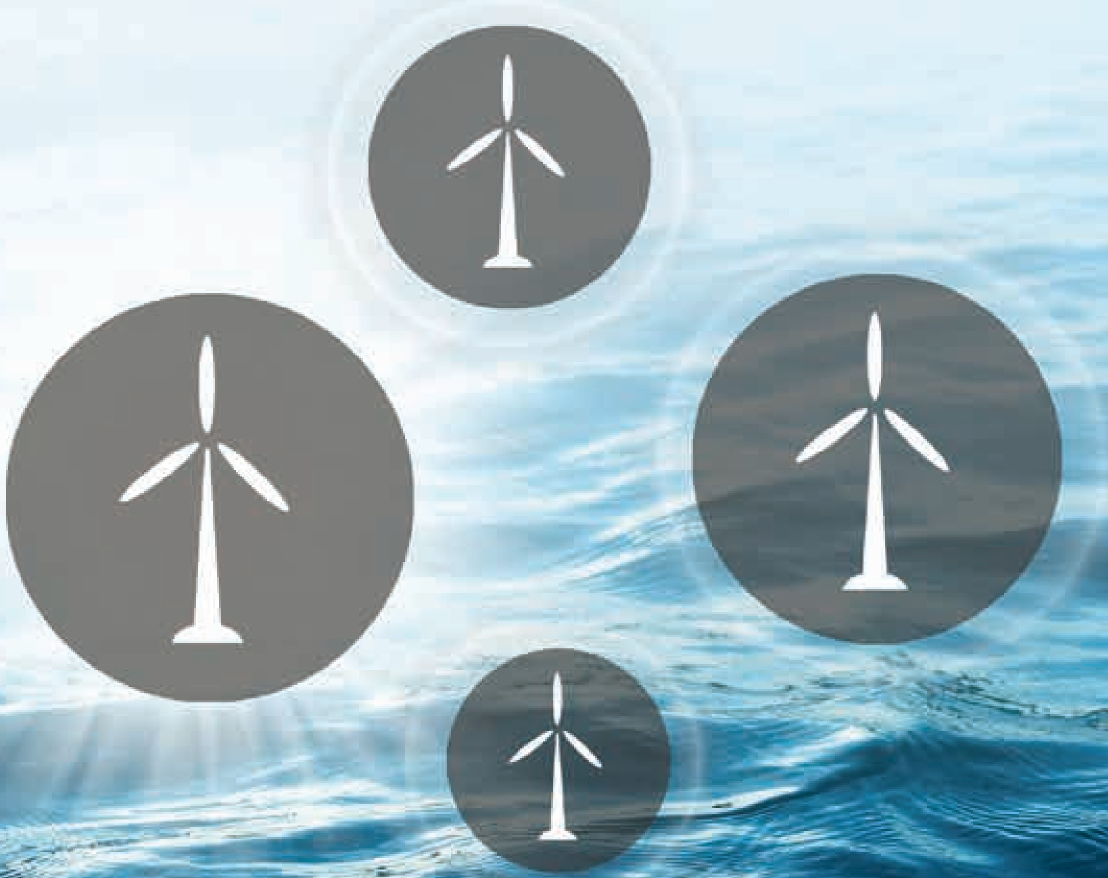
FINAL REPORT



NOWITECH

Norwegian Research Centre for Offshore Wind Technology

CENTRE FOR ENVIRONMENT-FRIENDLY ENERGY RESEARCH

The Research Council of Norway

NOWITECH - Norwegian Research Centre for Offshore Wind Technology – was an international precompetitive NOK 320 million (2009-2017) research cooperation on offshore wind technology co-financed by the Research Council of Norway, industry and research partners.

NOWITECH was part of the FME-scheme, i.e. Norwegian Centres for Environment-friendly Energy Research *(in Norwegian: FME = Forskningssenter for miljøvennlig energi)*. These are time-limited research centres which conduct concentrated, focused and long-term research of high international quality to solve specific challenges in the field of renewable energy and the environment.

This report summarizes the achievements of NOWITECH (2009-2017), and marks the completion of NOWITECH in the form of an FME. NOWITECH will continue as a research network. The research partners of NOWITECH include SINTEF Energy Research (host institution), Norwegian University of Science and Technology (NTNU), Institute for Energy Technology (IFE), SINTEF Ocean and SINTEF AS.

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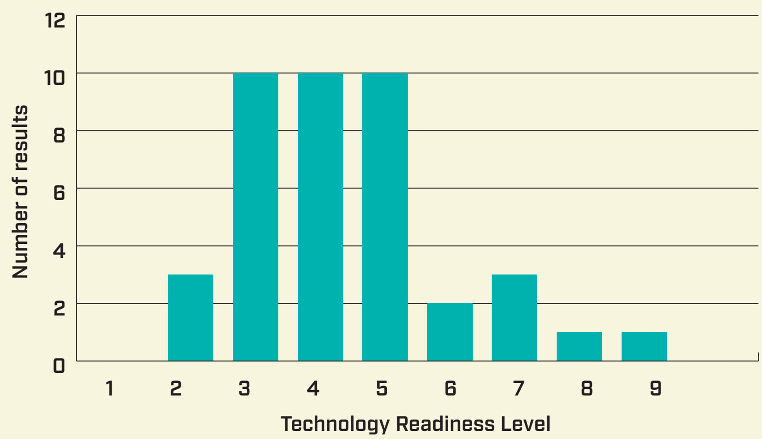
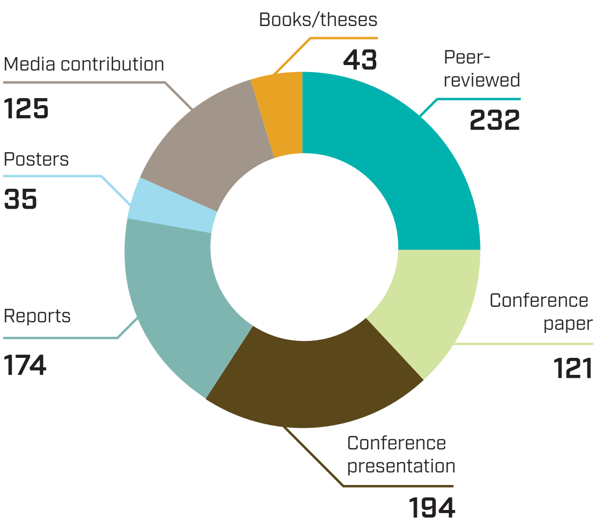
KEY PERFORMANCE INDICATORS

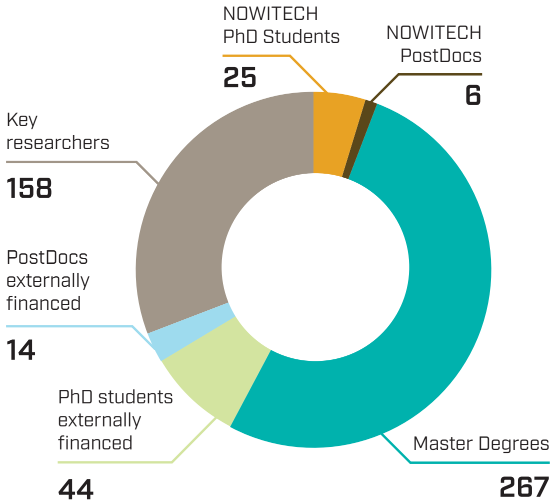
Innovations



Publications



People



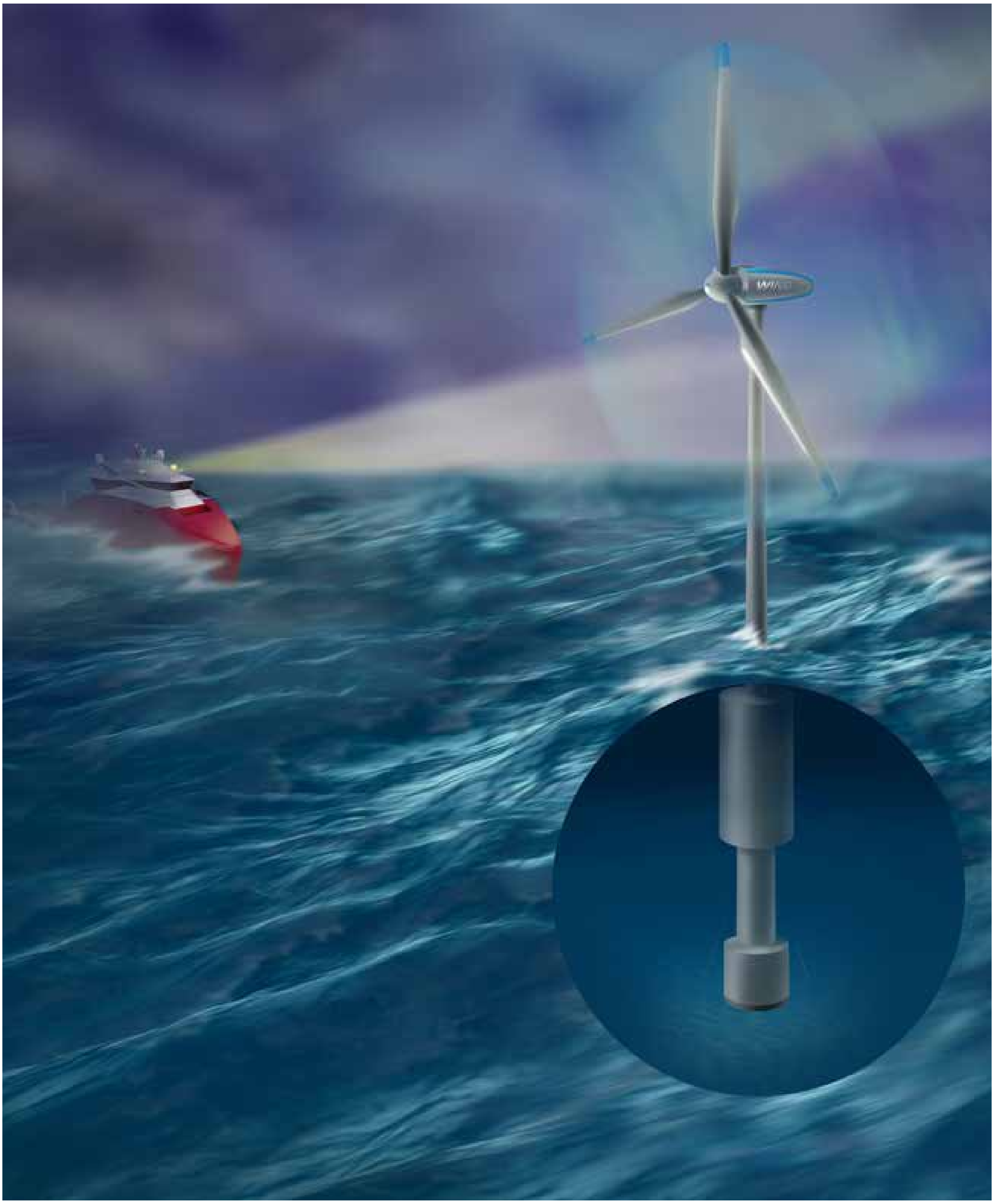


Figure 1: *NOWITECH has focused on "deep sea", i.e. +30 m water depth, both bottom-fixed and floating technology. A key target was innovations reducing cost of energy from offshore wind farms. Main areas of research were numerical modelling, materials, substructures, grid connection, maintenance and control. The research methodology includes both desktop studies and lab scale experimental testing bringing developments towards TRL 4 or 5 and ready for takeover by more commercial industry driven projects.*

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FOREWORD BY THE CENTRE DIRECTOR

John Olav Giæver Tande, Director NOWITECH

I remember the excitement I felt when starting NOWITECH in 2009. We formulated a bold vision for NOWITECH to contribute to large scale deployment of deep sea offshore wind turbines, and to be an internationally leading research community on offshore wind technology enabling industry partners to be in the forefront. I am now very pleased to see that NOWITECH has delivered results according to this vision, and realised its objective to provide pre-competitive research laying a foundation for industrial value creation and cost-effective offshore wind farms.

We have carried out multidisciplinary research at a high international standard with a joint aim to provide new knowledge, education and innovations for reducing the cost of energy from offshore wind farms. Emphasis has been on "deep-sea" technology (+30 m) including bottom-fixed and floating wind turbines with attention towards development of knowledge and technology that can be applied in the international market. NOWITECH has been successful in this. In total 40 innovations have been brought forward for further development and application in more commercial-oriented projects. The potential value is huge, and has been estimated by an independent consultancy company to yield more than hundred times the total expenditures of NOWITECH. The research partners have become recognized as internationally leading within specific areas and are engaged in close to all European research projects within offshore wind energy technology. NOWITECH has contributed strongly to education bringing forward attractive candidates for employment in industry. The large majority of PhD students in the centre are now engaged in Norwegian industry and working towards increased supplies towards the international offshore wind market.

The offshore wind industry has come a long way since we started NOWITECH in 2009. In Norway, the offshore wind industry now represents the renewable energy technology with the biggest export of goods and services, according to Eksportkreditt Norge yielding about NOK 5 billion annually. Globally, the accumulated offshore wind capacity has increased from 2,1 GW in 2009 to 18.8 GW by end of 2017. It is still small compared to more mature energy technologies, but with great potential supported by a strong European commitment to develop offshore wind to be a significant part of the future sustainable energy supply, creating jobs, prosperity and reaching climate targets. The cost of offshore wind energy has declined tremendously, and there are examples of bottom-fixed offshore wind farms now being planned to be built and operated relying purely on market price of electricity to be economic. Floating offshore wind farms are still more expensive, but have also shown remarkable development. In this, Norway is in a leading role. Statoil installed Hywind, the world first full-scale floating wind turbine at the west-coast of Norway already in 2009, and in 2017, they took it to the next step, constructing the world's first floating wind farm outside Scotland applying an upscaled version of the Hywind concept.

It has been a great pleasure to work as centre director among highly skilled researchers and students, knowledge-seeking user partners and interested third parties. I am also greatly thankful to the Research Council of Norway and all user partners for the financial support, which has given us a long-term perspective to produce high-quality results and applicable solutions for the offshore wind energy sector. NOWITECH will continue as a research network, and research on offshore wind technology will continue amongst the partners through a strong portfolio of projects. Although we have come a long way in developing offshore wind technology, it is compared to other more mature energy technologies, still in its infancy with continued need for strong R&I and great future potential. I am eager to see the continued journey.

This final report describes important achievements and results from eight years of precompetitive research carried out within NOWITECH. Further information about the results and activities in the centre can be found in the many publications from NOWITECH, counting close to one thousand in total and including more than 230 peer-reviewed articles. The public website gives an overview, and for the innovations, a separate report is published providing summarizes and references for further details for each of the 40 innovations.

FOREWORD BY THE HOST INSTITUTION

Inge Gran,
President
SINTEF Energi AS

I believe the achievements of NOWITECH are truly astonishing. The centre has taken an exemplary approach to develop and communicate innovations, but also succeeded with a great educational programme and research at high international level. I am thankful for the great collaboration between the partners of NOWITECH, and I am proud that SINTEF Energy Research has hosted the centre.

A returning question in managing research, and in particular for a large effort like a Centre for Environment-friendly Energy Research (FME) such as NOWITECH, is "does it pay off?". This is hard to measure for precompetitive research, as the pay-off in general does not come before some years after the completion of the research, and only after some further development to bring the results from research to practical use. I still felt confident in using NOWITECH as a test case to see if a fair and transparent assessment of its value creation could be made by an external consultancy company.

The report prepared is published in full at the NOWITECH web, and shows an astonishing future potential value of the results prepared by NOWITECH to yield EUR 5 billion. Also, it verifies an already achieved value creation of EUR 35 million, being equal to the total budget of NOWITECH.

No less than three spin-out companies have been established based on results from the centre. Seram Coatings AS has an innovative method for thermal spraying of silicon carbide (SiC), being a generic technology with a large range of future application, SIMIS AS has developed the Ashes wind turbine simulation software and EMIP AS is commercializing technology for remote inspection and maintenance of offshore turbines.

The high potential value of NOWITECH is truly in line with SINTEF's vision, "Technology for a better society". I am certainly also very pleased to see that the centre has generated a large portfolio of new research projects, and that the partners have become very well established in the European research arena. NOWITECH has proven a very effective spearhead for research, providing international visibility and impact. A set of separate projects could not have achieved this, thus with NOWITECH now being completed in its current form, I am pleased to see that the research collaboration continues as a network, and I am confident, continued strong results with emerge from the partners contributing to the development of offshore wind as a significant part of the future energy mix, to meet climate targets, generate new jobs and prosperity.

SUMMARY

NOWITECH - Norwegian Research Centre for Offshore Wind Technology – was an international precompetitive NOK 320 million (2009-2017) research cooperation on offshore wind technology co-financed by the Research Council of Norway, industry and research partners. The research partners of NOWITECH include SINTEF Energy Research (host institution), Norwegian University of Science and Technology (NTNU), Institute for Energy Technology (IFE), SINTEF Ocean and SINTEF AS.

NOWITECH was part of the FME-scheme, i.e. Norwegian Centres for Environment-friendly Energy Research (in Norwegian: FME = Forskningssenter for miljøvennlig energi). These are time-limited research centres which conduct concentrated, focused and long-term research of high international quality to solve specific challenges in the field of renewable energy and the environment.

This report summarizes the achievements of NOWITECH (2009-2017), and marks the completion of NOWITECH in the form of an FME. NOWITECH will continue as a research network.

The bold vision for NOWITECH was to contribute to large scale deployment of deep sea offshore wind turbines, and to be an internationally leading research community on offshore wind technology enabling industry partners to be in the forefront. NOWITECH has delivered results according to this vision, and realised its objective to provide pre-competitive research laying a foundation for industrial value creation and cost-effective offshore wind farms.

The Centre has carried out multidisciplinary research at a high international standard with a joint aim to provide new knowledge, education and innovations for reducing the cost of energy from offshore wind farms. Emphasis has been on "deep-sea" technology (+30 m) including bottom-fixed and floating wind turbines with attention towards development of knowledge and technology that can be applied in the international market. NOWITECH has been successful in this. In total 40 innovations have been brought forward for further development and application in more commercial-oriented projects.

The research partners have become recognized as internationally leading within specific areas and are engaged in close to all European research projects within offshore wind technology. They are also represented in key European fora such as being in the Steering Committee of the European Technology and Innovation Platform on wind energy (ETIPwind) and heading the offshore wind activity within the European Energy Research Alliance Joint Programme on wind energy (EERA JPwind).

NOWITECH has contributed strongly to education bringing forward attractive candidates for employment in industry. The Centre has funded a total of 25 PhD students and 6 post-docs, and the large majority of these are now engaged in Norwegian industry working within the offshore wind market.

Publications from the Centre includes more than 230 peer-reviewed articles, together with numerous reports, popular media articles, presentations and monographs, counting in total about 900. The text-book "Offshore Wind Energy Technology" published by Wiley, April 2018, is based on research material developed in NOWITECH and comprises a comprehensive reference to the most recent advancements in offshore wind technology. Written for students and professionals in the field, it gives value for the future.

Very significant spin-off activities have been achieved. Since the start, more than 60 new projects with an accumulated budget in excess of NOK 1500 million of which about NOK 300 million was for one or more of the research partners in NOWITECH. These projects are with separate contracts external to NOWITECH, but carried out in alignment with NOWITECH, providing added value.

Examples of results and innovations from NOWITECH are:

- Advanced methods and models for integrated design of the substructures and wind turbines have been implemented in state-of-the-art numerical design tools (eg. SIMA and 3DFloat) and these are now used in the development of new offshore wind farms for commercial operators.
- New coatings to provide reduced maintenance have been developed. This includes: a) a thermally sprayed coating with zinc and paint for maintenance-free corrosion protection, b) highly resilient coatings for blades and c) a thermally

sprayed silicon-carbide coating with low friction and high wear resistance especially suited for use in large main bearings and other rotating machinery. The company Seram Coatings was established to commercialize the innovation (c) and one of the inventors, professor Nuria Espallargas, NTNU has won several awards, amongst others Norway's Female Entrepreneur 2017.

- New design of fixed and floating foundations, jackets, semi-sub and spar designs have been developed with significant cost savings relative to conventional solutions.
- A new adaptive blade technology with improved weight / strength ratio has been verified through simulations and laboratory experiments.
- Numerical simulation models, concepts and laboratory installations for grid connection and system integration of offshore wind farms have been developed, including a physical model of a future offshore HVDC grid realized at the laboratory scale.
- The use of offshore wind farms to supply oil and gas installations have been assessed through numerical simulations. It was found that significant savings in fuel and CO2 emissions from the oil and gas platforms could be achieved, and further development towards implementation have been initiated with leading industry partners.
- A new segmented direct-driven generator (HVDC generator) that can connect directly to the HVDC transmission network has been verified through simulations and laboratory experiments. The technology can potentially make large offshore substations superfluous and give significant cost savings.
- Tools for simulation and optimization of offshore wind park operation, maintenance and logistics has been developed. The tools can be used to estimate operational costs and availability depending on chosen strategy (NOWIcob), find optimal setup of the support fleet (boats, ships, helicopters) or find the optimal routing and scheduling of these.
- A system for "remote presence" using a robot with camera, microphone etc has been developed for use in offshore wind turbines. The innovation has also been tested in a wind turbine and commercialized through among others the EU LeanWind project, the RCN BIA project eMIP-REACT and the company EMIP that was established for sale and supply of the system.

An important goal for NOWITECH has been to get promising results transferred to industry for further development and commercialization. Several results are already in this phase, e.g. SIMA, 3DFloat, Seram Coatings, NOWIcob, Remote Presence and more are on the way. This gives value creation and cost reduction for offshore wind power. The value has been assessed by the independent consultancy company Impello Management AS. In their assessment they considered a subset of the innovations by NOWITECH, and calculated the net present value of these to yield excess of EUR 5 billion, i.e. more than hundred times the total expenditures of NOWITECH. Also, the report verifies an already achieved value creation of EUR 35 million, being equal to the total budget of NOWITECH. The report prepared is published in full at the NOWITECH web.

Although the offshore wind technology has gone through an astonishing development during the last few years, it is compared to other more mature energy technologies, still in its infancy with continued need for strong R&I and great future potential. This is confirmed by the Norwegian research strategy Energi21 and the European SET-plan both prioritizing research on offshore wind technology.

NOWITECH has proven a very effective spearhead for research, providing international visibility and impact. A set of separate projects could not have achieved this, and an ideal continuation would be to again have an FME or similar on offshore wind.

In the meantime, NOWITECH will continue as a research network, and research on offshore wind technology will continue amongst the partners through a strong portfolio of projects. A continued effort should be made to realize the value of NOWITECH, and new more long-term research should be initiated to generate new knowledge and innovations. It is time for the next wave!


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SAMMENDRAG

NOWITECH - Norwegian Research Centre for Offshore Wind Technology – var et internasjonalt prekompetitivt NOK 320 million (2009-2017) forskningssamarbeid om offshore vindkraftteknologi finansiert av Forskningsrådet, industri og forskningspartnere. Forskningspartnerne i NOWITECH var SINTEF Energi AS (vertsinstitusjonen), NTNU, IFE, SINTEF Ocean og SINTEF AS.

NOWITECH var del av FME ordningen (Forskningssenter for miljøvennlig energi). Dette er tidsbegrensede sentere som skal ha en konsentrert, fokusert og langsiktig forskningsinnsats på høyt internasjonalt nivå for å løse utpekte utfordringer på energi- og miljøområdet.

Denne rapporten summerer resultatene fra NOWITECH (2009-2017), og markerer slutten av NOWITECH som en FME. NOWITECH vil fortsette som et forskningsnettverk.

NOWITECHs visjonen var å bidra til storskala utbygging av offshore vindkraft, og å bli en internasjonalt ledende forskningsgruppe innen offshore vindkraftteknologi. NOWITECH har levert resultat i henhold til denne visjonen, og realisert sitt mål om å levere prekompetitiv forskning som et fundament for industriell verdiskapning og kostnads-effektive offshore vindkraftverk.

Senteret har utført multidisiplinær forskning på høyt internasjonalt nivå med et felles mål om å frambringe ny kunnskap, utdanning og innovasjon for å redusere kWh-kostnaden for offshore vindkraft. Teknologi for å bygge og drifte vindparker på dypt vann (+30 m) har vært vektlagt (både bunnfast og flytende), og med fokus på utvikling av kunnskap og teknologi som kan benyttes i det internasjonale markedet. NOWITECH har vært suksessfull i dette. Totalt 40 innovasjoner er blitt frambragt for videre utvikling og anvendelse i mer kommersielt rettede prosjekt.

Forskningspartnerne er blitt internasjonalt anerkjent som ledende innen spesifikke tema, og er engasjert i tett på alle europeiske forskningsprosjekt innen offshore vindkraft. De er også representert innen viktige europeiske fora som i styringskomiteen for den europeiske teknologi og innovasjonsplattformen ETIP-wind og som leder av offshore vindkraft innen den europeiske energiforskningsalliansen EERA JPwind.

NOWITECH har bidratt sterkt til utdanning og frambragt attraktive kandidater for ansettelse i industrien. Senteret har finansiert 25 PhD studenter og 6 post-docs, og størstedelen av disse er nå ansatt i norske virksomheter med arbeid innen offshore vindkraft-markedet.

Publikasjoner fra Senteret inkluderer mer enn 230 fagfellevurderte artikler i internasjonale tidsskrift, og et stort antall rapporter, oppslag i massemedia, presentasjoner og monografier, totalt over 900. En lærebok er utgitt på det anerkjente forlaget Wiley: "Offshore Wind Energy Technology", publisert i April 2018, og basert på forskningsresultat fra NOWITECH. Dette er et omfattende referanseverk innen offshore vindkraftteknologi. Den er skrevet for studenter og profesjonelle innen feltet, og har stor verdi.

Flere vesentlige spin-off prosjekt er blitt etablert. Siden av starten av NOWITECH har det blitt etablert mer enn 60 nye prosjekt med et akkumulert budsjett på over NOK 1500 millioner, hvorav omlag NOK 300 millioner er for en eller flere av forskningspartnerne i NOWITECH. Dette er prosjekt med separate kontrakter utenom NOWITECH, men utført slik at de gir merverdi.

Eksempler på resultat og innovasjoner fra NOWITECH er:

- Avanserte metoder og modeller for integrert design av understell og vindturbiner har blitt implementert i state-of-the-art numeriske designverktøy (for eksempel SIMA og 3Dfloat) og disse benyttes nå i utviklingen av nye offshore vindparker av kommersielle aktører.
- Nye belegg for å gi redusert vedlikehold har blitt utviklet: a) et termisk sprayet belegg med sinkmaling for vedlikeholdsfri korrosjons-beskyttelse, b) et belegg med høy slitestyrke for blader og c) et termisk sprayet silikonkarbidbelegg med lav friksjon og høy slitestyrke spesielt egnet for bruk i store hovedlagre og annet roterende maskineri og turbiner. Det er startet et eget selskap Seram Coatings for å kommersialisere produktet (c), og gründeren professor Nuria Espallargas, NTNU har vunnet flere innovasjonspriser, bla årets kvinnelige entreprenør i 2017.
- Nye design av bunnfaste og flytende fundament, bla gittertårn, semi-sub og spar design er utviklet med vesentlige kostnadsbesparelser relativt til konvensjonelle løsninger.

- En ny adaptiv bladteknologi med forbedret vekt/styrke forhold er verifisert gjennom simuleringer og laboratorieeksperiment.
- Numeriske simuleringsmodeller, konsepter og laboratorieinstallasjoner for nettilknytning og systemintegrasjon av offshore vindparker har blitt utviklet, herunder er en fysisk modell av et fremtidig offshore HVDC nett realisert i labskala.
- En ny segmentert direktedrevet generator (HVDC generator) som kobles rett til HVDC transmisjonsnettet er verifisert gjennom simuleringer og laboratorieeksperiment. Teknologien kan potensielt gi store besparelser ved at offshore vindparker kan bygges uten store offshore plattformer for transformator og HVDC omforming.
- Bruk av offshore vindparker til forsyning av olje og gassanlegg har blitt analysert ved bruk av numeriske simuleringsverktøy. Det er konkludert at vesentlig besparelse av brennstoff og CO_2 utslipp fra olje og gassplattformene kan oppnås, og videre utvikling mot realisering er blitt igangsatt med ledene industripartnere.
- Flere verktøy for simulering og optimering av offshore vindpark drift, vedlikehold og logistikk er utviklet. Verktøyene kan brukes bl.a. for estimering av driftskostnader og tilgjengelighet avhengig av valgt strategi (NOWIcob), finne optimal sammensetning av vedlikeholdsflåten (båt, skip, helikopter) eller finne optimal rute og tidspunkt for bruk av denne.
- Et system for fjernovervåkning ("Remote Presence") av offshore vindturbiner ved hjelp av en robot med kamera, mikrofon, mv. er utviklet. Innovasjonen er også testet i en kommersiell vindturbin bl.a. gjennom EU prosjektet LeanWind, BIA prosjektet eMIP-REACT og selskapet EMIP som er etablert for slag og leveranse av systemet.

