilling
M5 Pilot projects with enhanced community involvement established
M6 All European wind project developments follow good practices of community involvement
M7 Governance models developed
M8 Implementation and assessment of governance models in wind energy projects
M9 Systematic method to identify relevant stakeholders and their (competing) interests in specific projects
M10 Assessment criteria of balanced coexistence

Theme 6 – Cross-cutting Research Themes

M1 Accurate validated models of wind farm cluster wake effects
M2 Comprehensive operational collaboration with weather and climate centres
M3 "Watch-list" established on most promising disruptive technologies
M4 Disruptive technology innovation validated
M5 Experimental assessment of novel approaches
M6 New engagement and assessment methods verified in different contexts
M7 Regulatory implementation across Europe
M8 Approaches for creating tangible benefits identified
M9 New governance models assessed and developed
M10 Regulatory implementation in all wind energy projects
M11 Risk factors impacting financing costs understood
M12 Updated finance and cost models fully implemented

7. Appendix 2

List of Existing Projects

Chapter 5 identified a comprehensive list of completed or ongoing projects involving members of EERA JP Wind and the wider European wind energy sector. These are included in a spreadsheet for future reference and can be found at the following link www.eera-wind.eu/projects/20-projects/259-newindeera-projects.html

ABOUT EERA JP WIND

The European Energy Research Alliance Joint Programme for Wind energy (EERA JP Wind) is a joint programme that brings together many of the major research and academic organisations from the European wind energy community. With circa 50 members in the joint programme, it provides strategic leadership for medium to long-term research activity in the field of wind energy and supports the European wind energy industry and societal stakeholders. The joint programme currently operates eight sub-programmes designed to identify and develop the solutions to the grand challenges facing the wind energy research community over the coming decades.

For more information, please visit the EERA JP Wind website (https://www.eera-wind.eu/) or follow us on social media:

LinkedIn: **www.linkedin.com/in/eera-jp-wind**

X: **@eera_jpwind**

THE THREE PILLARS OF EUROPEAN WIND ENERGY RESEARCH AND INNOVATION

We must have strong alignment with industry and a common set of research and innovation priorities with short, medium and longer term goals.

With this in mind, the new NeWindEERA research programme is one of three pillars that will enable a fully aligned delivery of the European wind energy research and innovation activity.

1

The first pillar is the ETIP Wind Strategic Research and Innovation Agenda
Shorter term R&I priorities for the next five years

2

The second pillar is the NeWindEERA research programme
Medium and longer-term R&I priorities for 2035 and 2050 targets

3

The third pillar is the European Wind Energy Centre of Excellence (EuCoE4Wind)
The emerging framework/vehicle that will carry us on the journey

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DISCLAIMER

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Wind Energy

The NeWindEERA project is funded by the EERA JP Wind membership. However, the views and opinions expressed are those of the author(s) of the NeWindEERA consortium* and do not necessarily reflect those of the wider EERA or EERA JP Wind membership.

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