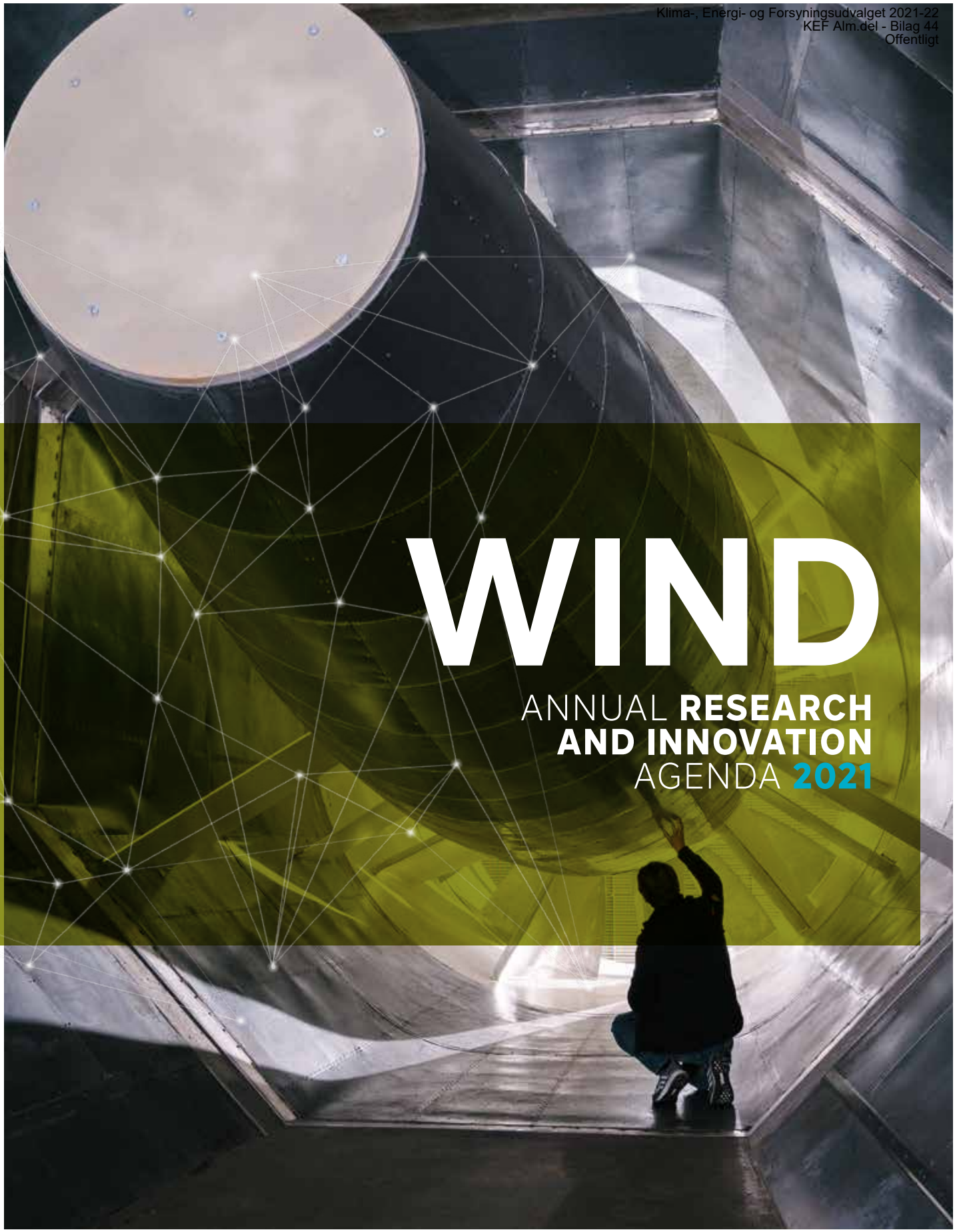

WIND

ANNUAL **RESEARCH AND INNOVATION** AGENDA **2021**

MEGAVIND

WIND POWER 2021

ANNUAL RESEARCH AND INNOVATION AGENDA

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A NEW MEGAVIND

Per Hessellund Lauritsen, Chairman Megavind

IN 2020, the Megavind Executive Committee agreed on organisational changes and a revised mission for Megavind. The new Megavind will incorporate a global outlook, extending its scope to R&D for wind energy systems including sector coupling, while creating a more agile organisation with permanent strategic sub-committees.

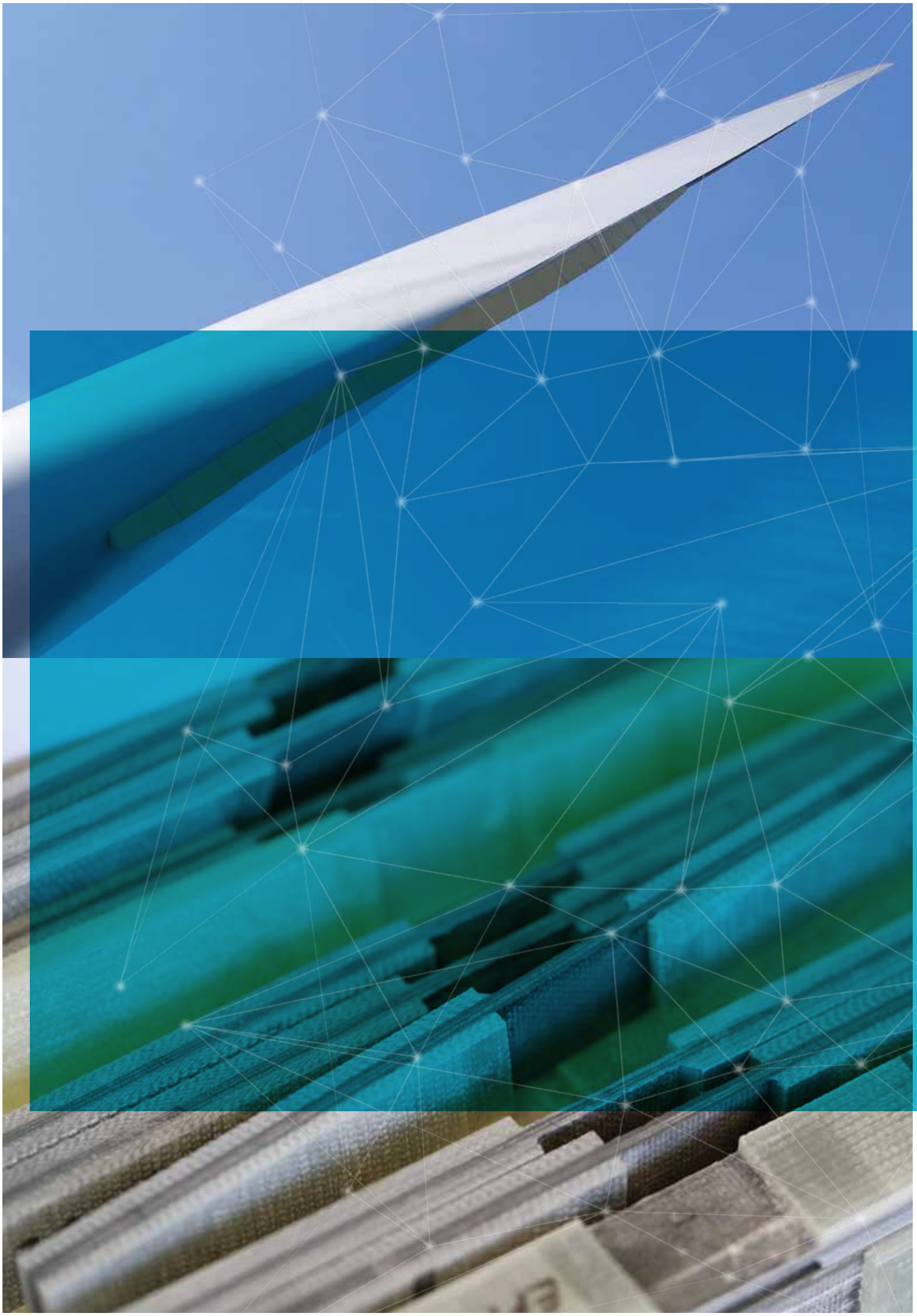
This year's Annual Research & Innovation Agenda reflects on this new role for Megavind.

When we published the first Annual Research & Innovation Agenda in 2017, we outlined four megatrends that characterised wind energy R&I at that time. This year, we revisit those megatrends.

