SWC – Swedish Wind Centre

Research agenda for Swedish wind power

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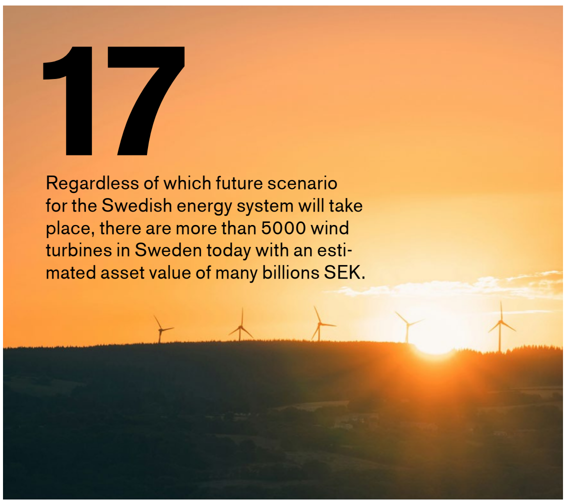

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Regardless of which future scenario for the Swedish energy system will take place, there are more than 5000 wind turbines in Sweden today with an estimated asset value of many billions SEK.

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Wind turbines play a significant role in the process of generation technology shift in the electricity system, where the direction is towards energy systems heavily based on renewable power, both in Sweden and many parts of the world.

Introduction

This research agenda outlines the opportunities and needs for Swedish wind energy research, emphasizing areas of national relevance while highlighting Sweden's contributions to international research efforts. The agenda aims to advance knowledge and innovation tailored to Swedish conditions, addressing gaps where international actors partly have limited engagement. By identifying strong Swedish competencies and aligning them with global challenges, the agenda aims to enhance Sweden's role in the international wind energy research community. Furthermore, this document serves as an internal strategic tool to prioritize critical research areas and guide future project funding. By fostering collaboration and directing resources towards high-impact research, the Swedish Wind Centre strengthens Sweden's position in the global transition to sustainable energy.

The plan is to update the research agenda every second year.

Motivation

As Sweden transitions toward a fully sustainable and fossil-free energy system, wind power will play a decisive role regardless of which long-term technological solutions are added to the energy system. The ability of wind power to rapidly scale up, provide cost-effective electricity, and complement other renewable energy sources makes it a cornerstone of Sweden's future energy security and way to reach climate goals. Sweden's energy system is undergoing a major transformation, driven by the need to phase out fossil fuels, meet increasing electricity demand, and secure energy independence. Sweden's electricity demand is expected to increase to 223–357 TWh per year in 2050, driven by the electrification of industry and transport. According to the Swedish Energy Agency and industry estimates, wind power will need to supply a significant portion of this demand, alongside hydropower, nuclear power, and other renewables. By 2045, at least 60 TWh of annual generation from wind power will be required, which corresponds to a doubling of the current installed capacity. The reasons for why wind power will dominate the Swedish power system are that it is one of the cost-efficient ways to generate electricity in Sweden and the world, making it an economically attractive option, as well as onshore wind is significantly faster to build than any other power production unit. This will allow Sweden to meet the increasing electricity demand in a timely manner. Moreover, wind power can be deployed both on land and offshore, ensuring geographical diversification and reducing dependency on single energy hubs.

A diversified energy mix with significant wind power contributions enhances grid resilience and reduces vulnerability to energy supply disruptions. Wind power complements hydropower exceptionally well, as Sweden's hydropower reservoirs can act as storage during periods of low wind. Future advancements in energy storage, demand-side management, and sector coupling (such as electrification of industry and transport) will further enhance the reliability of a wind-powered energy system.

With the large increase in wind turbines needed to meet the higher electricity demand, it is even more important to make sure that both the existing turbines and the coming are run and built in the best possible way. To ensure that, more research is needed, especially in Swedish conditions, i.e., forested areas as well as in the seas.

Regardless of future choices for the Swedish power system, wind power will remain a crucial pillar. Its ability to provide scalable, cost-effective, and renewable electricity makes it indispensable in achieving Sweden's climate neutrality goals, energy security, and industrial competitiveness. Sweden's path toward a fossil-free future will require a balanced mix of energy sources, but without a significant expansion of wind power, the country's energy transition will be slower, more expensive, and less resilient.

[1] Scenarier över Sveriges energisystem Vägar till ett energisystem med nettonollutsläpp 2050 Statens energimyndighet, mars 2025, ER 2025:13

Method

The research topics and questions presented in this agenda, have been developed with the industry partners within Swedish Wind Centre. The process started with going through the different international research agendas within wind power and rank the importance of the research topics, as well as add missing topics. This was done during a workshop at SWC's annual centre conference in November 2024, with groups consisting of both industrial and academic representatives in the Centre. The Centre management compiled the results from all groups into lists of highest ranked research topics within each of the themes in SWC. In a second workshop, in January 2025, the industry partners were gathered to prioritise among the research topics, leading to the topics presented here. At the centre conference in 2025, additional discussion was carried out, mainly on social, economic and planning aspects of wind power as well as environmental impacts. Mixed group with representatives from both industry and academia discussed which research questions that were important within these topics. After all workshops, the academic partners of the Centre have expanded on each topic and written research questions for each. Therefore, this agenda is based on both academic state-of-the-art research challenges as well as on industrial needs.

