Final report

1. Project details

Project title	EUDP18-II Deltagelse i IEA Wind TCP Task 26: Cost of Wind Energy - fase 4
File no.	64018-0577
Name of the funding scheme	EUDP
Project managing company / institution	Ea Energianalyse a/s
CVR number (central business register)	28985827
Project partners	DTU Management Engineering
Submission date	23 April 2024

2. Summary

2.1 Executive summary

The primary objective of IEA Wind TCP Task 26 is to provide information on cost of wind energy in order to understand past, present and anticipated future trends in wind energy economics related to both technology costs and market value. The analysed costs trends for both onshore and offshore wind confirm a continued cost reduction for LCOE of wind power, which combined with market value analyses show that wind power generation reaches grid parity (viable on market terms) in selected market regions. Auction results provide simple numbers for the costs of wind power generation, but they do not directly reflect the cost of wind power, nor are they comparable across countries. By analysing the levelized revenue of energy, differences in market and auction setups can be considered, thereby enabling a better view on the real cost of energy, as well as a comparison of auction results across different regions.

Regarding future cost of wind energy, an expert elicitation study supported by the IEA wind task group finds expectations for significant further cost reduction potential for LCOE of wind power of up to 37% and 49% between 2020 and 2050 for onshore and offshore wind respectively.

An international technology catalogue for wind power describes the different aspects that drive cost of wind power and how they vary depending on the region of deployment. Policy makers and energy planners need to be aware of these factors when trying to estimate the cost of wind power across different regions, as technology choices can have important influence on the levelized cost of energy.

An analysis of hybrid wind storage installations in the European Power market points out that potential benefits require careful optimisation and are mostly expected in solar dominated parts of the system. Low(er) wind speed turbines (lower specific power) will often show a better ratio between added value of generation in power markets and the additional costs.

The findings of the task work inform policy makers, energy planners and modellers about both past and future characteristics and economics of wind power and help shaping future efficient power systems.

2.2 Resumé

Det primære formål med IEA Wind TCP Task 26 er at indsamle, analysere og informere om omkostninger ved vindenergi for at forstå tidligere, nuværende og fremtidige tendenser inden for vindenergi relateret til både teknologiomkostninger og markedsværdi. De analyserede omkostningstendenser for både land- og havvind bekræfter en fortsat omkostningsreduktion for LCOE af vindkraft, som kombineret med markedsværdianalyser viser, at vindkraftproduktionen er konkurrencedygtig på markedsvilkår i udvalgte markedsregioner. Resultater fra især udbud om havvind giver enkle tal for omkostningerne ved vindkraftproduktion, men de afspejler ikke direkte omkostningerne ved vindkraft og er ikke sammenlignelige på tværs af lande. Ved at analysere de forventede indtægter over projektets levetid kan forskelle i markeds- og udbudsdesign udlignes, hvilket muliggør et bedre overblik over de reelle energiomkostninger samt en sammenligning af auktionsresultater på tværs af forskellige regioner.

Vedrørende fremtidig omkostninger for vindenergi, peger en ekspertundersøgelse foretaget af IEA Wind Task gruppen på et betydeligt yderligere omkostningsreduktionspotentiale for LCOE af vindkraft på op til 37% og 49% mellem 2020 og 2050 for henholdsvis land- og havvind.

Et internationalt teknologikatalog for vindkraft beskriver de forskellige aspekter, der driver omkostningerne ved vindkraft, og hvordan de varierer globalt. Politiske beslutningstagere og energiplanlæggere bør være opmærksomme på disse faktorer, når omkostningerne ved vindkraft på tværs af forskellige regioner estimeres, da teknologivalg kan have betydelige indflydelse.

En analyse af hybridanlæg af vind og batterier i det europæiske elmarked peger på, at potentielle fordele kræver omhyggelig optimering og forventes primært i soldominerede dele af systemet. Vindmøller med lav(ere) vindhastighed (lavere specifik effekt) vil ofte give et bedre forhold mellem merværdien af produktionen på elmarkederne og de ekstra omkostninger.

Resultaterne fra Task 26’s arbejde giver politiske beslutningstagere, energiplanlæggere og modelleringseksperter information om både tidligere og fremtidig karakteristika og økonomi i vindkraft og hjælper med at udforme fremtidige effektive elsystemer.

3. Project objectives

The primary objective of IEA Wind TCP Task 26 was 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. In addition to cost perspectives, another focus area was to go beyond the cost perspective and deepen the understanding the value of wind power in the power system. The IEA Wind TCP Task 26: Cost of Wind Energy concludes its fourth phase, building and extending findings in previous phases.

There are three primary aspects to understanding the cost of wind energy at 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 expert elicitation, engineering and learning models to inform potential future projections of wind energy costs
3) estimation of the value of wind energy in the broader electric system and economy in general.

The work packages to address the aspects mentioned above are the following:

- WP1: Historical Onshore and Offshore Wind Power Costs and Drivers
- WP2: Future Onshore and Offshore Wind Power Costs and Drivers
- WP3: Exploration of the Value of Wind Power

4. Project implementation

The project was organised around two workshops per year with the international collaboration group and monthly web-meetings. The meetings serve for discussion and feedback of ongoing analyses carried out by individual participants or sub-groups. Due to COVID19-related restrictions, only the first two workshops were held in-person, while the remaining workshops were held as online conferences over a three-day period. While the limited travel ability impacted the detailed cooperation, the IEA Wind Task 26-group coped with the situation to the best extent possible and managed to drive forward the different tasks. The main workshops and selected cores topics are listed below.

- In-person meeting, Kassel, hosted by Fraunhofer IEE, November 2018
    - Kick-off (prior to EUDP-supporting period)
    - Country updates on recent wind power related developments
    - Planning and scoping of overall work package and task dissemination
    - Cooperation opportunities with IRENA and IRENAs wind cost database
- In-person meeting Oslo, hosted by Norwegian Water Resources and Energy Directorate (NVE), May 2019
    - Country updates on recent wind power related developments
    - Planning and scoping of individual work package activities
- In-person meeting Bonn, hosted by IRENA, November 2019
    - Country updates on recent wind power related developments
    - Detailed discussion of LROE methodologies (WP3) and planning for technology catalogues (WP2)
    - Workshop with external stakeholder on financing of RE
- Web-conference, June 2020
    - Country updates on recent wind power related developments
    - O&M costs for wind power
    - Offshore innovation
    - LROE methodologies & value of wind
- Web-conference, November 2020
    - Country updates on recent wind power related developments
    - Expert elicitation study on cost of wind power – discussion of results
    - Offshore trends
    - Onshore data collection and reporting
    - Discussion of methodologies for technology catalogue
- Web-conference, May 2021

- Country updates on recent wind power related developments
- LROE-analyses presentation and discussion of results
- Value of wind and hybrids presentation and discussion of results
- Planning of potential follow-up

Over the project period, a number of delays were encountered on some of the deliverables. Those delays were reported in the annual reports. At this stage, Danish participants have finalised their deliverables and the delays did not impact the final results or the final dissemination, which was held as a side-event at WIND EUROPE in November 2021. The final full reporting by Danish participants was completed up to April 2022, with the exception of the Wind Technology catalogue, which is scheduled for publication in April 2022. Two deliverables by the overall IEA Wind Task group are forthcoming (The technical reports on onshore and offshore wind), as the IEA collaboration partners have not finished the deliverables. Danish participants have provided the needed inputs, and the final deliverables are scheduled for May 2022 prior to the IEA ExCO-meeting.

