Final report

1.1 Project details

Project title	Deltagelse i IEA Wind Task 26: Omkostninger ved vindkraft - fase 2
Project identification (program abbrev. and file)	Journal number 64012-0246
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	Ea Energianalyse a/s Frederiksholms Kanal 4, 3. th. 1220 København K
Project partners	J Lemming Rådgivning (previously DTU Vindenergi)
CVR (central business register)	28 98 58 27
Date for submission	February 12, 2016

1.2 Short description of project objective and results

The scope of IEA Wind Task 26 is to assemble and analyse estimates of past, present and future wind energy costs using transparent, consistent methodologies and disseminate this information in order to enable understanding and comparison of wind energy to other generation options within the broader electric sector.

Achieved results include:
• Enhanced international collaboration and coordination in the field of cost of wind energy
• Updated data, analysis and understanding of on-shore wind energy cost trends and comparison among countries
• Identification of the primary offshore wind energy cost drivers and the variation of these costs among participating countries
• Collaborative journal articles and publications summarizing and further analysing work conducted to understand trends in cost of energy
• Workshop or experts meeting on methods to value wind energy and methods to evaluate historical and future technology cost trends.

Gennem IEA Wind Task 26 samles og analyseres beregninger og estimater af tidligere, nuværende og fremtidige omkostninger ved vindenergi. Målet er at opnå viden og give mulighed for at kunne sammenligne vindenergi med elsektorens øvrige produktionsmetoder ved hjælp af transparente og ensartede analysemetoder.

Igennem IEA Wind Task 26 er følgende opnået:

- Øget internationalt samarbejde og koordinering inden for analyse af vindenergis omkostninger
- Opdateret data, analyse og viden om omkostninger ved at producere el fra vindmøller på land, herunder tendenser og sammenligninger mellem landende.
- Identifikation af de primære faktorer for omkostninger ved produktion af el fra havvindmøller, og dermed variationerne af disse omkostninger mellem de deltagende lande.

- Udarbejdelse af sammenfattende artikler og publikationer samt et yderligere analysearbejde udført for at forstå tendenser for energis omkostninger.
- Afholdte workshops med eksperter om metoder til at validere energi og metoder til at evaluere historiske og fremtidige teknologiske omkostningstendenser.

1.3 Executive summary

The objective of the project was to provide information on cost of wind energy in order to understand past, present and anticipate future trends using consistent transparent methodologies as well as understand how wind technology compares to other generation options within the broader electric sector. Task 26 in its 3rd Phase will continue to add data and analysis, develop methodologies, and enhance collaboration.

Project goals included:
• Enhanced international collaboration and coordination in the field of cost of wind energy
• Updated data, analysis and understanding of on-shore wind energy cost trends and comparison among countries
• Identification of the primary offshore wind energy cost drivers and the variation of these costs among participating countries
• Collaborative journal articles summarizing and further analysing work conducted to understand trends in cost of energy
• Workshop or experts meeting on methods to value wind energy and methods to evaluate historical and future technology cost trends.

In Work Package 1 (WP1), Onshore Wind, a report titled "Wind Technology, Cost, and Performance Trends in Denmark, Germany, Ireland, Norway, the European Union, and the Unied States: 2007 – 2012" (the main deliverable of WP1) has been published. Updated estimates of cost of wind energy for land-based wind plants have been made. The participants collected and analyzed wind plant data representing projects installed from 2007 to 2012 for each country, and a comparison was made across the countries to identify drivers and differences among the countries.

In WP2 (offshore wind), the cross-institutional and multi-national collaboration on the development (and verification / validation using market data) of a cash-flow model, as well as a representative Baseline project, has been a valuable knowledge- and experience-sharing initiative, resulting in a deepened understanding of cost components of offshore wind projects - and impact thereof – on the LCOE of offshore wind energy. Based on the analyses carried out by each country thereafter, a systematic understanding of regulatory and market impacts across countries has been established, to be consolidated in a publicly available publication in the next Phase of the project.