Et viktig mål for NOWITECH har vært å få flest mulig lovende resultat overført til industrien for videre utvikling og kommersialisering. Flere resultat er allerede i denne fasen, f.eks. SIMO RIFLEX, 3DFloat, Seram Coating, NOWIcob og Remote Presence, og flere er mulig. Dette gir verdiskapning og kostnadsreduksjon for offshore vindkraft. Verdien har blitt vurdert av det uavhengige konsulentselskapet Impello Management AS. De har vurdert verdien av noen utvalgte resultat fra NOWITECH, og beregnet nåverdien av disse til å være over EUR 5 milliarder, gitt at de blir videre utviklet og utnyttet. Dette er mer enn 100 ganger det totale budsjettet for NOWITECH. Rapporten angir også estimert verdi av allerede oppnådd verdiskapning av NOWITECH til å være EUR 35 millioner, dvs lik med det totale budsjettet for NOWITECH. Rapporten er publisert på NOWITECH web.

Selv om offshore vindkraftteknologien har gjennomgått en fantastisk utvikling i løpet av de siste få årene, er den stadig, sammenlignet med mer modne energiteknologier, stadig på et tidlig utviklingsstadium med fortsatt behov for betydelig FoU innsats og med et stort framtidig potensiale. Dette bekreftes av den norske energiforskningsstrategien Energi21 og av den europeiske SET-planen som begge gir prioritet til forskning innen offshore vindkraftteknologi.

NOWITECH har vist seg å være en effektiv spydspiss for forskning; senteret har gitt internasjonal synlighet og innvirkning. Et sett med enkeltstående prosjekt kunne ikke ha oppnådd dette, og en ideell fortsettelse ville være å igjen ha et FME eller tilsvarende innen offshore vindkraft.

I mellomtiden vil NOWITECH fortsette som er forskningsnettverk, og forskningen vil fortsette hos forskningspartnerne gjennom en sterk portefølje av prosjekt. En fortsatt innsats bør gjøres for å realisere verdien av NOWITECH, og ny mer langsiktig forskning bør iverksettes for å generere ny kunnskap og innovasjon. Det er på tide med den neste bølgen!

VISION AND GOALS

NOWITECH - Norwegian Research Centre for Offshore Wind Technology – has been an international precompetitive NOK 320 million (2009-2017) research cooperation on offshore wind technology co-financed by the Research Council of Norway, industry and research partners.

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NOWITECH has delivered results according to this vision, and realised its objective to provide pre-competitive research laying a foundation for industrial value creation and cost-effective offshore wind farms.

The research has been multidisciplinary, but carried out with a joint aim to provide new knowledge, education and innovations for reducing the cost of energy from offshore wind farms. Emphasis has been on "deep-sea" technology (+30 m) including bottom-fixed and floating wind turbines.

A total of 40 industry relevant results and innovations[1] have been prepared. These are shown on the next two pages and include new numerical models / software tools and new technology / processes. Some of these are still at a relatively low technology readiness level (TRL), being in line with NOWITECH's objective of precompetitive research, whereas other results already have been taken further by the industry and in projects outside of NOWITECH for commercial use, licence agreements, and business developments. The TRL scale applied in NOWITECH is shown in Figure 2. A generic interpretation is that TRL 1-5 represents research and development stages, while TRL 6-9 typically is industry driven towards deployment and commercial application.

The educational programme has provided for first-rate recruitment opportunities for the industry. NOWITECH has financed 25 PhD students and 6 post-doctoral researchers at NTNU. In addition, a total of 44 PhD students and 14 Post Docs at NTNU have carried out their research in alignment with NOWITECH, but with finance from other sources.

The scientific work has been of high international standard including publication of more than 230 peer-reviewed articles. The text-book "Offshore Wind Energy Technology" published by Wiley[2], April 2018, is based on research material developed in NOWITECH and comprises a comprehensive reference to the most recent advancements in offshore wind technology. Written for students and professionals in the field, it gives value for the future.

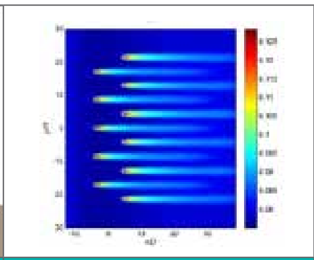
Very significant spin-off activities have been achieved. Since the start, more than 60 new projects with an accumulated budget in excess of NOK 1500 million of which about NOK 300 million was for one or more of the research partners in NOWITECH. These projects are with separate contracts external to NOWITECH, but carried out in alignment with NOWITECH providing added value.

TRL1	TRL2	TRL3	TRL4	TRL5	TRL6	TRL7	TRL8	TRL9
Basic principles observed	Technology concept formulated	Experimental proof of concept	Technology validation in lab	Prototype/ lab validation in relevant environment	Pilot system validation in relevant environment	Full scale prototype in operational environment	System Complete and qualified	System proven in operational environment

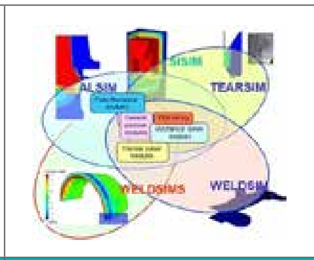
Figure 2: *The Technology Readiness Level scale has been used in NOWITECH to evaluate and communicate maturity of new numerical models / software tools and new technology / processes under development.*

1 The term "innovation" here means research results with potential to be further developed into new or significantly improved goods, services or processes enhancing value creation and/or benefit for society.
2 Olimpo Anaya-Lara, John Olav Tande, Kjetil Uhlen, Karl Merz, *Offshore Wind Energy Technology*, John Wiley & Sons Ltd. ISBN: 978-1-119-09776-1. May 2018. 456 pages

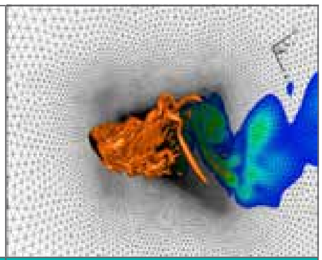
3DFloat integrated model
TRL7



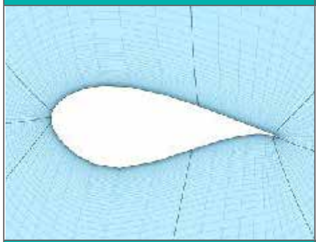
3DWind park wake model
TRL6



INVALS general purpose optimization
TRL8



Commercial grade rotor CFD
TRL5

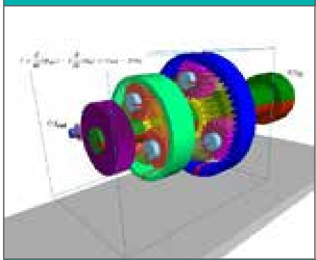


Variational Multiscale Error Estimator
TRL3

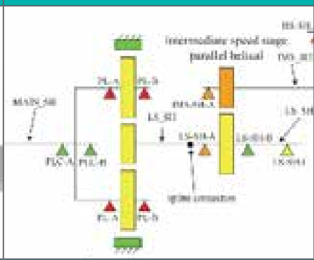
IFEM CFD
TRL3

ASHES
TRL7

Seawatch Wind Lidar Buoy
TRL9

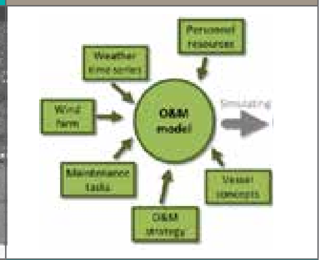


Gearbox fault detection
TRL3

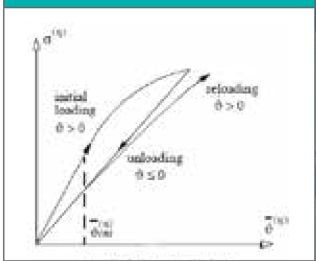


Gearbox vulnerability map
TRL4

Dual layer corrosion protection coatings
TRL5



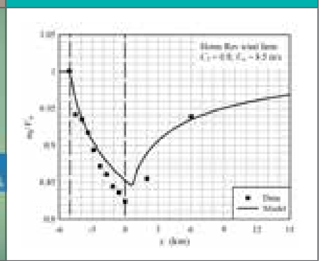
NOWIcob
TRL6



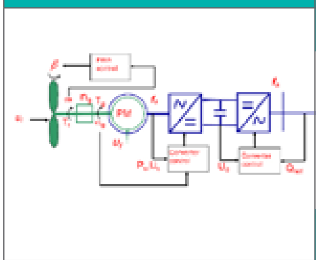
Fatigue damage simulation
TRL4

PSST/PowerGAMA System Simulation
TRL5

Net-Op network optimization
TRL4

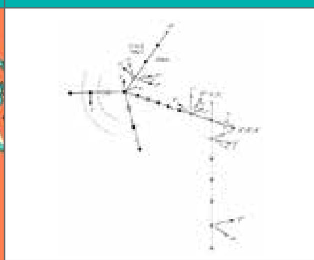


Viper Estimate Energy Output from Offshore Wind Farms
TRL4



Wind turbine electrical models
TRL4

Network Reduction
TRL3

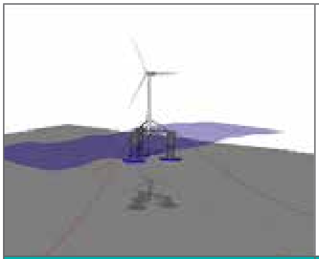


STAS linear State-Space Wind Power Plant Analysis
TRL4

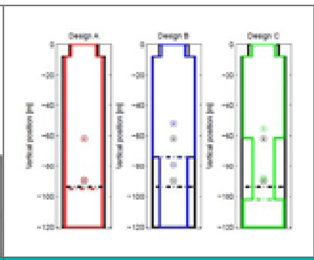
PM generator magnetic vibrations
TRL4

Technology/Process

Numerical model/method

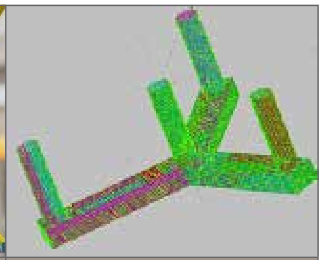


Simo-Riflex
TRL7

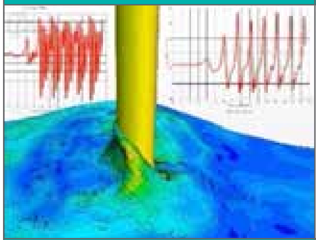


WindOpt
TRL4

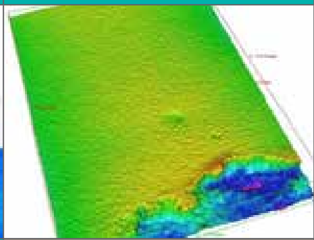
Real time hybrid model test in ocean basin
TRL5



Novel floater
TRL5



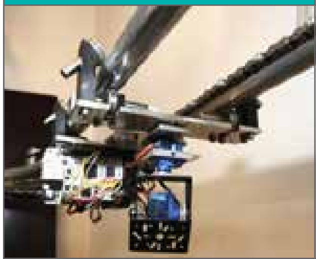
CFD simulation
TRL5



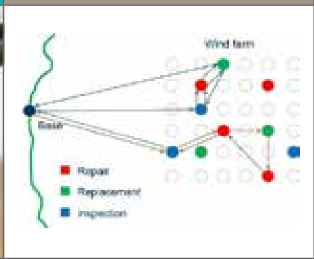
Droplet erosion resistant blade coatings
TRL3

Droplet erosion testing
TRL5

Fleet optimization
TRL5

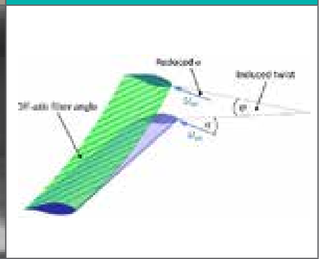


Remote Presence
TRL5



Routing and scheduling
TRL2

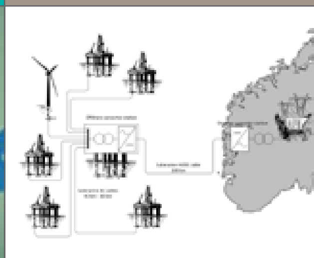
Thermally sprayed SiC coatings
TRL5



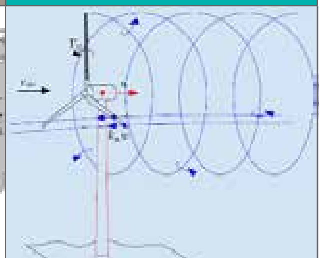
Buckling resistant blades
TRL3

Smartgrid Lab HVDC grid
TRL4

Control of multi-terminal HVDC grid
TRL4

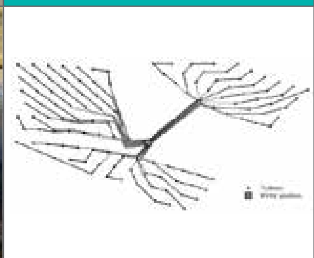


Wind Supply to Oil & Gas
TRL3

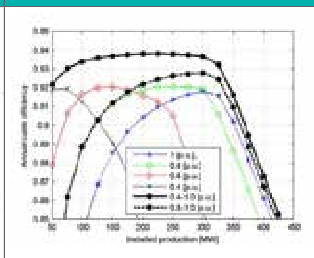


Turbine control
TRL3

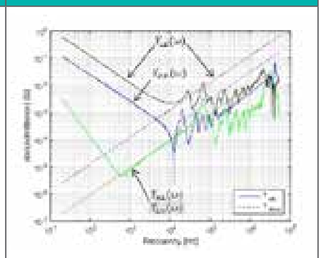
PM generator integrated design
TRL3



Wind farm collection grid optimization
TRL2



Long distance AC transmission
TRL3



Wideband model of wind farm collection grid
TRL2

Technology/Process

Numerical model/method

CENTRE PARTNERS AND ORGANIZATION

Nowitech partners

The NOWITECH research and industry partners have been

The Host Institution:
SINTEF Energy Research

Research Partners:
Norwegian University of Science and Technology (NTNU)
Institute for Energy Technology (IFE)
SINTEF Ocean and SINTEF AS

Industry partners:

Aker Solutions	[2009 – 2012]
Devold AMT AS	[2009 – 2012]
DNV GL	[2009 – 2017]
EDF Energy	[2009 – 2014]
Fedem Technology AS (SAP)	[2011 – 2017]
Fugro Norway AS	[2009 – 2012, 2015 – 2017]
GE Wind Energy	[2009 – 2012]
Kongsberg Maritime AS	[2013 – 2017]
Lyse Produksjon AS	[2009 – 2011]
Norsk Automatisering AS	[2015 – 2017]
NTE Holding AS	[2009 – 2013]
Siemens (CD-adapco)	[2013 – 2017]
SmartMotor AS	[2009 – 2015]
Statkraft Development AS	[2009 – 2017]
Statnett SF	[2009 – 2015]
Statoil Petroleum AS (Equinor)	[2009 – 2017]
Trønder Energi Kraft AS	[2009 – 2011]
Vestavind Kraft AS	[2009 – 2012]
Vestas Wind Systems AS	[2009 – 2012]
Ørsted (former DONG Energy)	[2009 – 2017]

Associate research partners:
Massachusetts Institute of Technology (MIT), USA
Michigan Technological University (Michigan Tech), USA
National Renewable Energy Laboratory (NREL), USA
DTU, Denmark
Fraunhofer IWES, Germany
University of Strathclyde, UK
TU Delft, Netherlands
Nanyang Technological University (NTU), Singapore

Associate industry partners:
Hexagon Devold AS
Enova
Energy Norway
Innovation Norway
Norwegian Wind Energy Association (NORWEA)
Norwegian Centres of Expertise Instrumentation (NCEI)
NVE
WindCluster Norway

Organisation of the centre

NOWITECH has been organized with a General Assembly (GA), a Board, a Centre Director, a Scientific Committee (SC), a Committee for Innovation and Commercialisation (CIC) and a Centre Management Group (CMG). The research activities were originally organised into six work packages from 2009 until 2014 when the work was combined into three work packages (WPs): Substructures and numerical tools (WPA), Operation & Maintenance and Materials (WPB) and Grid and Wind Farms (WPC). The organization of NOWITECH is shown in Figure 3.

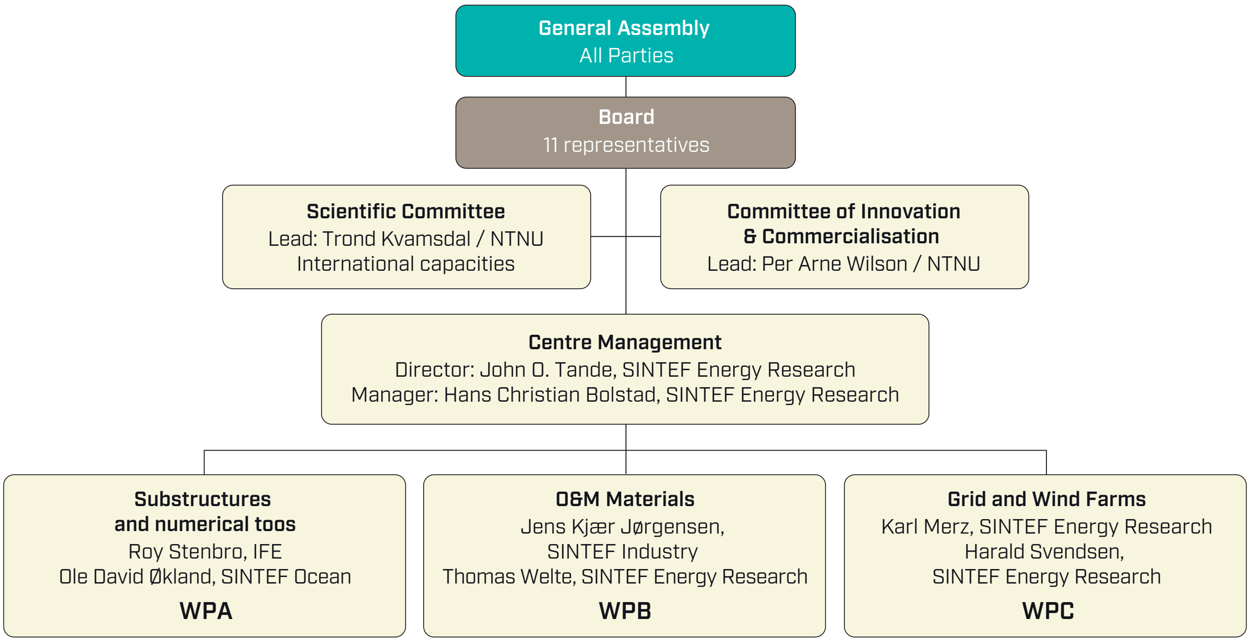


Figure 3: *Governance structure in NOWITECH.*

The cooperation within the centre has been excellent. The centre activities brought researchers, students and industry together, both to address specific scientific fields, but also across these, and fostered valuable relations, cooperation and accelerated research into offshore wind technology. The monthly management meetings, the meetings in the Scientific Committee, the WPs and engagement of the CIC, facilitated coordination, team building and gave focus towards excellence in research and innovations. The preparation of joint workshops like the NOWITECH day, the biannual Industry meets Science workshop, and the annual EERA DeepWind conference, as well as various more ad-hoc events and preparation of joint research strategies further strengthened the multidisciplinary team efforts. The board provided for excellent strategic guidance, and strengthened the interaction between industry and research. Figure 4 shows the main meetings, reporting events and how the annual work plans for the next year were prepared with spring and autumn industry meetings before approval by the Board in November/December.

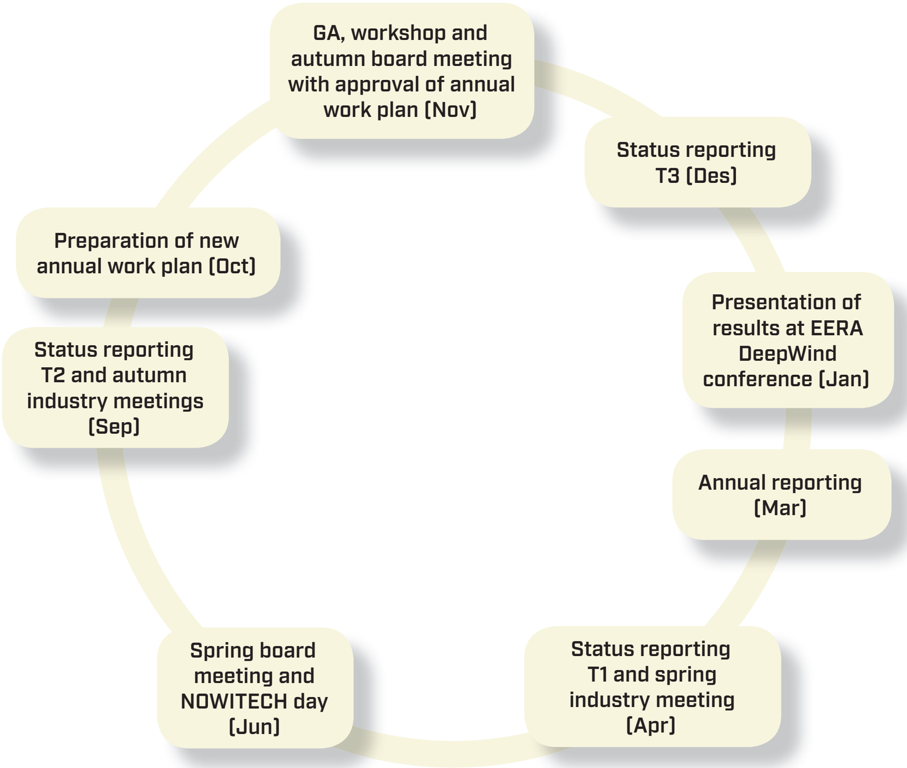


Figure 4: *NOWITECH annual cycle of works and main meetings.*

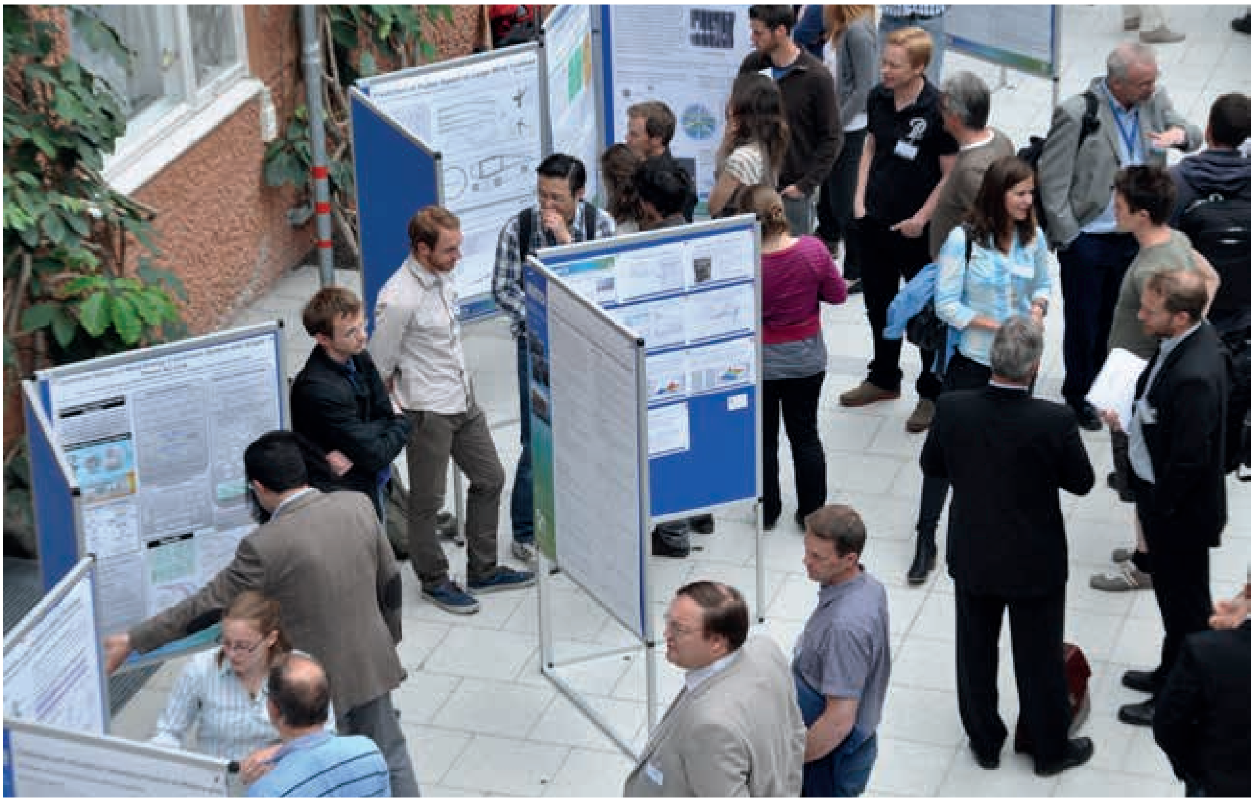


Figure 5: *The annual "NOWITECH day" workshop series was well attended with lively discussions, plenary presentations and posters by researchers and students. The picture is from the poster session of NOWITECH Day 2012.*

The board

The Board has been the operative decision-making body for the execution of the activities within the Centre. It has been comprised of eleven members whereof eight have been representatives of the industry partners and three have been from the research partners. The board reported to and was accountable to the General Assembly (GA). The Board monitored the implementation of the Centre and approved the annual working plans and budgets. It also oversaw that the activities described in the annual working plans were completed within the defined time frame, hereunder that the in-kind contributions are delivered as specified.

Board meetings have mostly been held in Trondheim, but also at the R&D and industry partner premises, including at Vestas in Denmark and at DNV GL and IFE in Oslo. One board meeting was held at the newly opened SINTEF Energy Lab in Trondheim in December 2015. Many board members also used the kind opportunity given by Statoil to participate in an excursion to the Hywind assembly site at Stord in May 2017.

The December meetings had a separate workshop connected to the Board meetings which presented the scientific results from the work packages and was combined with the annual GA meeting. Both board meetings had innovations and strategy for development of NOWITECH on the agenda. Separate strategy meetings have been well attended and in particular the May 2015 meeting at Gardermoen was a very fruitful meeting laying new strategic directions for the remainder of the centre period.

In the later years of the Board an additional fixed item on the Agenda was current status and outlooks as seen from each of the partner member. This gave a good overview of the ongoing industry and market activities and formed an integral part of the following discussions on NOWITECH priorities.

The strong commitment and competence of the Board has been highly appreciated.

Figure 6: *Board members and observers were thanked for their efforts in the final meeting in August 2017. Present were from the left Michael Muskulus, NTNU, Petter Andreas Berthelsen, SINTEF Ocean, Torbjørn Mansaker, DNV-GL, Trond Kvamsdal, NTNU, Olav Fosso, NTNU (chairman of the Board), John Olav Giæver Tande, SINTEF Energy Research, Eirik Skare, Kongsberg Digital, Amund Skavhaug, Norsk Automatisering AS and Knut Samdal, SINTEF Energy Research.*

Figure 7: *Actively engaged board members at the December 2015 meeting at SINTEF Energy Labs. The board members in 2015 were Olav Fosso (chairman), NTNU, Johan Sandberg/Marte de Piciotto, DNV GL AS, Martin Kirkengen, IFE, Knut Samdal, SINTEF Energi, Daniel Zwick, Fedem, Jørgen Krokstad, Statkraft, Gudmund Per Olsen, Statoil, and Oddbjørn Malmo, Kongsberg.*

Figure 8: *Meeting of the General Assembly November 2013. From left: Jørn Holm (Dong), Vincent De Laleu (EDF), Lars Kristian Vormedal (Statnett), Michael Muskulus (NTNU), Martin Kirkengen (IFE), Knut Samdal (SINTEF Energy), Øyvind Hellan (Marintek), Jan Onarheim (NTNU), Oddbjørn Malmo (Kongsberg), Gudmund Olsen (Statoil), John Olav Tande (SINTEF Energy), Johan Sandberg (DNV), Alexey Matveev (Smartmotor), Jørgen Krokstad (Statkraft) and Hans Christian Bolstad (SINTEF Energy).*

Centre management

John Olav Giæver Tande, Director NOWITECH

Hans Christian Bolstad, Manager NOWITECH

The objective of the Centre Management was to manage and coordinate the activities of NOWITECH, ensuring progress and cost control according to approved plans.