Megavind was born of the public-private partnership unique to Danish wind energy and this partnership has never been more vital than at the present moment. The potential for global cooperation and business opportunities is rivaled by a fierce international competition to attract companies, competences and test infrastructures for large components and wind turbines. How can we renew our partnership in Denmark to respond to the changing conditions? In this annual agenda we review the history of the partnership. What were its constituent parts and what set it apart from the development of wind energy in other countries? However, we are not only glancing backwards. Together, the Megavind partners have identified core elements that must be maintained, renewed or reinvigorated to prepare the partnership for the coming decades.

By navigating the megatrends, the new Megavind will continue to play a key role in Danish and international wind energy research and innovation. This year's annual agenda includes a set of updated recommendations for research and innovation that reflect these new opportunities and challenges.

When the European Commission presented its strategy for Offshore Renewable Energy in November 2020, the opening lines reflected on the creation of the first offshore wind farm, Danish Vindeby, and when Innovation Fund Denmark launched its 2020 strategy announcing the InnoMissions, the success of Danish public-private partnership in wind energy delivery was highlighted as an example worth emulating. Adapting, extending and strengthening our partnership as the green transition goes truly global is the next step for Megavind.



EXECUTIVE SUMMARY

The Annual agenda 2021 focuses on megatrends within wind power, the development and renewal of the Danish public-private partnership for wind energy systems and the coming demands for research and innovation enabling Denmark maintain its global lead in wind power while working with citizens and stakeholders to ensure wind power that is both socially and environmentally sustainable.

MEGATRENDS

In revising the megatrends identified in the 2017 annual agenda, Megavind identifies five megatrends shaping the evolvement of wind energy in the coming years.

1. **Energy Systems Transformation towards zero carbon economy** is influencing all aspects of society. From regulations to finance, consumer behavior to innovation investments, sector coupling and political frameworks.

2. **Industrialisation 2030** through digitalisation, modularised manufacturing and innovations in the supply chain will drive competitiveness across the value chain from first design to decommissioning.

3. **Globalisation of markets and companies.** Companies, including subcontractors, must adapt business models to scale, to cater for a global supply chain and adapt to demands for local content.

4. **Financially responsible markets.** Financial markets are altering the risk profile of wind power, and the potential for new business models raises issues about market design and regulations to balance risk and benefits for both investors and consumers.

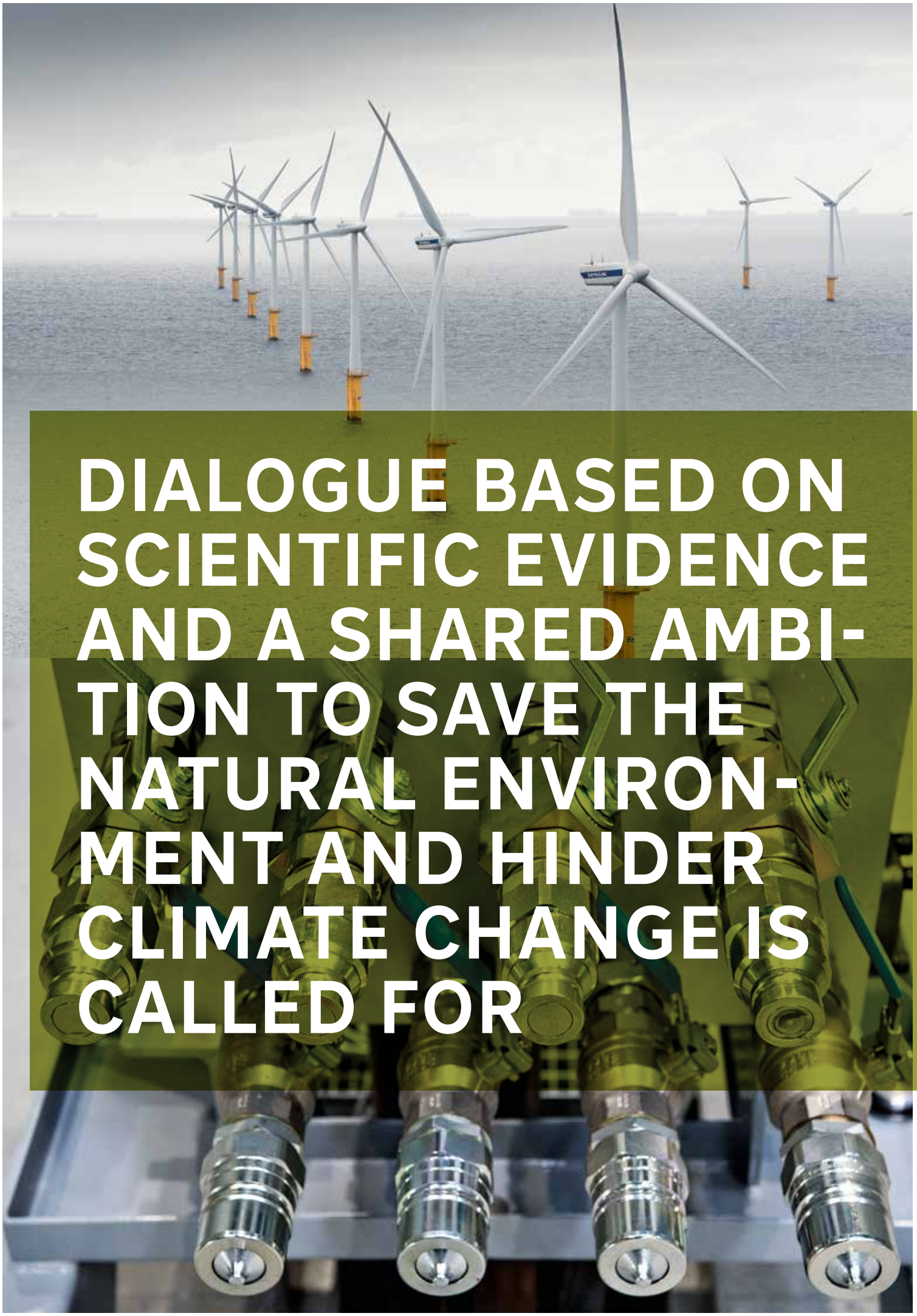
5. **Social and environmental sustainability** is a key megatrend for the wind energy and renewable technologies industries more generally. Recycling of turbine blades, sustainably circular wind farms and a new dialogue around the co-existence of renewable energy sources with ecosystems and communities are called for.

A revitalised public-private partnership for wind energy systems

We need a revitalised and strengthened public-private collaboration for the green transition. The current public-private partnership in the wind energy sector in Denmark has played a major role in the success of wind energy globally. To understand the trajectory of this development, how it should continue and where we need to plot a new course, a summarising of its constituent parts will be beneficial.

The renewed partnership should maintain a shared mission, building on a strong global position and outlook. Public R&D support, including suitable framework conditions for test facilities and infrastructures is vital. This will require political vision and a willingness to take risks to build on and extend the holistic policy approach that has characterised Denmark over the past 40 years.

A renewed engagement with the public and vice versa will establish a foundation for the future of wind energy in Denmark. Dialogue based on scientific evidence and a shared ambition to save the natural environment and hinder climate change is called for. Competences at all levels of expertise are the lifeblood of the industry. Colleges and universities should work with stakeholders to maintain high levels of education as well as encouraging entrepreneurship and nurturing talent that can establish and scale new wind energy companies in Denmark.



DIALOGUE BASED ON SCIENTIFIC EVIDENCE AND A SHARED AMBITION TO SAVE THE NATURAL ENVIRONMENT AND HINDER CLIMATE CHANGE IS CALLED FOR

RESEARCH AND INNOVATION CHALLENGES AND OPPORTUNITIES

How do the megatrends and mission statements translate into future research and innovation?

Wind power and other renewables have been given a mandate to deliver green power underpinning an electrified energy system. That trust carries obligations and a set of concrete challenges that need to be addressed and overcome.

Four areas of research and innovation are outlined below.

Delivering gigawatts of wind power to the green transition

WIND POWER and other renewables are recognised as the future mainstay of electricity generation in Europe. The delivery of gigawatts of wind power to fuel the green transition is now a necessity.