In WP3, the Danish – Irish collaboration project, consolidated into a scientific journal article, provided further insight into the potential impacts of an energy policy option debated between Ireland and the UK towards reaching the greenhouse gas reduction targets in the two countries, as well as a conceptual input to wind power integration and value of wind power investigations more broadly.
The Expert Meetings have served as fora for knowledge exchange across various representatives of the wind industry, and the outcomes thereof have been made public to provide insight and input to both the industry, as well as policy-making stakeholders.
Finally, the expert elicitation survey results (once consolidated into publicly available reports and publications) would make for value-adding contribution to informing policy and planning decisions, public and private R&D decisions, industry investment and strategy development, as well as electric sector modelling assumptions. It is one of the methods to help understand wind technology and cost reduction pathways.

The results of the project can be directly applied to planning for – and promoting - energy policy objectives. The project results enable the political decisions on the expansion of wind power be taken on an even better and updated basis, based on data from international con-

text based on consistent, verified methodology. Information regarding wind power value in the power system and future costs associated with the expansion of wind power can be used to illuminate the effect of political decisions and form the basis for decision-making on development of wind turbines in the future. At the same time, the results from the analyses of possible technical developments and their influence on the cost of wind power could help identify areas where there will be a need and economic benefits of publicly funded research and development.
The project contributes mainly to the formulated strategies within the area of wind energy, by shedding light and mapping out the potential in cost reductions of costs of wind energy, as well as indicating how cost reductions can help increase the value of wind energy. This illustrates how the political objective of reducing greenhouse gas emissions and use of renewable energy can be achieved in a cost-effective manner.

1.4 Project objectives

Wind power generation costs have dropped to a point where they are competitive with conventional generation costs in some cases. Technology development is intended to reduce the cost of energy, but certain market drivers, including commodity price increases, can create upward price pressures. These costs differ among countries, and comparison is difficult. The scope of IEA Wind Task 26 was to assemble and analyse estimates of past, present and future wind energy costs using transparent, consistent methodologies.

Task 26 was initiated in 2009, and the original work plan was complete by May 2012. A proposed extension was approved and is in effect from October 1, 2012 through September 30, 2015. Additional participation in the task was encouraged, and the UK joined in 2015.

The objective was to provide information on cost of wind energy in order to understand past, present and anticipate future trends using consistent transparent methodologies as well as understand how wind technology compares to other generation options within the broader electric sector. Task 26 in its 3rd Phase will continue to add data and analysis, develop methodologies, and enhance collaboration.

Project goals included:
• Enhanced international collaboration and coordination in the field of cost of wind energy
• Updated data, analysis and understanding of on-shore wind energy cost trends and comparison among countries
• Identification of the primary offshore wind energy cost drivers and the variation of these costs among participating countries
• Collaborative journal articles summarizing and further analysing work conducted to understand trends in cost of energy
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There are three primary aspects to understanding the cost of wind energy at the present and in the future: 1) accurate data applied using transparent assumptions and methodologies to represent current market conditions and expectations; 2) analysis of historic trends and application of engineering and learning models to inform potential future projections of wind energy costs; and 3) representation of the value of wind energy in the broader electric system and economy in general.

The project objectives were further divided into 3 Work Packages (WPs), each focusing on a particular sub-section of wind energy specifically.

WP1: Update analysis of land-based wind technology cost drivers and differences among participating countries with current data.

Providing transparency in the cost elements of wind projects among all participating countries would result in better understanding of the cost drivers of wind technology and the reasons for differences among participating countries. In the initial task, the Participants used a common model to estimate the Levelised Cost of Energy for typical land-based wind projects in their respective countries. In this extension, the spreadsheet models were to be updated with more recent data and documentation; new participants were to create comparable spreadsheet models representing typical land-based wind projects over the period from 2008 to present based on available data. The spreadsheets and associated documentation were to be made available on the publicly accessible IEA Wind Task 26 website. A report describing trends in technology, cost and performance from 2007 through 2012 for each participating country was to be published.