Sweden's energy system is undergoing a major transformation, driven by the need to phase out fossil fuels, meet increasing electricity demand, and secure energy independence.

About SWC

The research centre Swedish Wind Centre, SWC, conducts and collects research on wind power to contribute to a robust and sustainable energy system. The wind power industry has grown and developed considerably the last years and will be of further importance for the energy system. SWC has extensive experience from two previous centres, StandUp for Wind and SWPTC, both active for more than ten years. The two former centres complemented each other in fields of research and cooperated for example by arranging joint conferences. Now, SWC has gathered the activities of the former centres. Therefore, the Swedish Wind Centre serves as a national hub, bringing together key stakeholders in Sweden's wind energy sector.

SWC conducts interdisciplinary research in five research themes about wind power in Nordic conditions: Social, economic and planning aspects of wind power, Wind energy siting, Environment and materials, Operation & Maintenance and Integration in the power system. The SWC is financed and run by some 20 organizations, including universities, research institutes, wind power producers and a county council. The centre aims to advance knowledge and innovation tailored to Swedish conditions, addressing gaps where international actors partly have limited engagement.

www.swedishwindcentre.se

> Sweden's path toward a fossil-free future will require a balanced mix of energy sources, but without a significant expansion of wind power, the country's energy transition will be slower, more expensive, and less resilient.

Social, economic and planning aspects of wind power

The successful large-scale deployment of wind power in Sweden depends not only on technological progress and system integration but also on the social, economic, and institutional frameworks that enable a just, inclusive, and resilient energy transition. This research theme focuses on understanding and shaping the social and economic dimensions of technological change in wind power – from local community acceptance to new business and revenue models. The objective is to ensure that wind energy development strengthens societal trust, regional growth, and Sweden's long-term competitiveness in a sustainable way.

Academic competence

Sweden has internationally recognized expertise in interdisciplinary energy transition studies, socio-technical systems research, and environmental economics. Uppsala University, Lund University, Chalmers, and KTH all host research environments combining technology, social science, and policy perspectives. Together, these institutions provide a solid foundation for advancing knowledge on the human, institutional, and economic aspects of wind energy expansion.

Research questions

Governance and participation

Strong governance structures and participatory approaches are essential for ensuring public legitimacy and effective decision-making in the deployment of wind power. Research in this area seeks to understand how collaborative planning and transparent governance can improve social acceptance and institutional stability.

- How can new governance models enhance social acceptance and long-term legitimacy of wind energy projects?
- What roles can municipalities, regional actors, and citizens play in co-owning, co-managing, or co-financing wind power developments?
- How can transparent and participatory processes be institutionalized in planning and permitting frameworks?

Regional economic development, value creation, and business models

Wind power can generate substantial regional benefits if supported by strategic economic planning and innovative business models. Research focuses on how local and regional economies can capture value, promote entrepreneurship, and develop resilient supply chains tied to the wind energy sector.

- How do local and regional economies, including employment, skills development, and supply chains, affect wind power deployment?
- What mechanisms and policy tools ensure fair distribution of economic benefits and compensation to affected communities?
- How can new business models for wind power promote the deployment of wind power, e.g., through diversified value proposition and capture?
- How can regional and national policies stimulate entrepreneurship and innovation around the wind energy sector?

Support actors and institutional embedding

Successful wind power deployment depends on a network of support actors that bridge government, industry, and society. Research aims to identify which organizations can serve as facilitators or intermediaries and how they can become enduring elements in Sweden's socio-technical system.

- Which support actors (e.g., intermediaries, associations, local facilitators) are essential for successful deployment of wind power in Sweden?
- How can these actors become established and legitimate functions in the sociotechnical system?
- What types of organizational structures and long-term funding mechanisms can sustain these roles?
- How can collaboration between government, industry, academia, and civil society be structured to accelerate wind power deployment?

Economic and policy instruments

Economic and policy tools play a central role in shaping incentives, managing risk, and guiding long-term investments in wind energy. Research in this area examines how market designs and fiscal frameworks can integrate social and environmental objectives alongside economic performance.

- How can market design, auction models, and regulatory frameworks account for social value creation and long-term sustainability?
- What are the macroeconomic and fiscal effects of large-scale wind deployment under different policy scenarios?
- How can integrated cost–benefit and risk assessments include social, environmental, and system-level factors in investment decisions?

Wind power planning
Experiences with setting the course too late in terms of the actual feasibility of wind power projects hurt wind power development both economically and commercially, and with regard to timelines.

- How can planning and permitting for wind energy (and the relevant grid expansion) be effectively tiered between governance levels and marine/ geographical scales?
- Which solutions do other countries that qualify as forerunners pursue to benefit from a more scaled and binding planning approach?

Co-existence with Defence force
Conflicting interest and restrictions due to military use, such as radar, can be mitigated by further research. Solutions to these questions will enhance the defence capabilities of Sweden.
- How can future energy system with a large share of wind energy contribute to energy resilience? How will large offshore wind farms impact radar systems?
- How can wind energy infrastructures provide possibilities for military sensors?