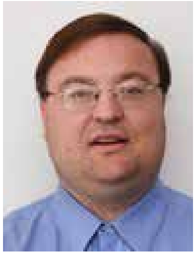
The Centre Management Group (CMG) was led by the Centre Director and consisted of a management team including Centre Manager, the Work Package leaders, the SC lead, vice-lead and secretary, the CIC chair and the project secretary of NOWITECH. Management staff was appointed to follow up on administrative, financial and legal issues supporting the Centre Director in the day-to-day operation of NOWITECH. The Centre Director and manager was responsible for progress and cost control of the project according to approved Working Plans. The Centre Director had the responsibility and the authority to execute management tasks in accordance with the Working Plan, the Consortium Agreement and the Contract and monitor Parties' compliance with their obligations.

The work was divided into Management and Outreach activites as outlined below.

The Management activity took care of the day-to-day operation of the Centre, scientific leadership and strategy development. The day-to-day operation included follow up on administrative, budgeting, financial and membership legal aspects, meetings in the CMG with WP leaders and representatives from the SC and CIC, preparations for the GA and Board, and reporting to the RCN. CMG meetings was held on a monthly basis through-out 2009-2017. These were for team-building, planning, follow-up, information exchange and strategic discussions.

The Outreach activity included preparing general presentations of the Centre, dissemination of results, keeping contact with industry parties, overall coordination towards other projects, relevant organisations and FMEs, in particular NORCOWE, and engagement in developing new offshore wind research projects and strategies. The Centre management was engaged in this also through CIC and SC. Dissemination activities by the management included hosting delegations visiting NOWITECH, preparation of media contributions, keeping web and e-room updated, preparation of newsletters, organization of the "Industry meets Science" seminars biannually together with WindCluster Norway and organization of the annual offshore wind R&D conference in Trondheim, EERA DeepWind.

Scientific committee



Trond Kvamsdal
NTNU, Chair SC

Michael Muskulus
NTNU, Vice-chair SC

The Scientific Committee (SC) developed a top-quality PhD and Postdoctoral programme in collaboration with the Centre Management. This included an active recruitment strategy, invitation of international experts for giving lectures, arrangements of scientific colloquia and seminars, and exposing scholars to industry and leading international research groups through NOWITECHs mobility programme.

The SC consisted of a core group with relevant NTNU professors and the Centre Director, and an extended group including researchers from SINTEF and IFE, the chair of NORCOWE's SC, and representatives of the associated international research partners.

The SC core group met more or less on a monthly basis to handle day-to-day operations regarding PhD and Postdoc programme, recruitment, educational issues, etc. The extended SC had two full meetings every year; one at the start of the year back-to-back with the EERA DeepWind conference in Trondheim, and one in the summer at various locations, both in Norway and in Germany and Denmark. These extended SC meetings involved an evaluation of the scientific content of NOWITECH's results and giving strategic advice on direction of research, and attention to the publication activity in NOWITECH.

Figure 10: *NOWITECH SC's meeting at DTU in Roskilde (Denmark) 17 June 2014 was very fruitful with review of research activities on grids, O&M and novel concepts, and with discussions on reference wind turbines and reference wind farms. The hospitality by DTU for hosting the meeting was greatly appreciated. From left: Tor Anders Nygaard, IFE, Thomas Buhl, DTU, Jørgen Krokstad, Statkraft/NTNU, Harald Svendsen, SINTEF Energi, Trond Kvamsdal, NTNU, Karl Merz, SINTEF Energi, Gerard van Bussel, TU Delft, Thomas Welte, SINTEF Energi, Olimpo Anaya-Lara, University of Strathclyde, Hans-Gerd Busman, Fraunhofer IWES, and Finn Gunnar Nielsen, Statoil/UiB (NORCOWE).*

Committee for Innovation and Commercialisation

Per Arne Wilson, NTNU, CIC Chair

The Committee for Innovation and Commercialisation (CIC) key task was to enhance the industry involvement and assuring that results from NOWITECH were tracked, analysed and communicated to the industry parties. Further CIC assured that the possibilities for establishing new projects, products, services or processes with one or more partners were pursued. Commercialisation was by transfer of knowledge to the industry parties and their use of this in developing their business, and through spin-off projects and the creation of new industry. The committee has been industry focused and chaired first by DNV and later by NTNU through Per Arne Wilson. CIC cooperated with NTNU's Entrepreneurship School (NEC) and NTNU TTO in commercialisation of ideas created in NOWITECH. Innovation Norway and Enova has assisted CIC in project development, including also between NOWITECH partners and SMEs outside NOWITECH. The CIC was instrumental in introducing the TRL-methodology in NOWITECH to ease communication of results, and has also been organizing the NOWITECH innovation award.

The NOWITECH Innovation Award was established in 2015 with the aim to stimulate and reward knowledge-based innovation and / or entrepreneurship within the field of offshore wind energy. The criteria for the award has been potential for reducing the cost of offshore wind energy, degree of novelty and commercial viability.

Figure 11: *NOWITECH Innovation award winners and illustration of innovations (from left) 2015 (HVDC generator), 2016 (hybrid test) and 2017 (long AC transmission).*

FINANCING

The financing of NOWITECH trough 2009-2017 is shown below.

Table 1: *Financing through 2009-2017 of NOWITECH including spin-off projects. The spin-off projects were carried out with separate contracts in alignment with NOWITECH providing added value, though the results of these projects are not listed in this report. Industry projects are not listed.*

Contributor	Cash	In-kind	Total
Host (SINTEF Energi AS)	0	18,2	18,2
Research partners (NTNU, IFE, SINTEF Ocean, SINTEF AS)	0	83,1	83,1
Private companies	52,3	27,2	79,6
RCN	160,0	0	160,0
SUM NOWITECH FME (MNOK)	**212,3**	**128,5**	**340,9**
Spin-off/affiliated projects			
RCN infrastructure	4,1	1,4	6,9
RCN competence projects	157,7	0	157,7
EU projects / International projects	91,1	22,8	113,8
SUM affiliated/spin-off projects*	**252,9**	**24,2**	**278,4**
TOTAL (MNOK)	**465,2**	**152,7**	**619,3**

* Estimated share of budget of affiliated/spin-off projects to one or more of the research partners of NOWITECH. The total budget of these projects was about NOK 1500 million.

RESEARCH

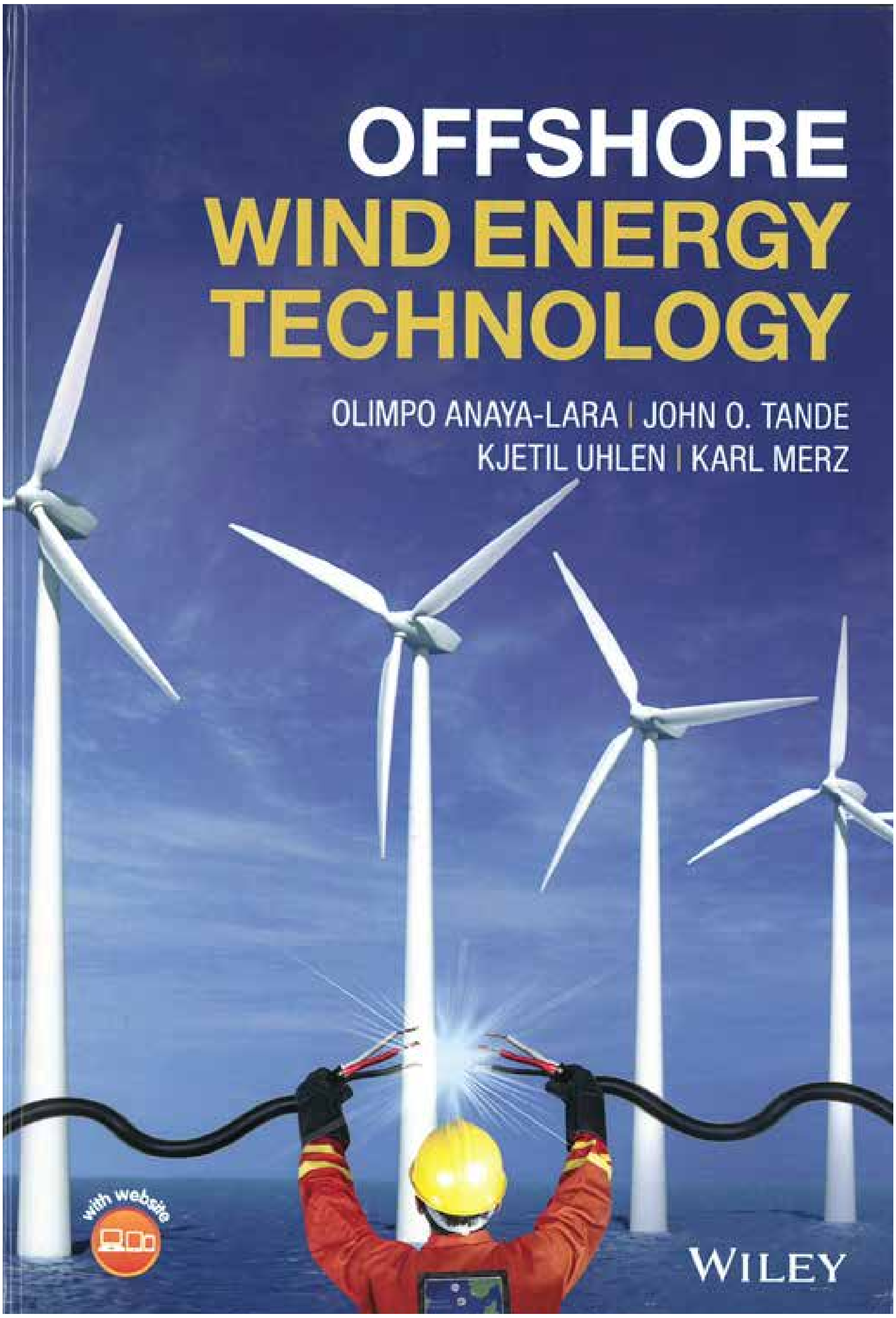


Figure 15: *Offshore Wind Energy Technology, ISBN: 978-1-119-09776-1, May 2018, 456 pages, offers a reference based on the research material developed by NOWITECH and material developed by the expert authors over the last 20 years. This comprehensive text covers critical topics such as wind energy conversion systems technology, control systems, grid connection and system integration, and novel structures including bottom-fixed and floating. The text also reviews the most current operation and maintenance strategies as well as technologies and design tools for novel offshore wind energy concepts*

Numerical tools and substructures

Ole David Økland,
WPA co-leader

Roy Stenbro,
WPA co-leader

The objective of WPA was to enhance development of novel substructures for offshore wind through development, validation and use of numerical tools and experimental campaigns. The work was divided into three tasks:

- Development and validation of numerical models,
- Assessment of novel design concepts
- Experiments and demonstrations

The main results of the work are summarized on the next few pages.

Numerical tools for the simulation of loads and load responses of offshore wind turbines are vital to those carrying out research, development and engineering of integrated wind turbines and their components.

This requires research within fields such as

- Wave, current and wind loads
- Subsystems (foundation, mooring, blades, etc.)
- Integrated models for global response

The verification and validation of tools has been an important aspect of research in NOWITECH, and has been achieved by means of extensive benchmarking and comparisons with available measured data.

Computational fluid dynamics (CFD) and fluid structure interaction

The state-of-the-art CFD tools used in NOWITECH offer the most insight into fluid dynamics phenomena, such as rotor performance under normal or abnormal operational conditions. They constitute part of our research and advanced engineering toolbox. IFE has used TAU software from DLR and STAR-CCM+ from CD-adapco to develop experimentally-validated and highly accurate methods for the use of these tools for wind turbine applications, see Figure 16.

More realistic predictions of wind turbine performance and loads offer many positive benefits to the wind energy industry. CFD is required when more realistic or detailed information is needed that cannot be provided by integrated simulations.

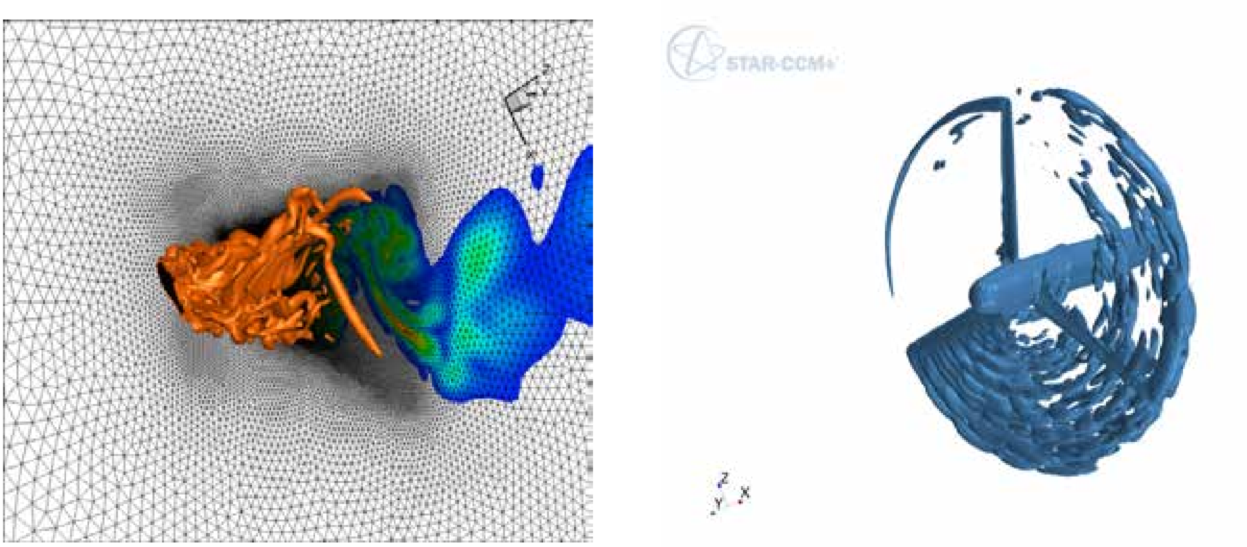


Figure 16: *Left: CFD simulation of an experiment involving a stalled wing section. Right: CFD simulation of an IEA MEXNEXT experiment involving a rotor in which one of the blades has a pitch fault.*

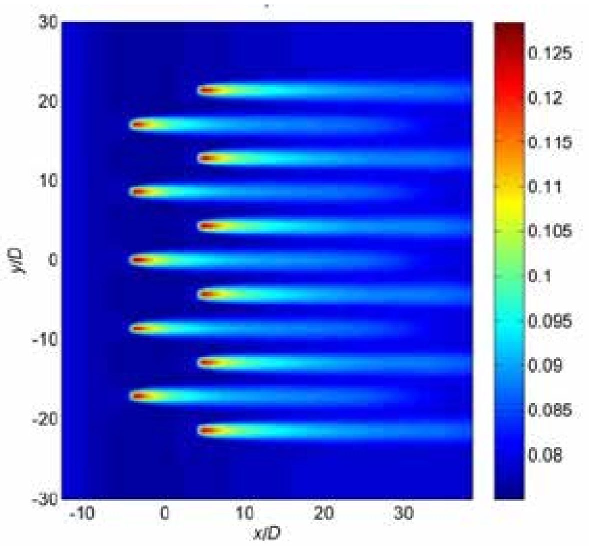


Figure 17: *Validation of 3DWind against measurements from the Vindeby offshore wind farm*

3DWind is CFD-based micro-scale wind and wind farm simulation software that has been under development at IFE since 1999. Its features include the simulation of complex terrain and/or marine conditions, turbines modelled as actuator discs, atmospheric stability, surface roughness and temperature, see also Figure 17. NOWITECH contributed to its development in the period 2010 to 2011.

The ability to accurately predict the behaviour of wind farm aerodynamics is important for power production forecasts, wind farm layout and turbine wind loads.

Isogeometric analysis is a recently developed computational approach that makes it easier to integrate finite element analysis (FEA) into conventional CAD design tools. Currently, data must be converted between CAD and FEA packages in order to analyse new designs during the development phase. This is a difficult task because the computational geometric approach for each package is different. Isogeometric analysis employs complex NURBS geometry (the basis of most CAD packages) directly in the FEA application. This allows models to be designed, tested and adjusted in a single step using a common data set. The Applied Mathematics Department, SINTEF ICT (SAM) and the Department of Mathematical Sciences at NTNU (IMF) have been working closely together to advance this new technology in the field of offshore wind engineering. This has been achieved by the development of an open source code IFEM written in C++ for modularity, and parallelised using the PETSc library to take advantage of state-of-the-art, high-performance computing facilities. The fluid structure interaction simulations are enabled by application of the same basic functions, see also www.fsi-wt.no.

Integrated engineering tools rely on simplification to make them straightforward and fast enough to meet volume engineering needs. The cost of this is a reduction in realism and increased uncertainties. CFD can be used when more accurate results are needed, such as in the case of larger waves or complex substructures. IFE has focused on developing experimentally-validated and highly realistic approaches to the CFD-modelling of sea loads on off-shore wind turbines using commercial CFD software. This work has been carried out using STAR-CCM+ soft-ware, and in collaboration with Siemens (CD-adapco).

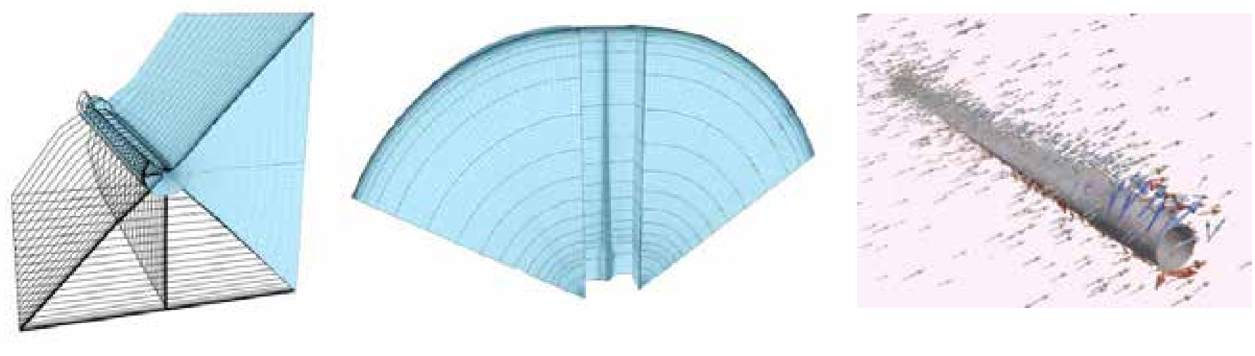


Figure 18: *Selected results of isogeometric analysis and fluid structure interaction.*

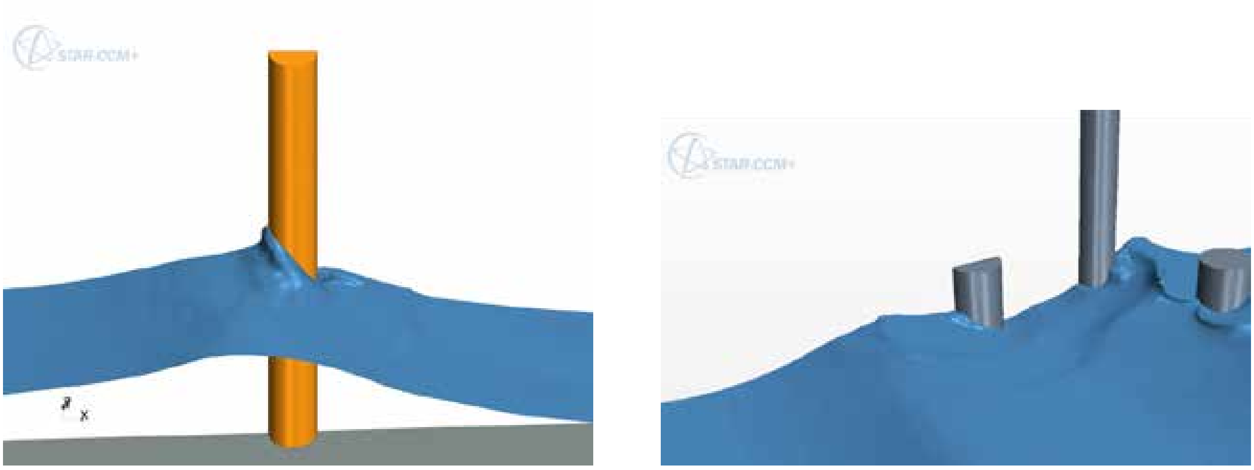


Figure 19: *Left: Validation of CFD-modelling against the NTU/DHI monopile experiments. Right: Validation of CFD-modelling against the model test of a semi-submersible conducted by IFE at Ecole Centrale de Nantes, France.*

SIMA and 3DFloat – Industry tools for integrated simulations of offshore wind turbines

NOWITECH has contributed to the development of two different tools for the simulation of integrated global responses.

SIMA (SIMO and RIFLEX) is a leading industry tool for the simulation and engineering analysis of marine operations and offshore structures. As part of NOWITECH, the numerical engines (SIMO and RIFLEX) in SIMA have been extended to include an ability to simulate wind turbines in operation.

The extension of the software to include offshore wind turbines contains new features such as (a) the application of 3D-turbulent wind fields, (b) rotor aerodynamic loads (BEM with dynamic inflow and correction factors), (c) internal and external wind turbine control systems, elastic towers and rotor blades, and (d) second order wave kinematics.

The tools are typically used for the following applications (including for wind turbines):

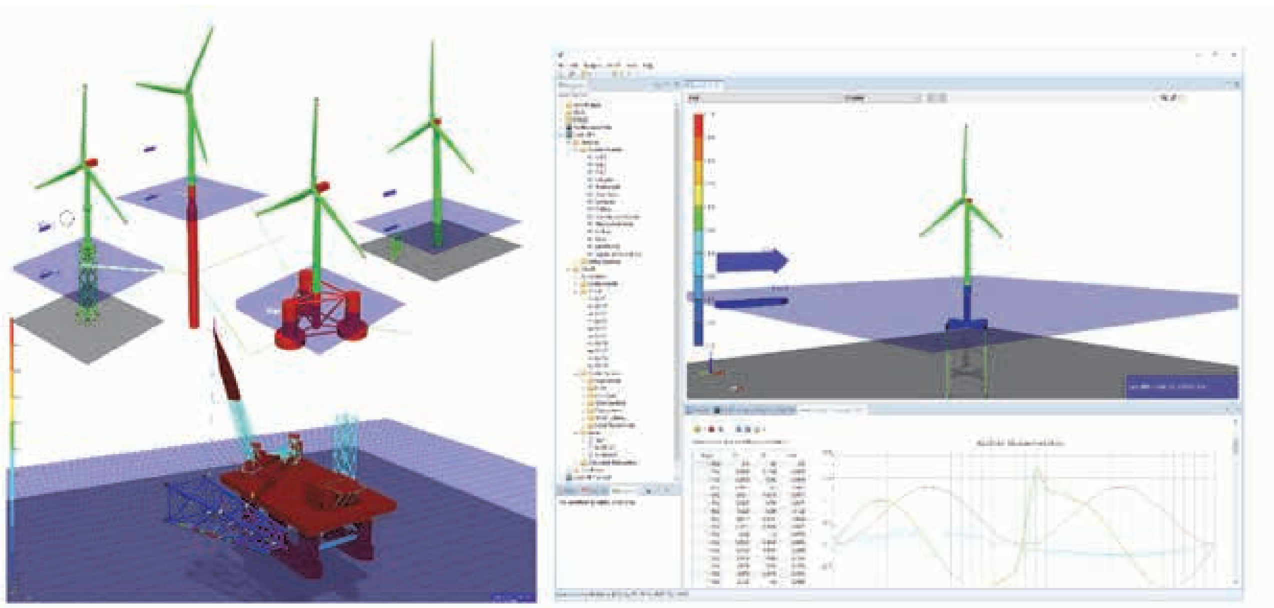


Figure 20: *SIMA (SIMO and RIFLEX) modelling tool used for integrated dynamic analysis*

- Motion analysis of floating structures
- Structural response analysis
- Mooring and power cable analysis
- ULS, ALS and FLS code checks
- Marine operations and installations
- Complex structures
- Multibody simulations
- Floating and bottom-fixed structures
- Design optimisation

SIMA (SIMO and RIFLEX) has been developed by SINTEF Ocean (formerly MARINTEK). NOWITECH has made an important contribution to the development, verification and validation of software used for the application directed at offshore wind technology. Statoil has also made an important contribution both to the development of the tools and to the inclusion of wind turbine features in the SIMA workbench.

IFE has developed its **3DFloat** software to enable simulations of onshore wind turbines, as well as bottom-fixed or floating structures offshore. The software can also be applied to other structures exposed to sea and/or wind loads, and has become one of the most advanced and complete fluid-elastic tools for offshore wind turbine simulation. It has, for example, advanced functionality for the modelling of aspects such as structural mechanics, wind fields, aerodynamics, wave kinematics, sea loads, mooring systems, geotechnics and controllers. NOWITECH's contribution has been important for the continuing development and validation of 3DFloat, and has enabled IFE to become one of the most active contributors to the IEA Wind OC3/4/5 project, in which most of the world's integrated model developers meet and work together to improve their simulation tools. The project has been key to raising the global level of integrated wind turbine modelling.

Figure 21: *3DFloat simulations of the OO-Star Wind Floater*

Assessment of novel concepts

Alternative and novel design concepts for offshore wind turbines have been assessed in analytical studies using numerical tools supported by experiments and demonstrations. An important outcome of this activity has been the assessment of relevant design criteria for a variety of bottom-fixed and floating concepts.

NOWITECH researchers have worked on many offshore wind turbine concepts, both during the development phase and with the investigation of optimal computer simulation approaches and model tests. Initially, focus was directed exclusively towards floating concepts, but in recent years bottom-fixed turbines have also been included in the research activities, see Figure 22.

The 5-MW-CSC is a design prepared as part of Chenyu Luan's Ph.D study at NTNU funded by NOWITECH. It was inspired by Olav Olsen's concrete semi-submersible concept, but differs being a brace-less steel semi-submersible platform designed to support the 5-MW NREL reference wind turbine at offshore sites exposed to harsh environmental conditions in areas such as the northern North Sea. Numerical analyses show that the 5-MW-CSC has excellent intact stability, well-designed natural periods and modes, and adequate structural design. Compared to spar and TLP wind turbines, the semi-submersible design exhibits greater flexibility with respect to water depth and is easier to install since it is fully assembled in dock. Conventional semi-submersibles consist of pontoons and columns connected by braces to form an integrated structure. At any given joint, a column could be connected by several braces. Joint welding can be a very complex and expensive process, and the fatigue life of joints can become a highly critical issue due to stress concentration in the joints. Structural

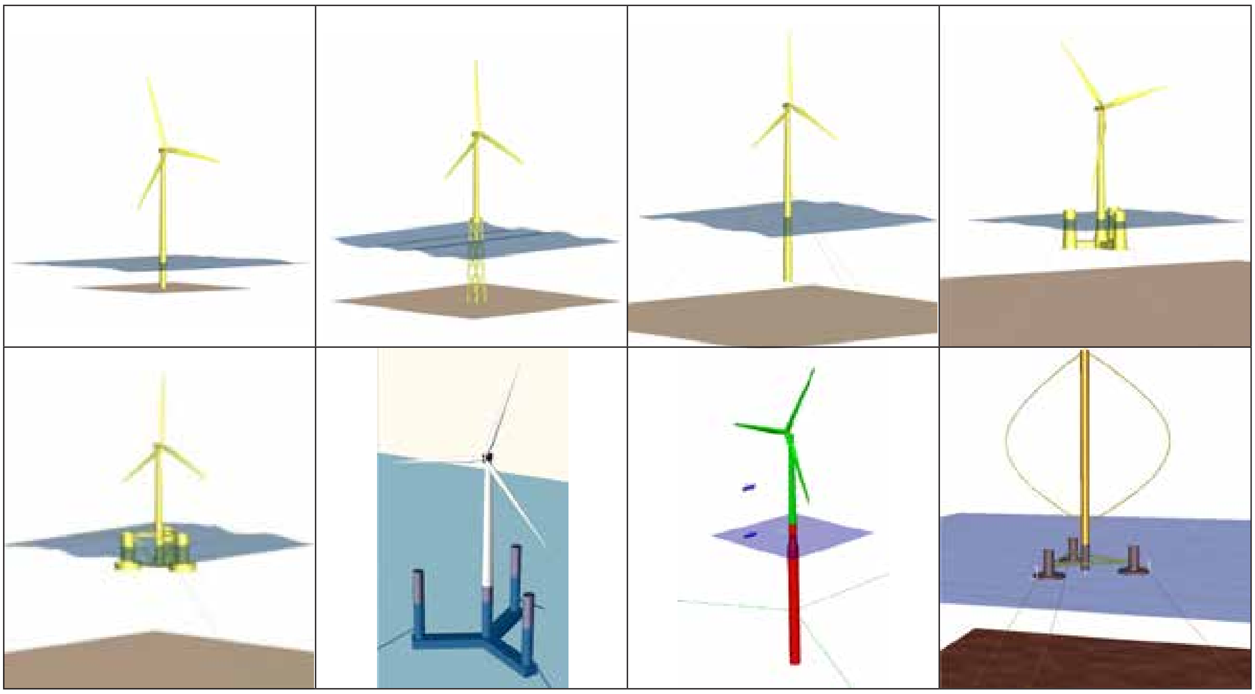


Figure 22: *Various substructures concepts investigated in NOWITECH. All are for a 5 MW turbine (from upper left): IEA Monopile, IEA Jacket, IFE TLB, Olav Olsen concrete semi, IEA semi, NTNU CSC steel semi, IEA Spar and VAWT Semi.*

complexity is reduced in the 5-MW-CSC by only using pontoons and columns. The pontoons provide considerable added mass and viscous damping in response to heave, roll and pitch. For this reason, complex and expensive additional heave plates, which could be used to prevent heave-resonant motions excited by first order wave loads, are not required. Considerations related to opportunities to combine wave energy convertors to reduce total levelized energy costs were included in the design procedure, enabling the design of the 5-MW-CSC to accommodate flap-type wave energy convertors as well.