WP2: Estimate cost of offshore wind energy and identify major cost drivers in each participating country.

Offshore wind technology has been installed by some participating countries, and others are exploring the potential uses of this technology. The approach developed in the initial phase of Task 26 to assess the cost of land-based wind projects was to be applied to describe cost elements of offshore wind projects. A taxonomy of offshore wind project cost elements was to be created building on previously published work. Based on available data from each participant, a composite representation of offshore wind project cost and primary differences in a sub-set of parameters, e.g., water depth, distance from shore, wind resource, and finance structure was to be developed. The spreadsheet model was then to be made available on the publicly accessible IEA Wind Task 26 website along with documentation of assumptions and the impact of variation in the parameters explored.

WP3: Explore methods and application of methods to understand future cost of wind energy and value of wind energy in electric system

Estimates of future cost and performance for wind technology are important for analyses of the potential for wind energy to meet national targets for carbon emission reductions or renewable electricity generation. Learning curves are one method for assessing the effect of technology development, manufacturing efficiency improvement, and economy of scale. Component level cost and scaling relationships can also be used to estimate future technology development pathways. Engineering models can isolate theoretical improvements associated with individual technical changes, e.g., larger rotors. These models can also project theoretical cost and energy production from future technology advances. All projections of future wind energy costs can be informed by analysis of historical trends that capture both technology and market-related influences.

Under the first term of Task 26 a paper was published that analysed historical data to attribute technical advances to historical cost and performance trends, and to examine the impact of both new generations of wind technology as well as improvements within a generation. Examples of the former include increased machine rating whereas examples of the latter include larger rotors, taller towers. In this extension, use of expert elicitation to provide insight into industry participant perspectives on cost of wind energy potential and drivers was to be investigated.

Wind energy technology ultimately operates in an electric system that includes conventional and other alternative electricity generation technologies. Wind energy technology adds value to a system in a number of ways including reducing carbon emission, diversifying fuel supply and moderating fuel price variation. In addition the broader economy is impacted by the wind energy sector, for example, through employment. Exploration of these system relationships and methods for quantifying such impacts was to be done through an expert meeting.

Figure 1 illustrates the planned work flow, milestones and deliverables for the project.

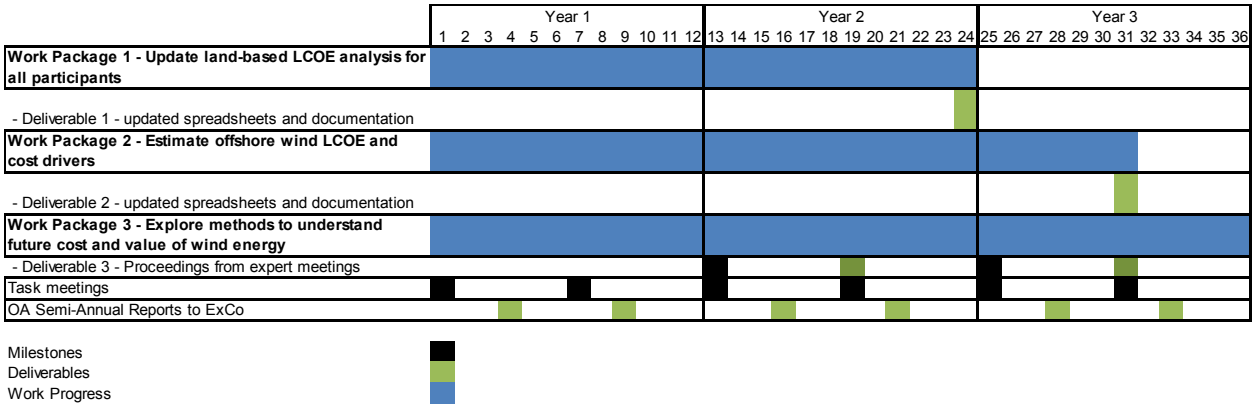

Figure 1: Work Plan chronogram

The project achieved all of the milestones and deliverables set forth. Certain changes of scope were implemented based on the discussions in the Task group, in order to more accurately address the most relevant research areas. The key project risk was the possibility of delays in the planned activities and deliverables due to the multitude of contributors and stakeholders involved.

