United States Government Accountability Office

Report to Congressional Addressees

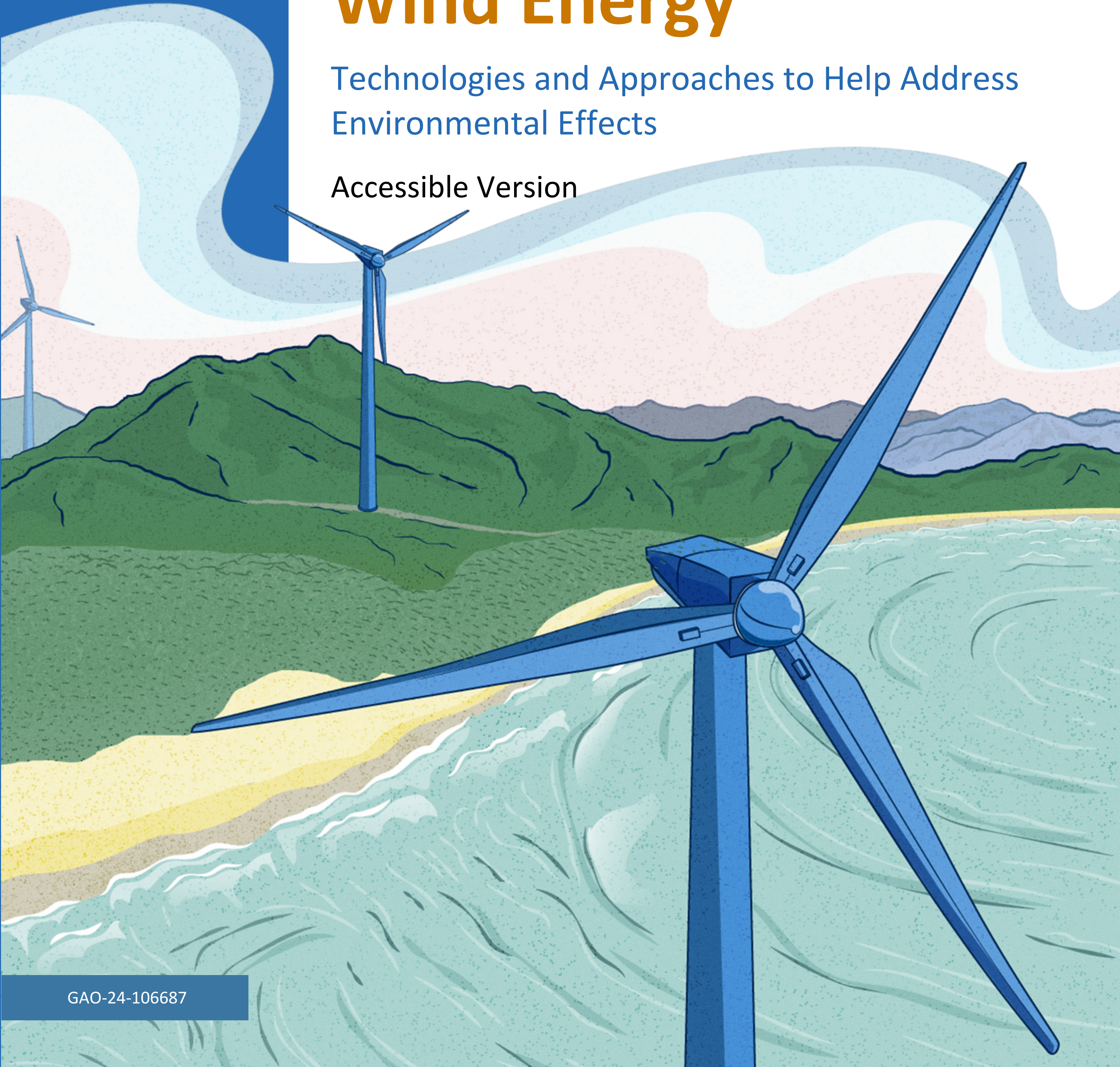
July 2024

TECHNOLOGY ASSESSMENT

Wind Energy

Technologies and Approaches to Help Address Environmental Effects

Accessible Version



GAO-24-106687

The cover image depicts onshore and offshore wind turbines.

Cover source: GAO (illustration). | GAO-24-106687

Highlights of GAO-24-106687, a report to congressional addressees

July 2024

TECHNOLOGY ASSESSMENT

Wind Energy

Technologies and Approaches to Help Address Environmental Effects

Why GAO did this study

Wind energy is one of the fastest-growing renewable energy sources globally. Onshore and offshore wind energy provide an abundant source of electricity with significant environmental benefits, including lower atmospheric greenhouse gas emissions during electricity generation. However, the increases in the development of wind energy facilities increases the potential environmental effects of these facilities, including greater use of natural resources like critical materials and steel, decommissioning and recycling difficulties, and ecological effects such as wildlife harm.

This report discusses (1) technologies or approaches to help reduce the potential environmental effects related to the life cycle of utility-scale wind energy projects, (2) challenges that might hinder implementation of these technologies or approaches, and (3) policy options to help address these challenges.