1. **Reduction of LCOE through turbine and wind farm R&I.**
2. **Solutions for flexible, resilient and secure energy infrastructure.**
3. **Improving security of supply through innovative new materials and alleviating shortages of current materials.**
4. **Financial and market instruments to improve the value of wind energy including better market design and incentives for investment in wind and alternative energy systems.**

Upscaling and industrialisation enabling cost reductions

RESEARCH AND INNOVATION to enable and balance upscaling as well as industrialisation across the value chain. This will require:

1. **Models and simulation tools for mega turbines, to alleviate the uncertainty in design parameters.**
2. **Test methods and facilities capable of assessing larger components or enabling smart testing and increasing the use of digital twins to reduce physical testing requirements.**
3. **Design for the manufacturing and operation of extremely large components.**

Sector coupling to increase value of wind for companies and society

THE ELECTRIFICATION of society through sector coupling is altering the technology and market dynamics that wind power operates in. This requires technology solutions and infrastructure based on market dynamics and energy systems.

1. **P2X systems and their dynamic interaction with wind energy units with variable energy production.**
2. **Load and production pattern optimisation, planning and scheduling with combined wind energy and P2X systems.**
3. **R&I in optimal wind power plant/turbine configuration based on future energy system market systems.**
4. **Efficient, grid-supporting and reliable short- and long-duration energy storage solutions.**
5. **Methods to assess and plan infrastructural impact.**

Sustainability for people and the natural environment

CIRCULARITY of wind farms and the construction of a value chain for recycling and reusing material goes hand in hand with engagement with local communities

1. **R&I of material substitution in wind turbines, to increase recycled content, to minimise environmental impacts and to enable recycling of waste streams.**
2. **R&I to create a market for recycling manufacturing waste and end-of-use wind turbines.**
3. **R&I to extend the operational lifetime of wind turbines.**
4. **Development of wind farms in harmony with surrounding ecosystems and communities.**

MEGATRENDS

The energy system and its role in society has changed significantly over the past five years, since Megavind published its first annual agenda that outlined four megatrends in wind energy.

2020 MARKED A watershed in the development of the green transition. Global investments in renewable energy reached 0,5 trillion dollars; NextEra overtook Exxon Mobile as the most valuable energy company in the US while China, India and many other countries set dates for reaching net-zero carbon emission by 2050-60. Financially, the challenge now is to find sufficient green energy projects to match the financial resources eager to bank on renewable technologies and services. And the climate needs these investments. According to the Global Wind Energy Council, we must install 180GW wind power globally every year to meet climate targets[1].

The financial market's appetite for wind and solar energy is a consequence of the continued cost reductions in these fields, as well as the increased trust in both technologies and developers, which in turn leads to lower costs of new project financing. These cost reductions must endure, and the industry must pursue them through a combination of upscaling and technology advancements as well as industrialisation. Lower margins and the requirements to supply higher volumes exerts pressure on the supply chain. The number of mergers and acquisitions are increasing. At the same time, climate technology venture capital has grown to be a multi-billion-dollar business that creates a new financial ecosystem for start-up entrepreneurs to grow their ideas into businesses.

The financial markets and governments have confidence in wind energy as a primary driver for the electrification of society. That trust comes with obligations and industry needs to deliver. But wind power and other renewable technologies cannot deliver a decarbonised system alone. The energy system and society must respond and react as well. In regions with a high share of wind and solar power, operators are forced to accelerate plans to modernise or adapt the electrical grid to control changing load patterns and encourage flexible consumption. Managing flexibility and market signals drives demand for sector coupling solutions while policy makers must adapt regulations and market design. More renewables result in a larger environmental footprint which increase the potential for clashes between technology, the environment and people.

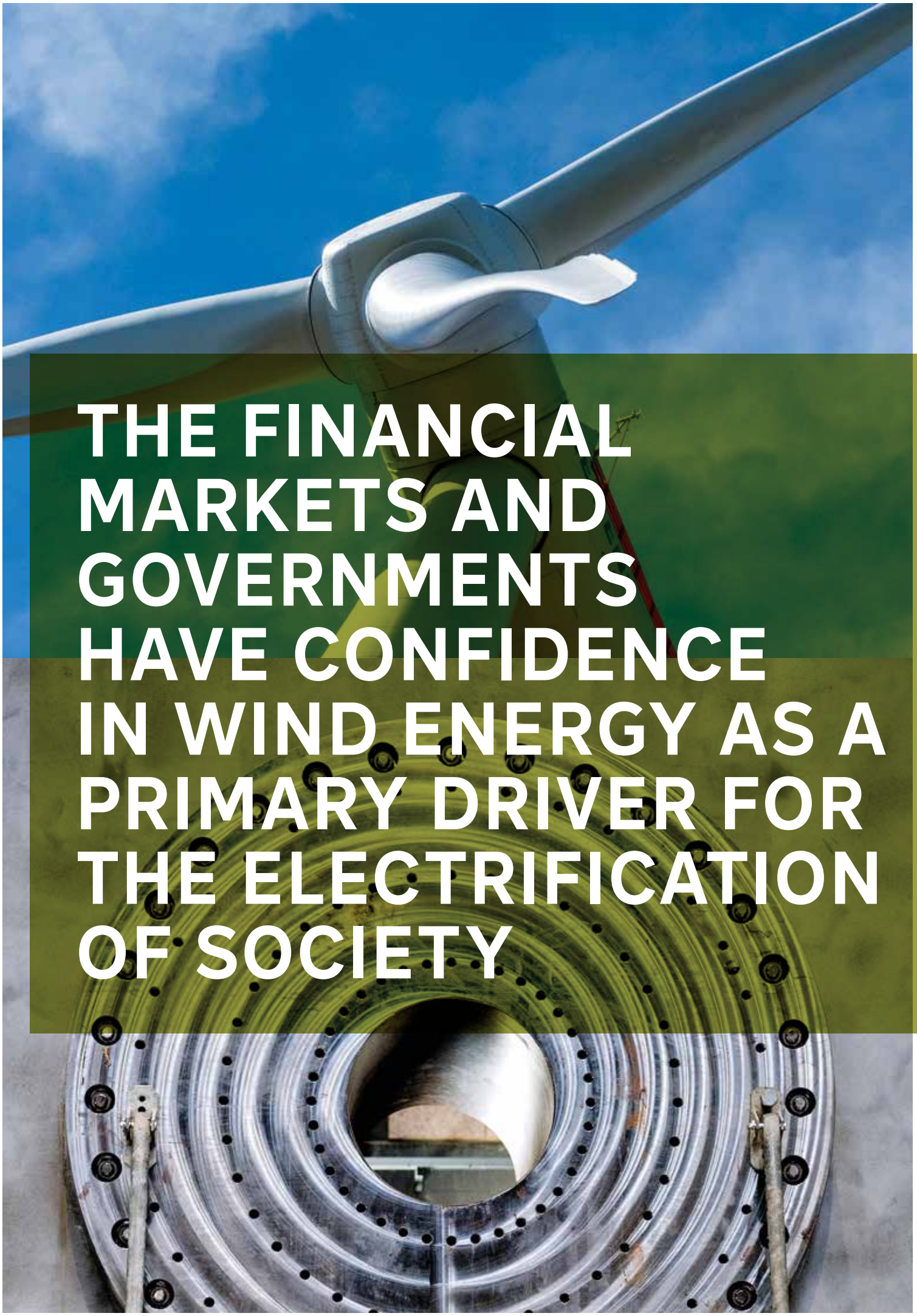
The developments outlined here called for a reflection on the megatrends that we defined in 2017. Digitalisation, for example, has become fully incorporated in the industrialisation of wind energy, while globalisation is more specifically linked to market development and innovation requirements across the value chain. Subsidy-free wind power was highlighted as a megatrend in 2017 following the zero-subsidy bids for offshore wind power that took the entire industry and energy community by surprise. Five years on, this is now seen as one aspect of a broader issue regarding how we shape financially responsible markets. Energy system integration is seen in the wider perspective of the energy system transformation and the move from cost to value. And finally, sustainability appears as a new megatrend.

Based on these factors, Megavind has identified five megatrends that influence wind energy and its interaction with the energy system and society. The new megatrends reflect the growing importance of wind power in the green transition and the wealth of business opportunities and societal challenges that the system transformation provides and poses into the future.

2017 MEGATRENDS:

1. **Maturation, industrialisation and globalisation**
2. **Subsidy-free wind power and technology neutral tenders**
3. **Digitalisation**
4. **Energy Systems Integration**

1. https://gwec.net/global-wind-power-growth-must-triple-over-next-decade-to-achieve-net-zero/



THE FINANCIAL MARKETS AND GOVERNMENTS HAVE CONFIDENCE IN WIND ENERGY AS A PRIMARY DRIVER FOR THE ELECTRIFICATION OF SOCIETY

MEGATRENDS 2021

Megavind has identified five megatrends that influence wind power and its interaction with the energy system and society.