5. Project results

The overall objective of the IEA Wind Task 26 was obtained through the different work packages, and the analyses carried out contributed to the understanding of wind power economics. Results from the different analyses are summarized below.

5.1 WP1 - Historical Onshore and Offshore Wind Power Costs and Drivers

5.1.1 Offshore wind power

Recent trends in offshore wind power show realised cost reductions in the period from 2010 to 2018 of around 14% on a global scale. The IEA Tasks has closely monitored cost and price developments of offshore wind in the past years. E.g., Europe has seen a number of subsidy-free auction rounds and dramatic cost reductions. In the UK, strike prices (announced in 2012 terms) have reduced from £140 per MWh for projects commissioning in 2018, to £39.65 for projects commissioning in 2023, a reduction of 72%. For the published journal manuscript (Joule) “Toward global comparability in renewable energy procurement”, we quantified and made comparable the cost of nine different offshore wind farms across the world through a collaboration in which experts from Germany, US, Denmark, and Japan collaborated and contributed with their sector and country specific knowledge.

In an analysis of future technology options and advancements, the IEA Wind Task has identified important cost reduction drivers and estimated potential cost reduction for a number of sites with different characteristics. Six main cost and value drivers are analysed and their impact on LCOE is estimated:

- Energy Islands – enabling large project sizes, O&M advantages, and potential colocation with other facilities
- Colocation with floating solar, aquaculture or as a way to decarbonise oil and gas platforms
- Access to new resources: Large offshore wind expansion will drive deployment to new sites at deeper waters requiring floating offshore wind installation which call for adapted installation and O&M processes
- Turbine upscaling – expectations for 20 MW turbines before 2030. Limits in the supply chain for handling large components may halt the development long term
- Next generation supply chain – improved port infrastructure and component innovation for especially floating offshore wind

- Colocation with hydrogen production to decrease total transmission cost

The potential combined impact of innovations is estimated to reduce cost by between 5 and 20% towards 2040, depending on site conditions.

5.1.2 Onshore wind power

The results of the analysis of land-based wind technology cost drivers in WP1 are summarized in the technical report *IEA Wind TCP Task 26 - Wind Technology, Cost, and Performance Trends Denmark, Germany, Ireland, Japan, Norway, Sweden, the European Union, and the United States 2016-2019,* which the collaboration partners from NREL in the US are working on. Danish participants have provided input to the discussion of trends and provided statistics on Danish data, which is available online together with data from the other regions: https://iea-wind.org/task26/data-viewer/.

Data for land-based wind includes both technical characteristics and 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 the data is incomplete. A variety of sources may be available, and each country's data availability and quality differ. An important part 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.

These project-level data illustrate how wind turbine technology, wind project investment and operation costs, wind plant energy production, and wind project financing costs have changed from 2008 to 2019. Since the latest update in 2016, a continued trend towards larger turbine ratings, higher towers and lower specific power is apparent across all analysed regions (Figure 1). These trends have contributed to further reduce LCOE of onshore wind power, while large differences between countries remain (Figure 2). With the mature market, and good wind resources, cost of onshore wind power in Denmark are at the very low end compared to other regions.

Figure 1: Turbine technology trends in participating countries shown for 2016 and 2019: (a) hub height, (b) nameplate capacity, (c) rotor diameter, and (d) specific power. (Source: Stehly, T., ed. 2022)

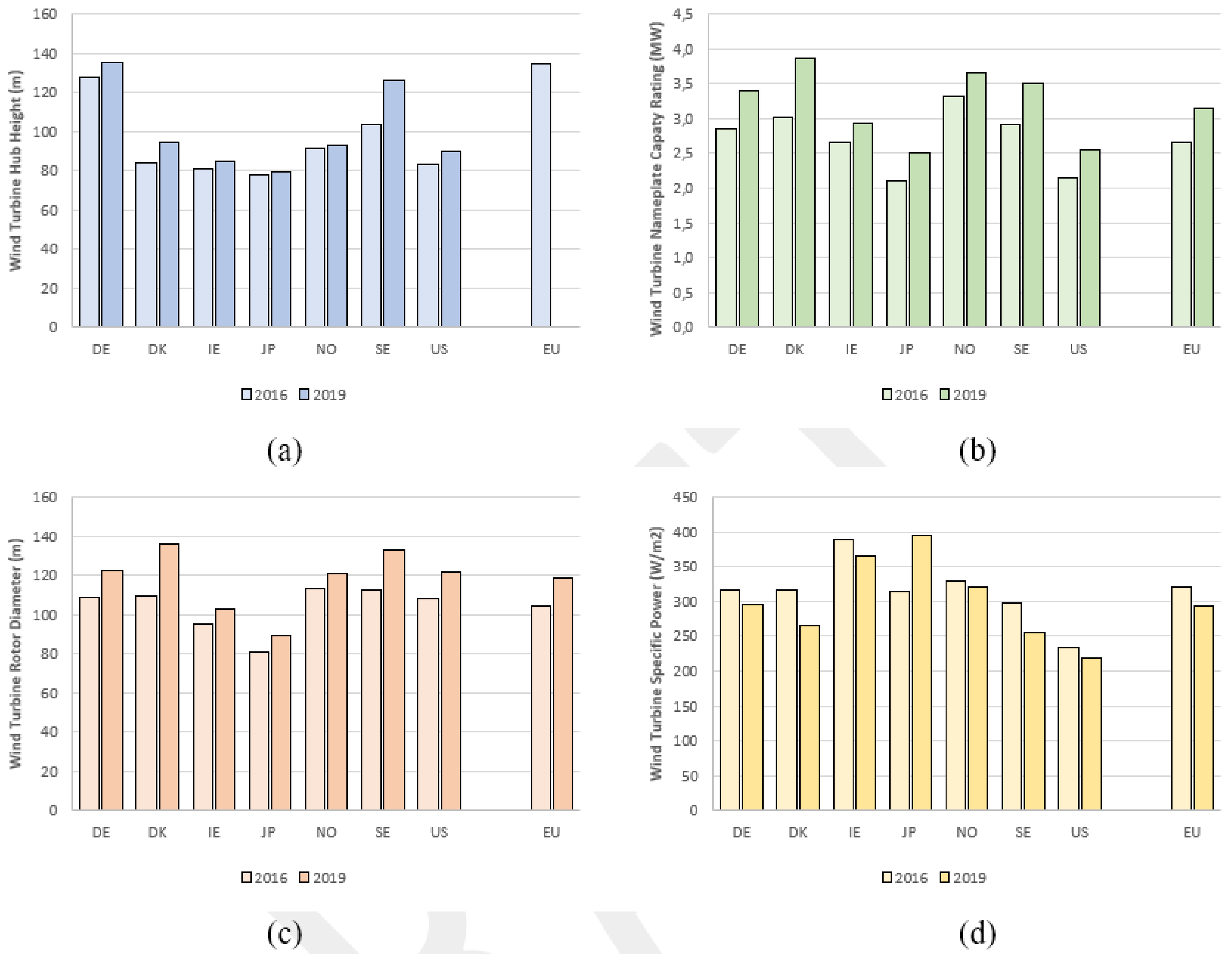
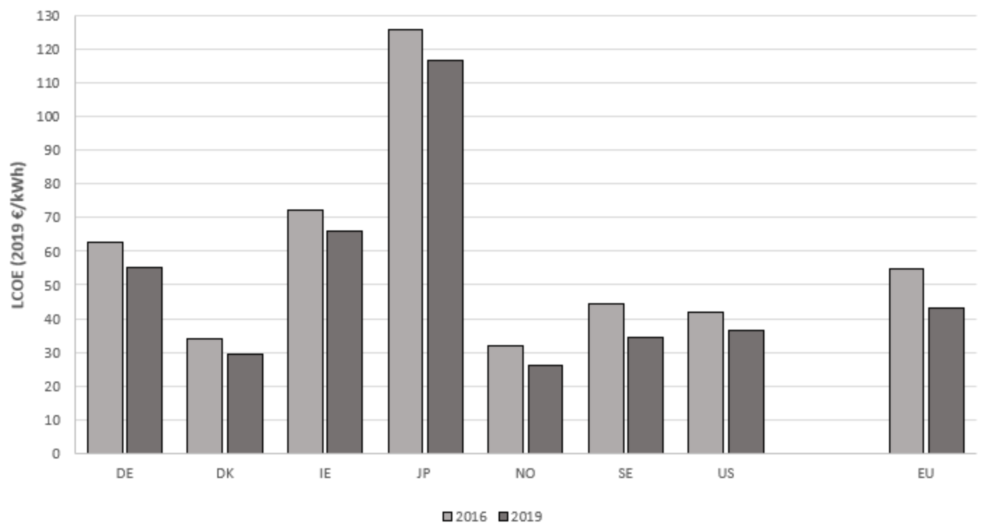