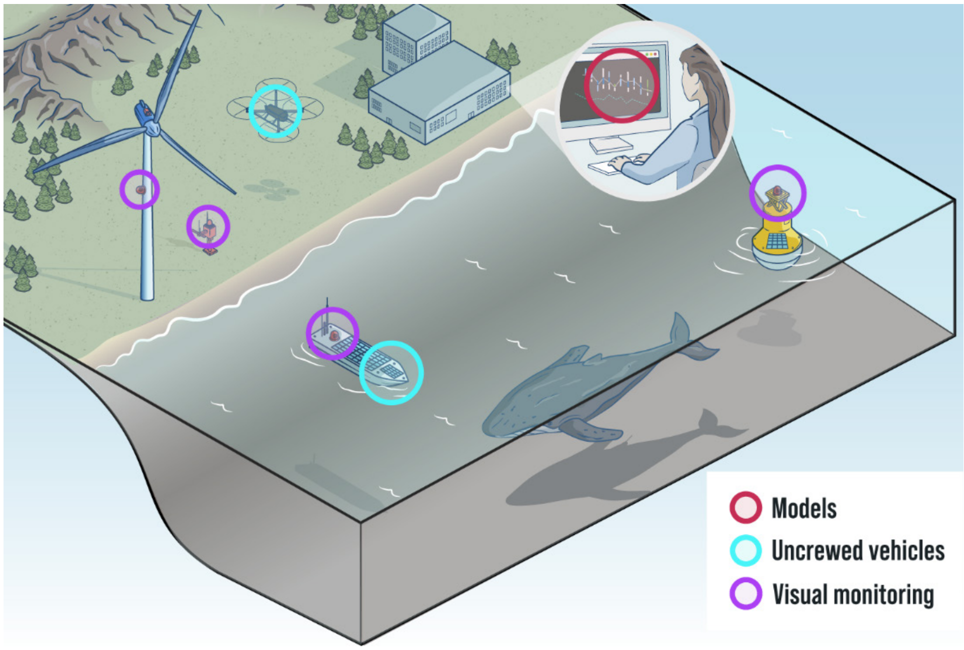
To conduct this technology assessment, GAO reviewed evidence, including articles and other reports; interviewed government, industry, and academic stakeholders; conducted a site visit; and convened an expert meeting with the assistance of the National Academies of Sciences, Engineering, and Medicine. GAO is identifying policy options in this report.

View GAO-24-106687. For more information, contact Karen L. Howard, PhD, at (202) 512-6888 or HowardK@gao.gov.

What GAO found

Total annual U.S. electricity generation from onshore and offshore wind energy increased from about 6 billion kilowatt-hours (kWh) in 2000 to about 430 billion kWh in 2023, an increase of over 7,000 percent and resulting in wind energy generation providing about 10.2 percent of the electricity in the United States in 2023. Because a continued scale-up in deployment of wind energy facilities could increase the potential environmental effects of these facilities, GAO identified technologies and approaches to address potential effects of wind energy to the physical environment, animals, or humans across a facility's life cycle. These technologies and approaches can be used individually or in combination to address environmental effects. For example, visual monitoring technologies can be placed on uncrewed vehicles to gather data on animal presence and abundance in challenging environments.

Select technologies or approaches in use or under development to help support data collection to address environmental effects



Source: GAO (analysis and illustrations). | GAO-24-106687

However, challenges may limit the use of technologies and approaches to address environmental effects. Some technologies and approaches may incur additional direct costs for a wind energy developer, potentially creating a barrier for use by making the facility's electricity less cost-competitive in the electricity marketplace. Technologies and approaches have to maintain quality assurance during the operation and lifetime of a turbine. Meanwhile, knowledge gaps about projects can make it difficult to determine how to most effectively use technologies and approaches to address challenging effects. Further, some technologies and approaches such as machine learning and modeling require large amounts of data and energy, and barriers to data access may limit the effectiveness of a technology or an approach.

GAO identified five policy options that could help address these challenges or enhance the benefits to technologies and approaches for addressing potential environmental effects of wind energy. These policy options identify possible actions by policymakers, which include Congress, federal agencies, state and local governments, academia, research institutions, and industry. See below for a summary of the policy options and relevant opportunities and considerations.

Policy Options to Help Enhance Benefits or Address Challenges

Policy Option	Opportunities	Considerations
Status quo (report p. 25). Policymakers could take no further intervention, allowing current activities to continue.	• Current efforts may address some of the challenges identified in this report without additional resources beyond those that have already been allocated. • Resources and time that may be required in other policy options could instead be used for other priorities.	• Some challenges may remain unresolved or may take longer to resolve than with intervention. • Maintaining the status quo may not be responsive to the wind industry or executive and legislative priorities and may not address unresolved environmental effects.
Encourage innovation and research (report p. 25). Policymakers, such as Congress, academic institutions, industry organizations, or others, could encourage research and development of technologies and approaches to address potential environmental effects.	• Additional research could help to better understand wind energy facility sites and inform appropriate and necessary technologies and approaches to address potential environmental effects. • Policymaker communication during research and development can reduce costs and improve access to information and resources.	• Innovation and research can require additional time, personnel, cost, and communication among policymakers.
Data sharing (report p. 26). Academic institutions or other policymakers could facilitate improved data sharing about potential environmental effects, technologies, and approaches.	• Having data in a central database may encourage collaboration among policymakers who otherwise might not interact. • Databases could also store other types of information about research alongside the raw data that may not otherwise be accessible.	• Establishing new or trusted data-sharing mechanisms may require additional maintenance, time, personnel, and other resources. • Sharing research that includes proprietary or sensitive data may require investing in data security or removing the proprietary or sensitive information from the data.
Establish consistent methodologies (report p. 27). Policymakers such as academic institutions or industry could encourage the use of consistent methodologies to study wind energy facility sites and to address data and research limitations.	• Consistent data collection methods could help establish uniformity in data. • The adaptive management process can encourage use of technologies and approaches to address potential environmental effects while researchers fill knowledge gaps.	• Policymakers may not easily accept voluntary methodologies that were developed by other groups.
Incentives (report p. 28). Policymakers such as government entities could consider incentivizing the use of technologies and approaches to address environmental effects.	• Incentives can help operators and companies collaborate to develop and use approaches to address environmental effects that may not be economically viable otherwise.	• Incentives could lead to unintended outcomes for governing authorities or developers. • Environmental and social costs and benefits could be difficult to quantify, making it challenging to set the appropriate level of incentives.