1

Energy systems transformation towards zero-carbon economy

The energy system transformation towards zero-carbon economies influences all aspects of society. From regulations to finance, consumer behavior to innovation investments, sector coupling and political frameworks. These developments are perhaps best summarised in the shift from LCOE driven growth to energy system development based on the tripartite elements of cost reduction, value creation and sustainability. This trend is reflected in companies expanding their scope beyond delivering turbines or wind farms to providing emission-neutral renewable energy.

2

Industrialisation 2030

Digitalisation, modularised manufacturing and innovations in the supply chain will drive competitiveness across the value chain from initial design to decommissioning. Digital twins can reduce the need for physical testing in the design phase and will result in improved real-time dates for operation and management of assets; modularised manufacturing and assembly can allieviate barriers to turbine upscaling, reducing the need for ever-increasing logistical equipment. Combined with standardised procedures and components, the next phase of industrialisation will allow the industry to both scale and reduce the cost of wind energy.

3

Globalisation

180GW annually installed capacity wind power will be necessary to meet climate targets. Countries around the globe are banking on wind energy not only to deliver cheap and green electricity, but simultaneously generate jobs and growth. A noticeable characteristic of wind energy is that it creates both blue and white collar jobs locally, and many countries are inserting requirements into contracts for *local content* including local production, supply chain and competence building to help boost their economies. Danish-based companies will need to adapt and evolve to respond to these new demands: how do you innovate novel solutions enabling the scaling up of the value chain in new geographical areas? How do you tailor technologies and services for new markets? Many companies will have to build new business models that include collaboration with companies in the new markets to deliver local content.

4

Financially responsible markets

Wind energy operating in financial markets will become the norm in the coming decade. The change in the risk profile of wind power and the potential for new business models raises issues regarding market design and regulations to balance risk and benefits for both investors and consumers. Companies are addressing new requirements and market signals to deliver reliable energy sources by pivoting towards hybrid and energy management solutions. How will this change the role of the citizens and consumers? To achieve a just and fair transition, regulators will play a critical role in accelerating market framework development to unlock the massive interest from investors while balancing an equitable distribution of advantages and disadvantages for consumers and citizens alike.

5

Social and environmental sustainability

In 2017, sustainability was not among the megatrends identified by Megavind. Five years later, the exclusion of sustainability as a key megatrend for the wind energy sector is unthinkable, and for renewable technologies in general. At the top of the agenda is the recycling of turbine blades, but improved solutions towards sustainably circular wind farms is the larger target and the wind energy industry is committed to ambitious sustainability goals. At the same time, a new dialogue around the co-existence of renewable energy sources with the natural environment and communities is called for. Onshore wind power deployment has almost come to a standstill in some countries due to local opposition or concerns about the impact on ecosystems and wildlife. Offshore tenders are progressing, but wind power is competing with fisheries, maritime transport and other stakeholders for space at sea.

A PUBLIC-PRIVATE PARTNERSHIP FOR THE GREEN TRANSITION

This new age of the green transition calls for a range of technologies to be matured and scaled up to enable a 100% decarbonised energy system by 2050. The scale, pace and complexity of the actions required are breathtaking, but also offer immense opportunities for all societal stakeholders. To seize the opportunities, public and private stakeholders will have to work together if we are to achieve a decarbonised energy system in a rapid, equitable, and cost-efficient manner.

A renewed public-private partnership for the green transition

Denmark needs a renewed and strengthened public-private collaboration for the green transition and Danish wind energy offers important lessons on its implementation. Building on the foundation of *the Danish model for societal organisation,* the public-private partnership that constitutes the wind energy sector in Denmark has played a major role in the success of wind energy globally. As we move towards a renewed partnership that expands into sector coupling and increases its global outlook, it is therefore worthwhile summarising the constituent parts that made the partnership a success in the past: to understand the trajectory that developed, in which direction it should continue and where it is necessary to plot a new course to avoid becoming trapped in outdated organisational forms and processes.

Partnership for an age of missions

In 2020, the Danish parliament called for Innovation Fund Denmark to set up Innovation Missions (InnoMissions). The success of wind energy was highlighted as an example to emulate. The InnoMissions reflect a new global trend: from Bill Gates' Mission Innovation to the Mission concept for the new EU Framework Programme for Research and Innovation, to national and even local levels of initiative. Tackling grand challenges is no longer enough; the world is on a mission to create an energy system to help curb global warming and we have 30 years to deliver on that promise. Partnerships will be one of the organisational foundations for these missions. It is important to understand how different stakeholders contribute to these partnerships and work together to deliver on our shared ambition to curb climate change.

A partnership of partnerships

The green mission of this decade – an electrified energy system powered by renewables - requires a partnership of partnerships. The partnerships developed in technology silos such as wind power, solar and hydrogen energy will collaborate with other sectors to create an integrated energy system. Megavind and its members will be actively involved in these new partnerships and the wind energy sector can contribute with its technological know-how and experience in maintaining strong partnerships for decades.

TO SEIZE THE OPPORTUNITIES, PUBLIC AND PRIVATE STAKEHOLDERS WILL HAVE TO WORK TOGETHER IF WE WANT TO ACHIEVE A DECARBONISED ENERGY SYSTEM IN A RAPID, EQUITABLE, AND COST-EFFICIENT MANNER.

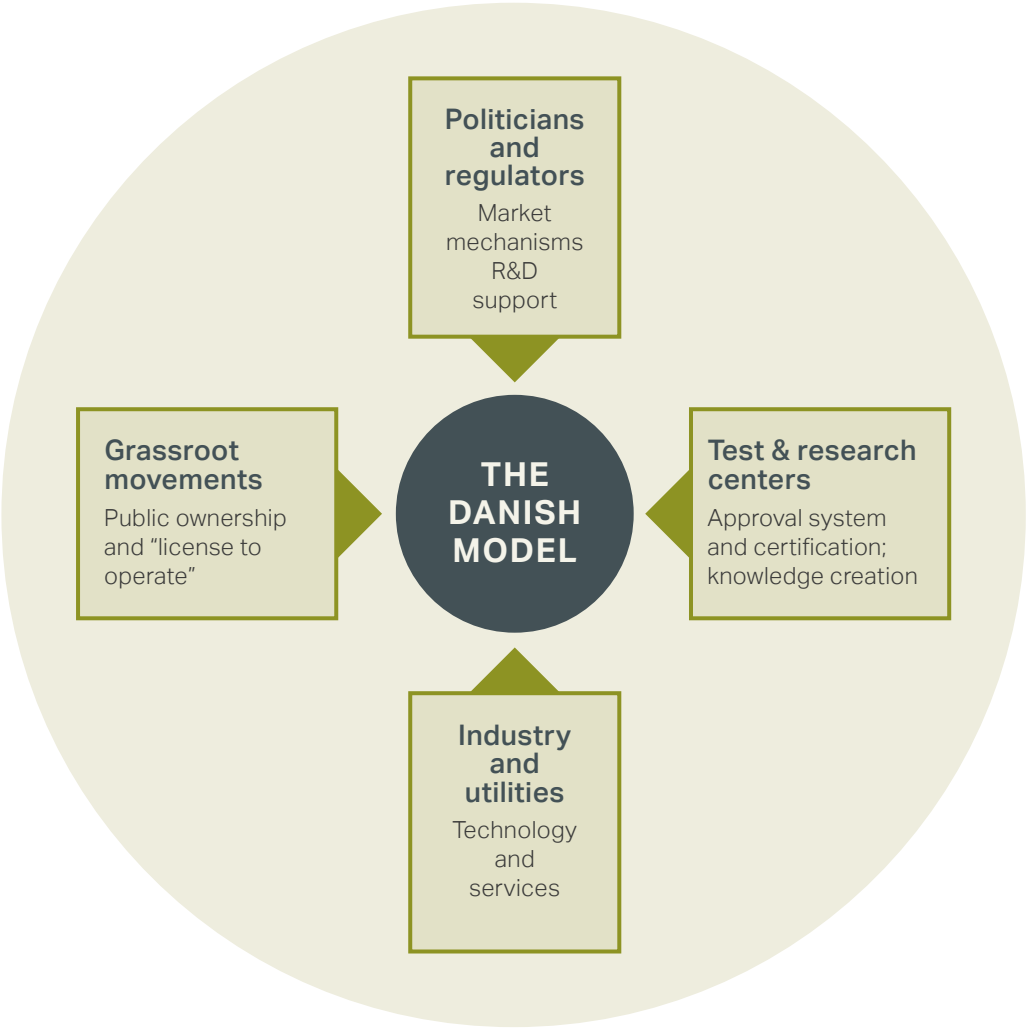
The Danish public-private partnership in wind energy - The early phase[2]

IN THE WAKE of the 1973 oil crisis, interest in wind power increased among citizens, politicians, industry and the research community. Denmark was not the only country to see public, industrial and political investments in wind power during the 1970's and onward. The US, Germany, Holland, Belgium, the UK and others were all active in the field. Yet Denmark was uniquely successful, especially during the 1980's and 1990's, where Danish turbine manufactures had cornered up to 80-90% of the global market.