Figure 2: Levelized cost of energy for 2016 and 2019. (Source: Stehly, T., ed. 2022)



5.1.3 Repowering of onshore wind in Denmark

Aging wind turbine fleets, increasing land-use constraints and rising relevance of societal factors make the deployment of land-based wind energy ever more complicated. Consequently, repowering is expected to become a significant point of focus for the wind industry.

Our analysis of onshore wind repowering in Denmark fostered a whole new thinking around repowering analysis. Previously, it was common to look at repowering as turbine-for-turbine replacements and site-specific activities. The approach involves studying repowering projects in their entirety, considering all commissioning and dismantling activity within a project. This includes existing turbines located at the same site as the new development project (on-site) as well as in other locations (off-site) for which the dismantling can be conditionally linked to the new development. Our work showed that an on-site focus is hardly representative for actual repowering activity at project-level, as we uncovered multifaceted drivers for onshore wind energy repowering decisions and their implications.

Through detailed project-level analysis, our study revealed that wind energy repowering involves consideration of more than just end-of-life replacement and space constraints. Dismantling decisions are multifaceted and result in the dismantling of a larger number of turbines and at an earlier age than physically required. We show this for Denmark, where more than a third (38%) of recent wind energy projects (2012-2019) involved repowering. We found that repowered turbines were dismantled at an average age of 18.6 years – 5.8 years less than those without repowering. Only two thirds (67%) of repowering projects were dismantled due to physical space needed for new turbines. This resulted in considerably lower achieved net capacity increases per project, with only 4.72 megawatt commissioned per dismantled megawatt, as compared to 7.05 megawatt if only space-related dismantling was considered.

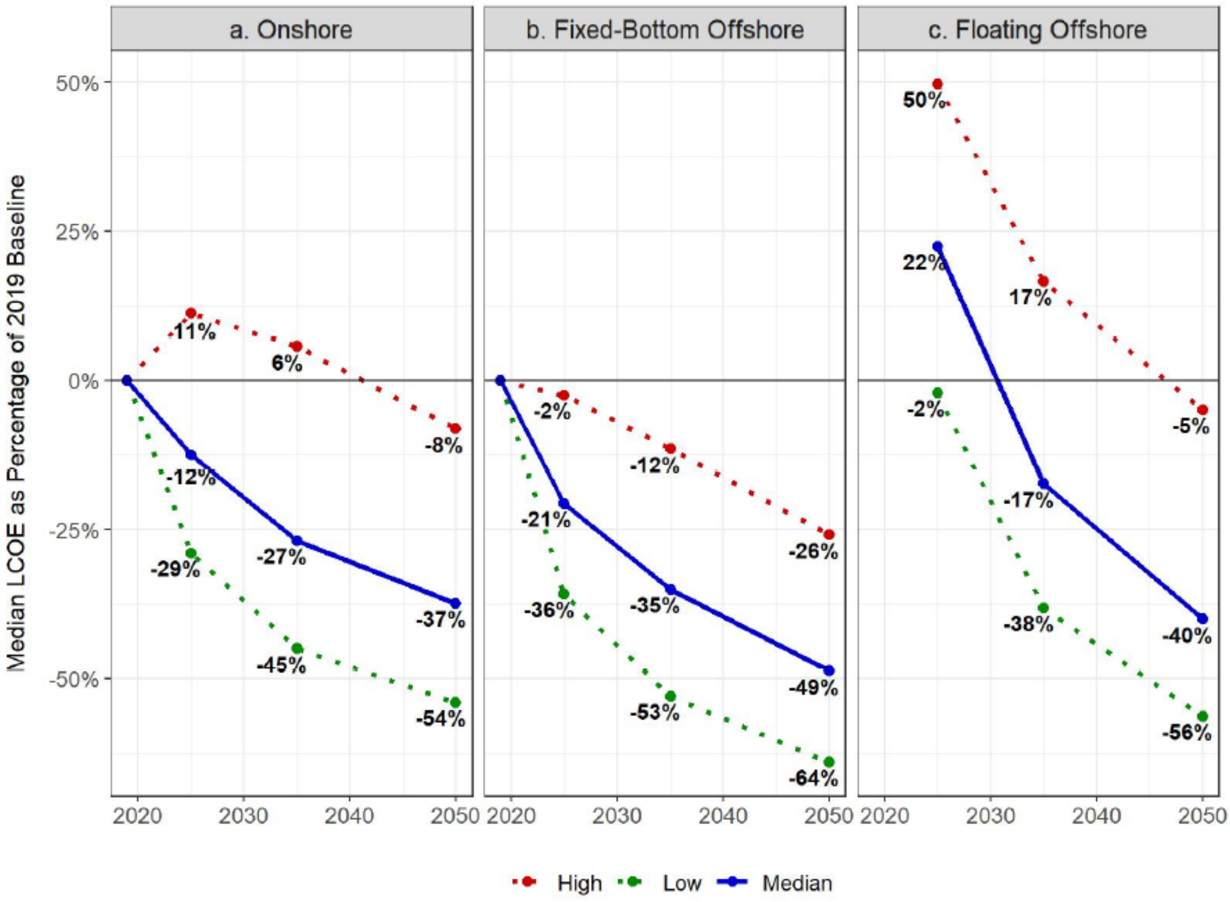
In the work, published as a journal article in the world-leading scientific journal Nature Energy titled “Multifaceted drivers for onshore wind energy repowering and their implications for energy transition”, we found that wind energy repowering decisions are multifaceted and depend on the physical, political, and social landscape, as factors such as noise regulation, aesthetics and political bargaining can significantly influence project development. Dismantling reasons besides physical space needs included regulation (noise-related, 8—17% of capacity), development principles (aesthetics, 7—20%), and political bargaining (4—13%). We find that repowering is also a negotiated process between developer and host community, used to reduce community impacts of wind turbines. The recognition of repowering as negotiated process between host communities and wind developers will likely be critical to unlocking the full potential of wind energy in the future.

