The Life of Giants: A Life-Cycle View of Wind Turbines

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As enthusiasm to harness offshore wind energy hits a high, here's the lowdown on what affects its long-term viability.

The amount of renewable energy available will be tripled and energy-efficiency improvements doubled by 2030. This pledge was made at the United Nations Climate Change Conference (COP28) in 2023. But way before this historic commitment, the use of wind power was set in motion, making wind one of the most promising sources of green energy today.

No doubt moving towards a net-zero energy system demands heavy investment, but advances in technology and falling costs have accelerated the deployment of wind turbines, especially in offshore wind farms since the first one in Denmark in 1991. The years between 2010 and 2022 saw a 20-fold increase in installed capacity, according to the International Renewable Energy Agency. During this period, the global weighted-average levelised cost of electricity of offshore wind **declined by 59 percent**, from US$0.197 per kilowatt hour (kWh) to US$0.081/kWh.

In the last two decades, Belgium, China, Denmark, Germany and the United Kingdom have been **leading** offshore wind energy deployment in the global market. The landscape today is in stark contrast to the days of the world's first offshore wind farm in **Vindeby**, with just 11 wind turbines not more than 3 kilometres off Denmark’s coast.

Bigger and further

Today, offshore wind turbines tend to be bigger and further offshore. Countries with plentiful coastlines and substantial seabed drops in Europe, Japan, China and the United States are tapping on the potential to increase capacity by positioning wind farms further from the coast. Larger blades are known to capture wind more efficiently, such that doubling the turbine blade length can result in four times more energy generated. Moreover, wind is stronger and blows more steadily at greater altitudes. Combining these factors, massive offshore installations are meant to generate more energy with less intermittency.

The 1.2-gigawatt (GW) **Hornsea Project One**, composed of 174 offshore wind turbines 120 kilometres off the UK’s Yorkshire coast, is a case in point. In the race to build bigger and better, the world’s tallest offshore wind turbine, the **Vestas V236-15.0 MW** in Jutland, Denmark, stands at 280 metres – almost as tall as the Eiffel Tower. In China, **Mingyang Smart Energy** introduced the world’s largest offshore wind turbine in capacity and rotor diameter, with rotor diameters ranging from 260 to 292 metres, covering a swept area of up to nine soccer fields.

Each of these massive wind turbines is expected to generate 80GW annually, which could power about 20,000 European households and amount to savings of more than 38,000 tonnes of carbon dioxide per year. In comparison, the first wind farm in Denmark covered the annual power consumption of around 2,200 households.

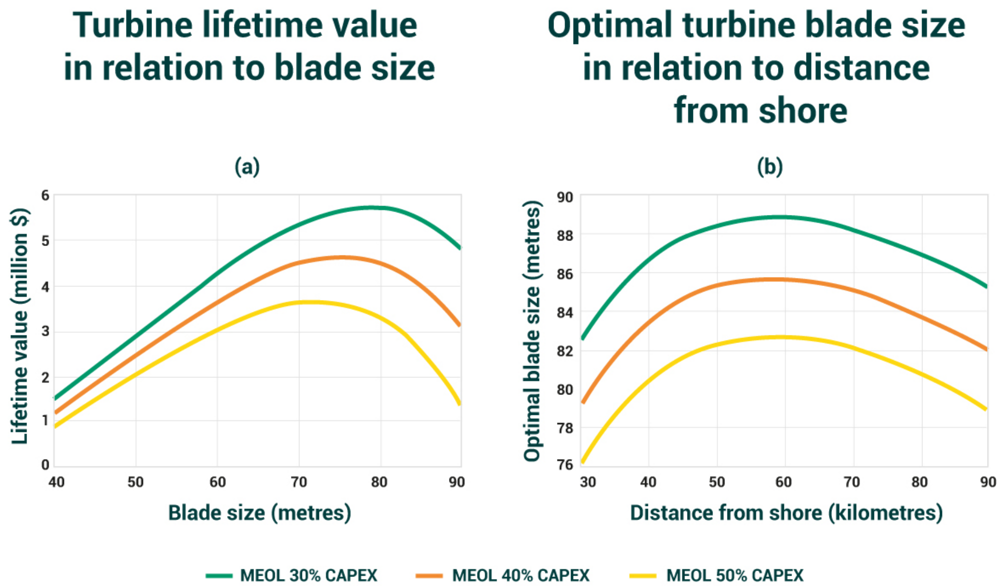
Size and distance matter

There is no stopping the race. In September, the UK announced plans to build **nine new offshore wind farms**, with two slated to be Europe's largest and second-largest wind farms. The question is: Is bigger and further offshore really better in practice?

Increasing power output and reducing supply intermittency are the typical goals that impact the planning and design of offshore wind energy projects, as well as governments' decisions in awarding these projects. But the effects of size and distance go beyond these two deliverables. From the life-cycle perspective, these factors also affect the maintenance and end-of-life management of wind turbines, among other aspects. Ignoring these can lead to suboptimal or even detrimental decisions that compromise the project's long-term viability.