The foundations for this success have been widely documented. They rest on a combination of social attitudes, institutions, and the organisation of Danish society; sometimes referred to as 'the Danish model'. Public and private partners have a tradition of working together to reach solutions that are both pragmatic and innovative while allowing society to grow and companies to prosper. This has not been altogether frictionless over the past 40 years, but the holistic approach has been key to sustaining the development.

The stakeholders and their contribution to Danish wind energy can be summarised in the following figure:

2. This chapter draws on work from Peter Karnøe, Flemming Petersen and Henrik Bach Mortensen



Public ownership and the license to operate

SPURRED ON BY the energy crisis of 1973 and the debate over which energy sources should power Danish society in the future (nuclear, coal, gas or renewables) a popular movement consisting of grassroot organisations, academics and engineers and individual entrepreneurs helped pave the way for Danish wind energy. The movement contributed in four ways to the development of Danish wind power. Firstly, they promoted wind power in opposition to the political establishment and the Danish utility providers who had placed their bets on coal and nuclear supply. Through a broad range of activities, the movement created a license to operate power sources independently that would eventually lead to the introduction of the Danish Energy Plan of 1976. Secondly, the movement consisted of people who invested in wind turbines privately, thus enabling the early Danish wind power pioneers to construct and sell their first turbines. Thirdly, they generated and disseminated knowledge about wind power and how to construct and operate wind turbines. Finally, they exerted pressure on turbine manufactures to improve the quality of turbines to improve safety and yield. The cooperatives that formed the backbone of the popular movement would go on to become the primary investor in Danish wind power. At the height of the Danish cooperative wind energy movement in the 1980's, cooperatives in Denmark owned a major part of Danish wind turbines.

Framework conditions and R&D

In a statement to the Danish Parliament in 1976 about the new energy law, then Minister of Energy Erling Jensen stated that renewables such as wind power and solar would require extensive research and development over the coming decades to contribute meaningfully to the Danish energy mix by the turn of the century (i.e. 2000). The political willingness to continuously create legislation and invest the necessary resources into renewables cannot be underestimated, when considering the success of Danish wind energy. In the decades that followed the 1976 energy law, the necessary elements were put in place to translate these ambitions into reality. Compared to other countries such as Germany, the Netherlands and the US that focused heavily on R&I funding, the Danish approach was, and is, characterised by a combined focus on four key elements:

1. **Market support mechanisms**
   Since the late 1970's and up to 2001, Denmark had a continuous set of market support mechanisms in place that created a stable market for wind energy, both for industry and investors. The absence of stop-go market development observable in other countries in the 1980's and 1990's allowed Danish companies to survive the early days of busts and booms synonymous with those periods. This was the result of an ongoing close dialogue between the public and the private sector. Since 2001, shifting governments have challenged the aspect of state market support, however the domestic market remains key to the Danish wind energy sector.

2. **Approval system and certification**
   The success of the market support mechanisms is closely linked to the introduction of a Danish approval and certification system for wind turbines in 1979. The system set a minimum standard for market quality of new turbines that pushed manufacturers to build more reliable machines. The reliability of Danish turbines led to their success in conquering a significant share of the largest export markets in California and Germany.

   The Danish standardisation system formed the basis for international standards for wind turbines. This gave Danish companies a head start when international standards were introduced since they already complied with Danish standards. In addition, because Risø test center was tasked with administering the approval system, researchers and industry had frequent interactions. This resulted in research organisations gaining first-hand knowledge and interest in the challenges facing industry while industry was exposed to the research-based know-how that were largely absent in production in the early days. This synergy between research organisations and industry was a distinctively Danish feature during the first decades compared to other countries where academic research remained far more insular from industry interaction.

A POPULAR MOVEMENT CONSISTING OF GRASSROOT ORGANISATIONS, ACADEMICS AND ENGINEERS AND INDIVIDUAL ENTREPRENEURS HELPED PAVE THE WAY FOR DANISH WIND ENERGY.

3. Test centers and facilities

The establishment of the test center for small turbines at Risø in 1979 was, in essence, a continuation of Poul La Cour's work in the late 19th century. La Cour provided test, approval and consultancy support to turbine developers, and the researchers at Risø started out in a similar vein. In addition to providing test facilities and managing the approval system, the test center played a pivotal role in bringing engineering and research know-how into play in a sector that up till then was primarily driven by machine manufactures with few or no engineers employed in the early phase. The Risø test center and the research groups at universities were therefore crucial in two ways. On the one hand, through the test and approval system, the engineers at Risø acted as consultants who, with a broad know-how from their involvement with the entire industry, thus improved knowledge circulation within the sector. On the other, the groups were critical in researching and developing software and hardware solutions for the industry.

4. Public R&D support

The innovations in wind energy were funded through several Danish and European programs including funding for developing and testing prototypes and 0-serie turbines. Funding for wind energy R&D went predominantly to testing and development in the early phase. However, from the end of the 1980's substantial funding for research in the different fields of wind energy was introduced. The Danish approach was initially based on a learning-by-doing incremental approach that brought all actors into close contact and enabled a positive knowledge exchange. This contrasts with the approach in other countries that saw very significant investments in advanced wind energy research combined with costly, large-scale demonstration projects.

Entrepreneurship and industry

POLITICAL FRAMEWORK CONDITIONS and support were vital to the success of the wind energy industry, but it was the entrepreneurship shown by the individuals, groups and companies who designed and constructed the turbines that would be decisive. A retrospective look at what differentiated the early wind industry from its international competitors reveals three key elements to this success:

Small, robust and reliable turbines

Vestas, Bonus, Micon, Nordtank and Nordex were machine manufacturing companies when they eyed the chance for a new business avenue in constructing wind turbines. Their approach to wind turbine manufacturing was to deliver low-tech, robust solutions. By today's standards these turbines were heavy, simple machines, constructed with little finesse when it came to aerodynamic properties. But they were reliable and reasonably safe and with an early domestic market already in place and a later Californian market coming onstream, the Danish turbine manufacturers were a success..

Learning-by-doing low tech approach

Photographs from Danish wind energy history in the 1970's and 80's are full of people climbing on turbines, testing the turbine blade's structural capacity by loading sandbags onto it, or conducting repairs on the small nacelles. These are images of a learning-by-doing approach that characterised the first decades of wind power in Denmark. Compared to the expensive, high-tech, large-scale approach in other countries, the Danish method allowed both industry and research organisations to collect substantial data and personal experience from the turbine operations at a much lower cost.

Collaboration

The story of Danish wind power contains stories of family feuds and conflicts between individuals, but the overall picture is one of collaboration. Employees moved back and forth between competing companies and because of the then popular skepticism surrounding wind power's contribution to the Danish energy system, there existed a strong sense of community among people in the business. This collaboration also extended to interactions between public and private organisations, which have grown in size and importance over the last ten years.

BECAUSE OF THE THEN POPULAR SKEPTICISM SURROUNDING WIND POWER'S CONTRIBUTION TO THE DANISH ENERGY SYSTEM, THERE EXISTED A STRONG SENSE OF COMMUNITY AMONG PEOPLE IN THE BUSINESS.

A renewed partnership for wind powered energy systems

Wind power today is a different technology and a different business than it was 20, 30 or 40 years ago, but the core attitude of Danish wind power remains. Denmark has maintained a significant wind industry and domestic market and the country is arguably the leading R&D hub for wind power in the world. What should we retain and what must change to maintain a strong public-private partnership in the coming decades?

Megavind has identified a set of characteristics for a renewed Danish partnership.

