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The Long-Term Costs of Wind Turbines

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Summary. Wind energy is experiencing a boom, but in a pattern eerily reminiscent of the nineteenth century Pennsylvania oil boom, wind farms are building ever larger turbines to farm wind energy further and further from shore. This trend carries risks, especially as... **more**

In 1859, the town of Titusville in Pennsylvania vaulted into the limelight when Edwin Drake struck oil, thereby marking the inception of America's oil industry. With an initial depth of 69.5

feet (roughly equivalent to the blade size of a 0.5 MW wind turbine), Drake's well set the stage for an unprecedented era of economic prosperity.

Companies and workers alike descended upon Pennsylvania's black-gold frontier, applying rudimentary cable-tool drilling technology to tap shallow reserves. However, as these reserves ran dry, the industry underwent a transformation. With improvements in technology and a better understanding of the geology of oil reservoirs, operators began to go deeper. Rotary drilling techniques, which were more effective than the earlier percussion methods, were introduced and made deeper drilling more feasible. Additionally, improvements in pumping technology enabled oil to be extracted more efficiently from greater depths.

For a while, it seemed like the fountain would flow endlessly. But eventually, Pennsylvania began to run out of extractable oil. Newer and more promising fields were discovered elsewhere, drawing attention and resources away from older sites. But in the absence of regulations, operators simply abandoned their wells without properly capping or decommissioning them. The result is that today Pennsylvania is plagued by more than 8,800 "ghost wells": abandoned oil wells that continue harming the environment and local communities. Emitting methane and leaking chemicals into groundwater, these wells degrade soil and make land unusable, stalling local development plans and reducing property values.

The development of the turbine industry is eerily reminiscent of Pennsylvania's forgotten oil rush. In 2021, global wind capacity increased by 94 GW, primarily led by six countries: the United States, China, Germany, India, Spain, and Brazil. This growth in wind power has been accompanied by dramatic cost reductions, making wind energy increasingly competitive. Onshore wind energy costs fell by 68% and offshore by 59%, with 2021 seeing further declines of 15% and 13%, respectively. Over the decade from 2010 to 2021, onshore wind capacity increased four-fold, while offshore capacity grew 11-fold.

Much of this growth has come from making the turbines bigger. Bigger blades on turbines located farther offshore capture wind more efficiently, require fewer turbines for the same output, and offer more consistent energy generation due to steadier offshore winds. These factors also reduce the costs associated with integrating the energy output with national grids. Keen to accelerate this trend, governments around the world offer various financial incentives. France, for example, subsidizes long-term wind-power purchase contracts and supports research and development programs aimed at enhancing the efficiency and cost effectiveness of offshore wind technology.

Unfortunately — and ironically — it also looks like the wind energy business could be repeating the mistakes of the Pennsylvania oil drillers, leaving the public with a legacy that is equally challenging for society. A rush to create power-generation capacity without a comprehensive approach that considers the entire lifecycle of wind farms can result in detrimental consequences for both the environment and the long-term viability of these projects. To ensure the long-term sustainability and viability of wind energy projects, designers and decision-makers should account for various factors throughout the entire lifecycle of a wind farm, including environmental impact and lifecycle costs: capital expenditures, operational expenditures, and end-of-life (EOL) costs.

As larger wind energy projects venture farther offshore to harness more consistent and powerful winds, a proportional escalation in costs across various categories is inevitable. Capital expenditures are not merely a factor of turbine costs; they also encompass the expenses associated with creating robust and durable offshore platforms, marine logistics, and extensive undersea cabling to connect these distant turbines back to the grid onshore. Operational expenditures also see a marked increase due to the complexity and challenge of routine maintenance and repair work in offshore conditions. These tasks become difficult and expensive as the distance from shore increases, often requiring specialized vessels and equipment, not to mention the increased risks that workers will face.

The most significant cost escalation is likely to occur in decommissioning, a complex and expensive endeavor involving the disassembly of turbines, removal of foundations and cables, reverse logistics of moving the blades and towers back to shore, and responsible waste management. Most economic analyses on wind farm design, however, assume that these costs will be negligible or diminish over time. They also underestimate maintenance costs, which are well known to increase over time. Moreover, they do not explore the implications of building larger turbines situated farther offshore on decommissioning and maintenance costs, which are typically set arbitrarily at 50% of the cost of making the turbine.

The industry cannot afford to brush over decommissioning and maintenance issues any longer. Through 2023, turbine operators such as Siemens Energy have incurred rising upkeep costs. (Shares in Siemens plunged 30% after the company announced it would have to spend an additional $1 billion in turbine maintenance.) The first major wave of decommissioning is also imminent, with around 34,000 onshore turbines close to retirement. Awareness of the problem is growing, triggering initiatives like the ZEBRA consortium in Europe, a research program that seeks to design a 100% recyclable wind turbine, while in the U.S., the State of Colorado now mandates the removal of decommissioned wind turbines.

In an effort to understand the economic implications of wind farm maintenance and decommissioning, we collected accessible wind farm data to estimate the construction cost of a single turbine as a function of its blade size and shore distance. We then estimated the total cost by assuming maintenance and end-of-life costs (MEOL) to be a fraction of construction costs and combined these estimates with physical principles of wind generation based on engineering equations involving wind speed distribution, energy generation, and other relevant factors to build a "lifetime value" model, which reveals the relationships between blade size, distance from shore, and turbine lifetime value (the total revenue generated from electricity produced by a turbine minus its total lifecycle cost), as depicted in Figure 1.