5.2 WP2: Future Onshore and Offshore Wind Power Costs and Drivers

5.2.1 Expert elicitation

In the former phase II and phase III an expert survey on future developments for LCOE of wind power was carried out by participants of the IEA wind task group to analyse future costs of wind energy. In this fourth phase, a new survey was set to follow up on the previous results, led by LBNL with contributions from NREL, the University of Massachusetts, under the auspices of IEA Wind. Danish participants have assisted in reviewing survey setup as well as discussions on result analyses. Expert elicitation is a tool - with established protocols - to develop estimates of uncertain quantities based on careful assessment of the knowledge and beliefs of subject-matter experts. Careful design and guidance of questions ensures the quality of the results. Relative to other elicitations, the survey included a large number of possible participants via an online survey, inclusive of a smaller set of pre-identified ‘leading experts’. Updated recent cost trends and the updated survey show, that previous results underestimated the actual cost development. Even with an updated lower starting point, significant relative cost reductions are projected in the new survey (Figure 3).

Figure 3: Projected developments of LCOE, relative to 2019 (Source: Wiser, Ryan et al. 2021.)



The survey finds expected cost reductions ranging from 37% for onshore wind to 49% for offshore wind between 2020 and 2050. In absolute terms onshore wind is generally expected to remain at lower cost than offshore wind. For offshore wind, the cost difference between floating offshore wind and fixed bottom offshore wind are expected to decline. Expected water depth at which floating becomes less costly than fixed-bottom declines from >80 m in 2019 to >60 m in 2035. However, for both fixed bottom offshore wind and floating offshore wind, the uncertainty range is in general higher. Contributions from different categories to the cost reductions are estimated and show that CAPEX-reductions are the single most important driver, while also increased design life, increased power generation, reduced O&M costs and reduced financing cost contribute to the total estimates.

5.2.2 Technology catalogue

Today, innovations and technology improvements within renewable energy are taking place at a very rapid pace. Wind and solar have experienced dramatic price drops (Figure 4) thanks to the convergence of various factors: increased deployment driven by renewable energy policies and support schemes, increased competition in driven by competitive auctions, increased technological maturity and innovation in the entire supply chain.

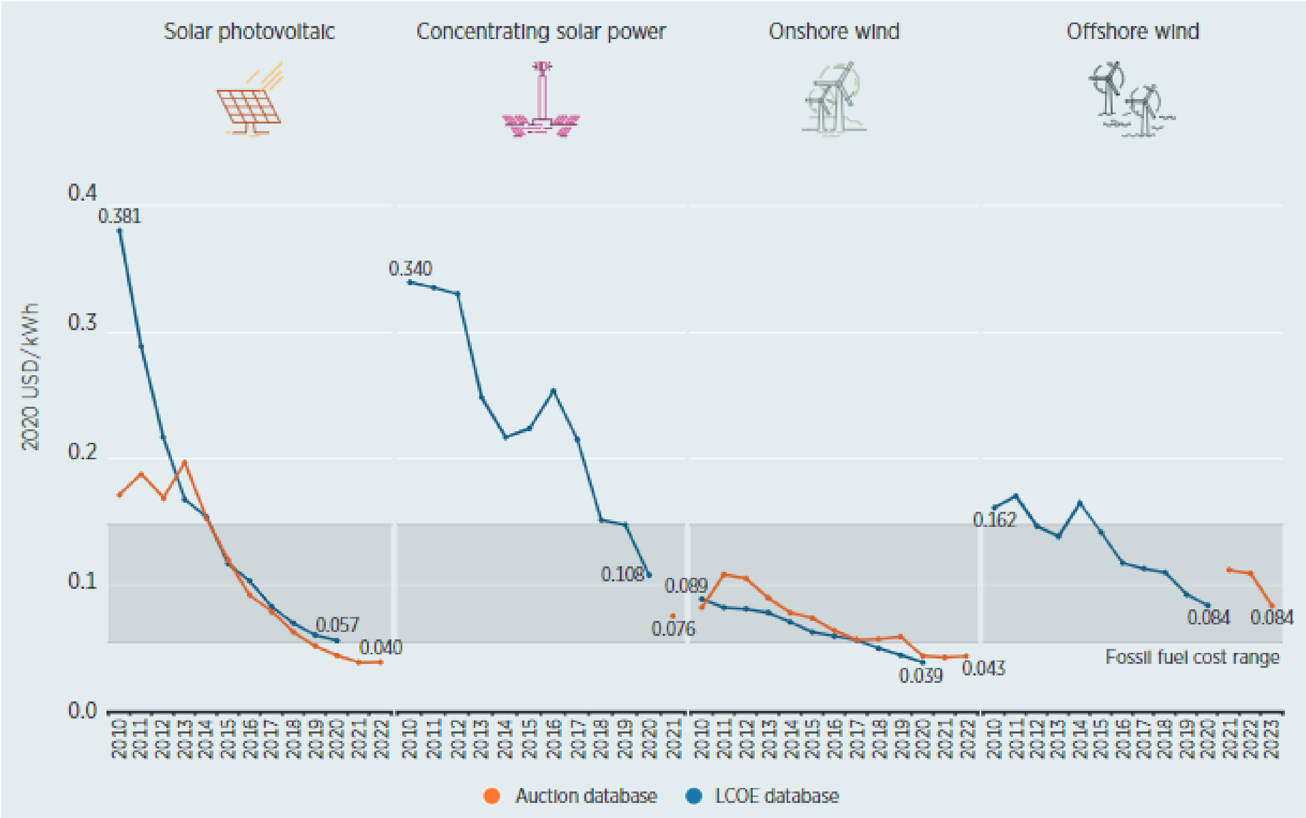


Figure 4: Generation cost of wind and solar has been reduced dramatically from 2010 to 2022. Source: Irena, Renewable Power Generation Costs 2020, 2021. Available: www.irena.org .

In such evolving landscape, in order to develop plans and policies that reflect the actual technology development, it is paramount to:

- understand the technology trends and dynamic re-shaping of the industry,
- use up-to-date technology information for policy analyses
- be transparent concerning the assumption about future investment costs and technical properties.

The objective of this technology catalogue is therefore to provide a qualitative description of characteristics and trends in **onshore wind power**, complemented by a quantitative overview of potential cost, performance and characteristics of onshore wind, in the form of data tables. This data could be used for energy modelling, energy planning, estimation of LCOE and PPAs and benchmarking of tariffs.

The technology catalogue will assist the energy modelling and support government institutions, private energy companies, think tanks and others with a common set of data. The data can be used for e.g. development of relevant policies and business strategies to achieve the government's long-term targets.