Benefit for society and industry

A strong socio-economic and socio-technological research foundation will support Sweden's ability to lead a just and competitive energy transition. For society, this research fosters trust, participation, and regional inclusion, ensuring that the benefits of wind energy – jobs, revenues, and climate mitigation – are distributed equitably. It strengthens the legitimacy of the energy transition and supports resilient local economies. For industry, it provides insights into social risk management, stakeholder engagement, and new business opportunities linked to sustainable value chains and hybrid business models. It enables companies to align technological innovation with societal expectations and policy trends, enhancing competitiveness and long-term stability in Sweden's renewable energy landscape.

Photo by OX2

Wind energy siting

Wind power siting is a crucial research theme in Sweden, focusing on identifying optimal locations for wind farms while balancing environmental, social, and economic factors. This theme connects to the state-of-the-art by integrating advanced modelling techniques with measurements including remote sensing technologies to optimize wind farm performance.

Today, research on wind power siting in Sweden involves detailed studies of local wind conditions, wind resource estimations in typical Swedish conditions, studies of farm optimization, turbine wakes, farm wakes and icing effects.

Academic expertise

Today, research on wind power siting in Sweden involves detailed studies of local wind conditions, wind resource estimations in typical Swedish conditions, studies of farm optimization, turbine wakes, farm wakes and icing effects. Sweden has significant expertise in wind power siting, both at the universities with Uppsala University being the main actor, and within academic partners, e.g. Swedish Meteorological and Hydrological Institute (SMHI), KTH, Research Institutes of Sweden (RISE) and Lund University (LU). These organizations contribute to a comprehensive understanding of wind power siting through collaborative projects and interdisciplinary research.

Research questions

Characterization of flow conditions

The wind flow reaching wind parks is subjected to the complex processes in the atmosphere in interaction with the surface. Changes in the diurnal cycle as well as the given terrain and vegetation, shape the wind with particular features that affect the park performance. The offshore conditions in the Baltic Sea have particular conditions compared to e.g. the North Sea.

- How is the prediction of the incoming flow to yield energy extraction as well as the dynamic loads on the wind turbines best achieved?
- How important is it to correctly predict events such as low-level jets or shallow boundary layers (offshore) and what methodology is applicable in research and industrial applications?
- What accuracy is needed to characterize wind in complex and forested terrains?
- How is prediction of degradation and failure best modelled?

Modelling wind, as an energy resource, in space and time

Modelling of the wind is carried out by employing computational methods to solve flow equations. Models include the representation of conditions of the atmosphere and the ground to assess how these affect the wind motion within a region and during a period of time. With larger rotors and larger farms, new modelling challenges needs to be addressed, e.g., rotor's interaction with the top of the boundary layer, blockage and gravity waves.

- How can the ability to accurately predict characteristics of the wind such as velocity, direction, turbulence, temperature, etc. on all relevant scales be improved?
- How do we best assess the ability to optimize the location and design of wind turbines and farms as well as to anticipate their performance from short to long periods of time and with it, securing the energy supply?
- There is a large gap between industrial and state-of-the-art modelling tools used in academy, how can we better validate when and how engineering tools are applicable?
- Can novel methods such as Lattice Boltzmann replace Navier-Stokes solvers and thereby increase industrial ability to use high fidelity modelling in daily workflow?

Wakes and farm-to-farm interaction

This effort focuses on how the disturbed airflow behind turbines and farms affects the performance of downstream turbines and farms. This includes studying the interaction between wakes, turbulence, and arrangement of turbines within a farm using e.g. large-eddy simulations.

- To what extent can research enhances the efficiency and performance of wind farms by minimizing wake-induced energy losses and mechanical stress on turbine
- Do wake and wake-wake interaction effects depend on near-wake and blade flow details? Can novel farm control techniques improve farm efficiency?
- What methodology fulfil future needs for wake simulations considering larger rotors in larger wind farms?
- How can farm to farm interaction be performed with best practice considering the spatial scale of the problem and corresponding balance between numerical accuracy and size of areas considered?

Wind power in typical Swedish conditions, i.e., forest and Baltic conditions
These environments present unique challenges for energy resource assessment such as complex wind patterns, turbulence, low-level jets and interaction with waves and ocean currents.

Can today's high-fidelity models, to a large extent developed by SWC partners, that partly can predict these events to a very large numerical cost, be represented with simplified engineering models?

- Do what accuracy can these hight fidelity models be developed and validated?
- Turbines located in complex terrain does to a larger extent experience difference between pre-assessment an actual loads and degradation, how can industrial practice, and their models, be modified to overcome this problem?
- Can machine learning approaches be used to identify why extreme or fatigue loads, resulting in degradation or failures, are overlooked by today's practice?

Icing effect on production, revenue and lifetime
Icing can significantly reduce energy output, increase maintenance costs, and lead to premature equipment failure. This research aims to mitigate these effects, ensuring reliable and efficient wind power generation in cold climates.