Figure 23: *Work by NOWITECH was awarded best poster at EWEA Offshore 19-21 November 2013, Frankfurt with the work: "Improved tower design for the NOWITECH 10 MW reference turbine" by Michael Muskulus, Eirik Christensen, Daniel Zwick and Karl Merz.*

Experiments and demonstrations

Experiments and demonstrations designed to validate numerical tools and support the development of innovative offshore wind farm technologies were assigned high priority in NOWITECH.

Researchers in NOWITECH have been involved in several model-scale test campaigns investigating wind, hydrodynamic loads, and the structural responses of a variety of offshore wind turbine concepts. Some of the tests have been carried out as joint efforts with other research programmes, while others are funded entirely by NOWITECH. Figure 24 shows some examples of such tests.

Experiments involving aerodynamic loads

A series of workshops were arranged as part of a collaborative blind-test effort between NORCOWE and NOWITECH to validate numerical models of wind turbine aerodynamic performance and wakes. The blind tests were carried out applying the wind tunnel at NTNU to generate experimental data, and thereafter the set-up was published and research groups were invited to try and recreate the data.

The first test focused on turbine performance and wake development behind a single model turbine. During the workshop, a total of 11 sets of predictions were submitted and assessed. This first blind test showed significant scatter in performance predictions, with a variation of several magnitudes in terms of predictions of turbulent quantities in the wake from the different contributions. In the second test, a second turbine aligned with the upstream turbine was included. Numerical results showed clear variations in the quality of predictions from the different modelling methods. During the third test workshop, held in 2013, the two model wind turbines were positioned with an offset equal to half a rotor diameter. The results showed that an LES simulation approach succeeded in simulating this complex flow case fairly well. During the fourth workshop held in Trondheim in October 2015, focus was directed on the effect of different turbulent inflow conditions on the performance of an aligned two-turbine setup. Test cases of low turbulent uniform inflow, highly turbulent inflow, and non-uniform, highly turbulent shear was investigated. The wake flow behind the upstream turbine was analysed. Five different groups contributed CFD simulations including RANS, LES and DES computations. A general improvement in results was observed over the years, and the workshops revealed the strengths and drawbacks of the various modelling methods, and emphasised the continuing importance of CFD code validation against well-constrained experimental datasets.

Hydrodynamic loads and responses for bottom-fixed offshore wind foundations

Slamming wave loads and soil structure modelling for bottom-fixed wind turbines have been important research topics in NOWITECH. NOWITECH has collaborated with NORCOWE in a laboratory experiment investigating wave slamming forces on shallow water truss structures as part of the EU HYDRALAB IV framework, conducted in 2013 at the Great Wave Flume (GWK) in Hanover.

A 7 metre-diameter monopile was evaluated in a test carried out at SINTEF Ocean's marine basin, in which the aim was to provide validation data for numerical codes related to second order load models, CFD calculations, short crested waves, slamming loads and ringing response.

An extensive array of instrumentation was used, providing measurements on wave profile and kinematics (with and without model), distributed forces acting on the pile, deflection of the pile, and global response (base shear and OTM). The results constitute a comprehensive set of data for computer code validation.

Figure 24: *Example tests carried out during NOWITECH. Upper left: Set-up of scaled wind turbines in wind tunnel at NTNU for one of the blind test workshops. Upper right: 1:50 model design test of the 5-MW-CSC, accommodating three flap-type wave energy convertors, carried out at ECN, Nantes. Bottom left: TLB model test carried out as part of the MARINNET programme in Nantes. Bottom middle: 1:30 hybrid model test of the 5-MW-CSC carried out at SINTEF Ocean. Bottom right: 1:40 model test of a 7 metre-diameter monopile carried out at SINTEF Ocean.*

Loads and responses for floating offshore wind turbines

A 1:30 model test, using a real-time hybrid model testing approach (ReaTHM^®), was carried out in SINTEF Ocean's marine basin in 2015. The ReaTHM^® approach is a NOWITECH innovation. The experimental and numerical results were compared and used to validate a numerical time-domain approach for determining the forces and moments in the structural components of floating wind turbines.

Real-time hybrid model testing involves combining advanced simulations and state-of-the-art experimental methods with an active control system to generate an innovative approach for the verification of the safety and efficiency of marine structures and operations.

Hybrid testing involves partitioning the physical system under study into two or more subsystems by which a physical subsystem is tested experimentally at model-scale while connected in real-time to a numerical subsystem, and simulated on a computer. The two parts interact with each other by means of a network of sensors and actuators.

The purpose of the real-time coupling of experimental and numerical methods is to address the issues inherent in classical (fully physical) wind-wave model tests of offshore wind turbines:

- The Froude/Reynold scaling conflict that necessitates a re-design of the rotor to achieve better modelling of aerodynamic loads
- A stochastic (uncertain) and inaccurate representation of wind generation, which can also have adverse effects on physical wave generation in the basin
- A lack of flexibility

The idea is to couple the following models in real time:

- A physical model of the substructure located in an experimental marine basin (subjected to waves and currents)
- A numerical model of the wind turbine (generating aerodynamic loads at the correct scale, from NREL's AeroDyn and TurbSim).

The network of sensors, actuators and control system that connect the aforementioned models required intensive development and validation. Figure 25 illustrates the method used.

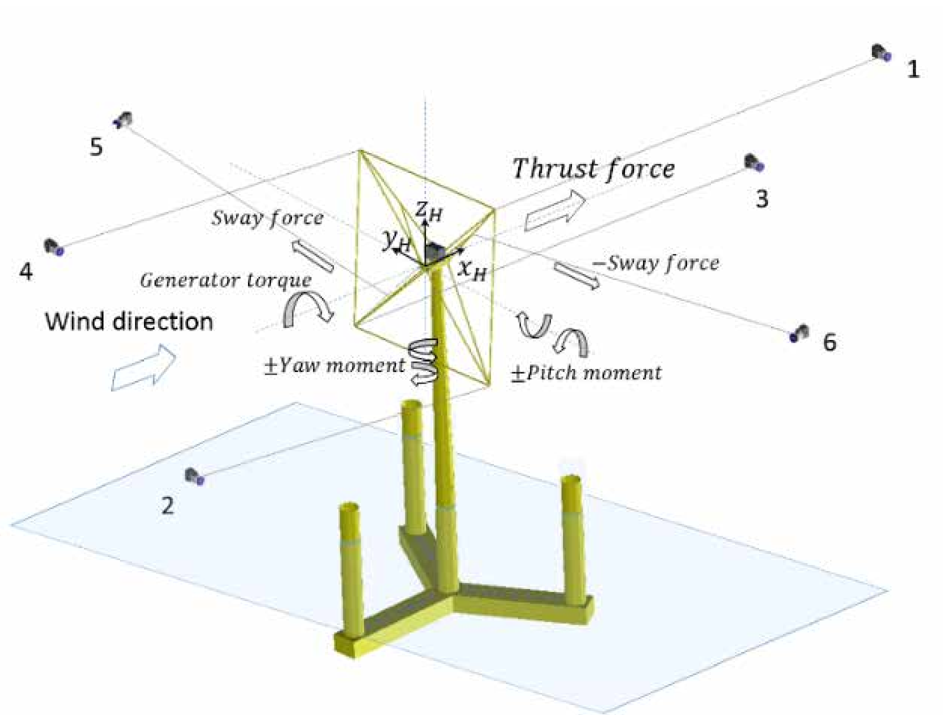


Figure 25: *Actuation of wind loads – conceptual design.*

Development of full-scale instrumentation

The Seawatch Wind Lidar Buoy is a floating meteorological ocean buoy that employs LIDAR (Light Detection and Ranging) to measure wind speed at different elevations above sea level. NOWITECH contributed to the start-up of the development phase. The buoy, which can drastically reduce the cost of data acquisition for currents, waves and wind at offshore sites, is now offered as a commercial product by Fugro Norway.

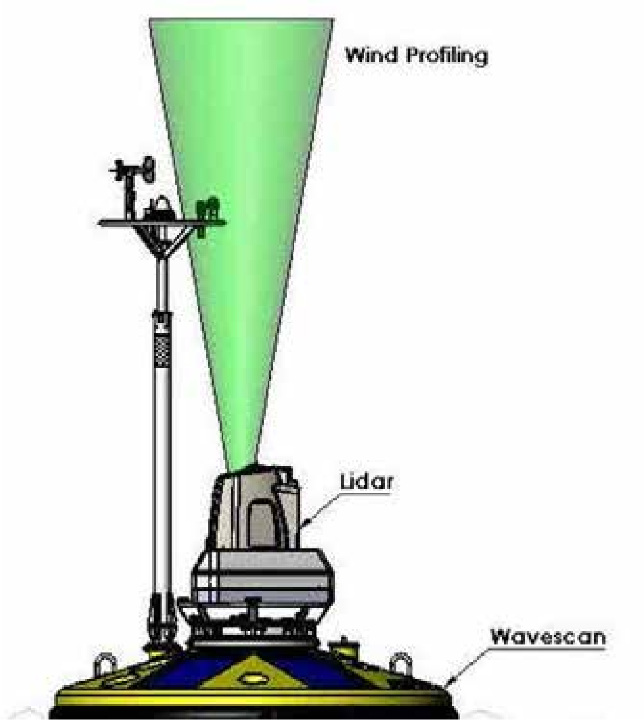
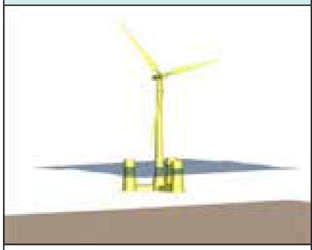
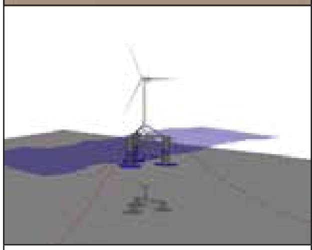
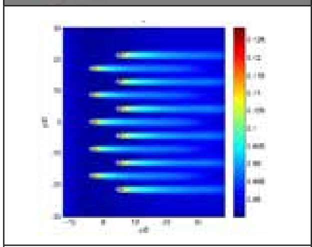
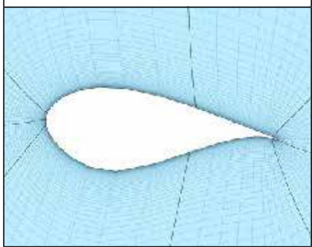
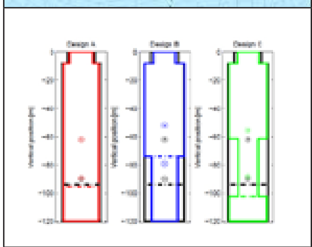
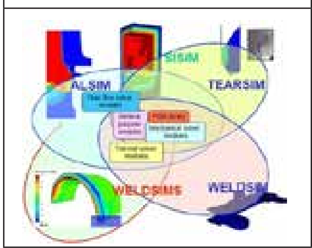


Figure 26: *The Fugro Norway floating meteorological ocean buoy that employs LIDAR to measure wind speed at different elevations above sea level.*

Technology/Process | Numerical model/method

RESULT/INNOVATION	DESCRIPTION	TRL	IMPACT
	**1 3DFloat integrated model** Simulation software for integrated modelling of offshore wind turbines (OWT) and substructures	7	Integrated OWT models are essential to research and engineering. The model is in commercial use in the OWT industry.
	**2 SIMO-RIFLEX** Simulation software for integrated modelling of offshore wind turbines and substructures	7	Integrated OWT models are essential to research and engineering. The model is in commercial use in the OWT industry.
	**3 3DWind** Offshore wind farm wake CFD simulation tool.	6	Understanding and simulation of the wake effects are essential to park layout, park energy prediction and important to turbine wind loads predictions.
	**4 IFEM-CFD** CFD fluid structure simulation tool	3	When further developed the model can be able to simulate how a deforming OWT interacts with sea and air, which can be important for example for advanced rotor research and engineering.
	**5 Variation Multiscale** Error Estimator	3	This method could be used to increased accuracy and/or speed numerical simulations, if it for example were implemented in CFD or FEM simulations software.
	**6 WindOpt** Spare buoy and semi-sub offshore wind turbine and mooring optimization software tool.	4	Can do cost optimized design of spar buoy and semi-sub type OWT substructure and mooring and minimize CAPEX in these areas.
	**7 INVALS** General and offshore wind turbine optimization software tool.	8	When coupled with another model this software is able to cost optimize systems or components and minimize LCOE. Such tools are commonly used in many industries. It has been used for rotor, mooring and tower optimization. Services provided to the OWT industry.

Technology/Process | Numerical model/method

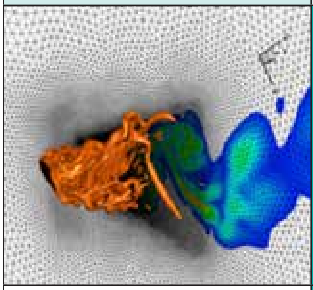
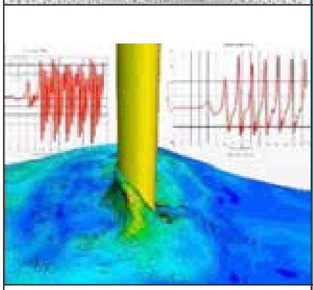
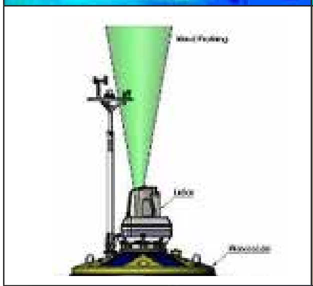
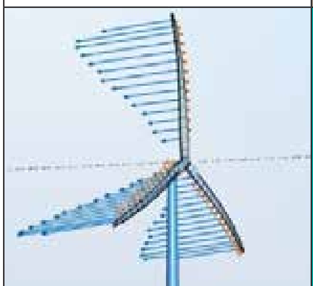
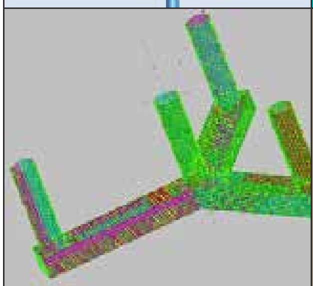
RESULT/INNOVATION	DESCRIPTION	TRL	IMPACT
	**8 Commercial grade rotor CFD** Use of commercial CFD software simulations for wind turbine aerodynamics	5	State of the art CFD tools are the computer tools we have that can offer the most insight into fluid dynamics phenomena, for example rotor performance under normal or faulty operations. It's part of the standard toolbox for advanced research and engineering.
	**9 CFD Simulation** Use of commercial CFD simulation tools for OWT hydrodynamics	5	Integrated engineering tools rely of simplification to be simple and fast enough for engineering needs. The cost of this is reduced realism and uncertainties. CFD can be used when more accurate results are needed, e.g. in the case of larger waves..
	**10 Seawatch Wind Lidar Buoy** Fugro Norway floating met-ocean buoy with LIDAR for measuring wind speed at different heights above sea level.	9	NOWITECH contributed to the start-up of this development. It is now offered as a commercial product by Fugro Norway. It can drastically reduce the cost of collecting data on current, waves and wind at an offshore site.
	**11 ASHES** Ashes is a software that performs integrated analyses of onshore and offshore wind turbines.	7	Since the beginning, a main focus for Ashes has been to provide the best user experience possible while at the same time still producing excellent numerical results.
	**12 Novel Floater** Design of braceless semi-submersible platform for 5 MW wind turbine	5	Novel design of braceless semi-submersible platform for 5MW horizontal axis wind turbine
	**13 Real-time hybrid** model testing in ocean basin	3	In real-time hybrid model testing, wind loads are applied via a set of actuators. This experimental technique allows obtaining correct non-thrust wind loads, which is a major improvement compared to tank tests with physical wind.

Figure 9: *From the visit May 2017 with the NOWITECH board and management at the Statoil Hywind Scotland assembly site in Stord, Norway.*


2°

Operation & maintenance, and materials

Thomas Welte,
WPB co-leader

Jens Kjær Jørgensen,
WPB co-leader

The objective of WPB was to contribute to the reduction of cost of energy of offshore wind power through development of new and cost-effective O&M concepts and strategies, through efficient and optimized use of material and coatings, and through development of new coatings and improved models for structures and materials. Selected results include:

- Offshore wind farm O&M and logistics modelling
- Remote inspection and condition monitoring
- Modelling and analysis of drivetrains in offshore wind turbines
- Self-adaptive blade design
- Protective coatings
- Testing and modelling of composite materials

The above points are summarized on the next few pages.

Offshore wind farm O&M and logistics modelling

Operations and maintenance (O&M) costs, i.e. operational expenditures (OPEX), constitute one of the major contributions to the Levelized Cost of Energy (LCOE) for offshore wind farms. A challenge facing offshore wind farm O&M is the limited opportunity to access the turbines to carry out maintenance. This calls for new O&M and logistics solutions and strategies. As assessment of the various approaches available, and subsequent selection of the optimum approaches, requires effective modelling tools for maintenance and logistics decision support. For this reason, NOWITECH has developed O&M and logistics models and tools that assist decision-makers, such as wind farm owners and operators, in identifying and selecting the best solutions and strategies.

The O&M and logistics tools developed in NOWITECH address decision-making issues at different time-scales. These range from strategic (long-term) decisions, such as those linked to the optimal O&M vessel fleet serving an offshore wind farm, to operational (short-term) decisions, such as daily visiting schedules for the various turbines. The tools employ both simulation approaches, such as Monte Carlo, and optimisation methods such as mathematical optimisation. The following tools have been developed in NOWITECH:

- NOWIcob: a simulation tool for strategic decision-making
- Vessel fleet optimization models: optimisation tools for strategic decisions regarding optimal vessel fleet size and mix
- A routing and scheduling model: an optimisation tool for operational decisions regarding maintenance scheduling and vessel routing, essentially answering the question: What turbines to visit in what order, and using what resources?

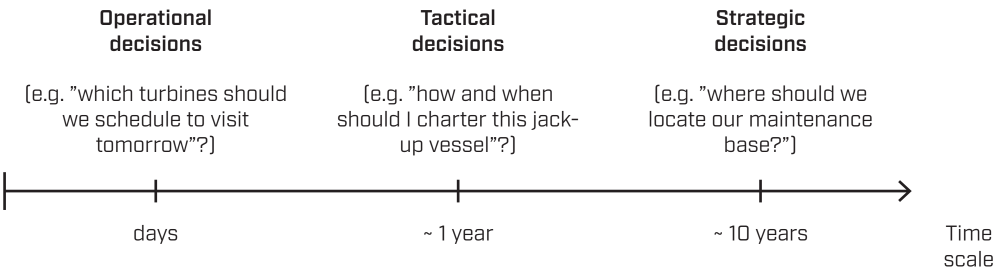


Figure 27: *Time scales of decisions linked to offshore wind O&M.*

Investigations have also been carried out into a concept combining condition-based monitoring with mathematical optimisation models (TeCoLog). NOWITECH O&M and logistics tools contribute towards reducing the economic risk inherent in wind farm maintenance and investment decisions. They result in cost savings by providing optimised O&M strategies and supporting better/optimal decisions. Other benefits include an ability to assess and quantify uncertainties that may influence risks and decision-making.

Research achievements

In the eight years since NOWITECH was established, the number and maturity of O&M decision support tools has increased substantially, and the work carried out in NOWITECH has been at the global cutting edge of this development. In particular, the Norwegian research community developed through NOWITECH has pioneered the use of advanced mathematical optimisation methods in combination with more traditional simulation approaches for solving O&M and logistics decision problems.

Moreover, a great deal of research has been focused on investigating the impact of a variety of modelling assumptions linked to aspects such as failure and degradation modelling, and the dependence of vessel accessibility on multiple met ocean parameters, as well as on assembling reference data sets that have subsequently been widely used by researchers for benchmarking and supplementary model verification and validation.

Increases in the size of current and projected offshore wind farms, and in their distance from shore, broadens the solution space for O&M and logistics decision support. Consequently, the benefits of complementing simulation models with optimisation models become more apparent. Research work carried out in NOWITECH, and especially that addressing O&M and logistics optimisation, has contributed by laying the methodological foundations that have enabled the international research community to address these future challenges. NOWITECH O&M models have made an instrumental contribution as a foundation for research carried out at European level.

Models developed in NOWITECH

NOWIcob

NOWIcob (an abbreviation for the Norwegian Off-shore Wind power life-cycle cost and benefit tool), is a strategic decision support tool based on a discrete-event Monte Carlo simulation model for maintenance activities and related logistics. It can be applied throughout the operational phase of offshore wind farms. It can be used as an analytical modelling tool for different aspects of offshore wind

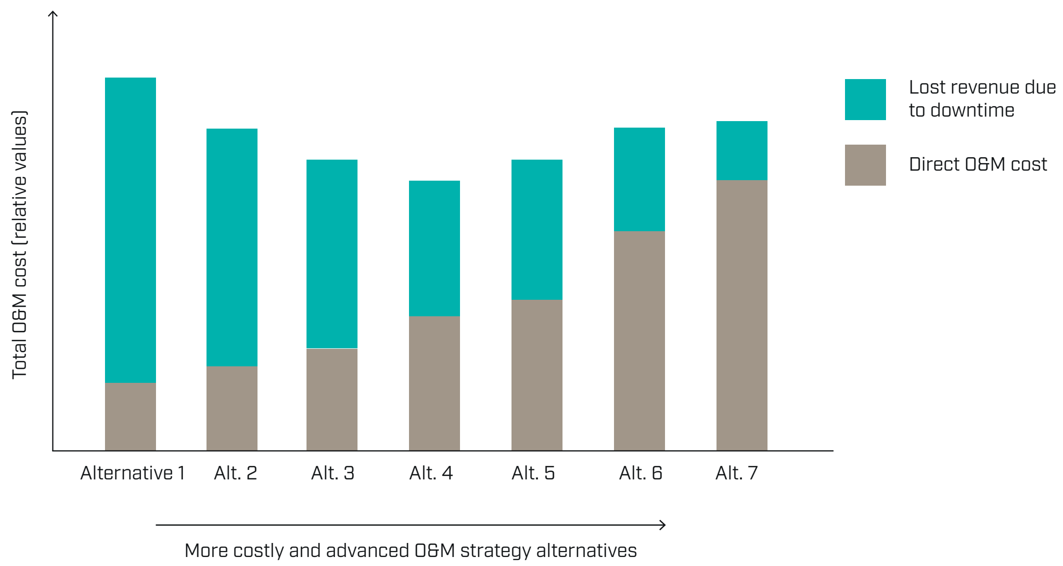


Figure 28: *Diagram illustrating O&M optimisation by means of identifying the optimal trade-off between O&M costs and lost revenues due to turbine downtime.*

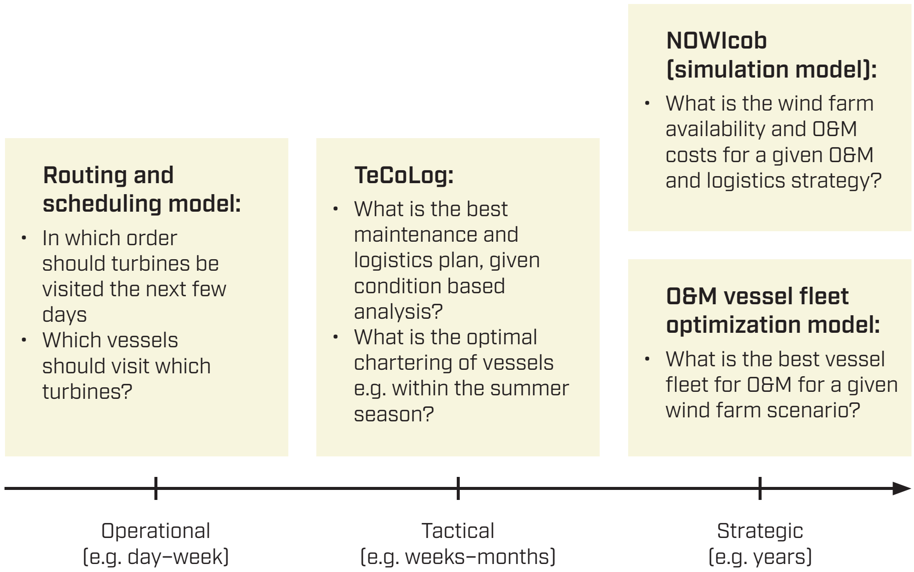


Figure 29: *Overview of operational, tactical and strategic decision support tools and concepts developed in NOWITECH and in connection with related projects, including examples of the problems they can address.*

farm maintenance and logistics strategies, such as the estimation of wind farm accessibility and decision support linked to the selection of maintenance vessels.

The model has been developed by SINTEF Energy Research as part of the NOWITECH project, together with spin-off projects such as FAROFF (an Innovation Project for Industry), and the LEANWIND EU FP7 project. Several of NOWITECH's industry partners have been granted user licenses for the tool for a variety of purposes. Moreover, SINTEF Energy Research has provided separate analytical services based on the tool. Most notably, NOWIcob has been used by NOWITECH's industry partners Statkraft and Statoil to perform analyses in connection with the development of the next generation of wind farms, such as Dudgeon and Dogger Bank. Several additional user licenses have also been granted to third parties as part of diverse collaborations.

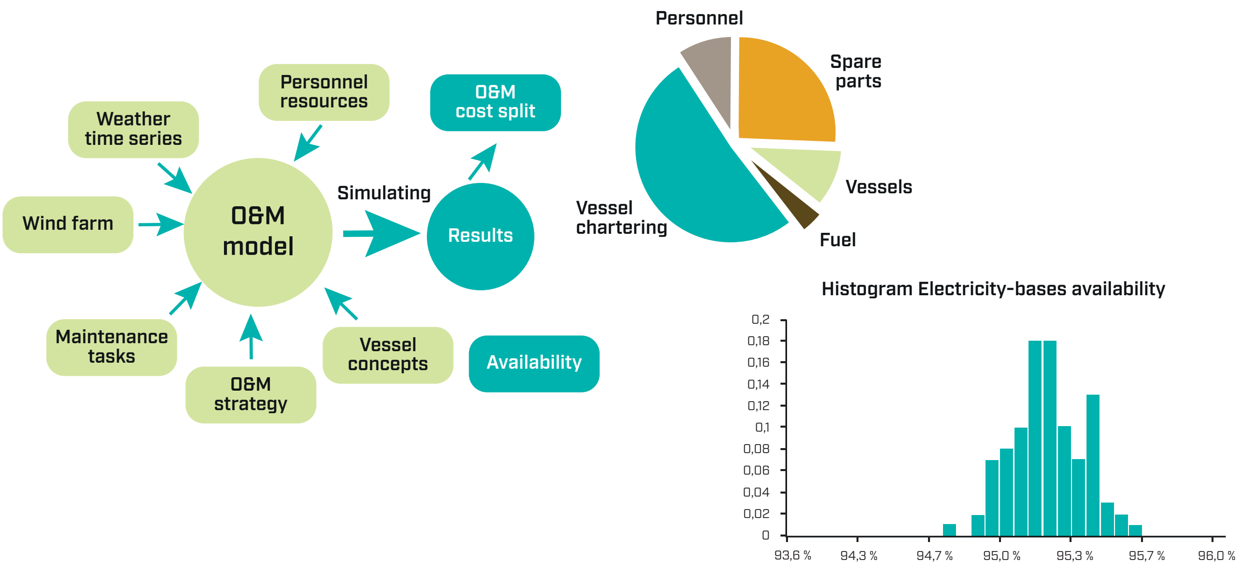


Figure 30: *Diagram showing input and output parameters to the NOWIcob model.*

Vessel fleet optimisation models

The vessel fleet optimisation models are logistics optimisation models aimed at determining cost-optimal vessel fleets and corresponding infrastructure (ports, offshore stations, etc.) for O&M carried out at offshore wind farms. The models will also generate optimal schedules for maintenance tasks, taking both task prioritisation and turbine accessibility into account.