Key inputs to the future development of the cost of wind are:

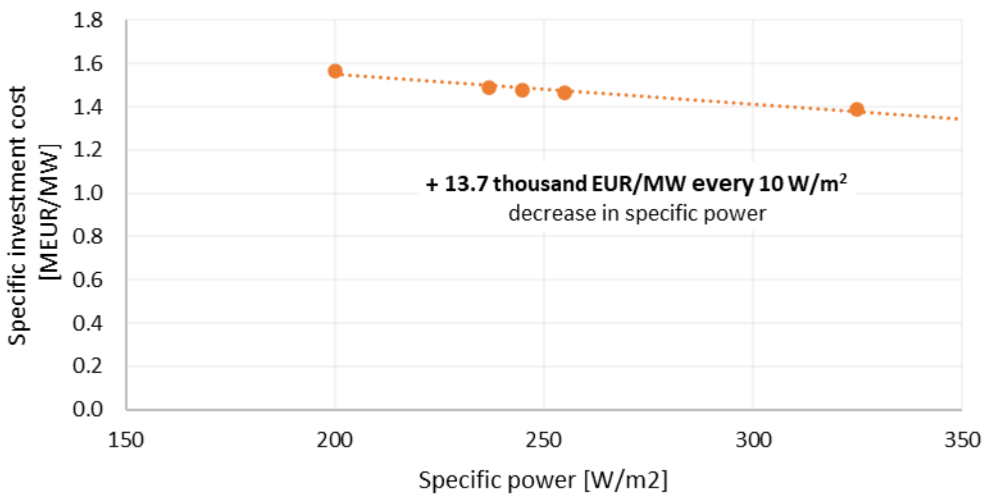
- The general technological development. Learning curves can be used to estimate the impact of the global expansion of wind turbine capacity. E.g., a learning curve of 12% indicate the investment is reduced with 12% each time the global capacity doubles. Historical data can be used to estimate leaning rates. And e.g., IEA World Energy Outlooks can be used as input, describing the future global expansion of relevant technologies.
- The historical development has resulted in reduction of the specific power (W/m^2) of new turbines. Lower specific power is a result of larger blades compared to the installed generator capacity. This

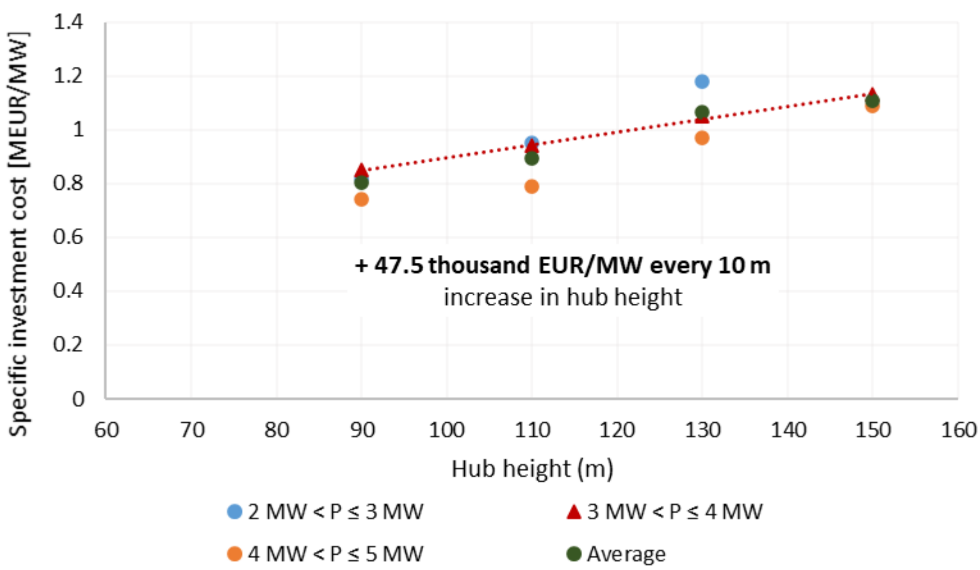
development is expected to continue and will increase the capacity factor – which is especially useful at low wind sites.

- A regional aspect, where investment costs are impacted by the development of logistics, supply chain, cost of labour, regulation and experience in the wind turbine construction, assembling and installation. While India and China have relative low costs, Africa experience higher costs.

In Figure 5 is illustrated the historical impact of the two key design parameters, hub height and specific power.

Figure 5. Impact of hub height and specific power for the specific investment cost. NREL data.





5.3 WP3: Exploration of the Value of Wind Power

5.3.1 Tracking value of wind

The market value of wind power varies across Europe, depending on both the average price levels and the integration of wind power. In analyses of historical data, Ea Energy Analyses has assessed the market value of wind power across the European power system for the period from 2015 to 2021. Figure 6 illustrates the close relationship between average market price and the price captured by wind turbines.

Market value differs significantly between regions, due to both differences in average power market prices as well as differences in how well wind power is integrated, which is impacted by both power system composition as well as wind power penetration. (Figure 6)

Figure 6: Market value of onshore wind in Denmark from 2015 to September 2021. Source: Ea Energy Analyses (2022)