- How can the entire modelling chain; from meteorological conditions, resulting in different types of ice structures, ice accretion modelling on the blades, to load and power estimations be achieved and improved?

Remote sensing
SODAR and LIDAR are key instruments for wind resource assessment and are often used in research. As turbine models become larger, the need to rely on remote sensing for wind measurements increases. Furthermore, to facilitate participation of wind farms in grid balancing services, independent wind measurements for operation is desired.

- How can the weak points of remote sensing (turbulence accuracy, sensitivity to complex terrain and general data availability) be improved?
- How can remote sensing contribute to independent site measurements used for wind farm operation?
- Can the industrial measurement standards be reformulated to take full advantage of the possibilities that remote sensing offers?
- How can remote sensing best be used for specifically Swedish conditions (such as measurements of icing risk, strong annual cycles and in the Baltic Sea and over forested terrain)?

Benefit for society and industry

Research in wind energy siting provides substantial benefits for both society and the wind energy industry by enabling more efficient and reliable methods. Accurate siting of wind turbines is essential to maximize energy yield, minimize environmental and societal impacts, and ensure long-term technical and economic viability of wind power projects.

From an industrial perspective, advancements in flow characterization, wake modelling, and high-resolution atmospheric simulations support the development of better predictive tools that can reduce the uncertainty in wind resource assessments. This leads to more reliable project planning and risk mitigation, which ultimately lowers the cost per produced kWh. By more reliable models and measurement methods used for optimizing turbine placement, park configuration, energy losses due to wake effects and complex terrain can be minimized, increasing the overall efficiency and profitability of wind farms. To coop with Baltic conditions, including both complex terrain and cold climate as well as specific conditions of the Baltic Sea (e.g. larger extent of shallow boundary layers, low level jets etc.), specific research question are of great interest for industrial action in this region, to overcome today not unusual unforeseen misprediction of both production and loads.

Therefore, developing models and methods tailored to typical Swedish conditions – such as forested or offshore Baltic environments – ensures that national strategies are grounded in high-fidelity science. The ability to translate complex simulations into simplified engineering tools enhances the everyday capabilities of consultants, developers, and operators across the country.

Research in wind energy siting provides substantial benefits for both society and the wind energy industry by enabling more efficient and reliable methods. Accurate siting of wind turbines is essential to maximize energy yield, minimize environmental and societal impacts, and ensure long-term technical and economic viability of wind power projects.

Environment and material

This research theme exemplifies an integrated effort to advance wind turbine technology toward greater sustainability. Innovations in material substitution are reducing dependence on rare-earth elements by developing alternative magnet and motor designs. Development of non-fossil-based polymer composites blades targets reduced environmental initial footprint, while parallel progress in recycling and reuse methods aims to recover valuable materials from decommissioned turbines and manufacturing waste, all fostering a circular economy. In addition, comprehensive, scalable life cycle assessments provide essential insights into optimizing design, material selection, and recycling, thereby guiding sustainable manufacturing practices and policy decisions to support the global transition to low-carbon energy systems. With its growing role in power system, the impact of wind power on the environment is ever important. Wind power affects the landscape, fauna and humans. Research on how to minimise and mitigate the impact is continuously important.

Academic expertise

Uppsala University specializes in analysing the security of supply chains for rare earth materials within a continuously evolving geopolitical environment. They also have large experience in generator design and especially in design of rare-earth free permanent magnet generator. Additionally, Uppsala has expertise in performing security analyses of wind power systems and energy systems. Luleå University of Technology (LTU) focuses on developing enhanced methods for in-field repair of fibre composite structures and carbon fibre-based integrated de-icing technologies. RISE is proficient in applying First Order Reliability Method (FORM) and Second Order Reliability Method (SORM) to wind turbine blades and towers. RISE and Chalmers Industriteknik also have extensive experience in establishing circular value chains for end-of-life wind turbine blades and advancing various mechanical and thermal recycling methods for these blades. KTH and RISE are experts in conducting life cycle assessments of wind turbines, encompassing individual components as well as entire wind farms. These assessments now include social LCA and site-specific LCA. Swedish University of Agricultural Sciences (SLU) has carried out several studies regarding different type of environmental impact from wind turbines, such as impact on marine life, eagles, bats, land-living mammals, reindeers as well as on how control programs for wind farms are executed. Lund University focuses on how birds and bats are affected by wind turbines and how this can be reduced. KTH is experts in sound from wind turbines and how humans are affected by it. LTU has looked into social benefits from wind power. Uppsala University has conducted landscape analysis connected with wind power.

Research questions

Biodiversity solutions

Biodiversity is a prerequisite for all life on Earth. With loss of biodiversity, the planet loses vital and irreplaceable ecosystem services that both people and society depend on to function. It is vital for food production, fresh air, clean water and the society will be more resilient towards global changes, heath threats and catastrophes.

- What can be assessed as ´best available science´ to effectively and affordably unfold the mitigation hierarchy to favour biodiversity, i.e. through macro-siting (impact avoidance), micro-siting (impact reduction), turbine operation (curtailments, camera systems), and compensation as a last resort?