Source: GAO. | GAO-24-106687

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Abbreviations

BLM	Bureau of Land Management
BOEM	Bureau of Ocean Energy Management
DOE	Department of Energy
EPA	Environmental Protection Agency
IRA	Inflation Reduction Act
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory

U.S. GOVERNMENT ACCOUNTABILITY OFFICE
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July 23, 2024

The Honorable Gary C. Peters
Chairman
Committee on Homeland Security and Governmental Affairs
United States Senate

The Honorable James Comer
Chairman
Committee on Oversight and Accountability
House of Representatives

Wind energy is one of the fastest growing renewable energy sources. Total annual U.S. electricity generation from wind energy increased from about 6 billion kilowatt-hours (kWh) in 2000 to about 430 billion kWh in 2023, an increase of over 7,000 percent. This enabled wind energy generation to provide about 10.2 percent of the electricity in the U.S. in 2023.[1] Onshore and offshore wind energy can provide an abundant source of electricity without producing pollution from fuel combustion during operation. This provides significant environmental and public health benefits, including lower atmospheric greenhouse gas emissions than more prevalent energy sources like fossil fuels. Further, wind energy does not emit nitrogen oxides and sulfur dioxide, gases that cause smog, ground-level ozone, and acid rain, as well as adverse health effects such as asthma, bronchitis, and heart attacks. However, the increase in the development of wind energy facilities could increase potential environmental effects, including greater consumption of resources like critical materials and steel, potential decommissioning and recycling difficulties, and ecological effects such as wildlife harm.

We prepared this report under the authority of the Comptroller General, in light of congressional and public interest in potential environmental effects of wind energy.[2] This report discusses (1) technologies or approaches to help reduce potential environmental effects related to the life cycle of utility-scale wind energy projects, (2) challenges that might hinder implementation of these technologies or approaches, and (3) policy options to help address these challenges.

We interviewed agency officials and other stakeholders, including nongovernment organizations and academic researchers; visited a national laboratory and wind energy manufacturers; held an

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[1] 2000 and had two operational offshore wind farms in 2022. These two offshore windfarms provided less than 0.05 percent of the total onshore and offshore wind generation capacity in 2022.

[2] 31 U.S.C. § 717(b)(1).

expert meeting; and reviewed agency documents and other literature. See appendix I for a full discussion of the objectives, scope, and methodology, and appendix II for a list of expert meeting participants.

We conducted our work from February 2023 through July 2024 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

1 Background

1.1 What is wind energy?

In 2023, wind energy was the source of about 10.2 percent of the total U.S. utility-scale electricity generation and accounted for about half of electricity generation from renewable sources, as seen in figure 1.[3]

Wind turbines generate electricity by turning blades around a rotor, spinning a generator to create electricity. Electricity generation depends on wind speed and blade length, among other factors. Wind energy is a variable electricity supply—the amount of electricity generated changes depending on wind conditions.