The software prototype was developed by SINTEF Ocean (formerly MARINTEK) in co-operation with industry participants in the NOWITECH project, FAROFF (a NOWITECH spin-off project) and the EU LEANWIND project. In the same way as for NOWIcob, the prototype has been used for analyses in connection with the development of the next generation of wind farms. Statkraft and Statoil have been the most notable industry participants.

Routing and scheduling model

The routing and scheduling model is an operational logistic decision support tool aimed at optimising vessel routing and maintenance schedules during O&M carried out at wind farms. Underlying challenges include the fact that while some turbines in need of repair require maintenance technicians only, others will require parts replacement and others an inspection. The operational challenge is to find a turbine visiting route and schedule for each vessel that minimises the total costs incurred in connection with vessel operation, technicians, spare parts and down-time costs up until the time when the tasks in question are completed.

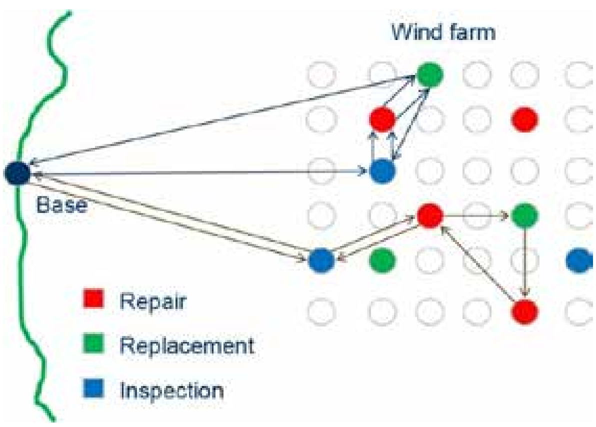


Figure 31: *Illustration of the routing and scheduling problem.*

Remote inspection and condition monitoring

The need for frequent manual (i.e. manned) inspections and maintenance visits to turbines are key cost drivers during O&M carried out on offshore wind turbines. For this reason, maintenance and inspection solutions that enable reductions in the number of turbine visits could result in significant economic benefits. This was the motivation behind the development in NOWITECH of remote inspection and condition-monitoring solutions for wind turbines, combined with cost-benefit analysis.

Relevant solutions that enable reductions in turbine visits include systems both for performing remote or automatic inspection and maintenance tasks, and for the continuous condition-monitoring of wind turbine components. A remote presence concept was developed and investigated as part of the NOWITECH project. Furthermore, NOWITECH conducted analyses of the benefits of installing remote inspection and condition-monitoring systems in wind turbines. These analyses were carried out in close collaboration with NOWITECH's industry partners, *Norsk Automatisering*, which has developed the remote presence concept, and *Kongsberg*, which has developed and provided condition-monitoring systems for wind turbines.

Remote inspection

The concept of remote presence, involving a system for remotely controlled inspections of a wind turbine, has been analysed and developed in NOWITECH in collaboration with NOWITECH's industry partner *Norsk Automatisering.* The resulting system consists of a remotely-controlled robot installed on a monorail arrangement inside the nacelle of the turbine. The aim was to enable the wind turbine operator to conduct visual and audio inspections inside a turbine nacelle as a means of improving decision support without the need to transport technicians to the turbines.

Parts of the development process for this system were carried out by Øyvind Netland, a NOWITECH-funded Ph.D student. He performed laboratory tests on a pilot installation to assess the feasibility and usability of a remotely-controlled robot. Netland and *Norsk Automatisering* jointly followed up the laboratory work with field tests using a remote inspection prototype installed in a real turbine. The tests demonstrated that remote inspection is a viable approach, and worth considering in situations where manned inspections are difficult or expensive to complete, as is frequently the case for offshore wind turbines. Thus, the remote presence concept was developed within the NOWITECH project period from a conceptual (TRL 2) to a prototype state (TRL 5). Further developments and additional pilot tests are currently being carried out by *Norsk Automatisering* and a new company called EMIP that was established in 2015 to further develop the remote inspection system to the level of a fully commercial product.

Cost benefits of remote inspection and condition-monitoring systems

The O&M simulation tool NOWIcob has been used to simulate a variety of strategies linked to the inspection and condition-monitoring of offshore wind farms. Several analyses were carried out and showed that both remote inspection and condition-monitoring systems contribute to increased accessibility and cost reductions. Cost reductions are a direct result of the need for less frequent visits to the turbines. Moreover, the number of unplanned, corrective maintenance tasks are reduced because information about the condition of the turbines' components captured by the remote inspection and monitoring systems enable the wind farm operator to plan, schedule and perform necessary preventive maintenance tasks that prevent costly failures. The cost-benefit analysis also shows that remote inspection such as the remote presence system by Norsk Automatisering gives added value compared to condition-monitoring only.

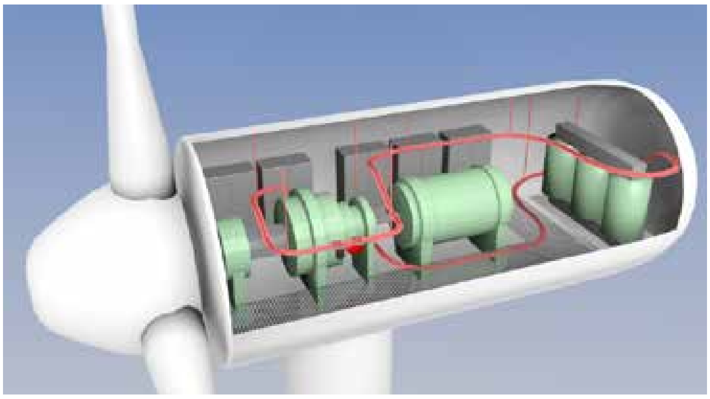



Figure 32: *left: A conceptual drawing of a remote presence system installed in a wind turbine nacelle.* Illustration: Ø. Netland. *Right: A remote inspection high-fidelity prototype.*

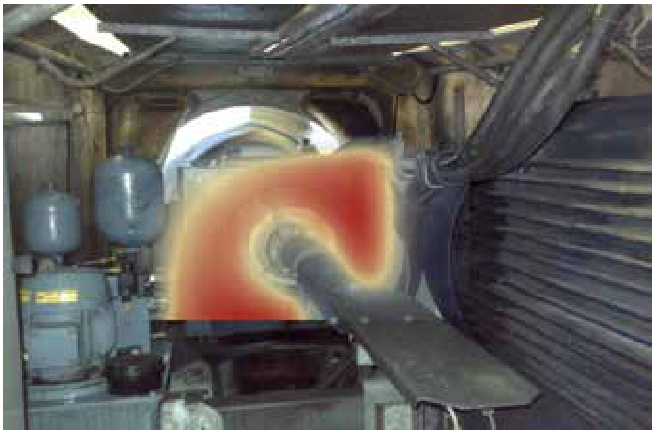



Figure 33: *Pilot installation of remote presence system (left) and sample image taken by the system (right).*

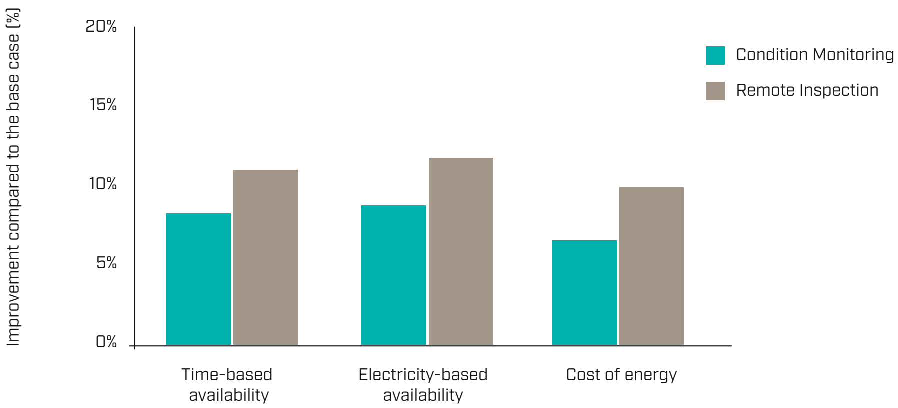


Figure 34: *Results from cost-benefit analysis condition monitoring and remote inspection systems. The analysis is carried out using NOWIcob. Details of analysis is given in Energy Procedia:* https://doi.org/10.1016/j.egypro.2014.07.233.

Modelling and analysis of drivetrains in offshore wind turbines

The drivetrain is the heart of the wind turbine, which converts kinetic energy into electrical power. A turbine's gearbox is not the component with the highest failure rate, and nor is gearbox reliability in the wind industry necessarily lower than that in other industries. However, extended periods of costly down-time mean that there is a great incentive to obtain new knowledge and information about potential failures in order to save time and money for the wind turbine operators. NOWITECH has been conducting several activities addressing gearbox reliability, carried out by Ph.D student Amir Nejad.

Work in NOWITECH has involved the development of drivetrain models and their use for a variety of analytical purposes. Modelling was based on the decoupled analysis approach consisting of (i) global response analysis to obtain forces and moments on the drivetrain main shaft, and (ii) a detailed gearbox model using Multibody System (MBS) modelling to obtain loads on gearbox components. The results from the analysis were used as input to studies on gearbox design, reliability, condition monitoring and inspection planning.

Gearbox design and reliability analysis

A 5-MW reference gearbox for offshore wind turbines was developed. In order to meet required fatigue and extreme load criteria, the design was based on first principles. A reliability method was also developed for these turbines.

Drivetrains for floating wind turbines

The lifetimes of gears and bearings in the gearboxes of floating wind turbines were studied and compared with those installed in fixed, land-based turbines. It was found that some components, such as main

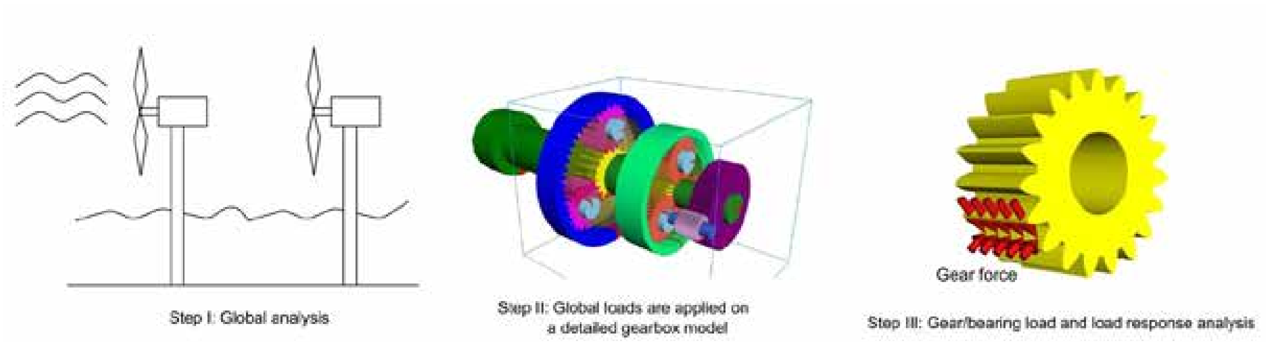


Figure 35: *The drivetrain decoupled analysis method.*

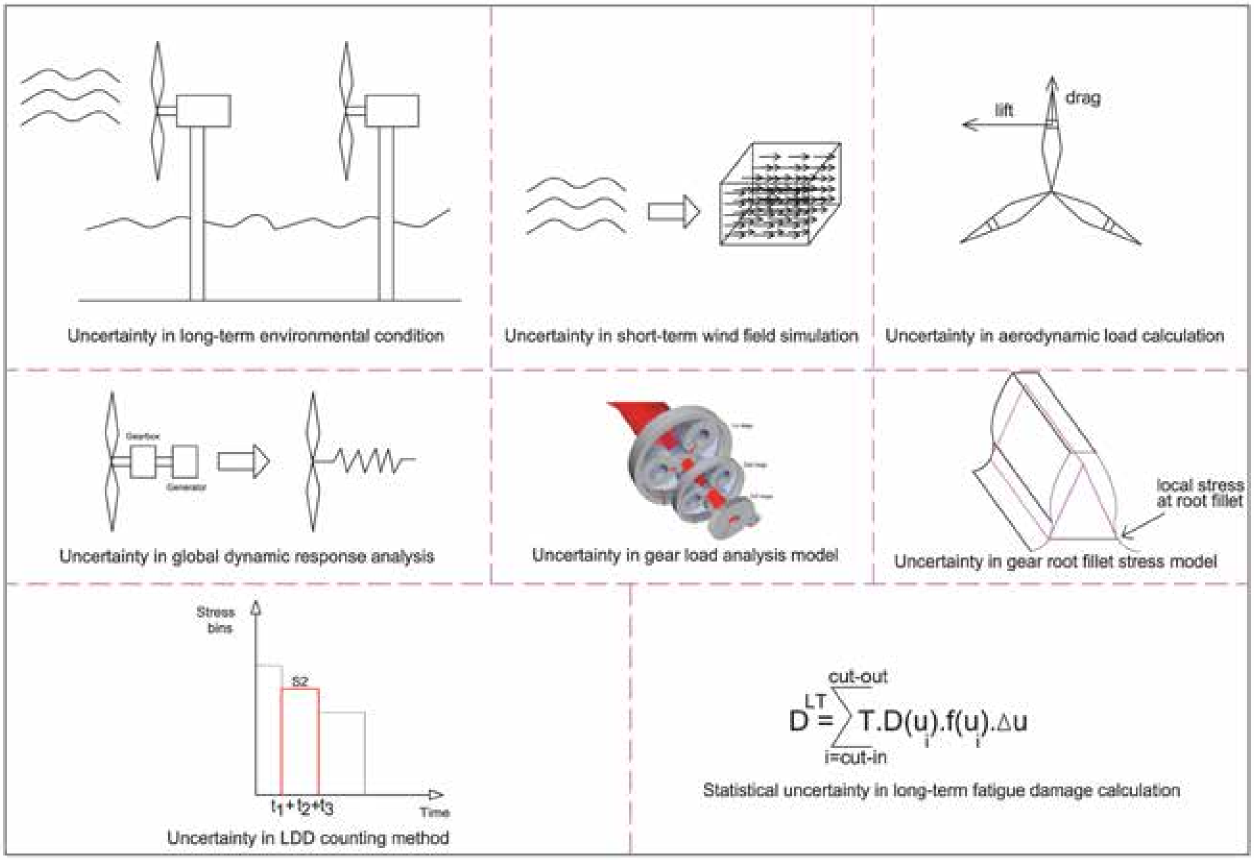


Figure 36: *Uncertainty assessment used in the reliability analysis of drivetrains.*

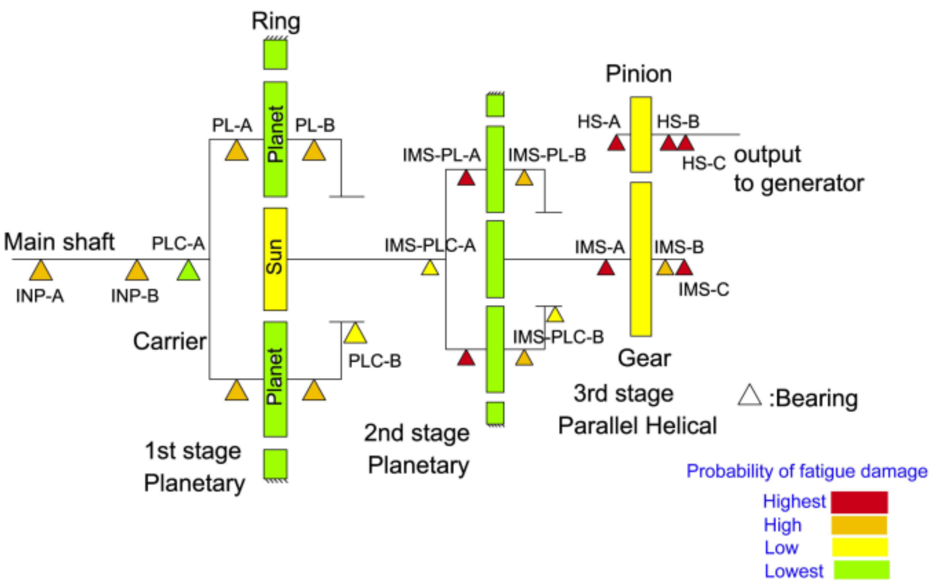


Figure 37: *A vulnerability map for the 5 MW reference gearbox showing the components most vulnerable to fatigue damage.*

bearings, can be damaged more quickly in some types of floating turbines compared to land-based ones.

Condition monitoring, inspection and fault detection

A model-based condition monitoring method was developed during this project. Existing sensors were used to identify faults and damage in the bearings and gears, and a vulnerability map was introduced to rank components based on their probability of fatigue damage. The map can be used during inspections in order to identify the most vulnerable components. Both the condition monitoring method and the vulnerability map contribute to cost reductions by increasing the probability of detecting incipient faults before they develop into catastrophic failures.

Self-adaptive blade design

Wind turbines are designed to reach their full power generation capacity at a rated wind speed. Above this speed, the forces generated by wind on the blades are reduced by pitching the blades, i.e., by rotation along the blade axis. Modern wind turbines are constantly changing pitch, even within a given rotation. This requires energy-demanding servomotors while, at the same time, the motor controlling pitching is not fast enough to compensate for gusts. An attractive alternative is the use of blades that twist self-adaptively when flexed by wind loads, thus providing instant regulation of the loads. A NOWITECH PhD student has explored this topic and, in his thesis, Kevin Cox has shown how intelligent design of the composite materials structure in blades can aid such self-adaptation. Bend-twist coupling was achieved using an unbalanced (off-axis) composite lay-up and carbon fibres, which have seen increased use in wind turbines in recent years. This approach turned out to be the most efficient for promoting bend-twist properties.

Protective coatings

Offshore wind turbines operate in harsh environments. The fast-rotating outer sections of the blades are impacted by rain and hail at speeds of 300 km/h that erode the blade edges. Tower foundations must also be constructed to withstand a highly corrosive environment. The choice of coating is key to protecting these essential structures from potentially damaging environmental conditions. NOWITECH has developed technology to improve protective coatings and address both these challenges.

Duplex coating systems for corrosion protection

Offshore wind turbine foundations are exposed to highly corrosive environments. The cost of using coatings for corrosion protection is the sum of the coating's initial application and its subsequent maintenance and renewal. Pure organic coatings are the least expensive in the short-term. However,

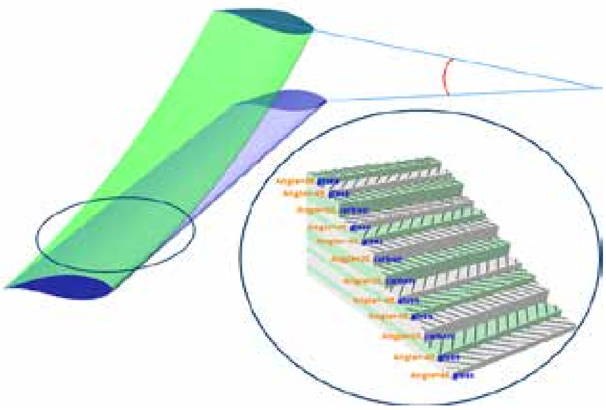
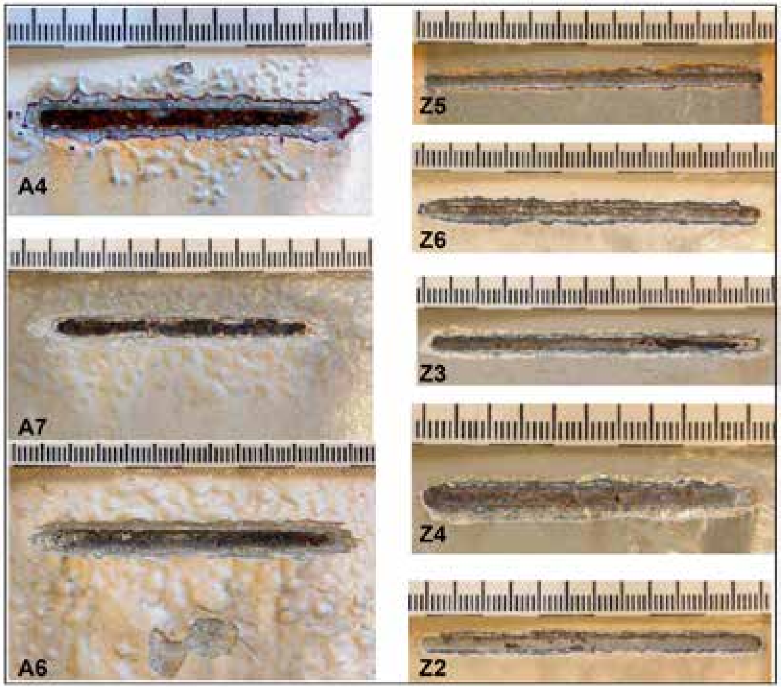


Figure 38: *Left: Traditional, motor driven, blade pitching. Right: Diagram showing the bend-twist principle in a blade section.*

experience has shown that dual-layer coatings that combine a metallic layer with organic coatings enhance foundation lifetimes and are thus less expensive in the long-term. Standard dual-layer coatings employ a metallic layer of aluminium or zinc/aluminium. SINTEF has tested a dual-layer coating consisting of pure thermally-sprayed zinc (TSZ). This has been shown to provide better corrosion protection than both dual-coatings based on thermally-sprayed aluminium (TSA) and 3-layer applications of organic coatings/paints.



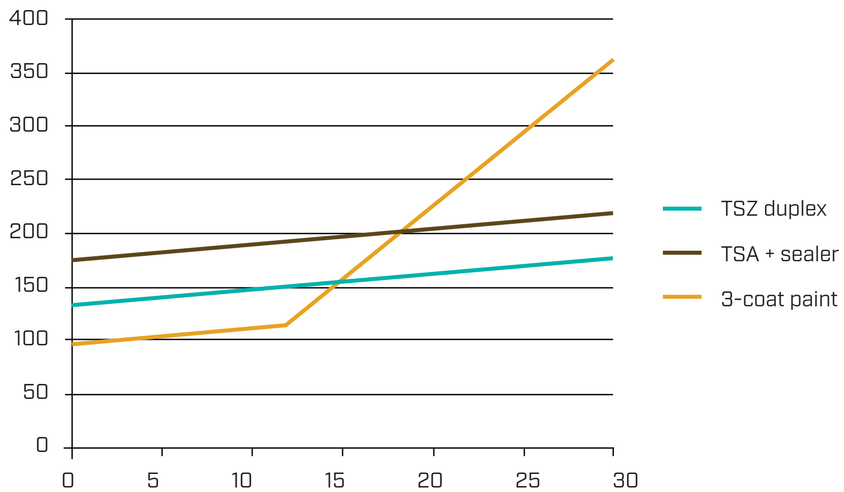
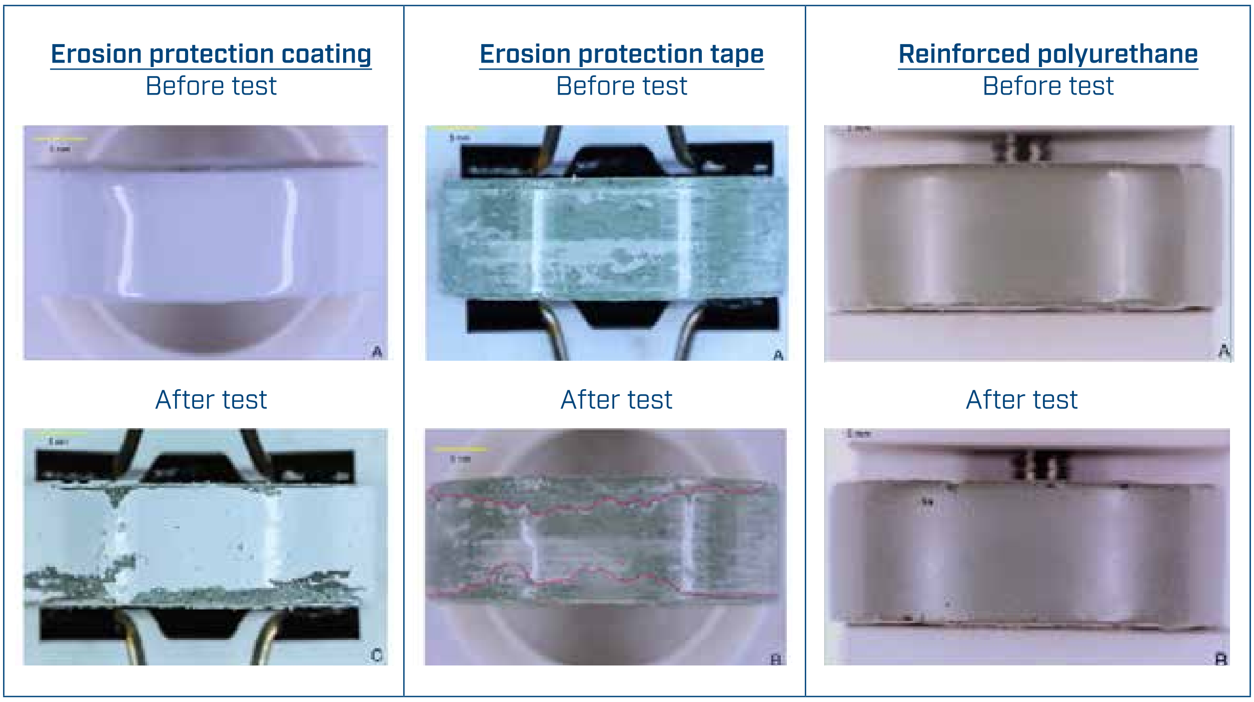
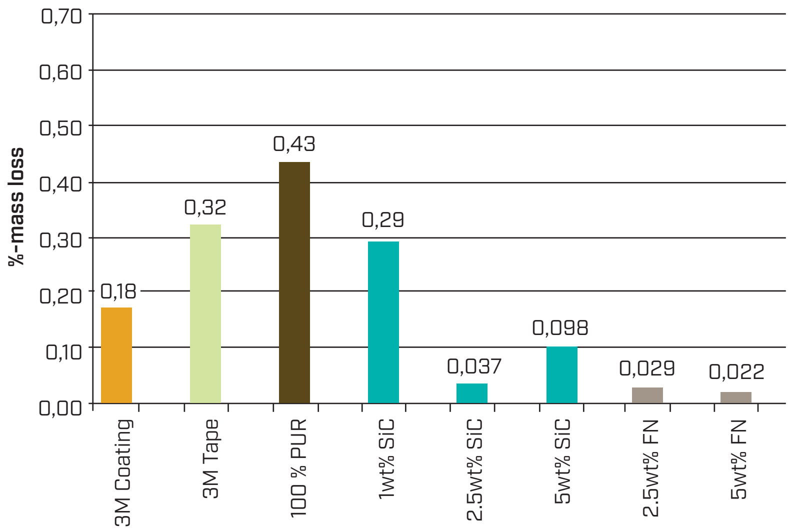


Figure 39: *Upper: Images of coating systems following exposure for five years in corrosive marine environments. A: Coating systems consisting of thermally-sprayed aluminium. Z: Coating systems consisting of thermally-sprayed zinc. Bottom: Life-cycle cost estimate as a function of construction lifetime (years).*

Droplet erosion-resistant blade coatings

The combination of rainfall and the high rotational speed of a wind turbine blade leads to high energy droplet impacts on the blade's leading edge. Unless proper erosion-resistant coatings are applied, such impacts can result in severe erosion of the leading edge, which in turn reduces aerodynamic efficiency and makes the composite structure of the blade vulnerable to more serious damage. SINTEF has taken a commercial polyurethane coating and improved its erosion resistance dramatically by reinforcing it with tailored nanoparticles containing molecular branches that are highly compatible with the polyurethane base.





Average %-mass loss from start to test stop for the coatings tested

Figure 40: *Upper: Samples showing a variety of erosion protection applications before and after an erosion test. Lower: Mass loss of different coatings during the erosion test.*

Thermally sprayed silicon carbide coating

The challenge of being able to thermally spray a silicon carbide (SiC) coating was addressed in the NOWITECH PhD study by Fahmi Mubarok completed in 2014, based on an idea by his professor Nuria Espallargas. This was very successful[3]. The process has been patented and the new company Seram Coatings AS was established in 2014 to commercialize the invention. The patented innovation for thermal spraying of silicon carbide (SiC) gives a superior coating that can be applied on sliding surfaces, valves, gears, etc. in wind turbines, but also in many other applications. It has according to recent media coverage the potential to become a billion NOK business, and Nuria's continued work to develop the technology and business has been attracting lots of positive attention and awards.