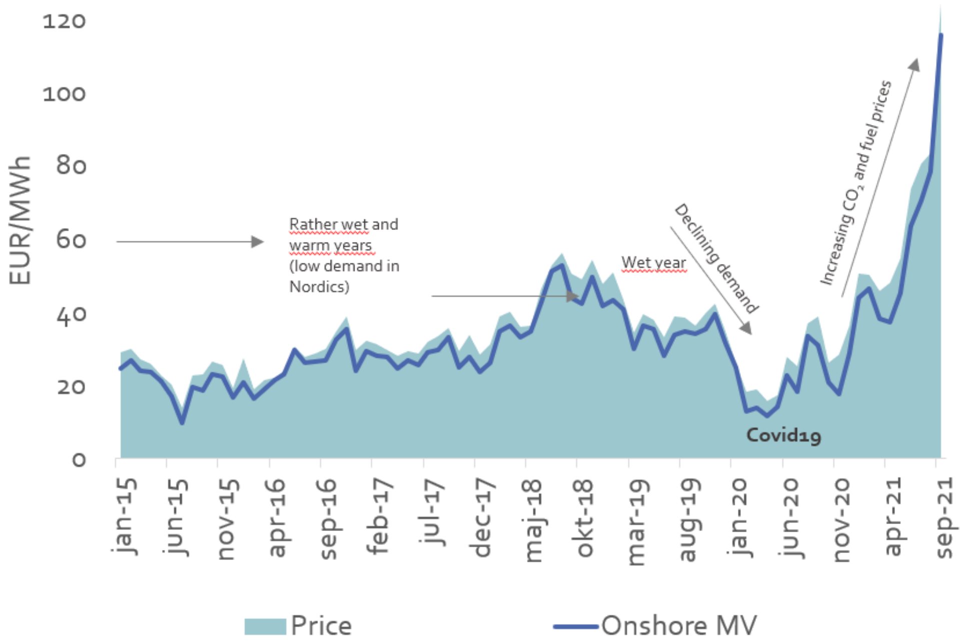
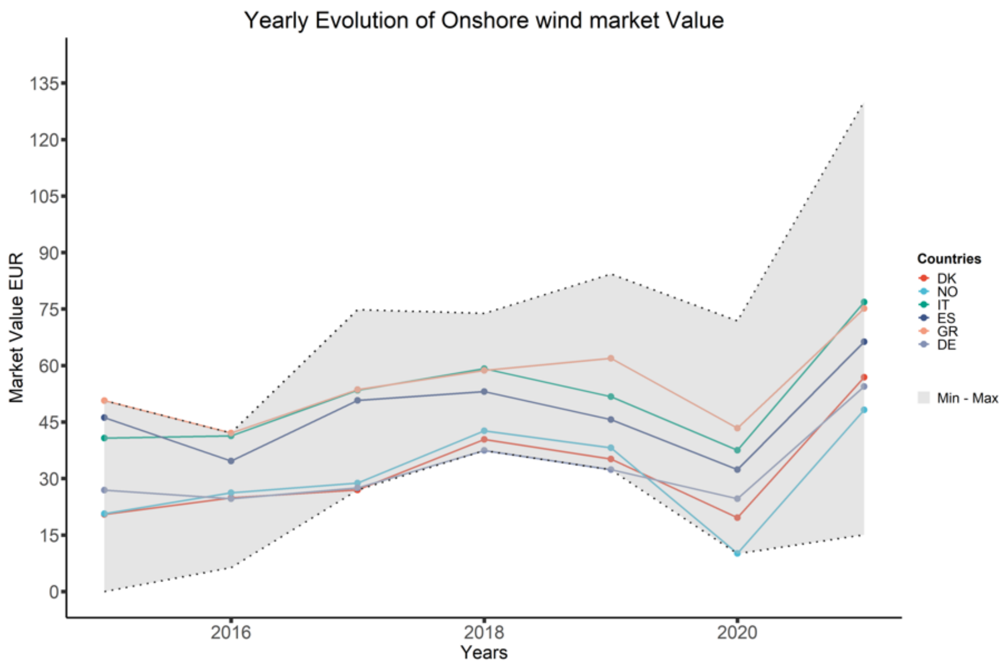
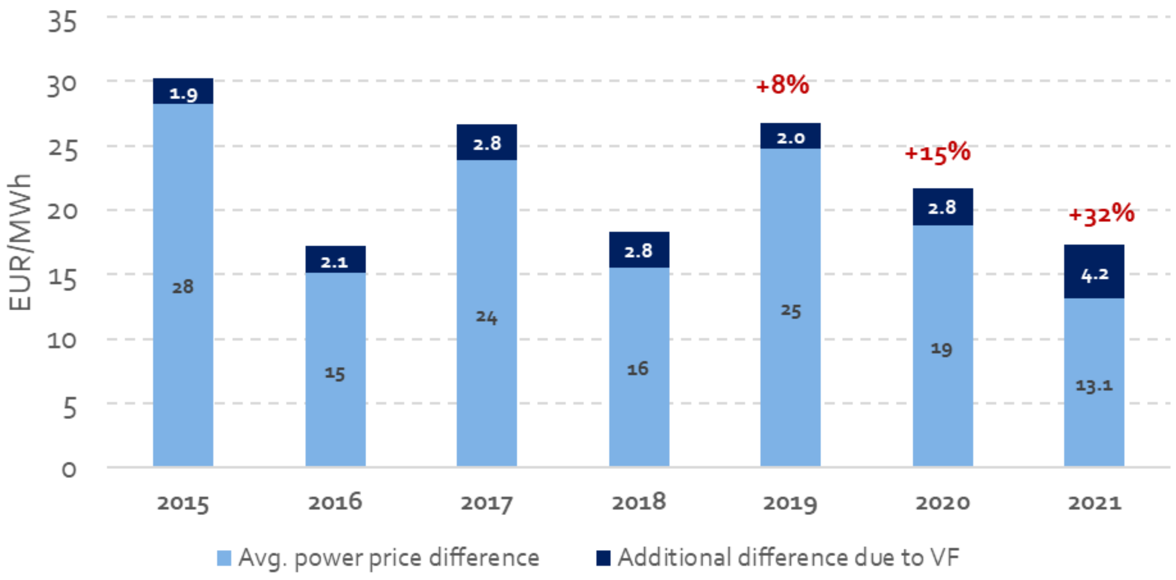


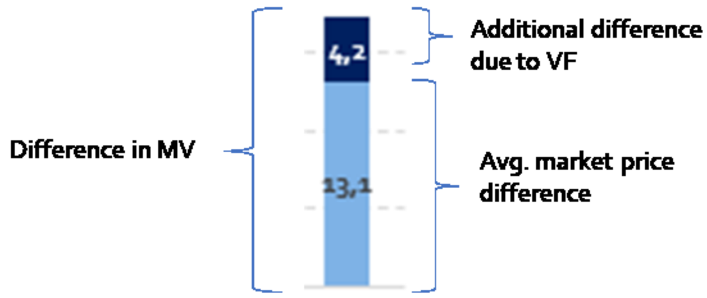
Figure 7: Absolute market value of onshore wind power across selected European countries. 2021 data covers Jan-Sept; Min-Max refers to the minimum and maximum of all countries in the sample under consideration Source: Ea Energy Analyses (2022)



As an example, the difference between the market value of wind power in Denmark and Greece is mainly owed to a general higher level of average power market prices, but since the value factor (ratio between captured price for wind power and average power market price) is lower in Denmark, the total difference cannot be explained by the average power market price difference only (Figure 8).

Figure 8: Example of market value difference between Denmark and Greece. Source: Ea Energy Analyses (2022)

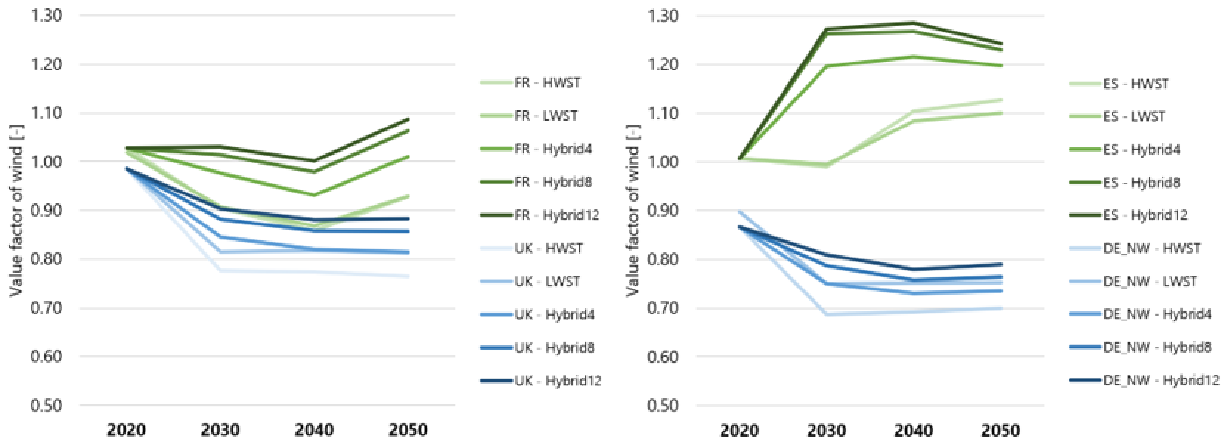




5.3.2 Market Value of wind-battery hybrids in the future European power system

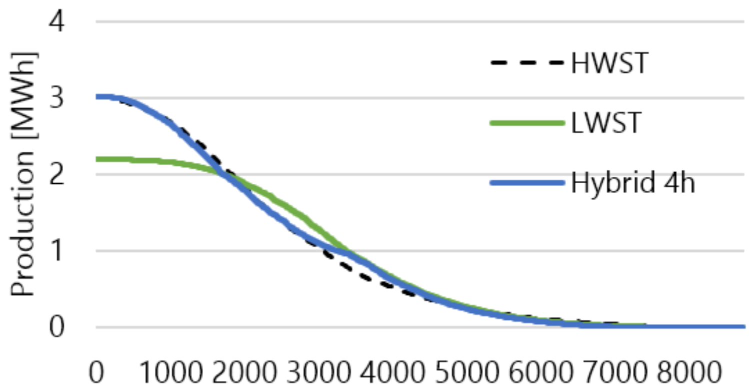
In a study of the market value of wind power in the European Energy system (Dalla Riva, A., Haaskjold, K., Hethey, J., Aly, A. (2022)), Ea Energy Analyses analysed to what extent hybridising wind with battery storage can increase the market value of wind and how this compares to the value obtained by other system options, such as deploying advanced wind turbines or standalone batteries. The analysis shows that depending on the region, hybrid solutions can add significant value to the market value of wind power (Figure 9). Hybridising wind with battery storage can increase the market value of wind by around 1-3 €/MWh on average across countries and years, corresponding to around 5%. However, the investment cost for the hybrid solutions outweighs their benefit.