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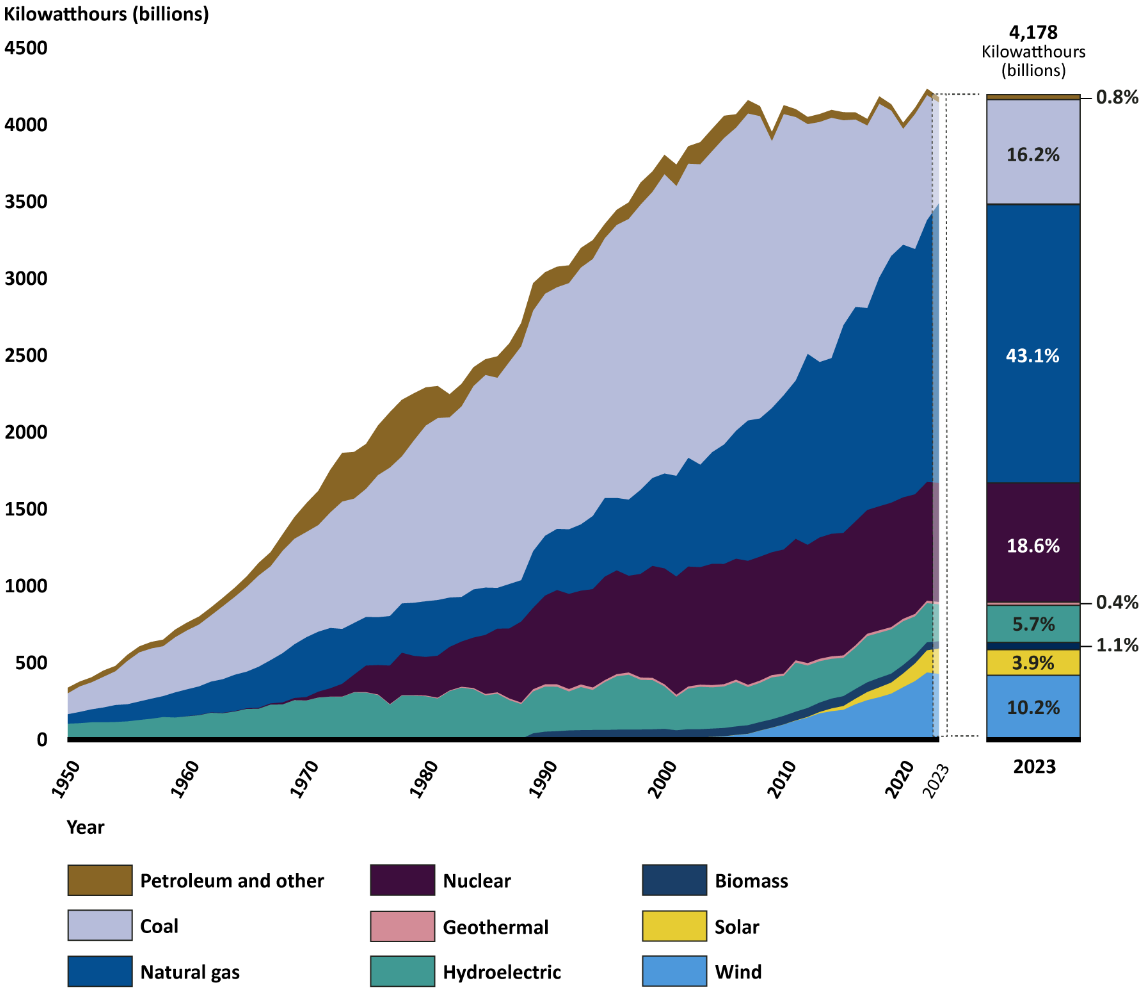
[3] U.S. Energy Information Administration, *Electric Power Monthly: February 2023*, (Washington, D.C.: February 2023). Utility-scale electricity generation is defined as electricity generation from power plants with at least one megawatt (or 1,000 kilowatts) of total electricity generating capacity.

Figure 1: **Electricity generation from renewable and nonrenewable sources**



Source: GAO analysis of data from U.S. Energy Information Administration (Feb 2023 and April 2024). | GAO-24-106687

Turbines can be categorized by where they are installed and how they are connected to the grid.[4] Onshore wind turbines range in generation capacity from 100 kilowatts (kW) to several megawatts (MW).[5] Larger turbines are more cost effective and are grouped together into wind farms, which provide bulk power to the electrical grid. Offshore turbines—often taller than the Statue of Liberty—tend to be taller than onshore turbines and can capture powerful ocean winds. The average turbine height for offshore turbines in the U.S. was about 300 feet in 2016 and is projected to increase to about 500 feet by 2035 (see fig. 2).

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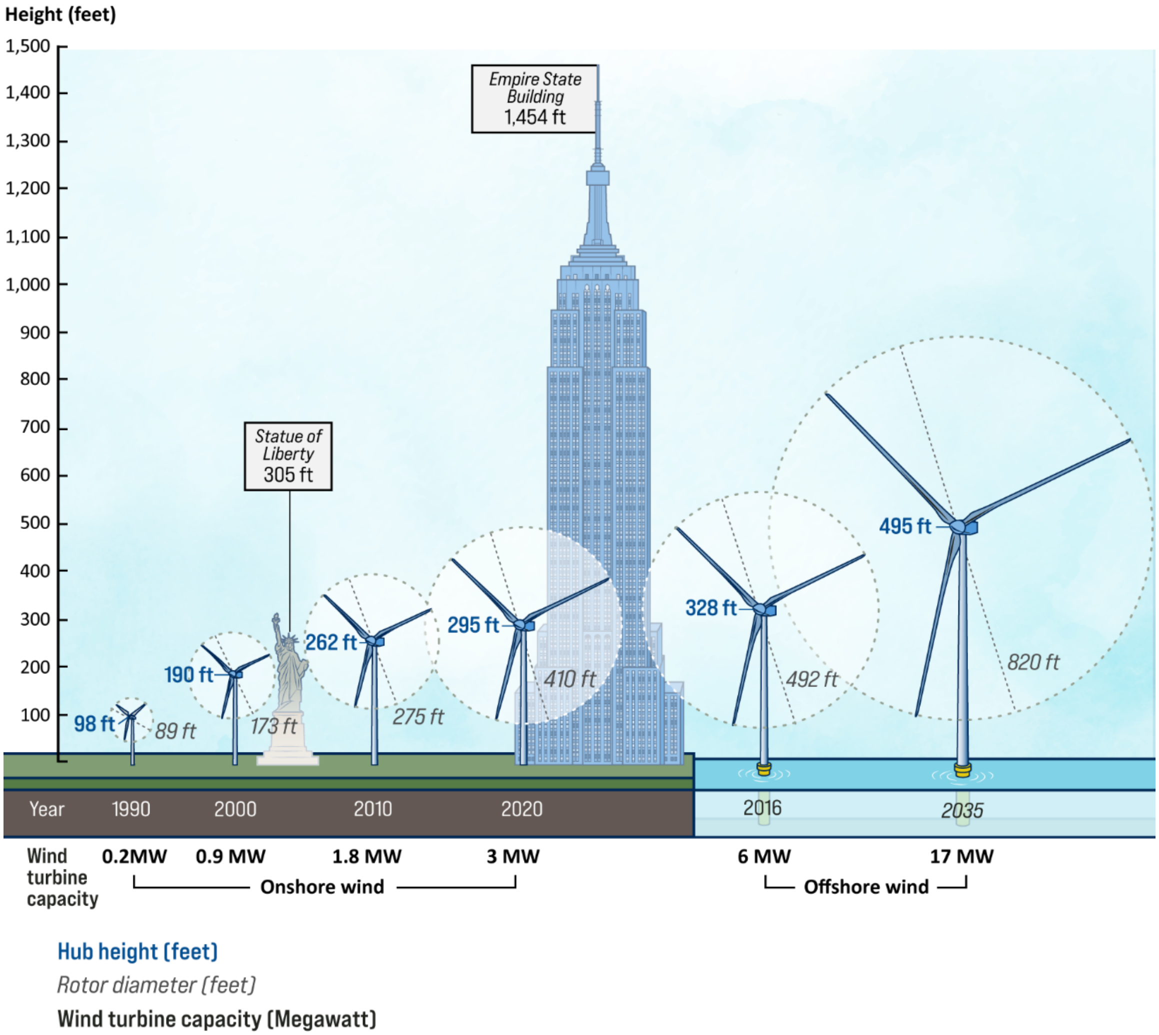
[4] According to the Department of Energy (DOE), there are three categories of turbines: onshore, offshore, and distributed wind. Distributed wind includes turbines of any size that are installed on the "customer" side of the electric meter. This report discusses onshore and offshore turbines because they are used in utility-scale electricity generation.