Figure 41: *Nuria Espallargas was awarded Norway's Female Entrepreneur of 2017. From left: Crown Prince Haakon of Norway; Anita Krohn Traaseth, Monica Mæland, Nuria Espallargas, Linda Hofstad Helleland and Crown Princess Mette-Marit of Norway. Source: Teknisk Ukeblad; Photo: Mathias Klingenberg.*

Figure 42: *Seram Coatings AS won the 2015 ACES Award for Academic Enterprise against stiff competition from other European university start-ups.*

3 E.g. see ***https://geminiresearchnews.com/2014/04/silicon-carbide-puzzle-solved/***.

Testing and modelling of composite materials

Wind turbine blades are large composite structures designed to withstand millions of load cycles. Material and structural modelling are fundamental to blade design. However, due to computational demands, the material models used to calculate fatigue life and crack growth are only a highly simplified representation of a highly complex real conditions. NOWITECH has developed models for the simulation of the fatigue and fracture mechanics of composites, as well as procedures to calibrate these properties by means of laboratory testing.

A nonlinear model used to simulate fatigue in composite materials has been developed and implemented in FEM software (Abaqus, LS-Dyna). The model predicts anisotropic progressive stiffness reduction, strength degradation and further fatigue based on current state. Numerical routines to extract model parameters from material test data have also been developed. Computational efficiency has required the implementation of a cycle jump routine that considers degradation of the composite layer structure in all directions. Efficient application requires further development of the calibration routines, consisting of a combined FEM – experimental test optimisation routine. This will be developed as part of the EU UPWARDS project (2018-2022).

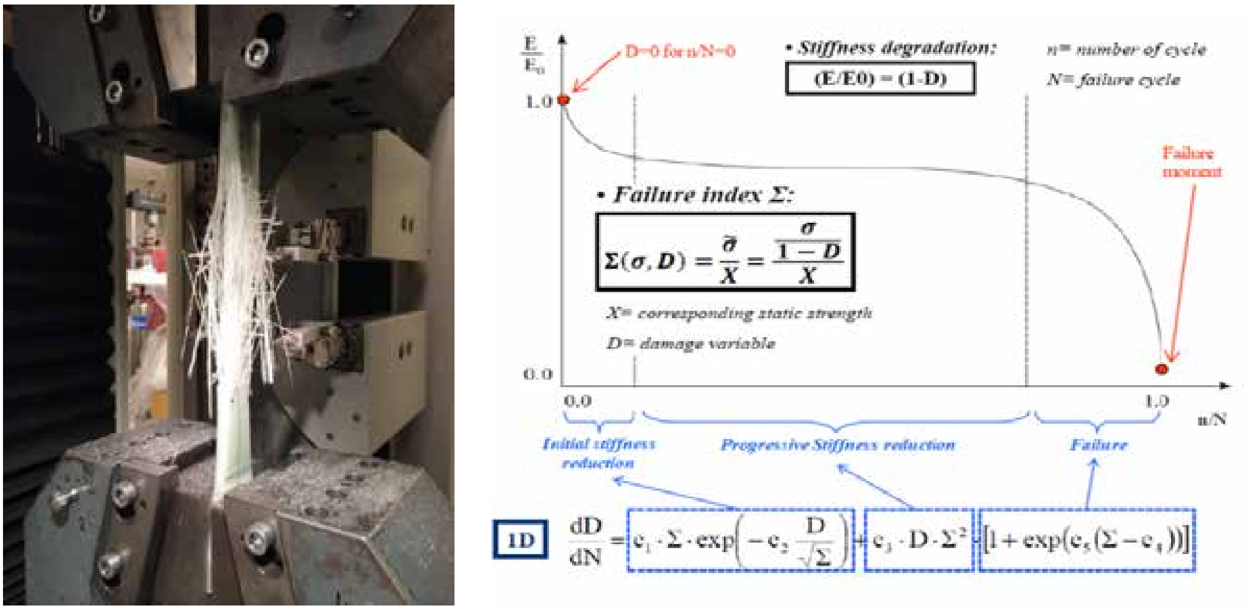
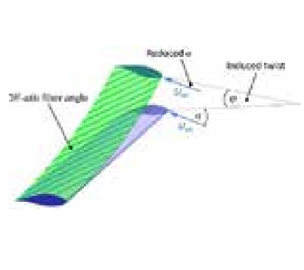
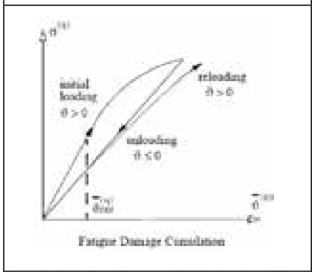
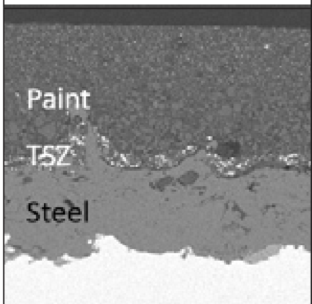
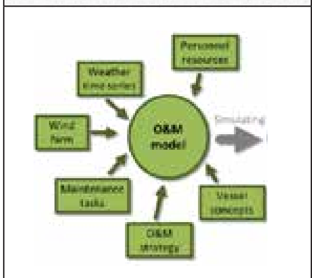
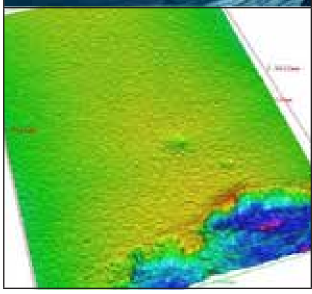


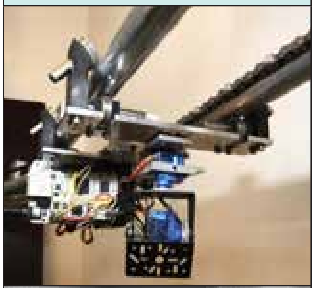
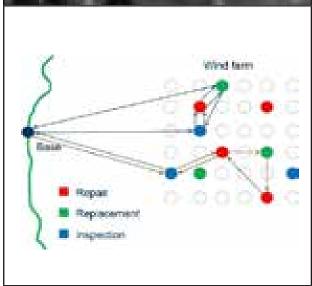
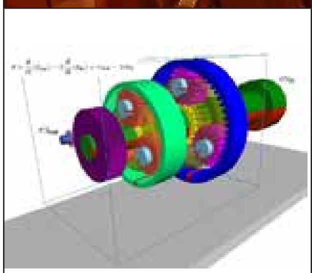
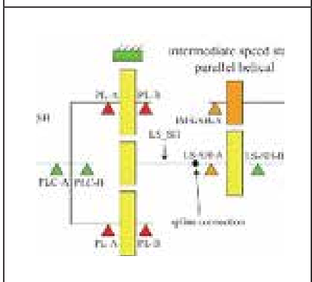
Figure 43: *Lab test of composite structure (left) and a simplified 1D formulation of the fatigue model (right).*

Technology/Process | Numerical model/method

RESULT/INNOVATION	DESCRIPTION	TRL	IMPACT
	**14 Buckling Resistant Blades** Increase buckling resistance in wind turbine blades through unbalanced fibre composite lay ups.	3	The potential for load alleviation and increased critical buckling load through use of unbalanced fibre layup has been documented for many design cases through simulations and laboratory experiments.
	**15 Composite fatigue damage estimator** Progressive fatigue damage stiffness reduction simulation models for composite materials.	4	The model can be used to simulate the change in stiffness and remaining life-time of composite structures subjected to fatigue loads as i.e. a wind turbine rotor blade spar.
	**16 Duplex coating system for corrosion protection** Novel protective coating systems for offshore wind turbines substructures. Maintenance-free comprising thermally sprayed zinc (TSZ) paint with self-healing properties.	5	Longer lifetime and reduced maintenance of steel structures. Cost savings can be obtained by introduction of coatings with improved corrosion resistance.
	**17 NOWIcob** A life-cycle profit analysis tool for offshore wind farms	6	A tool to simulate the O&M cost of an offshore wind farm over the lifetime. NOWIcob can serve as a decision support tool to analyse the consequences of different decisions regarding maintenance and logistic strategy.
	**18 Vessel fleet optimization** Optimization model and tool for making decisions about optimal vessel fleet to support the maintenance operations	5	Decision support tool for offshore wind farm operators. The model will give output results regarding (i) location of maintenance bases (onshore/offshore) and (ii) the vessel fleet size and mix i.e. which vessels/helicopters to invest in and/or charter
	**19 Droplet Erosion resistant blade coatings** Coatings based on nanoparticle modification of commercial coatings.	3	The maintenance of the leading edge of blades is expensive, thus a better drop erosion protective coating will increase useful life and reduce O&M costs.

Technology/Process

Numerical model/method

RESULT/INNOVATION	DESCRIPTION	TRL	IMPACT
	**20 Remote Presence** A remotely controlled robot installed inside wind turbine nacelle.	5	Remote inspection using the robot is an alternative to expensive and time consuming manned inspection. The low cost of a remote inspection allows for more frequent inspections, which potentially can increase the reliability.
	**21 Thermally sprayed SiC coatings** New cost effective thermally sprayed silicon carbide (SiC) coating useful for components that requires high wear resistance and low friction.	5	The properties of SiC makes the coatings highly attractive for many industrial applications as a new and cost-effective competitor to most hard coating materials on the market. The goal is to reduce wear of components and increase lifetime, and thus reduce O&M costs.
	**22 Routing and scheduling optimization** Tool for optimization of vessel routing and maintenance scheduling	2	An optimization model for daily scheduling of maintenance operations in an offshore wind park (which maintenance task to perform when and in which order and with which ships and personnel).
	**23 Droplet erosion testing** Laboratory set up for droplet erosion testing of wind turbine blade coatings.	5	Simplified and cost-effective drop erosion testing of coatings. This setup is used for testing erosion resistant coatings.
	**24 Gearbox fault detection** Wind turbine drivetrain and gearbox fault detection model. Prognostic model for fault detection in wind turbine drivetrains.	3	Model for early detection of wind turbine drivetrain faults based on condition monitoring data.
	**25 Gearbox Vulnerability Map** inspection and maintenance planning method. Method for fatigue reliability-based inspection and maintenance planning of gearbox components in wind turbine drivetrains.	4	Method can lead to more effective inspections and thus reduce the downtime for fault detection and routine inspection, because inspection and maintenance can be focused on those components which hold higher probability of damage.


2°

Electricity grid and wind farms

Harald G Svendsen
WPC co-leader

Karl O Merz
WPC co-leader

The objective of WPC was to develop technical solutions and methods for cost effective electro-magnetic and electrical designs, controls, grid connection and power system integration of offshore wind farms. Selected results include:

- High-voltage DC transmission
- Long-distance high-voltage AC transmission
- Wind power integration in the European power system
- Wind power integration with oil and gas platforms
- Integrated modelling and control systems
- Generator designs

The above points are summarized on the next few pages.

High-voltage DC transmission

For large offshore wind farms far from shore, high-voltage DC (HVDC) export cables are the most viable means of power transmission. For this reason, research in NOWITECH has focused on HVDC systems, and in particular on control concepts for multi-terminal HVDC (MTDC), including voltage droop for the communication-less control of active power flow in the DC grid, and robust control algorithms for HVDC converters. These concepts have been developed in simulations and subsequently tested in the electrical laboratory.

Multi-terminal HVDC grids and robust control have been major areas of focus in NOWITECH throughout the lifetime of the centre, and activities have been carried out in parallel with other projects addressing similar topics. HVDC systems are relevant applications in offshore wind farms in situations where the distance from shore makes AC cable connections no longer feasible. Multi-terminal systems that interconnect multiple wind farms and/or onshore connection points as part of a DC grid are especially relevant in the North Sea area, and offer potentially high cost reductions in the form of a shared transmission infrastructure and inter-area power exchange.

Results obtained in NOWITECH have demonstrated both the feasibility of DC droop control for multi-terminal offshore HVDC grids, and good agreement between simulation and laboratory results. The development of the laboratory and experience gained through this work has enabled the follow-up of research projects addressing topics such as the implementation and control of modular multilevel converters for multi-vendor interoperability.

The National SmartGrids laboratory at NTNU&SINTEF is an excellent research facility that offers major benefits for grid integration studies both in NOWITECH and beyond. Laboratory experiments are important for several reasons:

- The verification of simulation models
- The analysis of phenomena that cannot be simulated
- They enable testing that cannot be carried out in the field
- The enable testing of control systems and components in a controlled environment
- They provide data for improved modelling and the modelling of new components

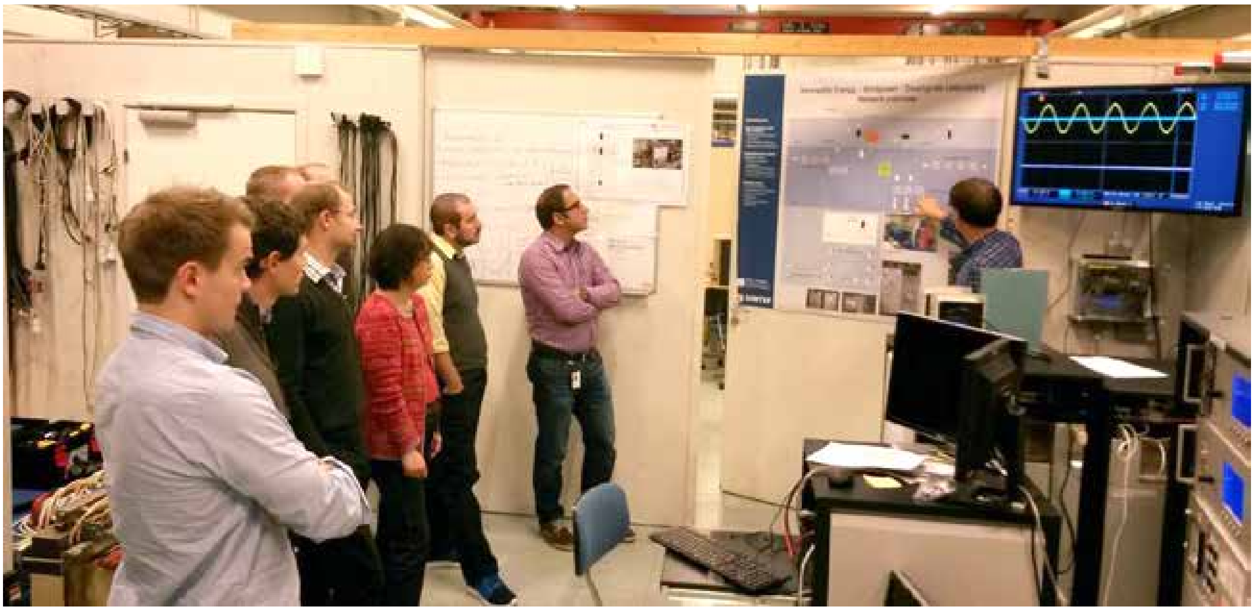


Figure 44: *A visit to the National SmartGrids laboratory at NTNU&SINTEF with the NOWITECH industry reference group.*

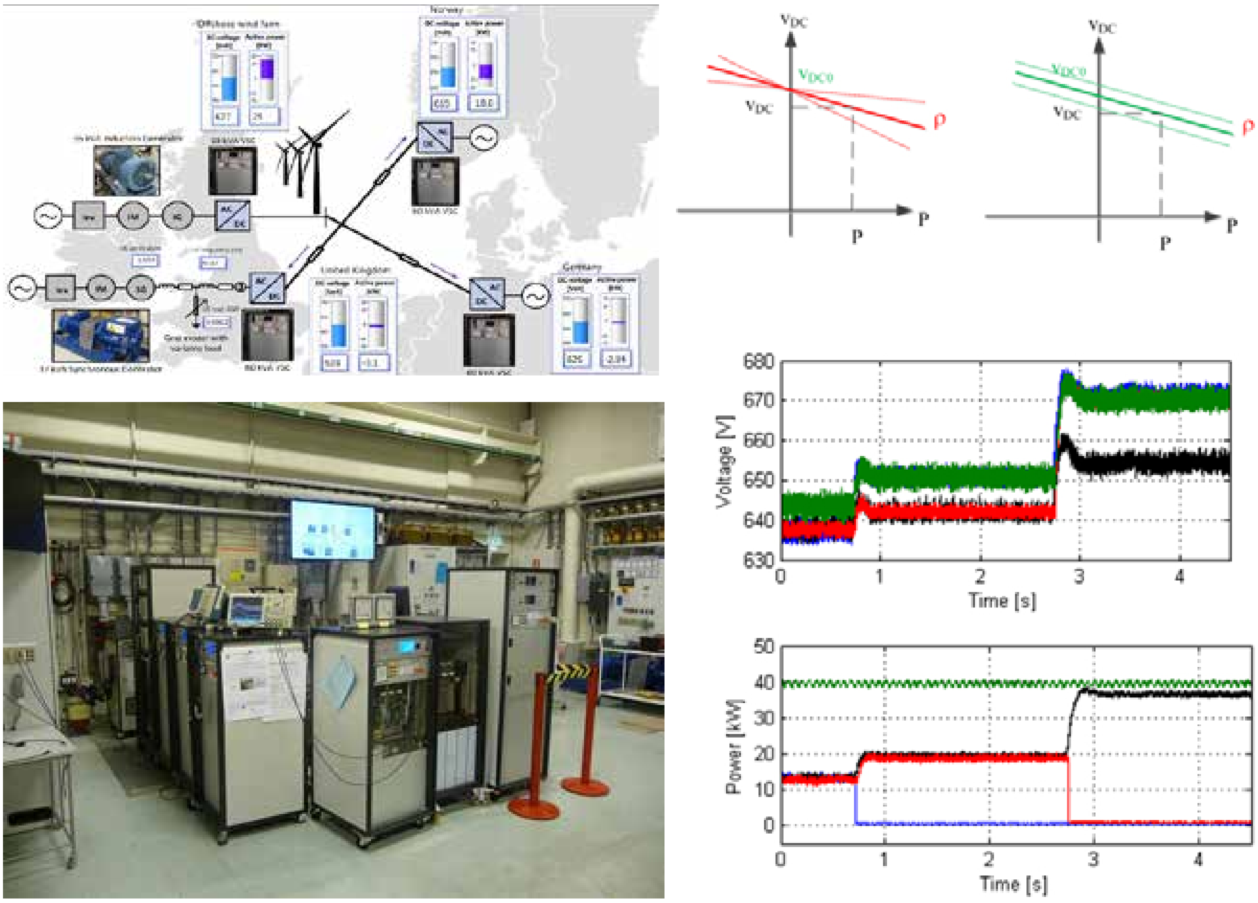


Figure 45: *Control of a multi-terminal DC transmission system. Laboratory set-up and experimental results.*

Long-distance high-voltage AC transmission

Research in NOWITECH has been looking into the feasibility of extending the distances at which AC export cables for offshore wind farms can function by developing a control strategy that minimises electrical losses. The concept utilises the standard tap-changers on the transformers at the feeding and receiving ends of the cable, in combination with a novel control strategy, to control the voltage for minimising electrical losses.

The approach is especially suited to wind farms because their production will be much lower than maximum cable capacity for extended periods. During these periods, losses can be reduced by reducing the transmission voltage, enabling overall efficiencies over a year to be increased. Calculations for a 320 MW wind farm connected to shore via a 200-km cable at 220 kV nominal voltage shows that an annual loss reduction of 9% is achievable simply by applying a ±15% tap changer voltage regulation on the two transformers.

The control concept can be applied without the need to develop new equipment, although it does require implementation of the control algorithm concept that uses the measured output power of the wind farm as input, and gives the optimal tap changer position for the transformer at the feeding and receiving ends of the HVAC cable. It can be implemented on both existing, extended AC transmission systems, and on new systems. In its simplest form, the control concept can be implemented as a look-up table, pre-calculated using numerical simulations. It provides the optimal tap changer position at the feeding and receiving ends of the cable as a function of wind farm output power. If the regulatory framework places constraints on the operational voltage range for the cables, an optimal voltage can be determined within that range.

It is frequently suggested that for large wind farms (more than 200 MW) and those far from shore (more than 100 km), high-voltage direct current (HVDC) may be the preferred option for grid connection. However, this requires the use of HVDC converter stations both offshore and on land. These are costly investments, and for this reason the industry has recently shown

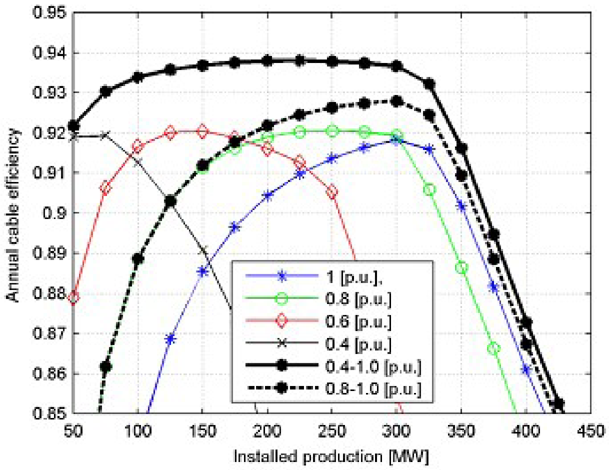


Figure 46: *Annual cable efficiency as a function of installed wind farm capacity for alternative voltage control strategies.*

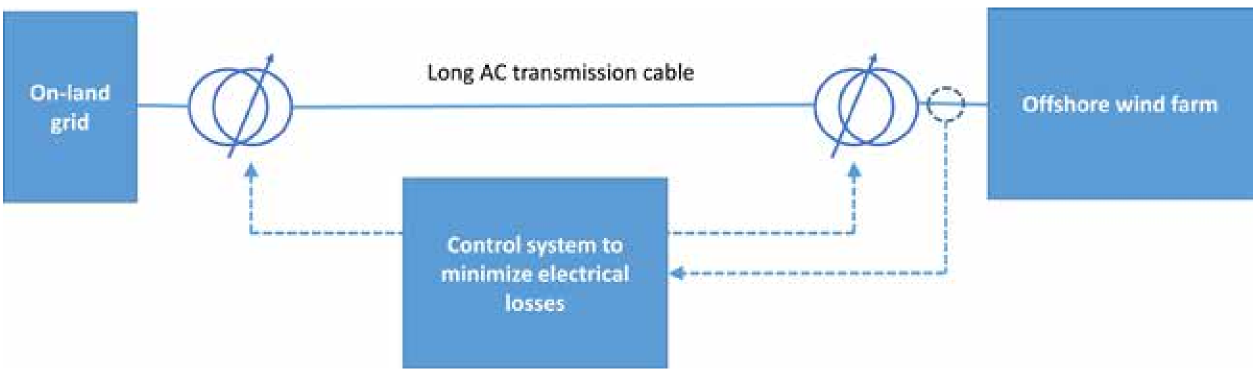


Figure 47: *Schematic of offshore wind farm connected to shore with long AC transmission cable. The control system can in its simplest form be implemented as a look-up table with pre-calculated tap-changer positions to minimize the electrical losses depending on the offshore wind farm power output.*

interest in also applying HVAC concepts for wind farms with higher capacities and at greater distances from shore. For example, DONG Energy intends to connect its 1.2 GW Hornsea offshore wind farm using a 170 km, 220 kV AC transmission. Application of the NOWITECH innovation to wind farms far offshore enables significant reductions in electricity losses compared with conventional HVAC transmission operations. This improves the economics of wind farms far offshore and may open opportunities for the development of more remote deployment locations, thus contributing to the achievement of renewable energy and climate change mitigation targets.

Wind power integration in the European power system

Forecasts predict the production of large amounts of wind power in northern Europe, both from mainland and offshore sources. This power source is intermittent, and has to be integrated within an inter-connected European power system. Research in NOWITECH has led to the development of analytical methods and software tools designed to investigate future scenarios involving the utilisation of large-scale wind power production, as well as energy provided by other intermittent sources. Topics addressed include the identification of future grid bottlenecks, the interplay with the Nordic hydropower storage system, the benefits of investing in grid infrastructure, and factors linked to geographical and seasonal variability. The results have provided insights into a variety of issues, such as: 1) the ability of the European power system to manage planned or expected renewable energy integration scenarios, and thus where grid bottlenecks will arise, 2) the extent to which Nordic hydropower can balance wind power in the North Sea region, 3) the benefits of grid investment in terms of reduced overall generation costs and 4) geographical and seasonal variability in electricity supply costs and other factors.

NOWITECH's approach was based on a linearised optimal power flow model computed over time in stepwise progression and involving the periodic update of factors such as available renewable power, demand, and energy storage considerations. It represents a simplification of both the electricity market and the power system, but retains the key characteristics of both, including the utilisation of the large energy storage reservoirs and the physical aspects of how power flows within the grid. This makes it possible to analyse large systems at relatively low computational costs, and is particularly useful for the analysis of future scenarios.

These grid integration analysis methods have been implemented in the form of a software tool, first in Matlab as the *Power System Simulation Tool* (PSST), and later in a Python package called *Power Grid and Market Analysis* (PowerGAMA). The latter has been granted an open-source licence (MIT) and has been utilised in several other research projects. It is of interest primarily to players involved in strategic grid development projects, such as researchers, governments, transmission system operators and others.

The tool supports power system and grid development planning by enabling the early detection of potential grid integration problems, thereby reducing the uncertainties and economic risks linked to grid development projects. This in turn enables the optimal use of power generation resources and minimises the socio-economic cost of energy supply.

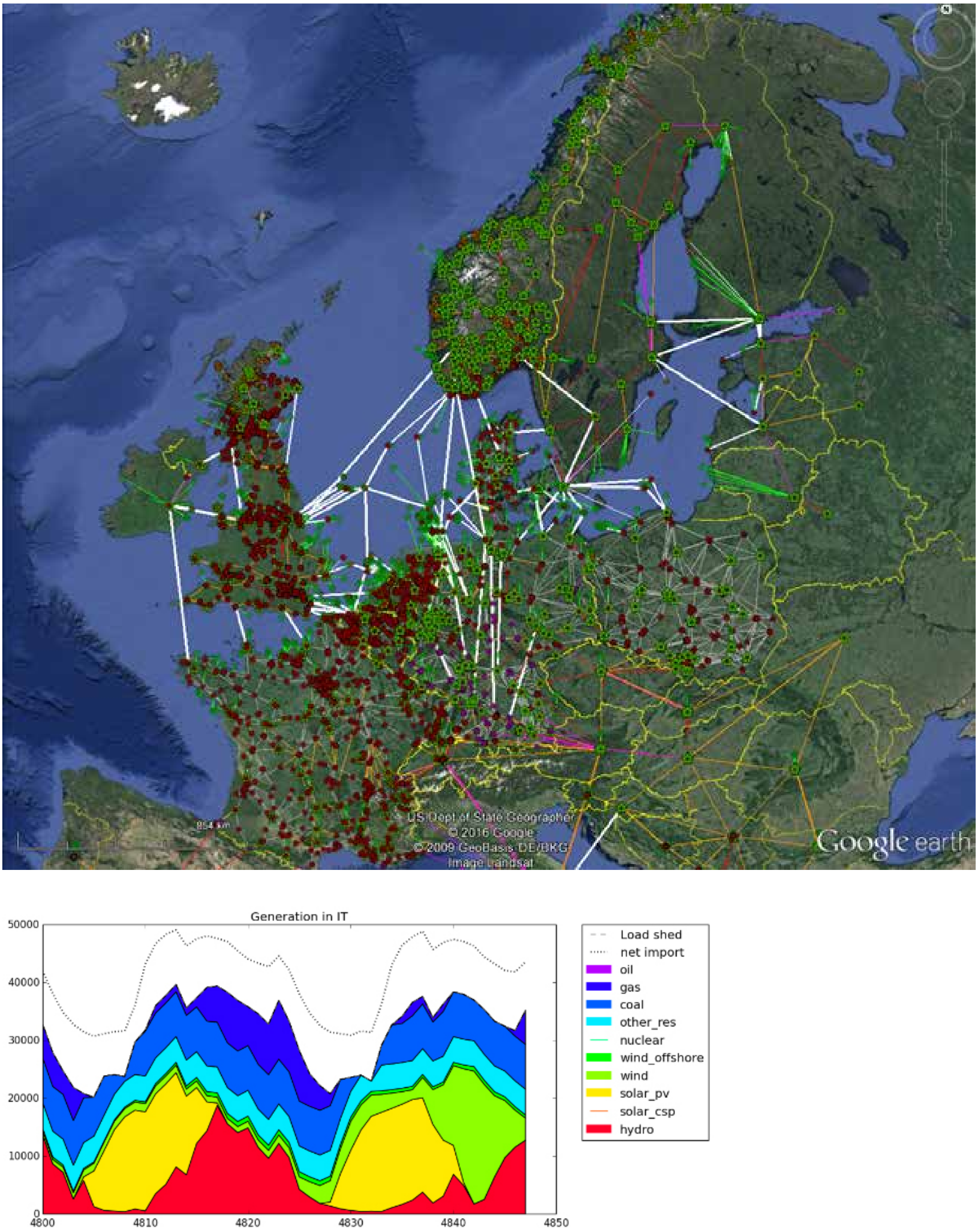


Figure 48: *Upper: The European grid model. Lower: Hourly simulation results showing variations in generation mix and prices according to energy source.*

Figure 49: The poster ”Step-wise stochastic optimisation of transmission grid for offshore wind farm clusters” *by Harald G Svendsen, Martin Kristiansen and Magnus Korpås received a poster award at the European Offshore Wind Energy 2017 conference in London on 7 June 2017. The poster describes a new method for optimising offshore grid layout taking into account investment costs, generation costs, variability in wind resources, the benefit of trade between price areas, as well as uncertainties in future developments. Recent improvements in the optimisation approach makes it easier to identify robust offshore grid investments. Here the award winner Harald Svendsen, SINTEF Energy, to the left being presented the award by Dr. Stephan Barth, Managing Director, ForWind.*

Wind power integration with oil and gas platforms

NOWITECH has also investigated the possibility of supplying offshore petroleum installations with power supplied by offshore wind turbines. The primary motivation here is to reduce carbon emissions associated with oil and gas production on the Norwegian continental shelf. Integration with wind power sources may be relevant to existing platforms, including those supplied with energy generated by installed gas turbines, as well as more recent installations that are supplied with electricity via cables from the mainland. In the former, wind power may enable the replacement of large volumes of gas fuel, and for the latter, integration with a wind farm may provide benefits by means of the sharing of a transmission infrastructure and better utilisation of cable capacity.