Sustainable and low-carbon value chains

Transitioning to sustainable and low-carbon practices is critical to minimize environmental impacts and strengthen circularity in wind power. Research explores institutional, technological, and policy pathways for achieving low-carbon supply chains and end-of-life management for turbines.

- What institutional frameworks and business models are needed to implement sustainable and low-carbon practices across the wind power sector – from design to end-of-life?
- How can policy incentives and procurement strategies drive the adoption of sustainable technologies and practices in the wind energy industry?

Development and demonstration of recycling methods for wind turbine components

Research on recycling and reuse methods for wind turbine materials, manufacturing waste, and components has mainly focused on the blades since already more than 90% of the turbine is recycled today. Research on End-of-Life solutions for wind turbine blades are demonstrating innovative ways of reusing decommissioned blades.

- How can the recycling techniques for composite blades, both mechanical and thermal treatments be further developed, to reduce waste and lower the environmental impacts even more?

> For the environment, lower-impact wind power helps protect ecosystems, landscapes, and biodiversity, while still delivering significant reductions in greenhouse gas emissions and air pollution.

- How can one or several sustainable value chain(s) for wind turbine blades be established, regardless of the material used or of the process used (repurposing/recycling/incineration/ cement coprocessing).
- How can metals from decommissioned wind turbines be repurposed?
- What are the economic benefits of recycling of turbine blades?

Life cycle assessments

Life cycle assessments (LCAs) of wind power provide a comprehensive evaluation of sustainability impacts across all stages – from raw material extraction and manufacturing to operation and end-of-life recycling – and allows for the integration and assessment of all kinds of environmental and societal impacts simultaneously, thereby addressing trade-offs among different types of impacts as well as impacts occurring in different life cycle stages. This broad assessment approach can identify critical hotspots across the life cycle of wind power plants, thus informing important decisions regarding design and materials selection that can minimize overall negative impacts.

- What are the potential environmental gains from different design and material use decisions for future wind power turbines, as well as various sourcing strategies of the required materials? How do these change based on onshore and offshore wind power plants?
- How can LCAs be designed to be parameterized and thereby made scalable to different sizes and types of construction?
- What are the potential societal implications in terms of impacts on people and their local communities as well as the society at large along the supply chain from future design and material use decisions? Further, what are the trade-offs between the environmental and societal implications at these points of decision? How do these change based on onshore and offshore wind power plants?
- How do the overall sustainability impacts from large scale wind power plants compare to the corresponding sustainability impacts from other technologies for electricity generation in the future? How do these change based on onshore and offshore wind power plants?
- What are the potential opportunities and risks from a sustainability perspective from increasing circularity in the wind power sector? How do these change based on onshore and offshore wind power plants?

Benefit for society and industry

Advances in turbine and materials research are streamlining both production and end-of-life management of wind energy assets. Substitution of rare-earth magnets with iron–cobalt composites and ferrite ceramics relieves pressure on critical mineral supplies and cuts the environmental footprint of generator manufacture. Novel magnet fabrication methods, such as additive manufacturing, minimize waste of limited materials, while emerging flux-switching generator designs eliminate permanent magnets altogether by using abundant copper windings. Concurrently, mechanical shredding, thermal depolymerization, and chemical recycling techniques recover fiberglass, resins, and metals from decommissioned blades and turbines, keeping up to 94 percent of material in circulation and reducing landfill reliance. Repurposing intact components in repowered installations and pilot projects, such as Vestas's circularity solution and the Re-Wind Network's pedestrian bridge, exemplify a circular economy that cuts raw-material demand and project costs.

Reducing the environmental impact of wind power brings clear benefits for both society nature. When wind energy is designed and operated with lower impacts – such as reduced noise, minimized material use, and better protection for wildlife – it increases public acceptance and trust in renewable energy projects. This makes it easier to expand clean energy systems that are essential for tackling climate change and reducing dependence on fossil fuels. For the environment, lower-impact wind power helps protect ecosystems, landscapes, and biodiversity, while still delivering significant reductions in greenhouse gas emissions and air pollution. This supports healthier ecosystems and contributes to cleaner air and water, which in turn benefits human health. Overall, improving the sustainability of wind power strengthens its role as a reliable, socially accepted, and environmentally responsible energy source, supporting long-term economic resilience and a more sustainable energy transition.

Photo by OX2

Due to the vast amount of operational data collected, wind energy research was in the forefront in the development of data-driven methods that are now getting widespread attention. The overarching issue is how to estimate the remaining useful life of a component or system, how to mitigate faults and failures, and how to control the turbine to take full advantage of the asset.

Operation and maintenance

Regardless of which future scenario for the Swedish energy system will take place, there are more than 5000 wind turbines in Sweden today with an estimated asset value of many billions SEK. Increasing revenue is key, both from an asset management point of view, but also to ensure future growth. This can be done by decreasing operational costs and/or increase income, for instance from ancillary services. Extending the lifetime of turbines can help reduce the CO_2 emission per produced kWh electricity, since most of the CO_2 emissions from wind turbines are associated with its erection and decommissioning.