[5] Watts are a measurement of power, describing the rate at which electricity is being used at a specific moment. One gigawatt (GW) is equivalent to 1,000 MW. One MW is equivalent to 1,000 kW which is equivalent to one million watts. One MW can power about 800 homes.

Figure 2: Onshore and offshore turbines over the years



Source: GAO figure adapted from the National Renewable Energy Laboratory (part of Department of Energy) and the New York State Energy Research and Development Authority. | GAO-24-106687

Turbines have a service lifetime of about 30 years.[6] However, some turbine components are not designed to last for the full expected service life, and operators may need to repair and replace components such as blades and generators.[7] This report focuses on

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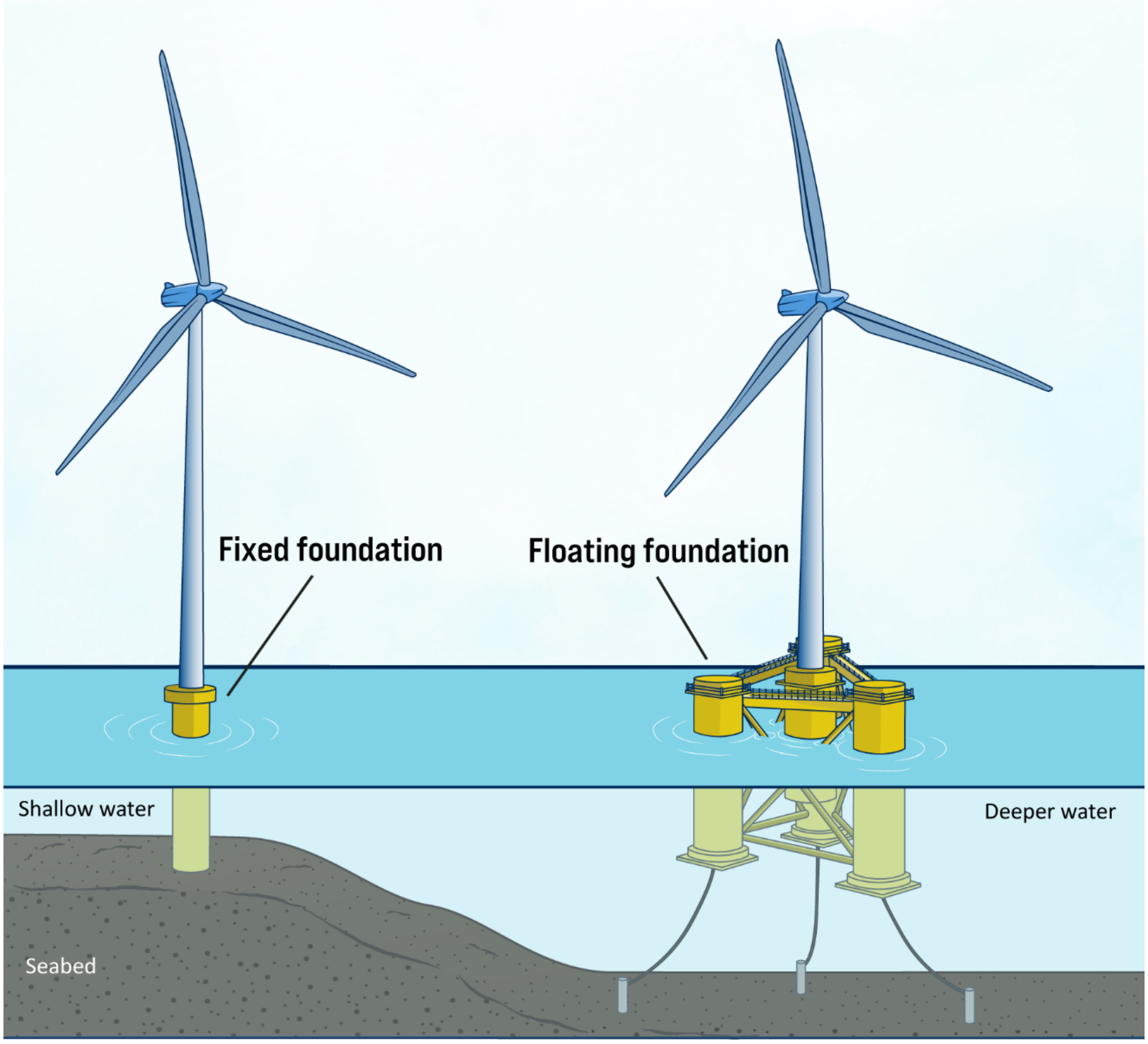
[6] Wind energy service lifetime assumptions range from 25 to 40 years, with an average of 29.6 years. Ryan Wiser and Mark Bolinger, *Benchmarking Anticipated Wind Project Lifetimes: Results from a Survey of U.S. Wind Industry Professionals*, (Berkeley, CA: Lawrence Berkeley National Lab, September 2019).