1.5 Project results and dissemination of results

In Work Package 1 (WP1), Onshore Wind, a report titled "Wind Technology, Cost, and Performance Trends in Denmark, Germany, Ireland, Norway, the European Union, and the Unied States: 2007 – 2012" (the main deliverable of WP1) has been published. A Launch Event for the report was held on June 15, 2015 in Copenhagen prior to the Task in-person meeting.

Building from the work conducted in the first phase of the task (Schwabe et al., 2011), updated estimates of cost of wind energy for land-based wind plants have been made. In the earlier work, participants had collected and analyzed wind plant data representing projects installed in 2008 for each country, and a comparison had been made across the countries to identify drivers and differences among the countries. In the current work, trends from 2007 through 2012 were updated by participants continuing in the task as well as expanded to include Norway and Ireland due to new task participation.

Data was required to represent the four primary elements of cost of energy: 1) total capital investment to bring a wind plant to commercial operation; 2) annual operating expenditures over the life of the wind plant; 3) annual energy production over the life of the wind plant; and 4) cost of financing the wind plant. Accessing such data for each project installed in a participating country is often difficult or incomplete. A variety of sources may be available, and each country's data availability and quality differs. A significant portion of the task has been spent sharing best practices for obtaining high quality project data and defining the scope of various cost elements to improve reporting consistency among countries.

For example, Figure 2 illustrates trends in the U.S. and the European Union related to wind turbine "specific power" and hub height. The wind turbine specific power is defined as the turbine nameplate capacity rating divided by the rotor swept area (W/m^2)[1]. A lower specific power indicates that more wind energy can be extracted for a given generator size, thereby boosting capacity factors, all else being equal. In the U.S. a trend toward lower specific power while maintaining a relatively consistent hub height is evident from 2007 to 2012. In the European Union, the reduction in specific power is not as dominant, and tower height increases are evident. Both of these trends tend to increase energy capture. The impact these types of trends have on cost of energy in each of the participating countries is discussed in the published report.