NOWITECH has addressed the various technical and operational issues in a series of studies that have subsequently been disseminated in a number of presentations and publications. The centre’s achievements were summarised in a milestone report in 2014. The power electronics in wind turbines or HVDC transformers enable a high degree of control that can be utilised to ensure stable voltage and frequency on an offshore platform, even during rapid fluctuations in wind power supply or the occurrence of component faults. A variety of operational strategies combining gas and wind turbines have been analysed to quantify their economic and environmental benefits.

NOWITECH has produced approximately ten publications providing detailed descriptions and analyses of the various concepts. The main outcome is that these studies have shown that systems involving the properly designed connection of wind power sources to oil and gas installations can be operationally stable and reliable, economically robust and environmentally sound.

The general aim of research in NOWITECH has been to optimise the design and operation of such systems with the dual objective of reducing fuel costs and environmental footprint. Three main themes have been addressed:

1) Operational strategies for reduced fuel costs and carbon emissions. The connection of a wind farm to an oil platform enables wind energy to replace supply from fossil fuels. However, safe operation of the platform requires back-up power, and security of supply has to be taken into account when determining optimal operational strategies. Saving gas turbine fuel is important for cost reduction, and for keeping carbon emissions associated with oil and gas production as low as possible.

2) Operational control to ensure frequency and voltage stability in isolated systems. On introducing wind power to such systems, it is beneficial to exploit potential control opportunities associated with the wind farm as a means of enhancing system stability in order to minimise frequency and voltage fluctuations. Integration with a larger system generally improves voltage stability since disturbances associated with

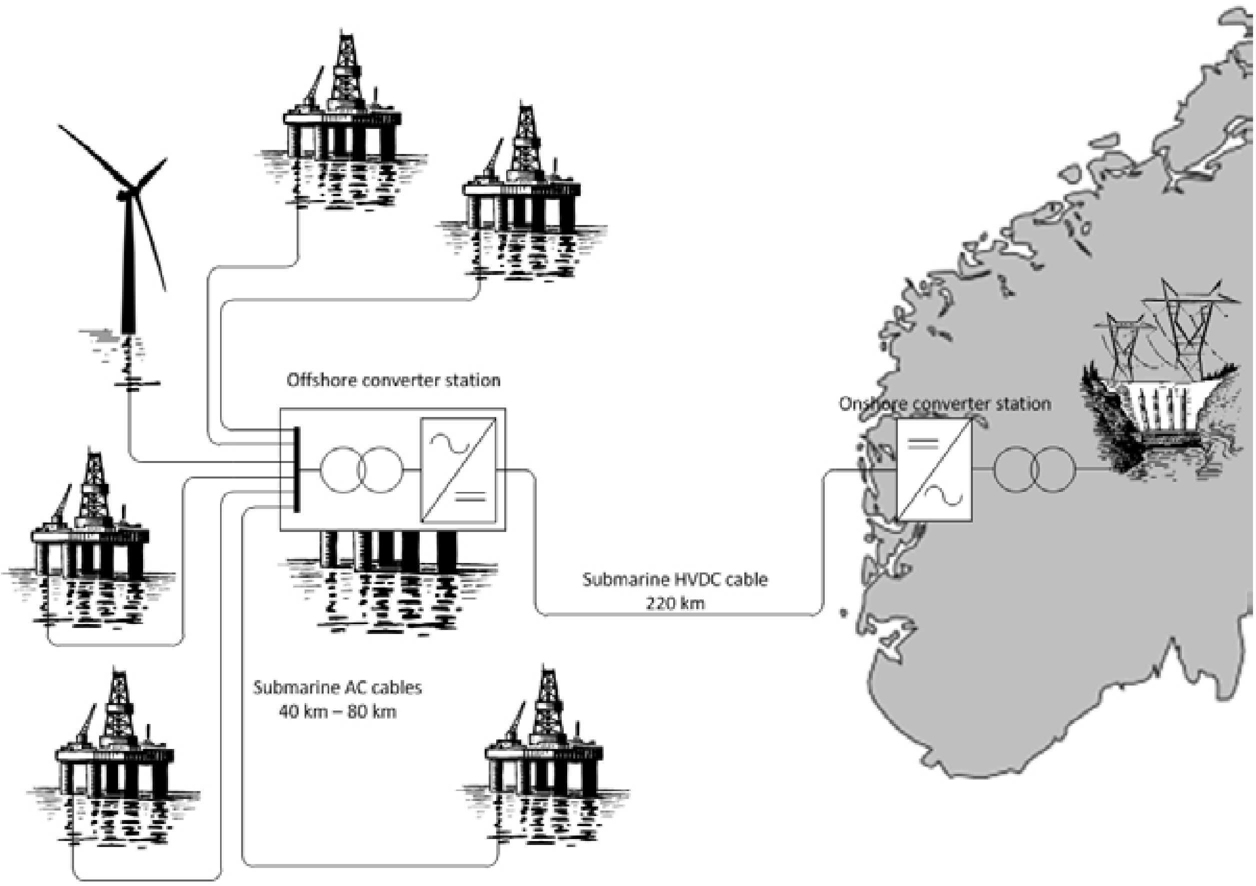


Figure 50: *Schematic diagram showing a group of electrified oil and gas platforms connected to a wind farm*

the largest voltage fluctuations, such as motor start-ups, are relatively smaller within a bigger system.

3) Operational control for frequency and voltage stability in mainland grid connected systems. The electrification of offshore oil and gas platforms may be carried out without integration with offshore wind farms. However, combined solutions enable the sharing of transmission capacity to shore, which in turn results in overall cost reductions.

These strategies can be applied to ensure the safe and economic operation of integrated systems, which will reduce both fuel costs and the carbon footprint generated by the production of oil and gas. Cost reductions may be obtained via the sharing of infrastructure linked to supplying electric power to offshore platforms and electricity exports from wind farms. Commercial revenue creation opportunities may be possible because the electrification of offshore oil and gas platforms may generate a significant domestic market for the Norwegian offshore wind sector.

Results of the NOWITECH studies have generated increased interest from the industry, and these concepts are being further developed by the centre's industry partners DNV GL and Statoil. Further development in the field of control strategies with the addition of offshore energy storage is being pursued by SINTEF and Statoil as part of a separate innovation project.

Integrated modelling and control systems

An understanding of the dynamics of a wind farm as a complete system involving interactions between aerodynamic, hydrodynamic, mechanical, electrical, and control domains requires an integrated

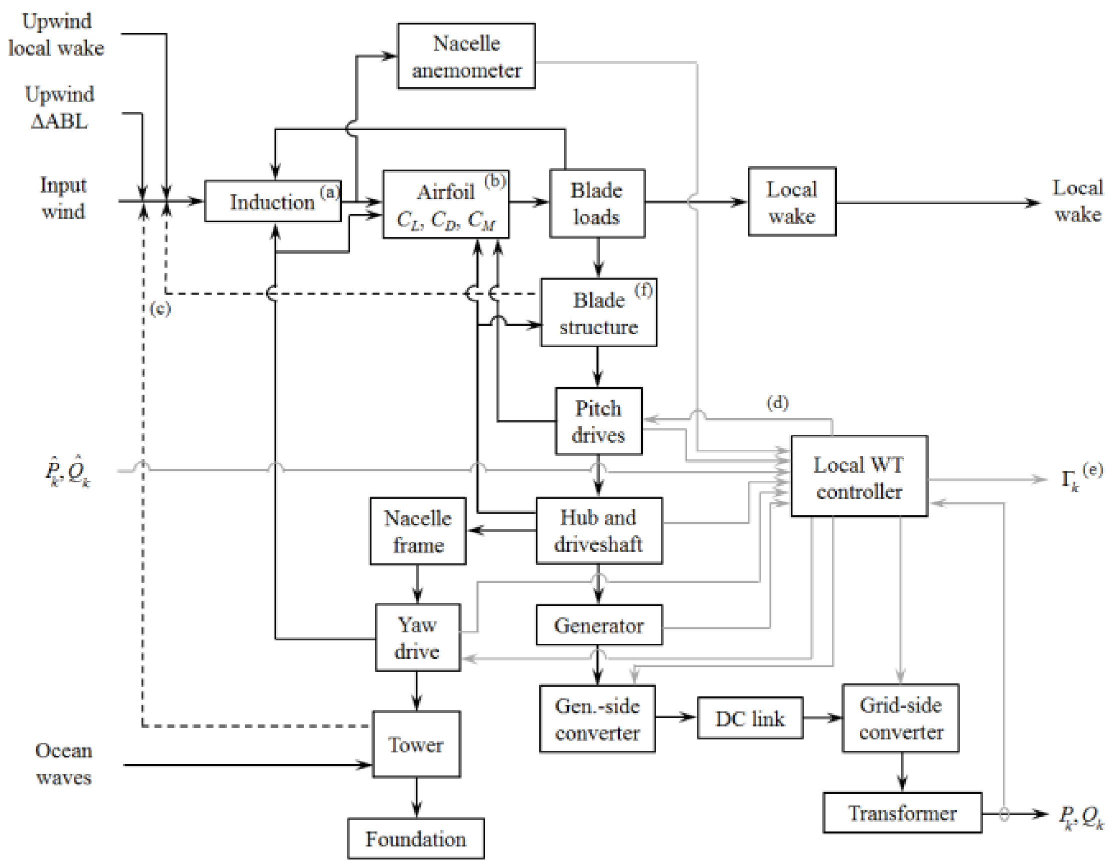


Figure 51: *STAS model representation of a single wind turbine. The model structure is so that the single turbine models can be linked together to represent an entire wind farm.*

description formulated in such a way that enables the application of analytical tools. NOWITECH has achieved this by using a linear state-space model (STAS), which is currently under development. STAS enables frequency domain analyses for the entire system, which is very useful in processes such as the development of wind farm control strategies.

STAS is a linear state-space model of a wind power plant, including the wind turbines, the electricity grid and a hierarchy of controls. In short, it is "a wind power plant in the form of a matrix". Its primary purpose is to analyse wind power plant dynamics, especially in connection with the design of turbine and plant control systems. The linear state-space framework is ideal for this purpose. It is also adapted for system optimisation using the complex-step gradient method.

STAS consists of several modules: turbine aeroelastic, turbine electrical systems, turbine controls, turbine loads and fatigue, atmospheric flow (from Viper), turbulent wind and ocean wave spectra, plant electric system and plant controls. NOWITECH's philosophy has been to begin with a high-order model of each subsystem, and then subsequently to reduce the order. In this way, there is no uncertainty linked to capture of the key dynamic effects.

The optimal control of wind power plants, enabled by the STAS model, will result in

- reduced operations and maintenance costs as a result of decreases in the effects of wake turbulence
- increased energy production and revenues as a result of optimisation of energy extraction from the atmospheric boundary-layer flowing through the plant.

Generator designs

The generator that transforms mechanical power into electrical power is a key component of a wind turbine. Since the generators are located in the nacelle of the turbine, potential reductions in size, weight and maintenance needs may have a large impact on overall turbine costs. NOWITECH has contributed to advancements in generator designs within the following three main areas.

1) Methods and models used to study radial magnetic forces and vibration in low-speed fractional-slot permanent magnet (PM) machines with concentrated windings. These methods have enabled the detailed analysis of vibrational magnetic forces in PM wind generators by focusing on the influence of a variety of factors such as pole and slot combinations, slot harmonics and loading. These methods have been useful during the generator design phase as a means of identifying generator designs with low vibrational forces, which in turn enable reduction in total generator mass.

2) A modular and integrated generator/converter system for a high-voltage transformer-less offshore wind turbine (HVDC generator). This concept consists of a series of connected voltage-sourced converters that bring the DC voltage up to transmission level, making the use of a transformer unnecessary. The concept and analytical tools developed by NOWITECH can be used to achieve an integrated, lightweight generator design. When fully developed, the concept will represent a step change in offshore wind turbine technology, enabling the power from large offshore wind turbines to be transmitted to shore without the use of a costly offshore substation. The technology has been demonstrated at laboratory scale using a 45 kW prototype of an axial flux ironless stator permanent magnet synchronous generator with three stator segments connected to three converter units. Pål Keim Olsen and Sverre Gjerde received NOWITECHs innovation award in 2015 for their work on this concept during their PhD studies, and the concept was also awarded by the Research Council of Norway in 2016[4]. Pål Keim Olsen is now an associate professor at NTNU and are working towards taking the concept further through EU funding or by other means.

3) A superconducting generator. In collaboration with the European INNWIND project, NOWITECH has been evaluating innovative designs for the next generation of 10MW turbines and beyond. Focus has been directed in particular at the use of superconducting materials in the generator field winding for direct drive generators. Under DC operation, superconductors carry current loss-free when cooled to low temperatures (typically 4 - 40 K) depending on the choice of superconductor. One

Figure 52: *The poster "Performance assessment of floating wind turbines during grid faults" by Olimpo Anaya-Lara (University of Strathclyde), Atsede G. Endegnanew (shown on picture), John O. Tande, and Harald Svendsen (all SINTEF Energy), Kjetil Uhlen and Sverre Gjerde (both NTNU), and Kristian Sætertrø and Svein Gjølmesli (Fedem) won a poster award at the EWEA OFFSHORE 2011 Conference; Amsterdam; 29 November - 1 December 2011. This research evaluates the performance of a floating wind turbine during grid faults using Fedem simulation software describing the hydro-, aero- and structural dynamics extended with sub-models of electrical components, control and power network.*

main advantage of this is that a magnetic field can be generated that is considerably higher, by a factor of two or more, than that developed in copper coil or permanent magnet-based generators. In this way the necessary torque can be achieved within a much smaller volume in a superconducting generator than in its conventional counterparts. The volume and weight reductions achieved by this approach may have significant economic implications, especially for wind turbines in deep seas areas installed on floating platforms.

The results of this work have led to generator design specification requirements that address the problematic issue of AC losses at low temperatures. These losses result from the fact that the magnetic field irreversibly penetrates the superconductor every half period. Although these losses are small, they are of key importance because, being generated at low temperatures, the energy needed to withdraw them is of the order of 10–100 times the actual losses generated. Furthermore, such losses complicate the cooling system, particularly if they are generated at positions located far from the cooling device.

A further result has been the building and testing of a superconducting generator pole. The pole demonstrator exhibits the same features as a full scale 10MW generator pole except that the straight section is made considerably shorter (0.5 metres long) in order to enable the coil to be installed into an existing test facility. This also reduces wire costs. The main objective of this coil demonstration has been to evaluate the feasibility of the one-step wet-winding technique, and the ability of such a coil to handle thermal contraction and the large Lorentz forces that arise during operation.

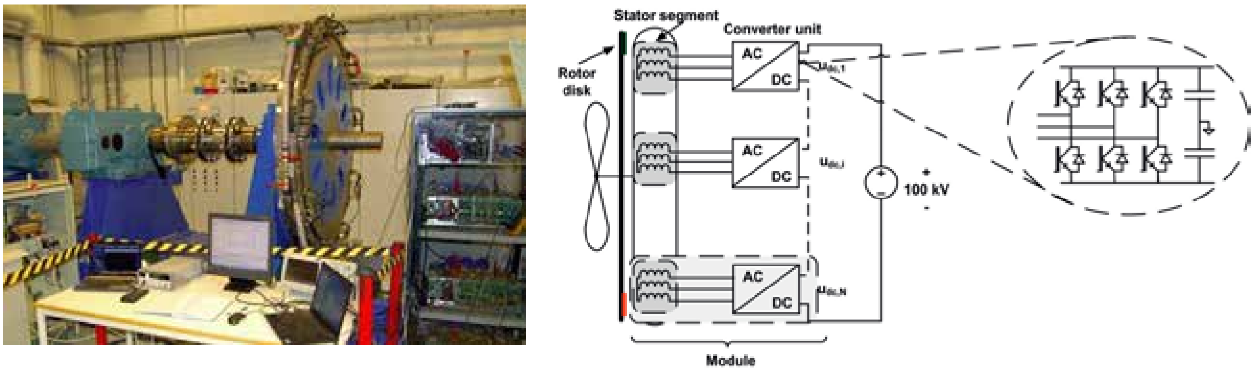
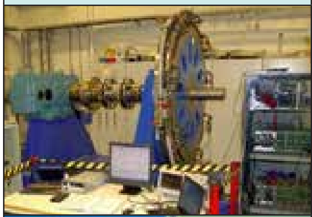
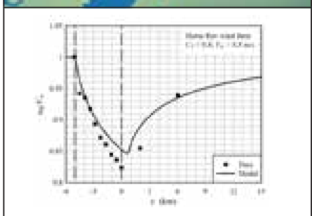
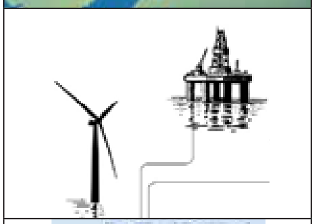
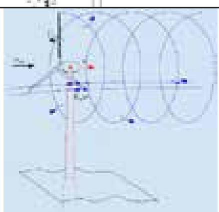


Figure 53: *Left: The permanent magnet generator prototype in the SmartGrid laboratory. Right: Diagram illustrating the HVDC generator concept.*

4 See https://www.forskningsradet.no/prognett-energix/Nyheter/Gronn_pris_for_revolusjonerende_generator/1254018686391&lang=no

Technology/Process | Numerical model/method

RESULT/INNOVATION	DESCRIPTION	TRL	IMPACT
	**26 PM Generator Magnetic Vibrations** Influence of slot harmonics on magnetic vibrational forces in PM generators	4	Identify generator designs with low vibrational forces which will allow reduction in total generator mass
	**27 Power System Simulation PSST / PowerGAMA:** Software simulation tools	5	The tool can be used to assess future scenarios for wind power integration, concerning cost of energy, nodal prices, grid bottlenecks, benefit of grid reinforcements etc.
	**28 Net-Op** Network Optimization Software simulation tool	5	Tool for optimising offshore grid layout, considering variability in wind power, demand and prices. It can be used to identify economic offshore wind farm clustering and grid structures
	**29 Viper** Estimate Energy Output from Offshore wind farms	4	Engineering tool for estimating energy production for an offshore wind farm. It can be used together with electrical models in order to optimise offshore wind farm layout.
	**30 HVDC Grid Lab implementation** Electrical laboratory with multiple converters, cable emulators and wind farm emulator	4	The laboratory can be used to demonstrate technical solutions and validate numerical models for grid connection and control of offshore wind farms, including multi-terminal HVDC set-ups
	**31 Wind Supply to Oil & Gas** Operational strategies for integration of wind power with oil and gas platforms	3	This knowledge can improve profitability and reduce risks for offshore oil and gas platforms powered partially by wind energy.
	**32 Turbine Control** Control of floating offshore wind turbines, advanced strategies and algorithms	3	Smart control systems for load mitigation and structural stabilization are important for optimal production of power and cost reduction.
	**33 PM generator integrated design** Design investigation of different ironless PM generator concepts	3	This knowledge and tools can be used to achieve integrated generator design with minimal weight per MW

Technology/Process | Numerical model/method

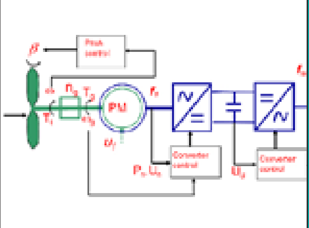
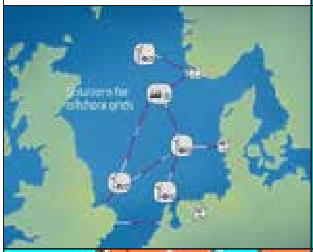
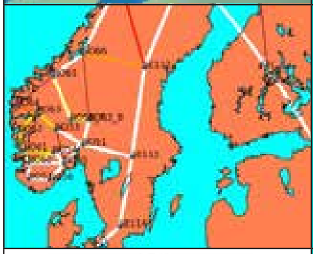
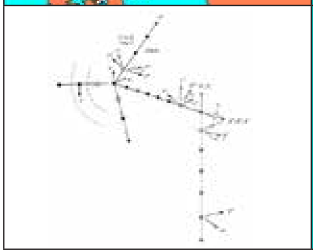
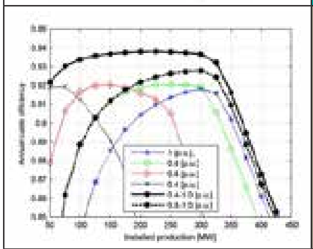
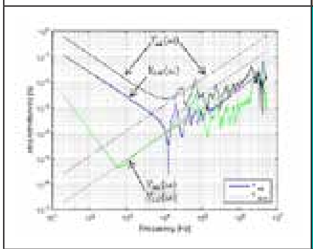
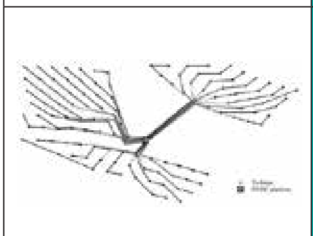
RESULT/INNOVATION	DESCRIPTION	TRL	IMPACT
	**34 Wind Turbine Electrical Interaction Models** Library of wind turbine models for electrical studies	4	Ready to use models for analyses of grid integration, control and stability
	**35 Control of multi-terminal HVDC Grid** Controls and algorithms for grid connection of offshore wind via multi-terminal HVDC grid	4	Cost-effective deployment of offshore wind in the North Sea, benefits from efficient and reliable sharing of off-shore transmission infrastructure
	**36 Network Reduction** Grid model reduction algorithm and software	3	Create simplified, equivalent power flow models that obscures sensitive information and reduces complexity, for simulation of large grids with hundreds/thousands of buses
	**37 STAS:** Linear State- Space Wind Power Plant Analysis	4	Fast engineering model to assess wind farm level control strategies The linear model enables fast analysis and in-depth analysis of phenomena, relevant for optimisation of design and control
	**38 Long distance AC Transmission** Cable operation optimisation tool	3	Optimise operational strategy for long distance HVAC cables – stretching the limits of HVAC transmission
	**39 Wide-band model of wind farm collection grid**	2	Apply in wideband frequency analysis to understand resonance phenomena, harmonics etc in 33 kV and 66 kV grids
	**40 Wind farm collection grid optimization** Internal wind farm grid assessment tool	2	Optimise/compare internal wind farm grid design

Figure 54: *Winding of superconducting test coils for wind turbine generators at SINTEF Energy Research.*

INTERNATIONAL COOPERATION

International cooperation has been emphasised in NOWITECH. This has been done through active engagement in prestigious international networks as listed below, but also through research mobility programmes, transnational laboratory access programmes, participation in EU projects, meetings and collaboration with the international associated research parties of NOWITECH, guest lectures, the involvement of international industry parties, hiring of internships etc. The international research cooperation has been mostly within Europe, including engagement in close to all EU research projects on offshore wind, but there has also significant collaboration with research groups in USA and Japan.

- European Energy Research Alliance (EERA) joint programme (JP) on wind energy, www.eera-set.eu; SINTEF, NTNU and IFE participate in EERA JP Wind Energy developing network, scientific work programmes, workshops and project proposals. John Tande (SINTEF Energy Research) coordinates the sub-programme on Offshore Wind Energy. The programme was enhanced with the EU FP7 IRPWIND project started in March 2014 with coordination by DTU and objectives closely aligned with EERA JPwind.

- European Technology and Innovation Platform on wind energy (www.ETIPwind.eu) involve the wind energy industry, political stakeholders and research institutions with an ambition to define and agree on research and innovation priorities and communicate these to the European decision-making bodies. John Tande (SINTEF Energy Research) is in the Steering Committee of ETIP wind.

- European Academy of Wind Energy (EAWE), www.eawe.eu; SINTEF, NTNU and IFE participate. EAWE members meet at least once a year at the annually PhD seminar.

- European Wind Energy Master (EWEM), www.windenergymaster.eu, is a joint (NTNU, TU Delft, DTU and University of Oldenburg) Erasmus Mundus MSc programme on wind energy providing for a 2 year specialization within Wind Physics, Rotor Design, Electric Power Systems and Offshore Engineering. NTNU is engaged in EWEM offering specialization in Electric Power Systems and Offshore Engineering.

- IEA Wind, www.ieawind.org; The research partners of NOWITECH are active in all relevant tasks of IEA Wind, including Task 25 (Design and operation of power systems with large amounts of wind power), Task 26 (Cost of wind energy), Task 29 (Mexnext: Analysis of wind tunnel measurements), Task 30 (Comparison of Dynamic Computer Codes and Models for Offshore Wind Energy (OC4, OC5) and Task 37 (Wind Energy Systems Engineering). The latter was started in 2015 with SINTEF Energy Research, NREL and DTU sharing the management and coordination of the task

- IEC TC88, www.iec.ch. The research partners of NOWITECH are active in working groups with relevance for offshore wind turbines. SINTEF Energy Research is heading the Norwegian sister-organization NK88 and represents Norway in TC88.

TRAINING OF RESEARCHERS

NOWITECH has funded 25 PhD scholars and 6 Post Docs at NTNU. In addition, a total of 44 PhD students and 14 Post Docs have carried out their research in alignment with NOWITECH at NTNU, but with finance from other sources.

The PhD and Post Doc positions were carried out as an integrated part of the work packages. The Scientific Committee (SC) had the overall responsibility for developing the PhD and Post Doc programme. This included an active recruitment strategy, organization of joint PhD forums and training, exposing them to industry and leading international research groups by organising the PhDs and Post Docs in groups. A total of nineteen PhDs has successfully defended their doctoral work by end of 2017 and at least 3 is expected to defend their thesis in 2018 at NTNU on offshore wind energy. A list of all PhD students and Post Docs associated with NOWITECH can be found in Appendix.

MSc students were engaged in summer jobs with the research partners, and the partners were also active in proposing relevant subjects for their final projects and theses. The MSc education on wind energy has been enhanced at NTNU through NOWITECH, with the PhD and Post Docs assisting in the education, and the engaged professors cooperating through the SC and other NOWITECH activities across faculties. During the years 2014-2017 professors and scientific staff at NTNU, with relations to NOWITECH, were supervisors for annually around 40-50 MSc students with topics specializing in offshore wind energy (see Appendix). This is a remarkable increase from the first years see, Figure 56. It demonstrates high and increasing interest in offshore wind energy among master students at NTNU. The Erasmus Mundus European Wind Energy Master (EWEM) programme gives further weight to the MSc education at NTNU, in particular in the fields of electro and marine which are areas of NTNU engagement within the EWEM.

Increased recruitment of women was promoted by active profiling of female candidates specializing within the field of offshore wind energy. In hiring students for summer job, PhD or Post Doc positions, women were especially invited to apply, and would be selected over male candidates if otherwise equally qualified.

The candidates graduating through the NOWITECH PhD program have been very attractive in the job marked, and notably, almost all candidates have chosen to pursue their carriers closely related to offshore wind.