Figure 9: Value factor for wind across different regions. HWST: High wind speed turbine LWST: Lowe wind speed turbine. Hybrid4/8/12: Hybrid installation with battery storage corresponding to 4/8/12 hours of storage volume compared to loading/unloading capacity. None of the hybrid installations allow charging from the grid. Source: Dalla Riva, A., Haaskjold, K., Hethey, J., Aly, A. (2022)



While hybrid systems can achieve similar benefits compared to low wind speed turbines by shifting generation from hours with high wind penetration to hours with lower wind penetration (Figure 10), low wind speed turbines provide a better business case for increasing the market value of wind power, due to lower investment costs compared to the additional value.

Figure 10: Grid feed-in based on a high wind speed turbine, a low wind speed turbine and a hybrid with a high wind speed turbine: Source: Dalla Riva, A., Haaskjold, K., Hethey, J., Aly, A. (2022)



The case for hybrid systems can be beneficial, if grid charging is allowed and the systems are placed in regions with high solar penetration that enable a high number of cycles and thus utilisation of the battery systems. In these regions, hybrid wind battery solutions are in competition with hybrid solar installations and stand-alone batteries, and the general potential benefit compared to stand-alone batteries are reduced costs for inverters, grid connection and grid tariffs in a combined setup.

The analysis also shows that large flexibilities on new demand side options (mainly P2X, but to some extent also flexible demand from other sources) can challenge the business case for batteries, when evaluating Day-Ahead markets only. Additional benefits can be sourced from ancillary services and reduced balancing cost for the wind power plants. This topic should be further analysed in future studies to further assess the value of hybrids.

The overall recommendation based on the results of the study is to consider hybridising wind in countries where solar penetration is increasing with a faster pace, ensure to design the hybrids with around 4h of storage, and allow for grid charging to take full advantage of hybrid setup. If the potential wind asset is located in Northern Europe in regions with higher wind penetrations, adding storage to the turbine is less valuable. Value creation from DA-markets should be combined with other system services to guarantee a positive business case.

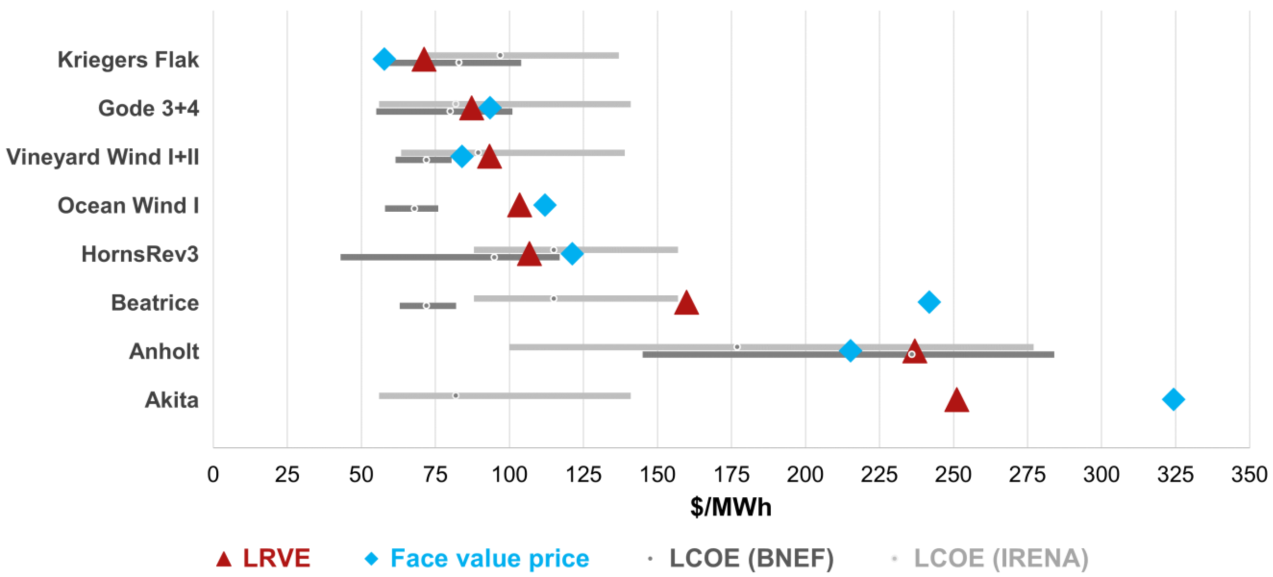
5.3.3 Levelised Revenue of Energy

Prices from competitive procurement of renewable energy sources are increasingly used for the comparative evaluation of financial and technology performance. Comparing prices from auctions or power purchase agreements at their face value is, however, often not meaningful, particularly across jurisdictions or over time. This is because differences in support regimes and the applicable market, tax, and regulatory environment can make a like-for-like comparison convoluted and result in misleading conclusions.

We have developed a new approach to making project profitability comparable over time, the ”Levelized Revenue and Value of Electricity” (LRVE). This resulted in a metric which enables decision-makers to compare the total cost of renewable energy procurement on equal footing and can be used in future research to validate established cost metrics.

In the study, published in the high-level journal Joule, titled “Toward global comparability in renewable energy procurement”, we have estimated project revenue and value holistically for eight global offshore wind projects. Using a cash-flow model, we considered applicable support regimes, wholesale markets sales, and the monetized value of tax incentives, depreciation, and transmission infrastructure. We find considerable variation in the absolute levels and relative composition of offshore wind project revenue and value streams, both over time and between jurisdictions.

Figure 11: LRVE, direct auction result (face value) and LCOE estimates for a number of recent offshore wind auctions. Source: Beiter, P., Kitzing, L., Spitsen, P., Noonan, M., Berkhout, V., Kikuchi, Y. (2021)



5.3.4 Dissemination of results

Results of the IEA Task 26 work have been continuously disseminated through different channels. The list of publications in the appendix provides a full overview on publications, and external dissemination events are mentioned below:

- Joint workshop co-hosted by IEA Task 26 and the International Renewable Energy Agency (IRENA) on November 14, 2019, in Bonn, Germany to explore a "Global Survey of Renewable Energy Financing Costs", including land-based and offshore wind energy technologies, resulting in funded follow-on collaborative work between Task 26 and IRENA
- Policy brief published based on scientific work undertaken in the task: Kitzing, L., Jensen, M.K., Telsnig, T. et al. Multifaceted drivers for onshore wind energy repowering and their implications for energy transition. Nature Energy 5, 1012–1021 (2020). https://doi.org/10.1038/s41560-020-00717-1
- 'Behind the paper blog', published based on scientific work undertaken in the task: Creative collaboration on wind energy repowering, Lena Kitzing, https://sustainabilitycommunity.springernature.com/posts/creative-collaboration-on-wind-energy-repowering
- IEA Wind TCP Task 26 Side event at WindEurope conference in Copenhagen, November 2021: The changing economics of offshore wind energy in high renewables futures. https://orbit.dtu.dk/en/projects/iea-tcp-wind-task-26-dissemination-event-the-changing-economics-o
- Site visit SMA production facilities. Discussion with developers on IEA Task work related to market value and storage options. In conjunction with meeting in Kassel, Germany, November 2018.
- Site visit Marker Windfarm. Discussion with developers on IEA Task work, site identification, logistical, and permitting processes with constructing this wind farm. In conjunction with meeting in Oslo, Norway, May 2019.