Shared mission in the wind energy community and beyond

We are on a mission to save the world from disastrous climate change and to build and maintain successful companies to achieve this goal. In competition with other regional wind energy hubs, Denmark must continue its tradition of collaboration to remain competitive. If we compete on investments, we lose. Smarter investment models for research and test infrastructures that continue to leverage both public and private resources, coordination of new industry standards and a shared responsibility to educate, train and attract talent are all significant elements required.

Global outlook

Wind energy is a global business, and a Danish partnership needs to orient itself towards global challenges and opportunities. The Danish wind power hub is closely connected with neighboring countries around the North Sea, but also internationally through the network of companies and research institutions. Acquisition and mergers create stronger companies, but there is also a significant potential for smaller Danish companies to expand if they can adapt to the megatrends outlined earlier in this report.

Public R&D support

Continued public support for research and innovation remains vital for the Danish wind energy sector. This should include both national funding and the coordination of funding with other countries to utilise national strengths as well as Danish companies' presence in other countries. Public support allows collaboration on high-risk, high-rewards projects as well as the demonstration of new solutions. This in turn attracts companies from around the world and creates strong vocational and academic institutions to train engineers and scientists.

Test centers and facilities

Denmark boasts some of the finest test facilities in the world, but a new generation are required if we want companies to retain their R&D in Denmark. The blade test facility at Blaest or the facilities at LORC need to be upgraded to accommodate the growing size of turbines. Increasing the size of some test facilities is one possibility, but there is also genuine potential for new types of test systems. These include innovative test and measurement systems that combine virtual and physical testing, test facilities for modular manufacturing, and geographical test zones for new forms of energy system management and customer relations to enable the further testing of wind power and hybrid power systems.

Public ownership and the climate/environment movement

Cooperative ownership of wind farms in Denmark has declined from 80% at its height to 20% today. This shift from community to investor-owned wind farms and the ever-increasing size of turbines has fueled public opposition to wind energy in Denmark and elsewhere. This opposition must be addressed. The establishment of the Co-Existence Lab by WindDenmark and Dansk Energi is a concrete example of ways to foster constructive dialogues concerning the balance between renewable energy, environmental protection and social acceptance[3].

3. https://www.danskenergi.dk/sites/danskenergi.dk/files/media/dokumenter/2021-06/Forstaeelsespapir-CO-EX-Lab.pdf in Danish only

WHAT SHOULD WE RETAIN AND WHAT MUST CHANGE TO MAINTAIN A STRONG PUBLIC-PRIVATE PARTNERSHIP IN THE COMING DECADES?

Entrepreneurship and education

Developing megawatt turbines is a billion dollar investment and leaves little room for individual entrepreneurship. Nonetheless, the business needs the innovators and disruptors and there is still plenty of room for entrepreneurs to innovate new solutions and services. Schools and universities are educating skilled young women and men, but perhaps we need to promote more entrepreneurship and a go-do-it attitude in the wind energy sector. We need the facilities, the educational programmes and an interaction between academia and industry that encourages new start-up companies or future employees with the skills and attitude to make a difference. The good news is that investors are pouring into climate tech and are hungry for new companies to scale.

Political visions and willingness to invest and risk

Danish politicians must maintain a vision and a willingness to translate that vision into effective framework conditions to ensure our global lead in wind power. If there is one lesson learned from the last 40 years, then it is the importance of maintaining a holistic approach: enabling and supporting future infrastructures; maintaining an offshore and onshore market; ensuring efficient planning procedures and the right market incentives; fostering world-class research and innovation; and enabling an electrical infrastructure capable of managing a very high penetration of wind and solar power. The current endeavors in hydrogen are an area where those learnings can be applied.

R&D OPPORTUNITIES & CHALLENGES

How do the megatrends and the missions translate into future research and innovation?

WIND POWER AND other renewables have been entrusted the mandate to deliver green power as the cornerstone of an electrified energy system. That trust brings obligations and a set of concrete challenges that need to be overcome.

FIRST and foremost, thousands of gigawatts of wind power will need to be delivered in the coming decade. How do we ensure the right balance between the pace and cost of this expansion? New metrics for assessing best business models in different markets and locations, improved understanding of market dynamics and financial models, better infrastructure planning and awareness of the raw material supply chain will be key elements in achieving targets.

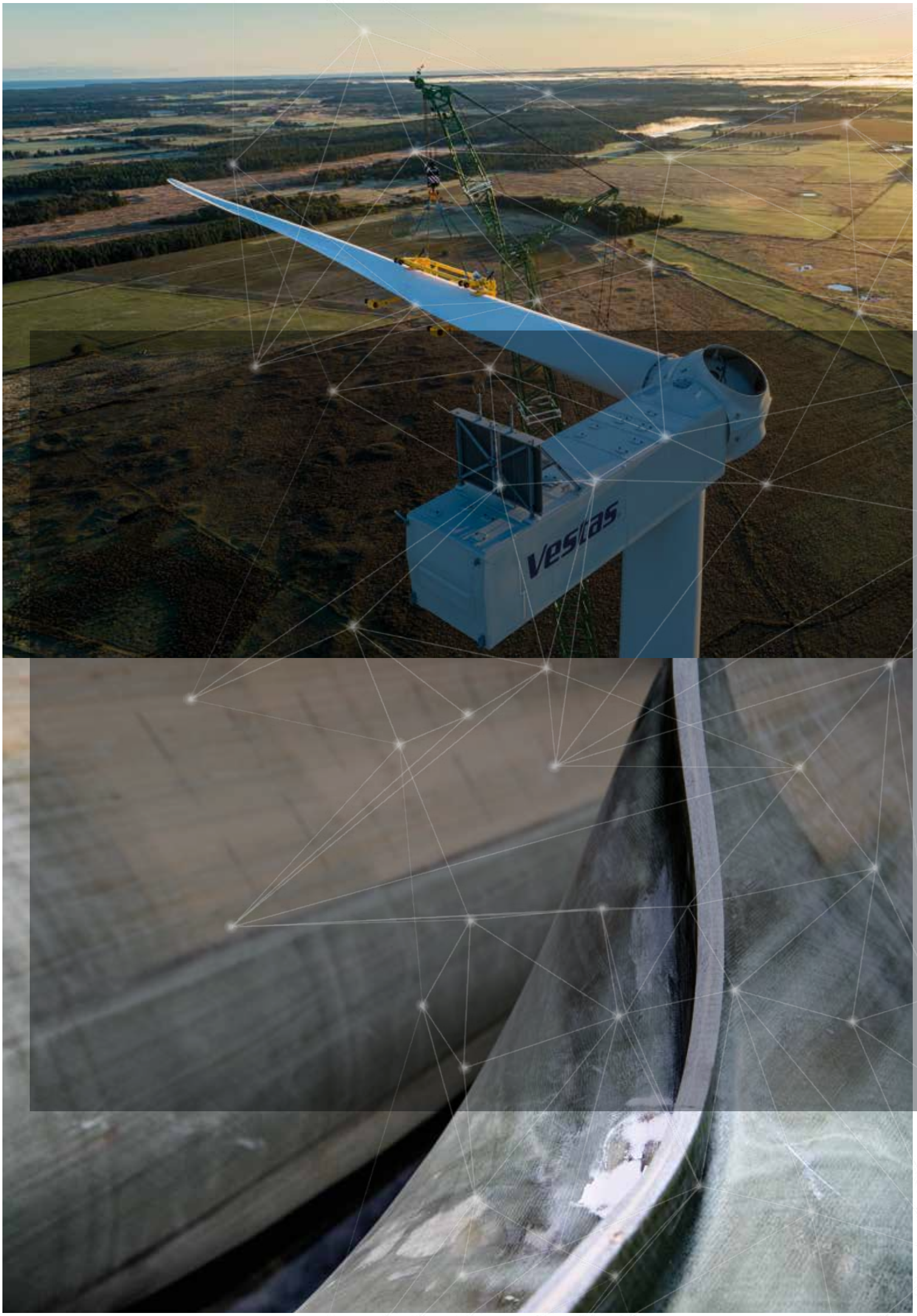
SECONDLY, the economic feasibility of a massive expansion of wind power requires new methods of increasing the value of wind through sector coupling and wind power technology innovations. Understanding the dynamic interaction between power2x equipment with variable production units must be addressed to reduce the cost of power2x. There will be no green hydrogen without cheap electrons from wind power. At the same time, research into market dynamics and methods to assess and plan infrastructure impact and optimised production patterns are also needed.