Centre company	Other companies	University	Research institute	Outside Norway	Other	Total
2	10	7	2	3	1	25

Table 2: *Overview of employment of PhD-candidates from NOWITECH by end of 2017.*

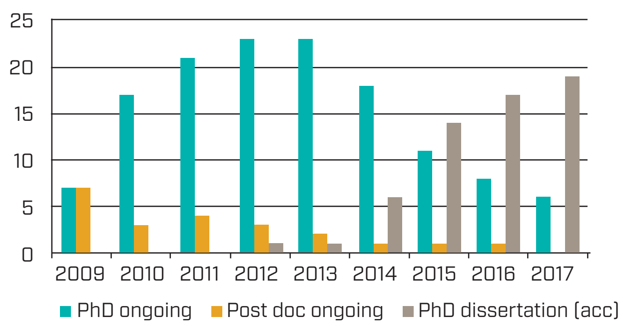


Figure 55: *Timeline of PhD and Post Doc programme funded by NOWITECH.*

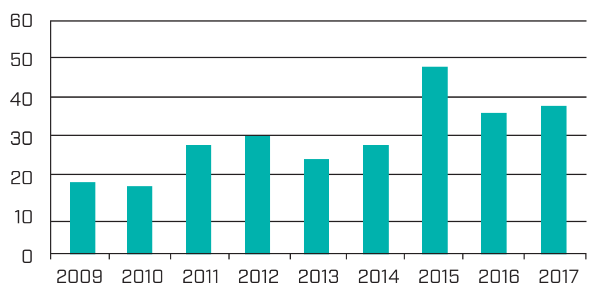


Figure 56: *Annual number of MSc theses in offshore wind energy at NTNU since start of NOWITECH.*

Figure 57: *During a Research Council review meeting with NOWITECH in 2016, 3 PhD students told their stories. The students (from left) Daniel Zwick is today a Senior Engineer at FEDEM, Tania Bracchi is an associate professor at NTNU, and Øyvind Netland is a scientist at CISCO.*

Dr Daniel Zwick defended his thesis in 2015 on the topic *"Simulation and optimization in offshore wind turbine structural analysis"*. He has followed NOWITECH closely also after his dissertation being employed at Fedem and representing Fedem in the board of NOWITECH. He pointed out the usefulness of the industry network of NOWITECH and learning how to work in teams and with other PhD colleagues. He is now a Senior R&D Engineer at FEDEM.

Dr Tania Bracchi defended her thesis in 2014 on the topic *"Downwind rotor: studies on yaw stability and design of a suitable thin airfoil".* She emphasised that being a PhD in NOWITECH meant being part of a group that gave a better scientific understanding and a bridge between academics and the industry. Tania has continued to work on offshore wind, now being an associate professor at NTNU.

Dr Øyvind Netland defended his thesis in 2014 on the topic *"Remote Inspection of Offshore Wind Turbines".* At the time of the presentation in 2016, Øyvind was working in the start-up company EMIP on further developing the remote sensing techniques for offshore wind turbines he had developed during this PhD study. Øyvind emphasised that he was particularly satisfied with the PhD-group meetings that established a scientific and social network. This, together with the industry meetings, the DeepWind conferences, the NOWITECH day and Industry Meets Science workshops, all gave an excellent basis for the PhD study to be successful.

COMMUNICATION AND DISSEMINATION

The scientific results of NOWITECH have been disseminated efficiently and are achieving international recognition. Publications since start-up include 232 peer-reviewed papers, 174 technical reports, and 39 PhD theses and books, including a textbook by Wiley based on NOWITECH research material. Further, 125 media contributions and 194 conference presentations of which more than 20 were invited keynotes. Details of the publications are given in the appendix. All NOWITECH partners have access to a project e-room, where all internal information, publications and project results are presented.

A main event for communicating open results from NOWITECH is the EERA DeepWind conference held every year in Trondheim. This has been a success with a mix of plenary presentations with broad appeal and presentations in parallel sessions and posters on specific science and technology themes. The conference is established as an important venue on deep sea offshore wind R&D. It is hosted by SINTEF and NTNU and organized in association with the European Energy Research Alliance (EERA) joint programme on wind energy. The presentations from the conference are available at the conference website, and submitted papers are after a careful peer-review process published in an open access journal (Energy Procedia (Elsevier), and Journal of Physics: Conference Series (2018). EERA DeepWind 2019 is already in planning.

Other main channels for open communication of NOWITECH activities and results are listed below:

- www.NOWITECH.no gives open information about NOWITECH, short news on offshore wind and announcements of relevant seminars etc. The site is mainly for the interested professional. The web page is continuously updated.
- The NOWITECH newsletters give short teasers of results and information on activities in NOWITECH. The newsletters are distributed through e-mail and public web. They are open and shall be understandable also for the educated non-expert, but with links for further reading to the NOWITECH e-room for partners only.
- The seminar series "Industry meets Science" is continued in cooperation with Wind Cluster Norway. The aim of the seminar series is to facilitate an improved interaction between the research in NOWITECH and relevant industry, also those that are not partners in NOWITECH.

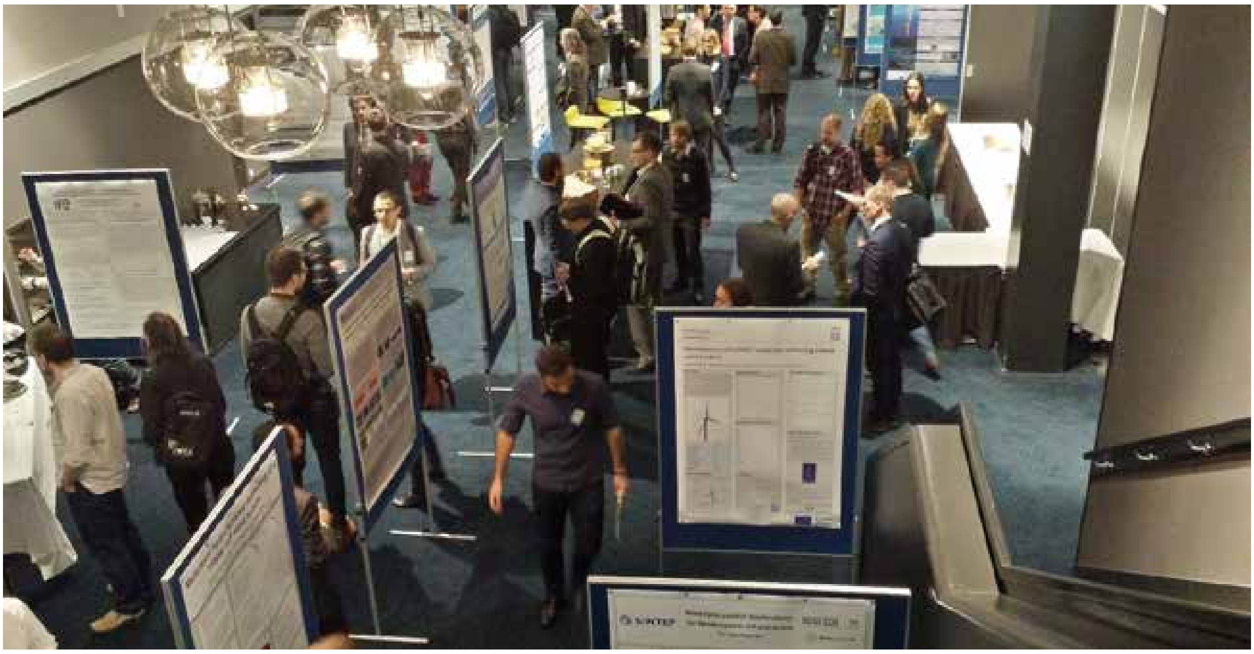


Figure 58: *The EERA DeepWind R&D conferences arranged in Trondheim annually in January are well attended with about 200 delegates, mainly from Europe but also from USA, Japan and other countries.*

IMPACT OF NOWITECH

The bold vision for NOWITECH was to contribute to large scale deployment of deep sea offshore wind turbines, and to be an internationally leading research community on offshore wind technology enabling industry partners to be in the forefront. NOWITECH has delivered results according to this vision, and realised its objective to provide pre-competitive research laying a foundation for industrial value creation and cost-effective offshore wind farms.

NOWITECH has carried out multidisciplinary research at a high international standard with a joint aim to provide new knowledge, education and innovations for reducing the cost of energy from offshore wind farms. Emphasis has been on "deep-sea" technology (+30 m) including bottom-fixed and floating wind turbines with attention towards development of knowledge and technology that could be applied in the international market. NOWITECH has been successful in this. In total 40 innovations have been brought forward for further development and application in more commercial-oriented projects.

The value of NOWITECH has been assessed by the independent consultancy company Impello Management AS. In their assessment they considered a subset of the innovations by NOWITECH, and calculated the net present value of these to yield excess of EUR 5 billion[5], i.e. more than hundred times the total expenditures of NOWITECH. Also, the report verifies an already achieved value creation of EUR 35 million, being equal to the total budget of NOWITECH. Three spin-out companies have been established based on results from the centre. These are Seram Coatings AS that has an innovative method for thermal spraying of silicon carbide (SiC), being a generic technology with a large range of future application areas, SIMIS AS having developed the Ashes wind turbine simulation software and EMIP AS that are commercializing technology for remote inspection and maintenance of offshore turbines.

NOWITECH has proven a very effective spearhead for research, providing international visibility and impact. A set of separate projects could not have achieved

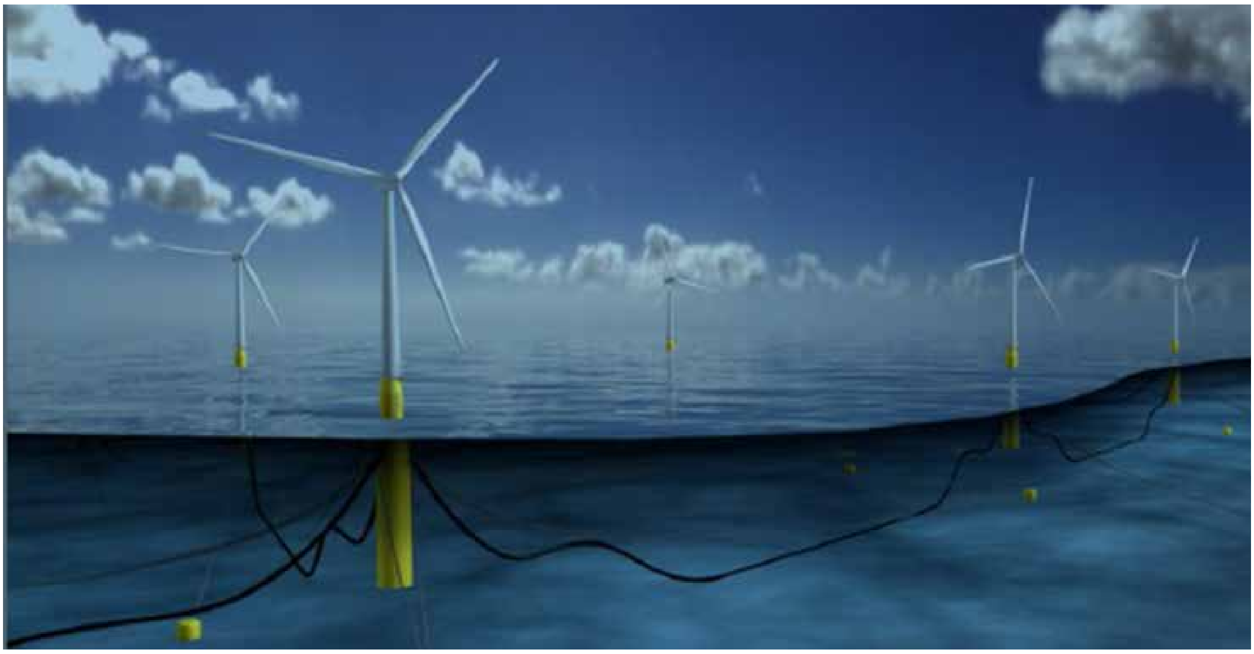


Figure 59: *Statoil has now taken the floating wind turbine concept, Hywind, to the next step with a 30 MW pilot wind farm installed in Scotland in 2017.*

5 The net present value is calculated as the socio-economic value of applying the innovations to a share of new offshore wind farms expected in Europe up to 2030. The full report by Impello is available at www.nowitech.no.

this. The research partners have become recognized as internationally leading within specific areas and are engaged in close to all European research projects within offshore wind energy technology. NOWITECH has contributed strongly to education bringing forward attractive candidates for employment in industry. The large majority of PhD students in the centre are now engaged in Norwegian industry and working towards increased supplies towards the international offshore wind market.

Host institute, SINTEF Energi AS

Knut Samdal, Research Director

SINTEF has extensive research expertise in the field of energy systems, renewable energy and power transmission, which have been key focal areas in NOWITECH. The coordination of a major international research center such as NOWITECH has been crucial to our research strategy and activity. SINTEF's vision is "Technology for a better society", and research to contribute to large scale deployment of deep sea offshore wind turbines will help us to achieve our vision.

Norway has huge offshore wind power resources and also a wealth of knowledge developed through the oil and gas industry from operations in offshore conditions. Offshore wind is a key enabling renewable resource in many countries. It has considerable advantages such as reducing the need for land area and can supply energy from close to densely populated coastal cities.

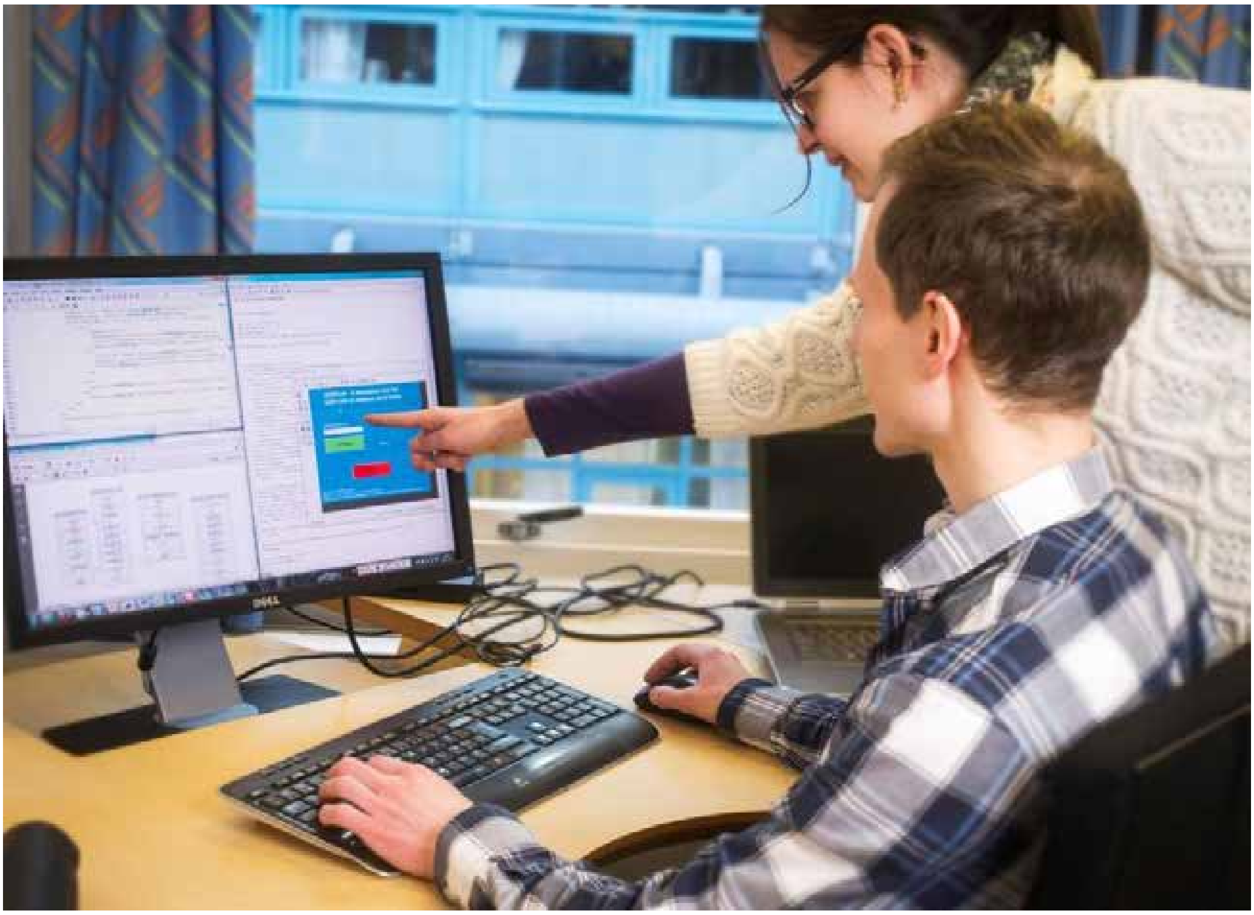


Figure 60: *Hanne Vefsnmo was one of many MSc students that completed their thesis related to offshore wind energy in 2013. Her thesis was "Determining the Optimal Vessel Fleet for Maintenance of Offshore Wind Farms". Here in discussion with Researcher Iver Sperstad Bakken regarding the tool "Nowicob". She now works as a researcher at SINTEF Energy Research.*

SINTEF Energy Research has conducted research into wind power for more than 20 years, involving projects linked to effective grid operation and system services. In FME NOWITECH SINTEF, NTNU and IFE have - in partnership with the industry - applied both theoretical and analytical design as a key contribution to elevate floating wind power into the present day first time full scale deployments offshore. NOWITECH has been a unique center for multidisciplinary collaboration between research and technical groups from different backgrounds, including the biggest industrial players in Europe within offshore wind, such as Ørsted, Statoil and EDF.

Through our R&D collaboration, the NOWITECH partners have created innovative cooperative teams, spin-off projects and spin-off companies. NOWITECH has resulted in closer collaborations between the partners, and will live on in the form of its spin-offs and network.

It has also led to closer collaboration with the industry through joint activities and networking. By attracting worldwide attention through the annual EERA Deep-Wind conference, research from the center has helped offshore wind and the partnering industry to achieve an entirely new competitive status.

The coordination of a major and long-term research efforts such as FME NOWITECH means that SINTEF Energy becomes an even more attractive employer due to the greater visibility and a boosted reputation. In this way, NOWITECH, together with our other FME centers, has had a very visible and important role in the recruitment of new talents.

Research partners

NTNU, Trond Kvamsdal, Professor

NTNU has extensive track record of research and education related to many aspects relevant for offshore wind technology which is the topic of NOWITECH. In particular, structural and fluid mechanics applied to offshore structures and electrical engineering. Furthermore, NTNU have strong groups in enabling technologies as applied mathematics and material science. NOWITECH has been a catalysator for multidisciplinary research involving 8 departments and more than 20 professors together with about 50 PhD/Post Docs (25 funded directly by NOWITECH). Few other universities in Europe can address offshore wind technology in such breadth and depth, and our involvement in NOWITECH has really put NTNU at the international front regarding research and development of offshore wind turbines.

About 80 % of all engineers on master's level in Norway are educated at NTNU, as well as a very high share of PhD candidates in the technology field of which the industry employs roughly 70 %. The NTNU's participation in NOWITECH has helped ensuring a high quality in the education of master and PhD candidates relevant for offshore wind technology, among other factors due to coupling master theses to ongoing PhD projects.

NTNU's current strategy expresses the vision: Knowledge to a better world. NOWITECH has enabled significant knowledge transfer from oil and gas industry to renewable energy sector, which contribute very well to NTNU's overall vision.

SINTEF Ocean AS, Bård Tveiten, Research Director

SINTEF Ocean has extensive expertise in the field of ocean hydrodynamics and ocean engineering, which are key areas of focus in NOWITECH. The participation into a major international research centre such as NOWITECH has been crucial to our strategy and activity related to offshore wind energy research and technology transfer from the maritime and offshore oil&gas industries into new areas of application. SINTEF vision is 'Technology for a better society'. The development of offshore wind turbine designs for green energy production help us achieve our vision.

The offshore wind industry is expanding rapidly around the world. The demand for green energy is increasing. Wind resources are stronger in offshore areas relative to onshore wind power, with less social and geographical constraints. Technology developments and cost-efficient innovations makes offshore wind energy a favourable and competitive alternative for power production.

SINTEF Ocean has conducted research on ship and ocean structures for close to 80 years. The NOWITECH project has given the opportunity to expand this knowledge into other areas of applications. It has given the opportunity to expand our collaboration with NTNU and other Norwegian research institutions,


2°
Solutions for
offshore grids

and attract new generations of ocean engineering and naval architecture candidates. And finally - it has given the opportunity to contribute to the 'green shift' and a wider energy mix.

Our focus areas within NOWITECH have been related to the development of robust and reliable design tools for wind energy concepts, development of experimental procedures for qualification of offshore wind turbines, and development / qualification of specific concepts by numerical analyses and physical experiments. Furthermore, SINTEF Ocean has been deeply involved in development logistics systems and maintenance systems for offshore wind farms.

IFE, Roy Stenbro, Group leader

IFE have had Norway's only research group dedicated to wind energy for more than 40 years now. FME NOWITECH has played in important role in our shift to offshore wind turbines.

The long-term efforts of FMEs allows us to execute strategic changes that are not possible in shorter projects. NOWITECH was for example a backbone that enables us to lift 3DFloat to a state of the art software for simulations of offshore wind turbines.

FMEs also represent valuable and stable long-term meeting place for education, research and industry that has brought the whole Norwegian offshore wind community closer together. NOWITECH has also strengthened IFE's international R&D position since it has enables long term commitment to international research activities such as IEA projects.

SINTEF Industry, Jens Kjær Jørgensen, Senior Research Scientist

SINTEF AS is a discipline focused research institute covering areas as material & structures, production technology, computational techniques & digitalisation and economic & societal topics applied in a broad range of sectors and applications. At the initiation of NOWITECH Wind Energy was a marginal market for SINTEF AS and the organisation had limited knowledge of the needs and challenges of the wind energy sector. Today SINTEF AS is well positioned within various parts of the wind energy value chain ranging from materials and components to wind park design and control, and SINTEF AS takes part in several commercial and research focused wind energy project. Among these are two H2020 project coordinated by SINTEF AS. NOWITECH has been and irreplaceable arena for SINTEF AS to establish the required knowledge of wind energy technology and market needs and to build a comprehensive national and international network with industries and researcher.

Associate research partners

DTU Wind Energy, Peter Hauge Madsen, Head of Department

The NOWITECH programme has put Norway on the map as a center of excellence in offshore wind energy. The research, the innovation and the PhD-programme has been of very high quality, making the NOWITECH participants attractive partners in future international research. Also, the annual Deepwind conference has successfully provided a venue for bringing international researchers and industry together for discussions and dissemination for everybody's benefit. Well done.

NREL laboratories, Amy Robertson, Researcher

I was impressed by the level and quality of research that came from the NOWITECH project. At its inception, there was little research being performed on offshore wind, especially for floating systems, and this project really helped to develop a broad interest in research related to deep-water wind turbines. The annual DeepWind conference also supplied a venue for open dialogue and discussions on the topic, which I saw grow from a Norway-focused event to a worldwide one, helping to foster collaboration and push the industry forward.

Strathclyde University, Olimpo Anaya-Lara, Professor

NOWITECH successfully conducted innovative research on all key aspects of offshore wind technology with intense interaction with industry. The research activities on wind farm control and grid integration were in particular outstanding introducing exciting new methods and ideas, some of which are being further explored in follow-on programmes. The mobility scheme was an excellent platform for knowledge exchange and networking among researchers in NOWITECH.

Fraunhofer IWES, Dr. Arno van Wingerde, Chief Scientist
I got into contact with the NOWITECH project via the DeepWind conferences. Year after year the conference grew in size and quality, with the final result a virtual explosion of high-quality research in every imaginable way, be it Ph.D. thesis, patents, research projects.
I feel the great value-for-money for the Norwegian taxpayers is due to the coordination, rather than competition, which is a tribute to the Norwegian system. I am contemplating to suggest a similar system for Germany.

Industry partners

Statoil, Gudmund Per Olsen, Leader of RD NEH OWI
Through our active participation in NOWITECH, we have gained access to new knowledge and technology. We have closely collaborated with scientific research institutions and the research community associated with NOWITECH. This has increased our knowledge and understanding within several important academic fields associated with the development of offshore wind fields.

NOWITECH has delivered research results that are implemented in Statoil (Equinor) work processes and analysis tools that are used for developing our wind projects.

DNV GL, Marte Riiber de Picciotto, Head of Renewables Advisory
Working together with NOWITECH has provided excellent opportunities for the development of the offshore floating wind industry. As a leading technical and market advisor to the industry and pioneers in developing the industry standard for floating wind, DNV GL has appreciated the opportunities our relationship with NOWITECH has provided us to meet and discuss with key industry players and academia."

FEDEM Technology, Daniel Zwick, Senior Engineer
Cooperation with NOWITECH researchers gave Fedem the possibility to benchmark and further develop our wind turbine analysis software. The partner network established within NOWITECH enabled new project opportunities for Fedem in the wind business. The participation in NOWITECH also provided valuable background knowledge for Fedem during business plan development in a process that ended with SAP in May 2016 acquiring all shares in the company.

Ørsted, Jørn Scharling Holm, Technology Partnership Manager
Ørsted Wind Power (formerly DONG Energy Wind Power) participated for the full 8-year period of the NOWITECH program.

We have followed all areas of work with interest, but our participation in NOWITECH was based on two primary areas of interest: Floating wind power systems and Electricity systems and components.

The development of floating wind power is currently gaining increased momentum and the work thin NOWITECH has carried out within this field will be of help in the development of a floating wind power industry that will enlarge the total market for offshore wind power. Norwegian companies and academic institutions are well positioned to make significant contribution to the development, and NOWITECH has produced both useful projects and candidates that can be of help in the development of the industry.

So far, Ørsted has decided to focus our resources on development of bottom fixed offshore wind farms. So, we are only monitoring the development of floating technology, costs and markets. However, if we decide to move into floating at some stage, it will be obvious for us to investigate how we can build on the knowledge thin NOWITECH has produced within floating wind power.

Within the electrical systems, the NOWITECH program has also focused on issues that are very relevant and of help in developing present and future offshore wind power solutions. The NOWITECH participation has formed basis for a fruitful collaboration between Ørsted and NOWITECH partners that has continued after NOWITECH has finished.

Finally, Ørsted has had a good collaboration with NOWITECH on a geoscience PhD project with relation to installation of monopiles for offshore wind turbines foundations.

Ørsted would like to take the opportunity to thank the NOWITECH partners for their contribution to pushing offshore wind knowledge and technologies forward and for good collaboration over the years.

FUTURE PROSPECTS

Offshore wind farms will be an important part of a future sustainable energy system. IEA expects offshore wind to supply 5 % of the global electricity demand in 2050[6]. In Europe alone, investments in offshore wind farms over the next ten years are expected to sum up to approximately NOK 1000 billion. This represents a golden opportunity for development of new knowledge-based jobs.

Norwegian industry is competitive with supplies to the offshore wind market within several branches, e.g. marine operations, substructures, power collection and transmission, and within wind farm control, monitoring and asset management. Norwegian entities are also active in European research projects. Still, there is very significant potential to increase the Norwegian engagement, both in research and as suppliers to the international market, but also to build and operate offshore wind farms. As for the latter, Statoil is active as a major global actor and a frontrunner in the development of floating offshore wind farms.

Norway has large offshore wind resources, and an offshore demand for electricity to supply oil and gas installations. This give promising prospects for future offshore wind farms that can be linked to oil and gas platforms, for reducing the emission of climate gasses from these. A longer-term vision is to utilize the platforms to produce hydrogen, providing large-scale clean supply of energy. Larger offshore wind farms can also be built and operated in concert with the Norwegian on-land power system that is dominated by hydropower with superior balancing capabilities being an excellent match with variable renewables like offshore wind.

Although the offshore wind technology has gone through an astonishing development during the last few years, it is compared to other more mature energy technologies, still in its infancy with continued need for strong R&I and great future potential. This is confirmed by the Norwegian research strategy Energi21 and the European SET-plan both prioritizing research on offshore wind technology.

NOWITECH has proven a very effective spearhead for research, providing international visibility and impact. A set of separate projects could not have achieved this, and an ideal continuation would be to again have an FME or similar on offshore wind. In the meantime, NOWITECH will continue as a research network, and research on offshore wind technology will continue amongst the partners through a strong portfolio of projects. The potential value of further maturing and utilizing the innovations from NOWITECH is estimated to yield excess of EUR 5 billion. A continued effort should be made to realize this value, and new more long-term research should be initiated to generate new knowledge and innovations. It is time for the next wave!

Figure 61: *NOWITECH will continue as a research network between SINTEF, NTNU and IFE together with international partners. It will leverage on results from NOWITECH and keep momentum of the collaboration. Research priorities include a) support structures, marine operations and materials, b) grid connection and system integration and c) asset management, wind farm control and digitalization.*

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6 IEA Technology Roadmap (2013) 2DS scenario https://www.iea.org/publications/freepublications/publication/Wind_2013_Roadmap.pdf

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