The operation and maintenance question is in many aspects: For a given asset, what is the operational cost for producing electricity at a certain instant in a certain mode of operation (full production, curtailed etc), and how can it be reduced? This is closely connected to the question: What is the remaining useful life of the asset and its components? Most of these aspects are currently studied throughout the international research community. This includes predictive maintenance strategies, methods to estimate remaining useful life of components (especially blades, main bearings, and gearboxes), condition monitoring. Novel control strategies can be developed to take full advantage of these findings. Due to the vast amount of operational data collected, wind energy research was in the forefront in the development of data-driven methods that are now getting widespread attention. The overarching issue is how to estimate the remaining useful life of a component or system, how to mitigate faults and failures, and how to control the turbine to take full advantage of the asset.

Academic expertise

LU, Chalmers and RISE are the main actors within this research. RISE and Chalmers have for a long time conducted research in context of using system simulation tools for evaluating load histories on critical components, such as blade, tower and drivetrain, validated by measurement data. These component load histories are used to quantify component fatigue life (considering transient event, such as torque reversals, as well as long time cyclic loading) under a large variety of wind and site conditions in combination with control strategies, curtailment and other operation conditions. Additional research on Chalmers have focused on fatigue and stability of steel structures and foundations applied to wind turbines. LU have long experience on decision analysis and various types of reliability, risk and resilience analysis, especially when combined with structural health information systems. RISE also have experience from practical design and certification of wind turbines.

Research questions

Lifetime assessment

The overarching issue is how to estimate the remaining useful life of a component or system, how to mitigate faults and failures, and how to control the turbine to take full advantage of the asset.

- How can a digital twin be built based on reasonable available turbine data (SCADA, CMS, more) to accurately describe the turbine status (including RUL of components) and guide the owner in operation and maintenance decisions? What are the critical additional data and information needed to reach this goal?

Lifetime extension

Lifetime extension (LTE) means a technical assessment for continued operation of the turbine (possibly with minor repairs) over a given time horizon.

- What data is needed to do conduct LTE (already available or from additional instrumentation)?
- How shall the turbine be operated in an LTE scenario?

Impact of wind turbine control on operation

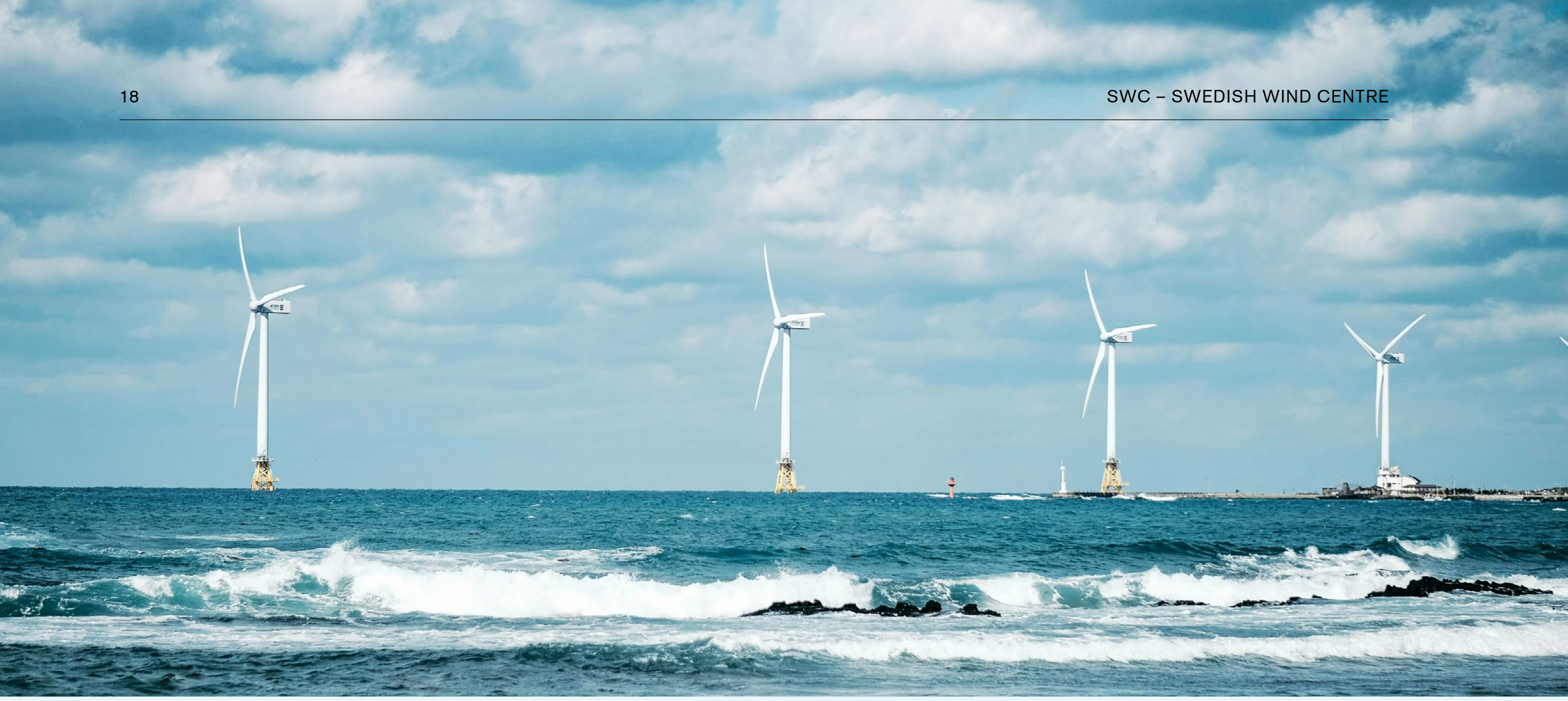
Wind turbines can play a much bigger role in the energy system, especially considering that wind turbines can, from a technical point of view, offer an enormous potential in instantaneous adapting production to the demands of the grid, at different timescales.