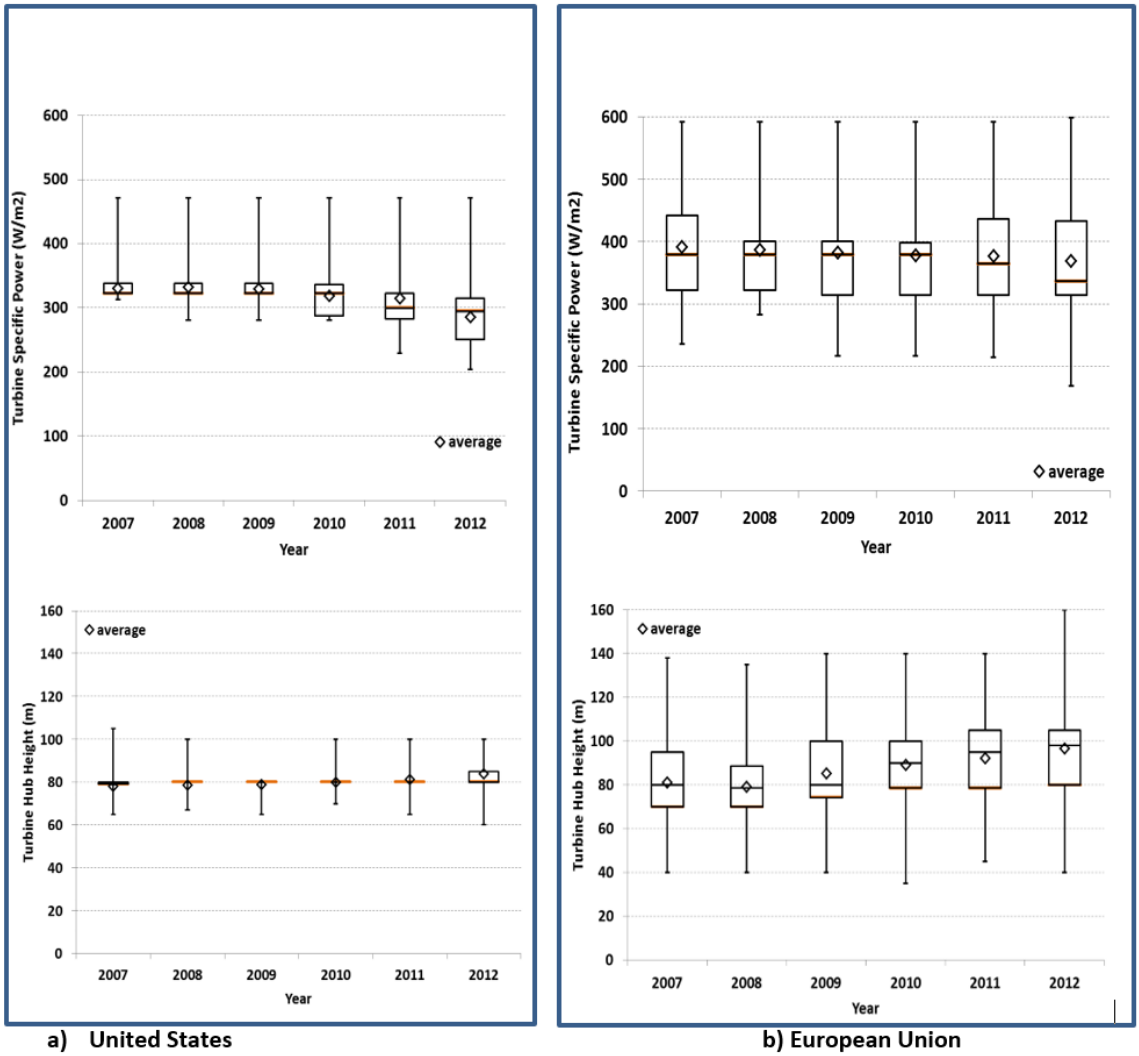

Figure 2: Trends in wind plant specific power and hub height from 2007 to 2012 in the U.S. (a) and the European Union (b).

In Work Package 2 (WP2), Offshore, because offshore wind cost of energy is very site-specific and currently concentrated in a small number of markets, an approach for consolidating data among participating countries was devised. Data and model estimates for existing and planned offshore wind projects were combined and compared. A baseline representation of the physical characteristics of a typical offshore wind plant was developed. This approach allows analysis of cost drivers based on information provided from the various participants and represents offshore wind project costs generically – rather than specific to those countries where projects are in operation. Using this baseline, each of the participating countries were exploring country-specific deviations in market and policy conditions in order to identify and quantify both technical and policy-based cost drivers.

The project participants submitted the results of the updated TKI/FLOW model investigating the impacts of the market and regulatory characteristics of their respective countries on the Offshore Baseline project (upcoming deliverable within WP2, to be finalized in 2016). There has been a continuous iterative process involving both improvement and refinement of the TKI / FLOW model used within WP2, as well as feedback loop from the project participants applying the model to the respective country market and financing conditions. As a result, an Offshore Baseline project has been finalized. A technical report elaborating on the

[1] A box and whiskers format is used to represent the projects or turbines that achieved commercial operation in a given year including the median (horizontal line), average (diamond), 25th to 75th percentile (box), and minimum and maximum (whiskers).

characteristics, rationale and methodology underlying the creation of the Baseline model was being produced.