6. Utilisation of project results

The results of the 4th phase of the IEA Wind TCP Task 26 are used in several activities on energy system analyses, which are dependent on using consistent wind power technology data and modelling approaches. The methodologies and results are relevant within energy policies and energy system planning, and serve us input to identify important areas for future research and development.

Both Ea Energy Analyses and DTU use obtained data and knowledge in their energy system modelling activities as well as for educational purposes at the Technical University of Denmark, supporting the education of qualified candidates, who will contribute to shaping the future energy systems and state-of-the-art research. The project results have been publicly disseminated and shared among the participating institutions, enabling them to use the insights in relevant work. By contributing to insights into important matters of wind technology, the project supports the political objective of enabling a cost-efficient transition to a low-carbon energy system.

The work and methodologies will be further used and developed in a continuation of the IEA Wind Task collaboration carried out under a new name: IEA Wind Task 53 - Wind Energy Economics. The continued work (further specified in the perspective section below) will further widen the scope in order to ensure continued relevance, and thus touch upon new areas, such as the impact of hydrogen production on the value and cost of wind energy.

7. Project conclusion and perspective

7.1 Conclusions

The IEA Wind Task 26 provides statistics and insights on technological and cost developments for wind power, which can help policy makers as well as developers in energy system planning. The findings of the task work inform policy makers, energy planners and modellers about both past and future characteristics and economics of wind power and help shaping future efficient power systems.

Market intelligence on historic and current cost trends get increasingly complicated by the competitive nature of the market. While auction results, especially for offshore wind power, provide single numbers for anticipated costs, the design of auctions and markets significantly hinders a direct comparison across regions and countries. To overcome this obstacle, the suggested LROE-methodologies provide options to compare auction results on a level playing field.

The expert elicitation study points out significant cost reduction potentials for wind power, underlining the continued importance of wind power as one of the main generation sources in future power systems. Power system analyses show that measures to increase the value of wind power in power markets can add important contributions to efficient power systems. At the same time, a flexible power system can ensure that even high penetrations of wind power do not erode the value of wind power to critical levels.

An international technology catalogue for wind power describes the different aspects that drive cost of wind power and how they vary depending on the region of deployment. Policy makers and energy planners need to be aware of these factors when trying to estimate the cost of wind power across different regions, as technology choices can have important influence on the levelized cost of energy.

An analysis of hybrid wind storage installations in the European Power market points out that potential benefits require careful optimisation and are mostly expected in solar dominated parts of the system. Low(er) wind speed turbines (lower specific power) will often show a better ratio between added value of generation in power markets and the additional costs.

7.2 Perspectives

Each of the work packages has contributed to knowledge creation, exchange, and dissemination on the topics of cost and technology for land-based and offshore wind, application of methods to understand future cost of wind energy, and value of wind energy in electric systems, respectively.

Based on the successful completion of Phase 4 of the IEA Wind TCP Task 26, an extension to its' 5th Phase for the period from 2022 to 2026 has been approved by the ExCo, ensuring the continuation of the activities relating to the Cost of Wind Energy. EUDP has confirmed continued support for this work. To properly include the widened scope of the purpose of the task, the continued work will be carried out under a new name: IEA Wind Task 53 - Wind Energy Economics. The work is organised in six work packages:

- WP1: How does the design and operation of wind energy change in a deep de-carbonisation future and impact the value of wind energy?
- WP2: How do specific and novel technology innovation and operational trends impact the economics of wind energy?
- WP3: How does uncertainty impact wind energy economics and financing?

- WP4: What data and methods best inform our understanding of current and historical wind energy economics?
- WP5: How does transmission infrastructure and hydrogen affect the cost and value of offshore wind energy?
- WP6: How does the wind energy supply chain evolve and change in established and future markets?

Danish participants have key roles in WP2 on analyses of cost and value of wind, within WP3 on the impact of uncertainty, within WP4 on data and methods development, and within WP5 on analyses of hydrogen and transmission infrastructure.

8. Appendices

8.1 Publications

IEA Wind TCP website
https://iea-wind.org/

IEA Wind TCP Task 26 website
https://iea-wind.org/task26/

IEA Wind TCP Task 26 Web viewer for data on land-based wind
https://community.ieawind.org/task26/dataviewer

Beiter, P., A. Cooperman, E. Lantz, T. Stehly, M. Shields, R. Wiser, T. Telsnig, L. Kitzing, V. Berkhout, Y. Kikuchi. 2021. *Wind power costs driven by innovation and experience with further reductions on the horizon*. WIREs Energy Environ. 2021.

Kitzing, L., M. K. Jensen, T. Telsnig, E. Lantz. 2020. *Multifaceted drivers for onshore wind energy repowering and their implications for energy transition*. Nature Energy, VOL 5, December 2020

Duffy, A., M. Hand, R. Wiser, E. Lantz, A. Dalla Riva, V. Berkhout, M. Stenkvist, D. Weir, R. Lacal-Arántegui. (2020). *Land-based wind energy cost trends in Germany, Denmark, Ireland, Norway, Sweden and the United States*, Applied Energy, Volume 277, 1 November 2020

Wiser, Ryan et al. 2021. *Expert Elicitation Survey Predicts 37% to 49% Declines in Wind Energy Costs by 2050.* Nature Energy 6(5): 555–65.

Beiter, P., Kitzing, L., Spitsen, P., Noonan, M., Berkhout, V., Kikuchi, Y., 2021 *Toward global comparability in renewable energy procurement* Joule, Volume 5, Issue 6

P. Beiter *et al.*, 2021 Wind power costs driven by innovation and experience with further reductions on the horizon, *WIREs Energy Environ.*, vol. 10, no. 5, p. e398

Stehly, T., ed. 2022 (forthcoming). *IEA Wind TCP Task 26 - Wind Technology, Cost, and Performance Trends Denmark, Germany, Ireland, Japan, Norway, Sweden, the European Union, and the United States 2016-2019*, National Renewable Energy Laboratory, Golden, CO (US).

Noonan, M., P. Beiter, L. Kitzing, Y. Kikuchi, F. Devoy McAuliffe, M. Wold, T. Telsing. 2022 (forthcoming) *IEA Wind Task 26 – Offshore Wind Farms of the Future*, International Energy Agency.

Dalla Riva, A., Haaskjold, K., Hethey, J., Aly, A. (2022) Market Value of wind-battery hybrids in the future European power system, March 2022

Ea Energy Analyses (2022), Tracking Market Value of Wind - Analysis of the historical Market Value of Wind in Europe, March 2022.