- How can costs and income for wind turbines providing ancillary services (e.g. lost production, reduced loads) be quantified?
- How can model-predictive control be used to improve operation (reducing harmful loads without sacrificing production).

Digitalisation

Although digitalization in theory offers a huge potential in improving O&M practice, several practical obstacles stop a widespread use. This topic connects to ongoing work in IEA-TCP 43.

- How can operation and maintenance data be made available to increase O&M knowledge?
- How can data tools efficiently re-sort and organize data from several sources and formats?
- How can alarm codes from different turbines be systemized?



Modelling and synthetic data
It needs to be determined when different kinds of models are needed and the pros and cons with each. Synthetic data can be a valuable tool for many research projects and also increase the possibility to compare results.

- When and where are detailed physical models needed to predict degradation and failure?
- Which are the best-suited stochastic models and parameters for performing adequate and accurate systems reliability assessments?
- How can these models be used to estimate RUL of turbine and components in a practical setting?
- How can wind turbine internal load time-series be recreated from SCADA data?
- How can synthetic wind data be created to be used for operation modelling?

Remote turbine inspections
O&M costs are largely driven by site visits. Remote turbine inspections topic covers a range of use cases involving asset inspection assisted in real time by remote specialists such as safety walks, fire alarms, etc. The industry needs a cost-effective approach for real-time collaboration between site and off-site teams. Technologies such as augmented reality may help to perform O&M with minimal risks and costs.

- How can remote turbine inspections be developed?

Blade reliability and maintenance
Enhanced methods are being developed for in-field repair of composite structures using carbon fibre based integrated de-icing technologies.

- How can the repair reliability and predictability for blades be improved, using i.e. fibre lay-up, anisotropy, or contact resistance?
- Can integrated heaters provide de-icing capabilities but also allow precise temperature control during repair curing, ensuring robust repairs under the harsh, cold conditions typical of the Nordic climate?
- How can structural health monitoring be used to detect early signs of damage and extend blade service life?
- Which novel composite materials can be used to extend blade lifetime?

Benefit for society and industry

The benefits for the Swedish society with more efficient operation and maintenance of wind turbines would be lower electricity costs, reduced costs for balancing the grid and improve the public image of wind power. With better knowledge on how to estimate the remaining useful life, how to mitigate faults and failures, and how to control the turbine, the owner can use the wind farm to the full advantage. The benefit for the industry would be increased value and profitability of existing assets, improved economy in new projects, decreased unplanned downtime and less CO_2 per kWh. For lifetime extension the benefits would be technical knowledge on the LTE option, to compare with other options (e.g. re-powering, decommissioning), and the cost for e.g. permit process. FAIR data opens a market for third-party service providers and is one of several components that is needed to use data-driven approaches for improved operation. Improved models and synthetic data will be improved tools for predicted maintenance and to estimate component remaining useful life.

Ensuring reliable, continuous operation further amplifies these gains. Integrated de-icing heater systems embedded in blade composites facilitate on-site repair and reduce weather-related downtime, while fibre-optic and sensor-based structural health monitoring detects micro-cracks early, enabling targeted maintenance that extends blade service life. Scalable life cycle assessments quantify impacts from raw-material extraction through manufacturing, operation, and end-of-life stages, pinpointing hotspots, often in the construction phase, and guiding optimization of design, materials, and recycling strategies. Policymakers and developers leverage these insights to set sustainable procurement standards and incentives, accelerating the deployment of low-impact wind farms that deliver clean energy and broader societal benefits.

Integration in the power system

Wind turbines play a significant role in the process of generation technology shift in the electricity system, where the direction is towards energy systems heavily based on renewable power, both in Sweden and many parts of the world. There will be a paradigm change when wind power becomes a dominating power production source in Sweden and then, wind power has to significantly increase its role to support different types of system services. The variability and uncertainty associated with wind are two of the main challenges that the electricity system is facing now and in the future.

The reduction of existing dispatchable power generation and the increase and re-location of weather dependent generation calls for an increasing amount of flexibility resources that could handle power shortage, grid capacity shortage and other grid-related issues. The lead time and the cost to upgrade or expand the Swedish grid is long and high, therefore it is prudent to better utilise the existing grid so that more wind power can be installed. How this can be done should be further developed. Wind farms will need to contribute to the ancillary services markets that are developing in Sweden, such as reactive power and frequency control. In order to increase the grid properties of a wind farm as well as giving a complementary income for the owner, wind turbines can be coupled with different solutions of storage. This could for example be with batteries, methanol or hydrogen.