To understand the operational reality and complexity in decision-making, we built a **lifetime value model** that captures the economic and environmental impact of wind turbines throughout their life cycle. This lifetime value is a comprehensive measure that captures the total revenue generated from electricity produced by a turbine minus its total life-cycle costs, including wind turbine production, installation, operation, maintenance and end-of-life costs.

To build this model, we collected accessible wind farm data to estimate the construction costs of a single turbine as a function of its blade size and shore distance, and estimated the total cost by assuming maintenance and end-of-life costs to be a fraction of construction costs. Combining these estimates with physical principles of wind generation (based on engineering equations involving wind speed distribution, energy generation and other relevant factors), our model shows the relationships between blade size, distance from the shore and turbine lifetime value (see figures a and b below).



Figures a and b: The optimal profit and turbine size for a wind farm do not consistently increase with distance from the shore when this distance is fixed in the model. Furthermore, as maintenance and end-of-life costs represent a larger portion of the initial investment, the ideal blade size decreases.

What our model shows

As energy companies continue to install bigger wind turbines further offshore in the name of maximising energy output, our results counter the conventional wisdom that associates larger turbines with higher efficiency and profitability. The findings shed light on the inherent trade-offs in turbine size and wind farm site selection on economic viability.

Our results reveal that the trend can in fact undermine the economic viability of wind farms. Specifically, we show that the relationship between profit and blade size and distance to the shore is an inverse U-shape. This means there are limits to the benefits of larger turbines and increased distance to the shore. Beyond an optimal point, the benefits will start to decline. Considering maintenance and end-of-life costs, alongside the reduction in offshore wind available downwind after passing through a turbine (i.e. wake loss), it can be optimal for turbines to be smaller and closer to the shore.

The model complements the engineering perspective by incorporating life-cycle thinking into decision-making, offering a strategic approach to optimise offshore wind projects and achieve both sustained economic viability and environmental sustainability.

Why pay attention to lifetime value

While harnessing offshore wind is a fairly recent development, existing structures are ageing. In Europe, where offshore wind development began in the early 1990s, several installations are reaching the end of their 20- to 25-year lifespan. By the mid-2020s, many of these turbines will need to be either repowered, dismantled or replaced.

For example, the Vindeby wind farm in Denmark, which was decommissioned in 2017, served as an early case study in the end-of-life management of an offshore wind farm, including dissembling turbines, removing foundations, cables and infrastructures and managing waste. But these first wind turbines are but a fraction of the size of those today, which can be made up of **over 30,000 components**. This means the costs and complexity of maintenance and decommissioning would have increased exponentially – and are too significant to ignore.

A case in point is how wind turbine operators such as Siemens Energy have incurred **rising maintenance costs** through 2023. After it announced an additional EUR1 billion expenditure on turbine maintenance, its shares plunged 30 percent. In practice, maintenance costs tend to be underestimated, even though they tend to increase over time. Decommissioning and maintenance costs, in fact, are typically set arbitrarily at a percentage of the cost of making the turbine, with little regard to the implications of building larger turbines situated farther offshore on capital and operational expenditures.

Capital expenditures include not only the costs of constructing turbines, but also the expenses associated with building robust offshore platforms, undersea cabling to connect far-flung turbines back to the grid and other marine logistics. In addition, the complexity and challenge of routine maintenance and repair work increase with the distance from the shore, which can drive up operational expenditures considerably.

Seeing the fuller picture

In the quest to accelerate the energy transition, governments are offering **financial incentives** such as subsidies, tax credits and grants for offshore wind projects, which have driven their phenomenal growth. The French government, for example, has implemented **policies** to encourage investment, including subsidies, tax exemptions and low-interest loans to offshore wind energy projects. It has also developed long-term power-purchase contracts and dedicated sites for developers, as well as facilitated R&D support programmes to improve offshore wind energy technology.

While governments rightfully should encourage the move towards more sustainable energy sources, our study reveals the dangers of short-termism and invites a more thorough understanding of lifetime economics and environmental impact. The over 8,800 abandoned "ghost wells" in Pennsylvania from the oil rush are a reminder to take a comprehensive view to ensure the sustainability and viability of energy projects in the long run.

More importantly, our work underscores the need for a nuanced, multifaceted approach to offshore wind farm planning and design. Sustainable development requires a long-term approach that considers all stakeholders, including the **environment**. The movement has started, with initiatives like the **ZEBRA** consortium in Europe seeking to design a 100-percent recyclable wind turbine blade, and the state of Colorado in the US mandating the **removal** of decommissioned wind turbines. More stringent environmental protection regulations are likely to push decommissioning costs up further in the future.

By balancing the maximisation of short-term energy output with broader considerations, wind farm designers and planners can create more sustainable and resilient projects that deliver long-term environmental and economic benefits.

Find article at

https://knowledge.insead.edu/operations/life-giants-life-cycle-view-wind-turbines

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About the research

"**Bigger and Further: An Operational Perspective of Windfarms Design and Planning**" is a working paper.

About the series

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