[7] The major components in wind turbines are the blades, hub, nacelle, and tower. The blades capture energy from wind. The hub supports the blades, maintains blade angle, and controls rotation speed. The nacelle is the shell resting atop the tower containing the equipment that generates electricity and the electronic components that allow the turbine to monitor changes in wind speed and direction. The tower provides the support system for the turbine. Wind energy facilities may include other components, including transformers, circuit breakers, fiber optic cables, and ground-mounted electrical equipment.

horizontal-axis turbines, which is the most common design in current use.[8]

While onshore turbines are fixed to the ground, offshore turbines are either fixed-bottom or floating as seen in figure 3. Fixed-bottom turbines are generally used for offshore wind in shallower locations. In deeper waters off the Pacific coast, Hawaii, and the Gulf of Maine, operators are planning floating turbines at depths greater than 200 feet.

Figure 3: Fixed and floating foundations for offshore turbines



Source: GAO adaptation of figure from the Bureau of Safety and Environmental Enforcement (part of the Department of Interior). | GAO-24-106687

Note: Fixed turbines are planned in shallow water less than 200 feet in depth. Floating turbines are planned in deeper water greater than 200 feet in depth.

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[8] Turbines can have a horizontal axis or a vertical axis, but very few vertical-axis turbines are in use because they do not perform as well as horizontal-axis turbines.

1.2 Selected agencies

The Department of the Interior's Bureau of Land Management (BLM) and Bureau of Ocean Energy Management (BOEM) play primary roles in the approval of wind energy projects on federal lands and in federal waters, respectively.[9] State and local governments provide primary approval for projects not on federal lands or in federal waters. The Bureau of Ocean Energy Management collaborates with the National Oceanic and Atmospheric Administration (NOAA), and other federal agencies on siting and environmental review under the National Environmental Policy Act and other environmental statues and implementing regulations. According to the National Oceanic and Atmospheric Administration, this collaboration is both informal and formal. Other state and federal agencies may have additional roles in the onshore or offshore wind project approval process or may contribute resources and information to the process. For example, the Department of Energy's (DOE) Wind Energy Technologies Office invests in activities that enable and accelerate innovations to advance onshore and offshore wind, while continuing to address market and deployment barriers. NOAA provides scientific review and consults with federal agencies for offshore wind as well as regulating authorization of developer's requests for incidental take under the Marine Mammal Protection Act, while the Marine Mammal Commission reviews and comments on proposed offshore wind activities.[10]

Support for increased wind energy has been part of recent legislative and executive actions that set national goals for renewable energy projects. For example, Executive Order 14008 seeks to double offshore wind energy by 2030, while the Energy Act of 2020 set a minimum goal for the Secretary of the Interior of issuing permits for 25 gigawatts of electricity from renewable energy projects on public land by 2025.[11] Recent legislation also contained funding and incentives for renewable energy, including wind energy. For example, the Inflation Reduction Act (IRA) extended the production tax credit for

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[9] The Bureau of Land Management (BLM) is responsible for issuing rights of way on BLM managed public land pursuant to title V of the Federal Land Policy and Management Act, as amended. Pub. L. No. 94-579, tit. V, 90 Stat. 2743, 2776-82, as amended, codified at 43 U.S.C. §§ 1761-1772. According to implementing regulations, BLM public lands are "any land and interest in land owned by the United States within the several states and administered by the Secretary of the Interior through BLM without regard to how the United States acquired ownership, except lands: (1) Located on the Outer Continental Shelf; and (2) Held for the benefit of Indians, Aleuts, and Eskimos." 48 C.F.R. §2801.5(b).

The Bureau of Ocean Energy Management issues leases, easements, and rights of way for renewable energy development, including offshore wind, on the outer continental shelf pursuant to authority provided by the Energy Policy Act of 2005. Pub.L. No, tit. III, subt. G, § 388, 119 Stat. 594, 744-47, codified at 43 U.S.C. § 1337(p). 43 U.S.C. §1331(a) defines the outer continental shelf as "(1) all submerged lands lying seaward and outside of the area of lands beneath navigable waters as defined in section 1301 of this title, and of which the subsoil and seabed appertain to the United States and are subject to its jurisdiction and control or within the exclusive economic zone of the United States and adjacent to any territory of the United States; and (2) does not include any area conveyed by Congress to a territorial government for administration."