Academic expertise

Chalmers, KTH, RISE and LU are the main actors in this area. Chalmers has driven the development of generators for high voltage as well as dc-collection grids, with both dc systems as well as dc-converters being developed on both a theoretical and experimental path. Chalmers also has a long history of research experience and state-of-the-art knowledge in wind power and their grid integration issues. RISE has experience from dc based offshore grid systems as well as frequency regulation of the grid based on wind power. LU has experience of non-synchronous generation and knowledge on fault behaviour and on frequency dynamics, as well as on using wind power for black start and how to connect more wind power to existing grid through active network management. KTH has since decades worked with many types of wind power integration: system reliability, balancing wind power with hydro power, balancing with electric vehicles, wind power for system voltage control and minimizing of wind curtailments. Uppsala University has experience in the variability of the grid with respect to wind power and are studying how the resilience of the grid is affected by wind power.

Research questions

Wind power and hybrid farms contribution to the Swedish power system

For the general power system, it is important to have a system which is flexible, both in the second-to-second balancing, to manage longer periods with high demand and low wind, as well as systems which mitigates the challenges with large changes from day to day. The research includes both technical challenges as well as market structures which promotes an efficient use of available resources as well as promotion of the right investments.

- How can the location of wind power reduce grid congestion and facilitate voltage control?
- How can wind power be placed to reduce public acceptance challenges and how does it compare to siting based on reduction of grid congestion and facilitating voltage control?
- How can different types of VRE (onshore wind with high and low specific power, offshore wind and solar PV) be combined to reduce variability and improve grid resilience?
- Which technologies and strategies are key complements to wind power to assure reliability and cost-efficiency?
- Is there an extra value, from system point of view, to combine wind power farms with storage, either as batteries, or hydrogen storage?
- Should wind turbines be available for ancillary services at nearly no wind?
- How can new loads for flexible electricity consumption be designed to make sure wind power is fully utilised?
- How can more cost-efficient investment decision be made when building hybrid farms?

Wind turbines and farms contribution to keeping the power system reliable and stable

Wind turbines and farms can contribute to ancillary services already today, but new ways of supporting the grid can be developed.

- How can wind power further contribute to the existing system services?
- How can wind turbines contribute to new services such as black start capability, island operation, reactive power support (dynamic, regulation and bulk) and power oscillation damping?
- How to implement and provide grid-forming capability in wind-turbine systems both under normal operation as well as when the converter enters into saturation? How to shape the frequency-dependent input admittance of the converter?
- How should the market for ancillary services be designed for an optimal use of wind power?
- How should one choose the rated wind speed and capacity of a wind farm?
- When and how should wind downregulate and deliver power system margins?

Use the existing grid to a larger extent
The flows on the lines will change much more in the future, with wind and solar power all over the system. This means a high value of grid control (e.g. FACTS of different kinds), but also on-line systems for estimation of available transmission capacities in the system between different areas. It is important for wind power investors to understand the connection between the grid capacity and what is reasonable to connect in a certain point. The question is both technical, contractual and a market design issue.

- How much flexibility in the production from wind and solar farms can be expected and provided in order to utilise the grid in the optimised way?
- How can hosting capacity in the grid increase, without building new power lines?
- How can flexible contracts be written?
- How should the availability of transmission and distribution system capacities be calculated/measured?

Benefit for society and industry

From a societal perspective, increased knowledge on how to integrate renewables in the best way would lead to more efficient use of the available resources, reduce the risk of power shortages and accelerating the transition to a renewable power system. Smart design, location and complements to wind power can facilitate wind power integration dramatically. Well-planned location of wind power has the potential to mitigate grid congestion, reduce the need for reactive power compensation and/or increase public acceptance. Increased participation by wind turbines in the ancillary services market could reduce overall system costs, improve system resource efficiency and enhance system stability through increased controllability of resources. By using the existing electricity grid in an optimal way, cost for connection renewable power production can be reduced, but also increase the possibility of added electricity consumption in many places.

For the industry, one benefit with more flexibility in the system will be that the prices will be less sensitive to wind variations, which will increase the value of wind power. With more services provided by wind and/or hybrid farms, a more secure revenue can be obtained for the owners and investors.

> Well-planned location of wind power has the potential to mitigate grid congestion, reduce the need for reactive power compensation and/or increase public acceptance. Increased participation by wind turbines in the ancillary services market could reduce overall system costs, improve system resource efficiency and enhance system stability through increased controllability of resources.

SWEDISH WIND CENTRE

www.swedishwindcentre.se

The research centre Swedish Wind Centre, SWC, conducts and collects research on wind power to contribute to a robust and sustainable energy system. The wind power industry has grown and developed considerably the last years and will be of further importance for the energy system.

SWC has extensive experience from two previous centers, StandUp for Wind and SWPTC, both active for more than ten years. The two former centers complemented each other in fields of research and cooperated for example by arranging joint conferences. Now, SWC has gathered the activities of the former centers.