THIRDLY, the upscaling in volume and scale, combined with the globalised market, challenges the entire value chain from developers to subcontractors. Designing, manufacturing, transporting, installing, operating and eventually decommissioning turbines up to 15MW and more is pushing current equipment, model and simulation tools to their limits.

FOURTHLY, we need solutions to address the environmental and social sustainability of wind energy. New materials to minimise waste must go hand in hand with innovations to create markets for recycling turbine waste and solutions that extend the operational lifetime of turbines. At the same time, wind power enjoys broad public support in general, but opposition locally when new wind farms are installed. This is a paradox that must be addressed.

FINALLY, the green transition is powered by people. Denmark faces its own challenges in this regard, but this is first and foremost a global challenge: to educate a qualified work force and to retrain those transitioning from the oil and gas industry. Countries will take different approaches to these particular challenges, but Danish R&I can help by enabling synergies in Danish projects with company competences based in other countries.

WIND POWER AND OTHER RENEWABLES HAVE BEEN ENTRUSTED THE MANDATE TO DELIVER GREEN POWER AS THE CORNERSTONE OF AN ELECTRIFIED ENERGY SYSTEM. THAT TRUST BRINGS OBLIGATIONS AND A SET OF CONCRETE CHALLENGES THAT NEED TO BE OVERCOME.


Vestas

Delivering gigawatts of wind power to the green transition

Competences and framework for the green transition

WIND POWER AND other renewables are recognised as the future cornerstone of electricity generation in Europe. Now is the time to deliver Gigawatts of wind power to fuel the green transition. The wind energy sector can play its part through sweeping industrialisation measures in its value chain, continued cost reductions as well as increased value of wind power through R&I. But the access to raw materials and a flexible and speedy regulatory framework including market design must also be in place. Achieving these goals is not only important for wind power. The entire electrification of our society is premised on the availability of cheap and abundant clean electrons from wind and solar energy. There will be no competitive green hydrogen without cheap wind power.

These challenges call for research in four areas:

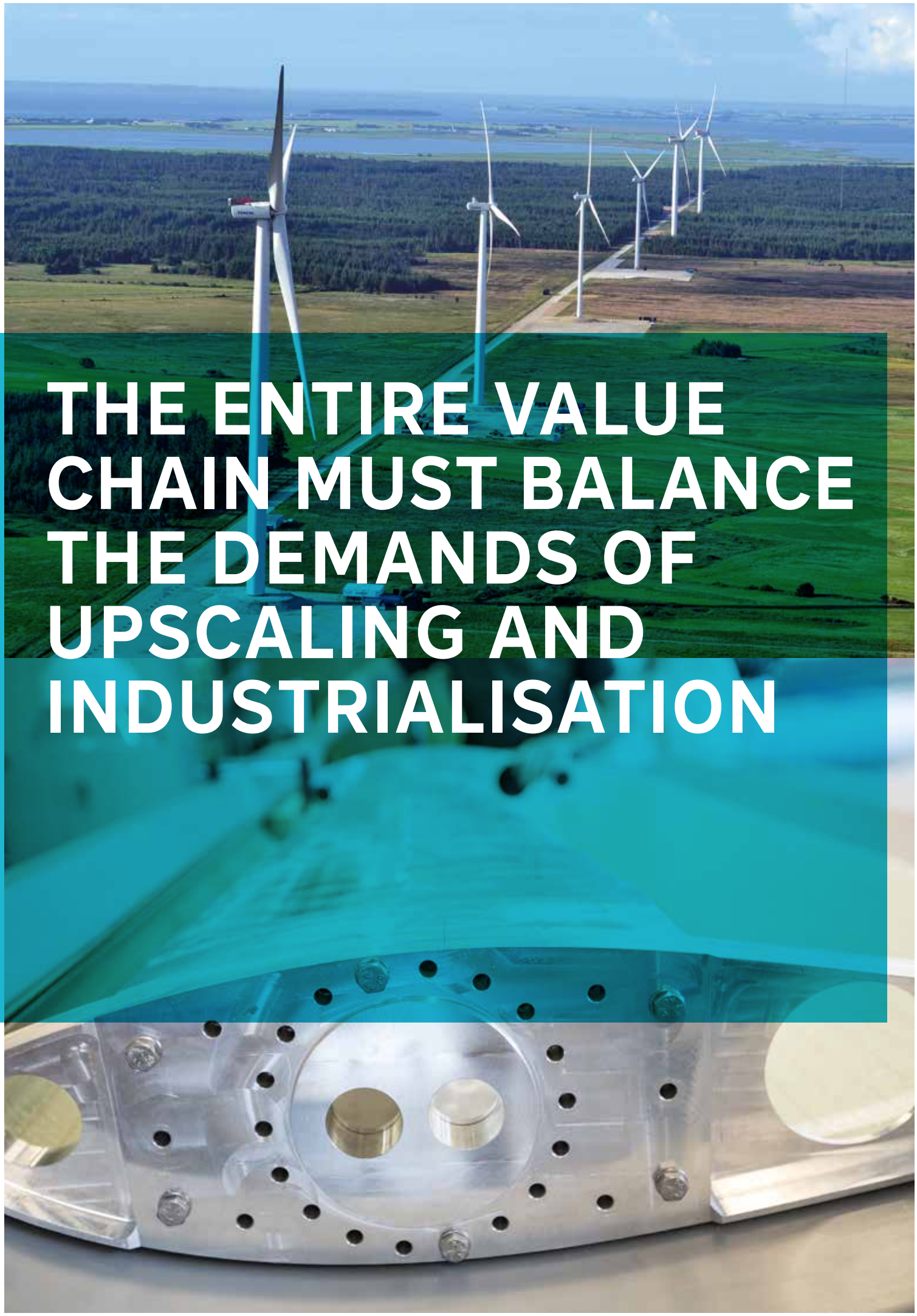
1. **Reduction of LCOE**
   through classical wind energy research areas (meteorology, aerodynamics, dynamics, materials, grid integration), focus on further reduction of LCOE and retaining the competitive strength of the Danish Energy Hub. It represents the foundation of the Danish R&D hub in wind power and is a unique strength in the public-private partnership

2. **Infrastructure**
   Recent years have seen very little investment in research to increase the flexibility and resilience of our energy infrastructure. This must be addressed if we are to achieve 100% renewable penetration without increasing the number of high-voltage additional power lines. The research in infrastructure should also include regulatory test zones for developing 100% renewable-based local and regional systems.

3. **Availability of raw materials**
   Improve security of supply through innovating new materials to alleviate shortages of current materials. Optimised design to reduce material use or waste and the use of novel materials is a priority, and is directly linked to the sustainability agenda.

4. **Financial and market instruments**
   Research and innovation to improve the value of investing in renewables is required. The same is true of analysis and solutions in market design to identify and understand efficient incentives for investments in wind power and energy systems.

NOW IS THE TIME TO DELIVER GIGAWATTS OF WIND POWER TO POWER THE GREEN TRANSITION



THE ENTIRE VALUE CHAIN MUST BALANCE THE DEMANDS OF UPSCALING AND INDUSTRIALISATION

Upscaling

Upscaling and industrialisation to achieve cost reductions

UPSCALING IS A consistent feature of wind power, but as we move from achieving price parity with legacy fuels to delivering gigawatts of wind power the entire value chain must balance the demands of upscaling and industrialisation. 180GW annually installed wind power capacity will not be achieved without increased levels of industrialisation in the wind energy sector. In addition to accelerating production and deployment, industrialisation also provides new avenues for significant cost reductions. But so do larger turbines. Finding the right balance to avoid the loss of the benefits that the upscaling of turbines and wind farms provide, through the roadblocks this creates for efficient industrialisation (as larger turbines requires larger installation vessels, larger furnaces for cast iron components etc.) will be a necessary area of focus in the future too.

Megavind sees three core areas of research and innovation to pursue in this regard.

1. **Models and simulation tools for mega turbines.**
   The physics of larger turbines and wind farms are insufficiently captured by current design tools. Research and innovation to develop and adapt models and simulation tools to alleviate the uncertainty in design parameters will be a major driver for cost efficient upscaling.

2. **Test methods and facilities**
   capable of engaging with larger components or enabling smart testing and increasing the use of digital twins to reduce physical testing requirements. This allows for innovations in areas including AI, additive manufacturing and test equipment and tools.