In Work Package 3 (WP3), the collaboration project between Denmark and Ireland has been completed, and a joint journal article has been published in the Journal of Energy Policy. The collaboration project, carried out in Plexos and Balmorel modelling frameworks, focused on estimating the impacts of large scale wind energy exports from Ireland to Great Britain. The share of wind generation in the Irish and British electricity markets is set to increase by 2020 due to renewable energy targets. The United Kingdom and Ireland have set ambitious targets which require 30% and 40% of electricity demand to come from RE, mainly wind, by 2020, respectively. Ireland has sufficient indigenous onshore wind energy resources to exceed the RE target, while the UK faces uncertainty in achieving its target. A possible solution for the UK was to import RE directly from large scale onshore and offshore wind energy projects in Ireland; this possibility has been explored by both governments but is currently on hold. Thus, the aim of the paper was to estimate the effects of large scale wind energy in the Irish and British electricity markets in terms of wholesale system marginal prices, total generation costs and CO2 emissions. The results indicated that when the large scale Irish-based wind energy projects are connected directly to the UK there is a decrease of 0.6% and 2% in the Irish and British wholesale system marginal prices under the UK National Grid slow progression scenario, respectively.

In addition, two Expert Meetings (milestones in WP3) have taken place: in Petten, Netherlands in November 2013, and in Golden, Colorado in November 2014. Joint Research Centre (JRC) has published a report based on the former Expert's Workshop.

Finally, an expert elicitation survey on future wind energy costs and related technology advancement possibilities has been carried out. 482 world-leading wind industry experts were identified, including representatives from industry, R&D, academia and other institutions, and covering onshore, fixed-bottom offshore, and floating offshore technologies. A web-based survey was then elaborated to gain insight on the magnitude of possible future wind energy cost reductions, sources of future cost reductions, as well as enabling conditions to realize innovation and lower costs. In addition, expert views on the factors and developments expected to contribute the most to reducing LCOE towards 2030 were gathered: the expectations for turbine characteristics in 2030 (capacity, rotor diameter, hub height), the development, technology, design, manufacturing, construction, operational, and market changes etc.

The project succeeded at achieving the milestones and objectives stipulated, addressing the research areas and issues set out in the project proposal.

This project was an international collaboration project, so no direct commercial results have been generated.

Project deliverables and result dissemination activities have included:

- Industry Day Event, Norwegian Water Resources and Energy Directorate (NVE), Oslo, Norway, October 29, 2015.

- Launch Event for the "IEA Wind Task 26: Wind Technology, Cost, and Performance Trends in Denmark, Germany, Ireland, Norway, the European Union, and the United States: 2007–2012" report, Vindmølleindustrien, Copenhagen, Denmark, June 15, 2015.

- Expert Meeting "Explore Methods and Application of Methods to Understand Future Cost of Wind Energy and Value of Wind Energy in Electric System", National Renewable Energy Laboratory, Golden, Colorado, US, November 6, 2014.

- Seminar "The Cost and Value of Wind Energy", Sustainable Energy Authority of Ireland, Dublin, Ireland, May 24, 2014.

- Expert Meeting "A System-based Approach to Assessing the Value of Wind to the Society", European Commission-Joint Research Centre, Petten, Netherlands, 13-14 November, 2013.

- Report based on an experts' workshop held in Petten, Netherlands, 13-14 November, 2013: Lacal-Arantegui, R.; M. M. Hand; D. Radu; D. Magagna; 2014. A System-based Approach to Assessing the Value of Wind to the Society. European Commission-Joint Research Centre.