[10] 16 U.S.C. § 1371(a)(5). Implementing regulations define an incidental take as "an accidental taking. This does not mean that the taking is unexpected, but rather it includes those takings that are infrequent, unavoidable or accidental." 50 C.F.R. § 216. 103. Take is defined at 50 C.F.R. § 216.3.

The Marine Mammal Commission is an independent federal agency established by the Marine Mammal Protection Act (Pub.L. No. 92-522), that provides oversight of policies and actions of federal agencies addressing human impacts on marine mammals and their ecosystems.

[11] Exec. Order No, 14008, Tackling the Climate Crisis at Home and Abroad, Jan. 27, 2021; Pub. L. No. 116-260, div. Z, tit. III, subt. B, § 3104(b), 134 Stat. 2418, 2516.

electricity from renewable resources, including wind.[12]

1.3 Wind energy benefits

According to the National Renewable Energy Laboratory (NREL), wind energy's total life cycle greenhouse gas emissions are similar to other renewables and lower than nonrenewable sources.[13] Wind energy produces 11 grams of carbon dioxide per kWh of electricity generated, compared to approximately 1,000 grams produced by coal and 486 grams by natural gas. Similar to some other renewables, wind energy does not deplete natural resources or consume water during operation, unlike nonrenewable sources such as coal and natural gas.

Wind energy projects provide revenue to their local communities through land-lease payments, tax payments, and employment. According to the American Clean Power Association, wind projects delivered an estimated $2 billion in tax payments and land-lease payments in 2022. According to DOE, over 125,000 people work in the U.S. wind industry, and this number is expected to increase.[14]

1.4 Potential wind energy environmental effects

While wind energy offers a number of environmental benefits, like other energy producing technologies it also brings potential negative, beneficial, or unknown environmental effects that may become more apparent as the use of wind energy increases. Wind power generation is expected to grow 11 percent from 430 billion kWh in 2023 to 476 billion kWh in 2025.[15] Potential environmental effects are possible changes to the physical environment, animals, and humans from actions relating to the life cycle of wind energy facilities: source materials, manufacture, construction, operation, and decommission (see fig. 4).[16]

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[12] Pub. L. No, 117-169, tit. I, subt. D, pt. 1, § 13101, 136 Stat. 1818, 1906-1913 (2022), codified at 26 U.S.C. § 45.

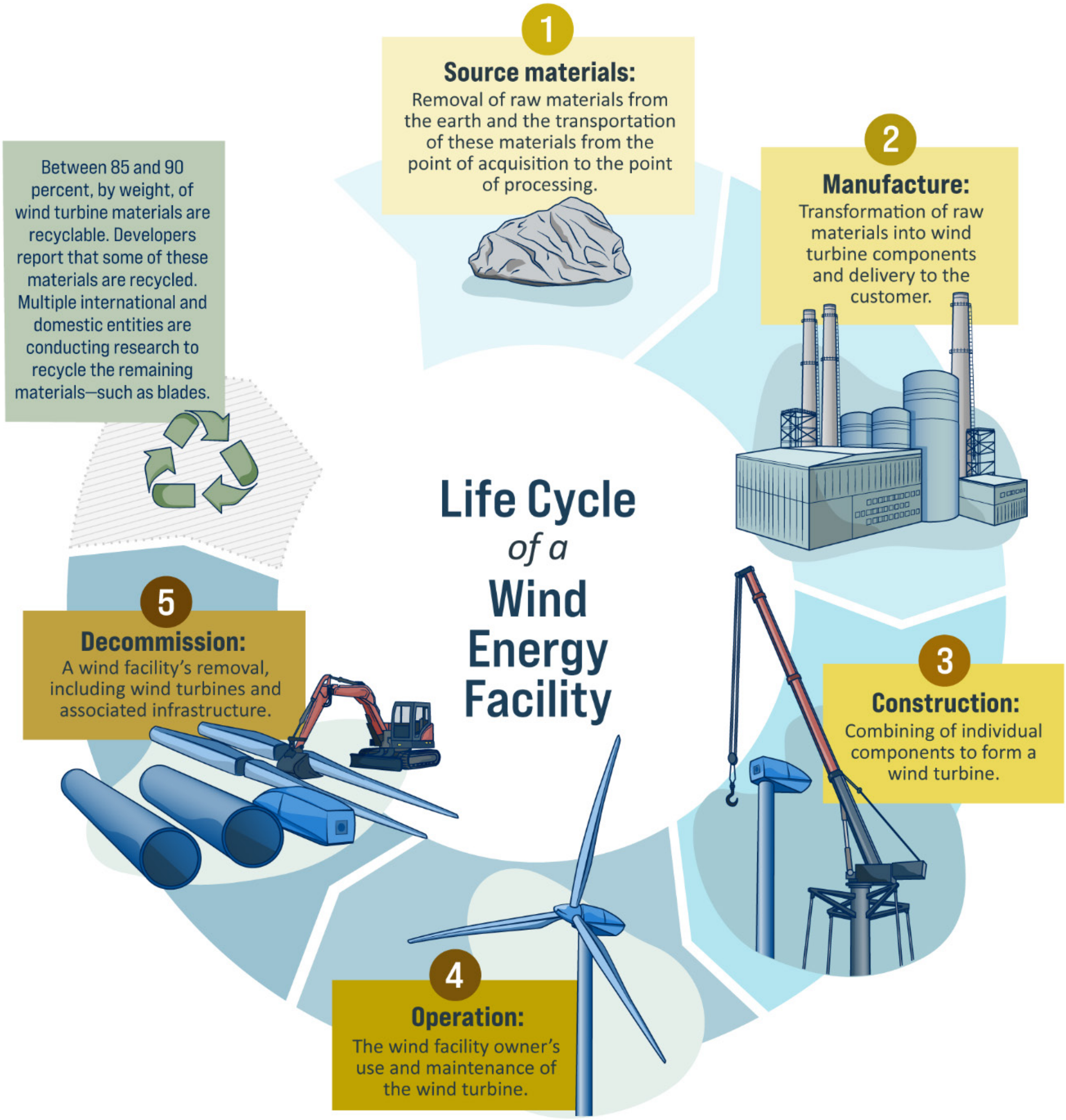
[13] National Renewable Energy Laboratory, *Life Cycle Greenhouse Gas Emissions from Electricity Generation: Update*, (September 2021).