The Relationship Between Turbine Size, Location, and Lifetime Value

Chart A tracks the relationship between turbine blade length and lifetime value, measured as the dollar present value of all electricity generated by a turbine less lifetime costs, for scenarios where maintenance and end-of-life (MEOL) costs are 30%, 40%, and 50% of the total capital investment in a turbine. It shows that while optimal blade sizes peak between 70 and 80 meters, the blade length delivering the highest value is partly determined by the level of MEOL costs. Chart B identifies cost-optimal blade sizes for the three scenarios over varying distances from shore. In general, it shows that optimal blade sizes rise sharply but peak between 50 and 60 kilometers from shore. Optimal sizes are also affected by the level of MEOL costs; higher MEOL costs imply shorter optimal blade lengths.

Chart A: Turbine lifetime value, by blade size

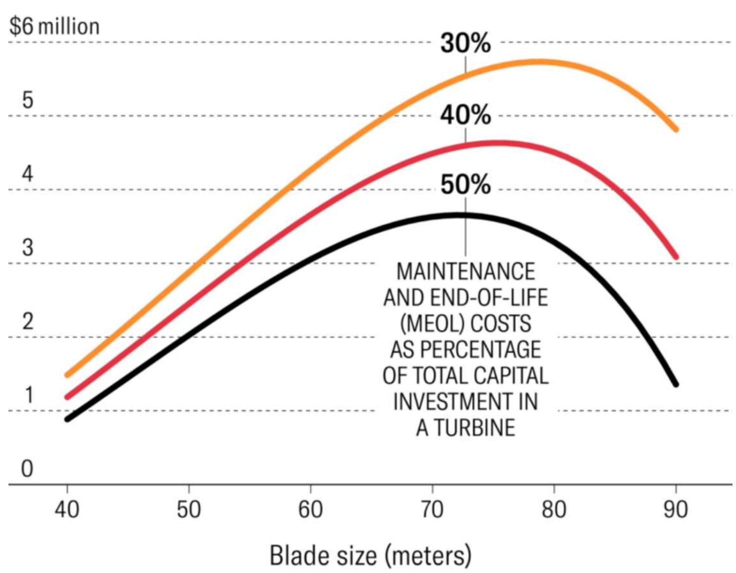
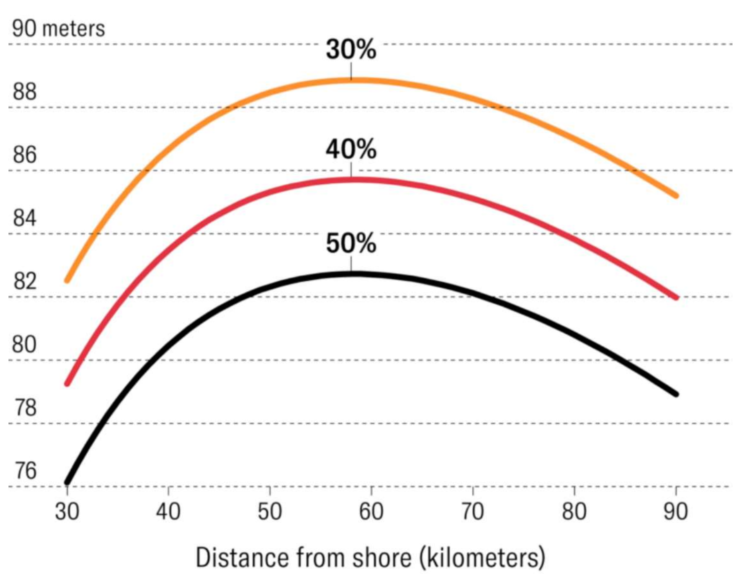


Chart B: Turbine blade size, by distance from shore



Source: "Bigger and Further: An Operational Perspective on Windfarms Design and Planning," by Sam Aflaki, Atalay Atasu, and Luk N. Van Wassenhove, INSEAD working paper, 2024. HBR

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As the figure shows, larger turbines are, up to a point, more efficient, absent other factors (chart A). But that efficiency varies with shore distance (chart B), and the optimal blade size is clearly affected by the level of MEOL costs (the apexes of the curves in both parts move leftwards). We can conclude, therefore, that smaller blades can be better suited for farther offshore projects. In other words, suppose that you are considering the construction of a wind farm 35 km shore distance. You have a choice between commissioning three turbines with 90-meter blades and four turbines with 75-meter blades. They would generate roughly the same amount of energy (the four smaller machines would supply slightly more). But the four smaller turbines would reduce maintenance and obsolescence costs by 14% and require 18.5% lower (composite) material requirement for the blades. Put simply, the wind industry's assumption that bigger is better might simply not be true.

While the parallel between wind farms and the oil rush example is already telling, our experiences with the electronics industry serve as another cautionary tale. Much like the wind energy industry, the electronics industry did not anticipate or plan for managing electronic waste, recycling of which turned out to be a major problem in the 2000s. When the European Commission's WEEE Directive came knocking on the door, many electronic device producers realized that the EOL costs imposed by the directive would simply shave their already tight margins even further. Not surprisingly, local governments quickly realized that when producers could not handle the retroactive responsibility, the financial burden would fall on the taxpayer. More recently — and even more relevant — similarly overlooked environmental costs are accumulating in solar energy, as we have already documented previously in HBR. The burdens can be heavy. In

Canada, for example, asset retirement in the oil and gas industry could leave taxpayers facing an estimated $72 billion in future liabilities.

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Those who cannot remember the past are condemned to repeat it, as the saying goes. The pioneers of the Pennsylvania Oil Rush could not have foreseen the social and environmental toll their actions would take more than a century later. They were leaders of their time, operating under the scientific understanding and ethical paradigms of their era. But in the rush and excitement of our transition to renewable energy, we must not forget that environmental degradation takes many forms — and we need to learn to look beyond short-term clean energy gains if we are not to replace one form of environmental degradation with another.

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