- Land-based wind report: Vitina, Aisma, Silke Lüers, Anna-Kathrin Wallasch, Volker Berkhout, Aidan Duffy, Brendan Cleary, Leif I. Husabø, David E. Weir, Roberto Lacal-Arántegui, Maureen Hand et al. IEA Wind Task 26: Wind Technology, Cost, and Performance Trends in Denmark, Germany, Ireland, Norway, the European Union, and the United States: 2007–2012. National Renewable Energy Laboratory (NREL), 2015.

- A journal article based on the Danish – Irish collaboration project: B. Cleary, A. Duffy, B. Bach, A. Vitina, A. O'Connor, and M. Conlon, "Estimating the electricity prices, generation costs and CO2 emissions of large scale wind energy exports from Ireland to Great Britain" Energy Policy, vol. 91, pp. 38–48, 2015.

1.6 Utilization of project results

The primary objective of IEA Wind Task 26 is to provide information on cost of wind energy in order to understand past, present and anticipate future trends using consistent transparent methodologies and understand how wind technology compares to other generation options.

Semi-annual meetings provide a valuable forum for exchanging ideas among the participants as well as engaging with other industry or research organizations. For example, a meeting held in Dublin, Ireland, in May 2014 included presentations and discussion from a number of Irish industry, government and academic perspectives. This informal information exchange is highly valuable to the task overall as well as for the participating national organizations.

In WP1 (land-based wind), establishing trends from 2007 to 2012 in order to identify changes in wind technology and its associated impact on cost of energy is anticipated to be a valuable addition to understanding cost of wind energy in each country. This format for presenting data regarding all wind plant elements required to estimate cost of energy may prove to be a valuable contribution to the broader industry. This format provides protection for proprietary project data while also providing a statistical representation of the population of data available. In future extensions of the task, annual updates to these figures are envisioned to provide more timely information at regular intervals. New participants will be able to develop similar representations of trends within their countries in parallel to updates from continuing participants. For each country trends are represented for project size, turbine nameplate capacity, rotor diameter, hub height, specific power, IEC class, average annual wind speed, full load hours, investment costs, O&M costs, and finance costs to the extent that data is available.

In WP2 (offshore wind), the cross-institutional and multi-national collaboration on the development (and verification / validation using market data) of a cash-flow model, as well as a representative Baseline project, has been a valuable knowledge- and experience-sharing initiative, resulting in a deepened understanding of cost components of offshore wind projects - and impact thereof – on the LCOE of offshore wind energy. Based on the analyses carried out by each country thereafter, a systematic understanding of regulatory and market impacts across countries has been established, to be consolidated in a publicly available publication in the next Phase of the project.

In WP3, the Danish – Irish collaboration project, consolidated into a scientific journal article, provides further insight into the potential impacts of an energy policy option debated between Ireland and the UK towards reaching the greenhouse gas reduction targets in the two countries, as well as a conceptual input to wind power integration and value of wind power investigations more broadly.

The Expert Meetings have served as fora for knowledge exchange across various representatives of the wind industry, and the outcomes thereof (e.g. the publication by the Joint Research Centre based on the Expert Workshop) have been made public to provide insight and input to both the industry, as well as policy-making stakeholders.

Finally, the expert elicitation survey results (once consolidated into publicly available reports and publications) would make for value-adding contribution to informing policy and planning decisions, public and private R&D decisions, industry investment and strategy development, as well as electric sector modelling assumptions. It is one of the methods to help understand wind technology and cost reduction pathways.

The results of the project can be directly applied to planning for – and promoting - energy policy objectives. The project results enable the political decisions on the expansion of wind power be taken on an even better and updated basis, based on data from international context based on consistent, verified methodology. Information regarding wind power value in the power system and future costs associated with the expansion of wind power can be used to illuminate the effect of political decisions and form the basis for decision-making on development of wind turbines in the future. At the same time, the results from the analyses of possible technical developments and their influence on the cost of wind power could help identify areas where there will be a need and economic benefits of publicly funded research and development.
The project contributes mainly to the formulated strategies within the area of wind energy, by shedding light and mapping out the potential in cost reductions of costs of wind energy, as well as indicating how cost reductions can help increase the value of wind energy. This illustrates how the political objective of reducing greenhouse gas emissions and use of renewable energy can be achieved in a cost-effective manner.