3. **Design for manufacturing and operation.**
   Upscaling of onshore and offshore wind turbines poses new challenges in relation to the design, production, transport and installation of very large components. A wide range of innovation opportunities are already being pursued by Danish companies, but many more exist.

System integration and sector coupling

Increased value of wind energy for companies and society through sector coupling

THE ELECTRIFICATION OF Society through sector coupling and the higher renewable energy penetration is changing the technology and market dynamics that wind power is operating within. It is therefore necessary to research and innovate technology solutions based on market dynamics and to understand and develop the energy infrastructure for electrons and molecules to facilitate the integration of large amounts of additional renewable energy sources.

At the same time, the opportunity to produce and use electricity directly through combined wind power and power2x facilities could remove the need for connection to traditional electrical infrastructures. This will dramatically reduce the cost of turbines by removing expensive components that are required for compliance with the electricity grid.

A 100% renewable energy system with superior grid stability and high security of supply requires research and innovation of processes and technologies to enable short- and long-durational energy storage as well as the reliable provision of ancillary services.

Megavind recommends research and innovation in the following areas:

1. **Wind power & P2X interaction**
   Power2x systems and their dynamic interaction with wind energy units with variable energy production. This includes stand-alone systems, and technology innovations in turbine and wind farm technologies to increase capacity factors.

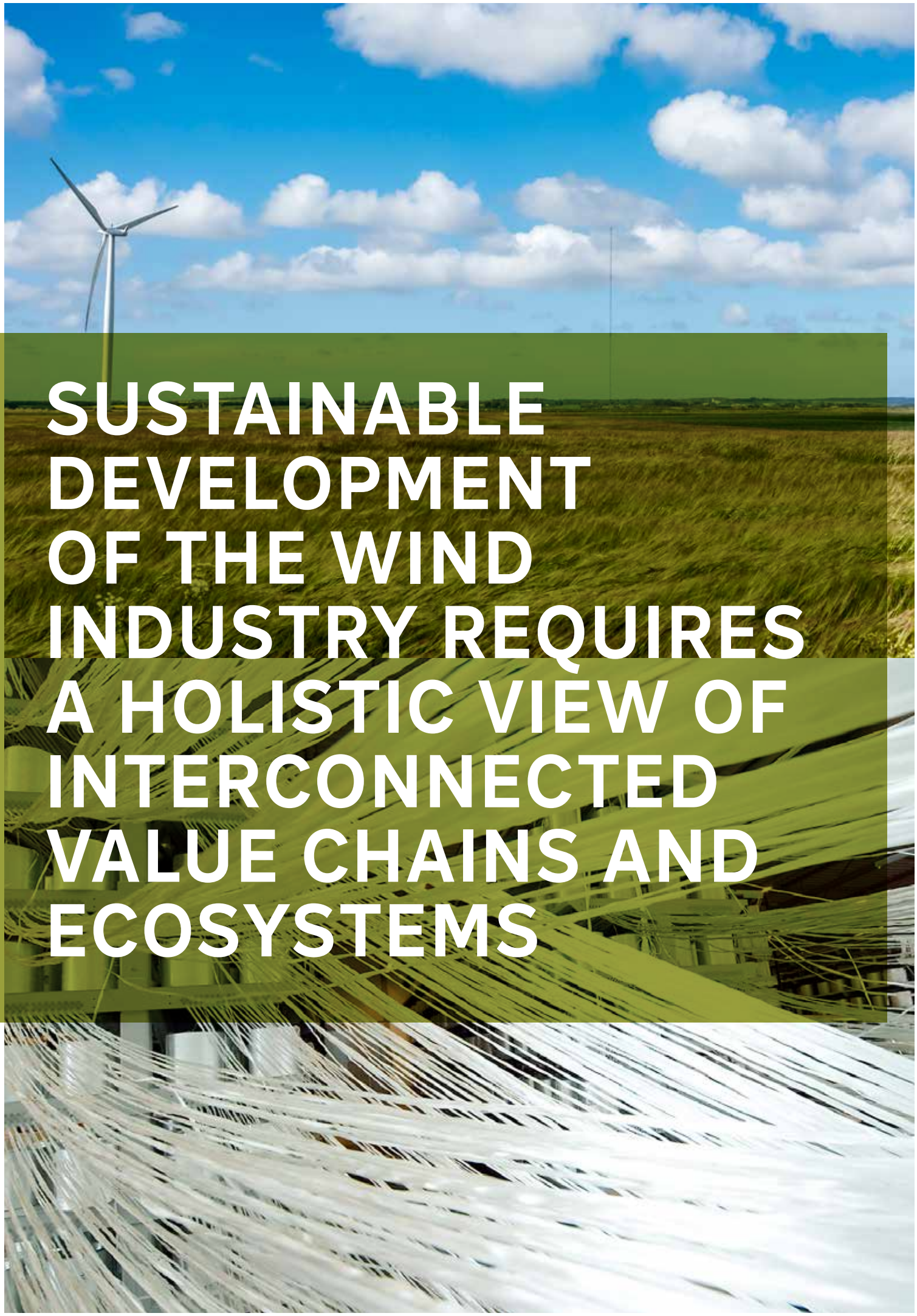
2. **Optimisation & planning**
   Reaping the full benefit of new systems also requires load and production pattern optimisation, planning and scheduling with combined wind energy and power2x systems.

3. **Wind power plant configuration**
   R&I in optimal wind power plant/turbine configuration based on future energy system market systems that will use hydrogen ammoniac systems to provide integrated storage capacity.

4. **Storage solutions**
   Efficient, grid-supporting and reliable short- and long-duration energy storage solutions enabling high renewable energy penetration with favourable supply profiles.

5. **Infrastructure planning**
   New methods to assess and plan infrastructure impact are called for.

A 100% RENEWABLE ENERGY SYSTEM WITH SUPERIOR GRID STABILITY AND HIGH SECURITY OF SUPPLY, REQUIRES RESEARCH AND INNOVATION OF PROCESSES AND TECHNOLOGIES



SUSTAINABLE DEVELOPMENT OF THE WIND INDUSTRY REQUIRES A HOLISTIC VIEW OF INTERCONNECTED VALUE CHAINS AND ECOSYSTEMS

Sustainability

Technology's co-existence with people and nature

BY SCALING UP to deliver GWs of wind power, the wind industry has the potential to provide renewable energy to help the world decarbonize in the face of the climate crisis. However, the next generation of wind turbines and wind farm sites, while drawing on natural resources, will impact their surroundings. Wind power can develop as a truly sustainable energy choice within a future circular economy if technologies are designed and introduced in harmony with the environment and surrounding communities.

Sustainable development of the wind industry requires a holistic view of interconnected value chains and ecosystems that only comes from strong partnerships, both business-to-business and public-to-private. Strong partnerships start with shared understanding and purpose. Denmark's public and private sectors share a common vision of sustainable growth based on the UN Sustainable Development Goals. Further embedding these global goals into the wind power industry requires a closer look at the road ahead: what is the starting point, what is the desired destination, what mechanisms can be implemented to accelerate the industry in its effort to grow in a sustainable way, and how will progress be measured? Megavind recommends the following research and innovation focus areas, where Denmark can play a significant role in enhancing the environmental and social sustainability of wind power developments through public-private partnerships.

1. **R&I of material substitution in wind turbines, to increase recycled content, to minimise environmental impacts and to enable recycling of waste streams.**
   This includes reducing emissions by developing alternative materials to avoid virgin raw material and make separation and recycling easier. Research into assessment of environmental impacts of materials to avoid toxic or scarce materials is also needed.

2. **R&I to create a market for recycling manufacturing waste and end-of-use wind turbines,** including efficient recycling processes and new products that incorporate recycled materials.
   A fact-based approach should be taken, and recycling solutions should be environmentally sustainable (based on life-cycle assessment or similar), cost-efficient and capable of handling large volumes of waste on a global scale. This includes developing facilities and equipment to process the waste streams as well as supporting the development of products/industries that incorporate recycled materials.

3. **R&I to extend the operational lifetime of wind turbines** including leading edge protection for blades, service and maintenance solutions and new monitoring systems for turbines.

4. **Develop wind farms in harmony with surrounding ecosystems and communities.**
   Research and innovative solutions to enable better interaction between developers, public authorities and local communities is a key area for future R&I activities. Research and partnership building to address wind farms effects on ecosystems both onshore and offshore is also imperative to address potential environmental impacts of wind farms.

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