This project was an international collaboration project, so no directly commercial use of the project results is expected.

The project results have been openly shared among all of the institutions involved, as well as general public through the project result dissemination activities.

No PhDs have been a part of the project.

1.7 Project conclusion and perspective

Each of the Work Packages has contributed to knowledge creation, exchange and dissemination on the topics of land-based wind, offshore wind and methods and application of methods to understand future cost of wind energy and value of wind energy in electric system, respectively. An extension to the IEA Wind Task 26 (its Phase 3) has been approved by the ExCo, ensuring the continuation of the activities relating to the Cost of Wind Energy.

In the next extension of the task, the onshore Work Package (WP1) will provide annual updates to the data and analysis carried out in the current project. New participants will be able to develop similar representations of trends within their countries in parallel to updates from the continuing participants.

The offshore wind Work Package (WP2) will focus on further model development, building on the activities and analyses completed during the current Phase of the project, and continuing knowledge and experience sharing. These envisioned developments would make further country-, site- and technology-specific sensitivity analyses possible.

In the next extension of the task, the expert elicitation study results (as per WP3) will be consolidated and published. In-depth analysis will be carried out, allowing for comparison of expert assessment across the respondent sample vs. leading-expert group, geography of familiarity, organizational type, expertise type, and application coverage. Comparison of in-

sights for onshore (land-based), fixed-bottom offshore, and floating offshore wind; and to existing literature will be carried out.

Annex
Relevant links:

B. Cleary, A. Duffy, B. Bach, A. Vitina, A. O'Connor, and M. Conlon, "Estimating the electricity prices, generation costs and CO2 emissions of large scale wind energy exports from Ireland to Great Britain" Energy Policy, vol. 91, pp. 38–48, 2015.
http://www.sciencedirect.com/science/article/pii/S0301421515302482

Vitina, Aisma, Silke Lüers, Anna-Kathrin Wallasch, Volker Berkhout, Aidan Duffy, Brendan Cleary, Leif I. Husabø, David E. Weir, Roberto Lacal-Arántegui, Maureen Hand et al. IEA Wind Task 26: Wind Technology, Cost, and Performance Trends in Denmark, Germany, Ireland, Norway, the European Union, and the United States: 2007–2012. National Renewable Energy Laboratory (NREL), 2015.
http://www.ieawind.org/task_26_public/PDF/IEA%20Wind%20Task%2026%20WP1%20Report%2064332.pdf

Lacal-Arantegui, R.; M. M. Hand; D. Radu; D. Magagna; 2014. A System-based Approach to Assessing the Value of Wind to the Society. Report based on an experts' workshop held in Petten, Netherlands, 13-14 November, 2013. European Commission-Joint Research Centre.
http://setis.ec.europa.eu/publications/jrc-setis-reports/system-based-approach-assesing-value-of-wind-society and ieawind.org/task_26.html

IEA Wind Task 26 website (all IEA Wind Task 26 publications are available on the website)
http://www.ieawind.org/task_26.html

Publications from the Phase 1 of the IEA Wind Task 26:

Lantz, E.; Wiser, R.; Hand, M. (2012). IEA Wind Task 26 – The Past and Future Cost of Wind Energy; Work Package 2 Final Report. NREL/TP-6A20-53510.
https://www.ieawind.org/index_page_postings/WP2_task26.pdf

Schwabe, P.; Lensink, S.; Hand, M. (2011). IEA Wind Task 26 - Multi-national Case Study of the Financial Cost of Wind Energy; Work Package 1 Final Report. 122 pp.; NREL Report No. TP-6A20-48155.
http://www.ieawind.org/task_26_public/PDF/task%2026%20wp%201%20report.pdf