[14] Department of Energy, "*Advantages and Challenges of Wind Energy*" (Washington, D.C.), accessed April 3, 2024, https://www.energy.gov/eere/wind/advantages-and-challenges-wind-energy.

[15] Note, however, that recently wind energy project cancellations have occurred due to various development challenges. Energy Information Administration, *Solar and Wind to Lead Growth of U.S. Power Generation for the Next Two Years*, accessed May 1, 2024 https://www.eia.gov/todayinenergy/detail.php?id=61242.

[16] For the purposes of this report, we did not compare effects between energy technologies.

Figure 4: The life cycle of a wind energy facility



Source: GAO (analysis and illustration). | GAO-24-106687

Physical environment. Effects on the physical environment include changes to the landscape, water composition, or air quality, and other effects. Some effects may be negative, such as the mining and production of source materials (e.g., steel and rare earth metals) and the generation of carbon dioxide and other emissions during the manufacturing process. Other effects can be beneficial, such as the reduction in emissions from wind power as compared to fossil fuel sources. There are some effects that may be helpful or harmful depending on the situation, like how land or marine habitats may form or change in response to wind turbines, and how turbines may affect the movement and condition of the air, land, or water during operation. Some effects are uncertain, such as effects to an environment after removal of all or parts of turbines during decommissioning.

Animals. Effects on animals include effects to animal health and safety, effects on distribution and abundance, as well as behavior changes. Some effects may be negative, such as activities during construction of onshore or offshore turbines that may disturb or injure animals, such as land animals displaced by construction or by marine mammal collisions with vessels.[17] Other effects can be beneficial, such as the formation of artificial reefs which, in some instances, may provide new habitats for marine animals on submerged parts of offshore turbine structures. Some effects are uncertain, such as animal behavior changes in response to a project site. Some animals may experience short-term negative effects but then recover as the wind energy facility enters the next life cycle stage.

Humans. Effects on humans include changes to the landscape and facilities occupying locations that could be used for other purposes. Some effects may be negative, such as unsightly visual changes to the landscape and adverse land use effects on communities during the construction and operation of turbines. Other effects can be beneficial, such as revenue from projects to communities through land-lease payments, tax payments, and employment. Some effects are uncertain, such as public acceptance and approval for the adoption of technologies and approaches to address potential environmental effects.

There is some uncertainty regarding the potential environmental effects of wind energy, and challenges exist that may limit technologies or approaches to address potential negative environmental effects. Databases such as Tethys and the Wind Data Hub exist to facilitate the exchange of information and data on environmental effects of wind energy technologies, among other things, but may not include data for proprietary or sensitive research.[18] Efforts to gather information regarding potential effects on the physical environment, animals, or humans are in various stages of development.

In this report, we describe technologies, approaches, and challenges for both onshore and offshore turbines unless specified. Chapter 2 discusses technologies and approaches to gather data on or address potential environmental effects of wind energy, and chapter 3 discusses challenges that may limit possible technologies and approaches.

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[17] Vessels are large watercraft designed to transport cargo, goods, and passengers across waterways. Vessels are used for siting, maintenance, construction, and decommissioning of offshore turbines.

[18] Tethys and the Wind Data Hub are online databases that were developed by the Pacific Northwest National Laboratory.

2 Technologies and Approaches to Address Potential Environmental Effects

We identified technologies and approaches to address potential effects to the physical environment, animals, or humans. These technologies and approaches, which are in various stages of development, can be used to gather data on or address potential effects across a facility's life cycle stages: source materials, manufacture, construction, operation, and decommission (see vignette, pg. 19-20). Each approach has different benefits and limitations, and multiple technologies or approaches may be needed to address some effects. The technologies and approaches described in this chapter are not a complete list and are intended to provide illustrative examples (see app. I, pg. 31-32). Technologies and approaches may avoid, minimize, or compensate for effects. For example, using certain siting processes before construction may help avoid effects, such as by locating facilities away from existing animal habitats. Once a project is sited, other technologies or approaches could minimize or compensate for additional effects.

Table 1 provides an overview of the technologies and approaches. Some categories may include multiple technologies or approaches with different levels of maturity or use.

Table 1: Technologies and approaches to address environmental effects

Technology and approach categories	Environmental effect addressed	Life cycle phase
Artificial reefs	Animals, physical environment	Operation
Construction noise reduction	Animals	Construction
Curtailment	Animals	Operation
Deterrents	Animals	Operation
Domestic manufacturing	Physical environment	Manufacturing
Limits on construction and speeds	Animals	Construction, operation, decommissioning
Manufacturing regulations and control technologies	Physical environment	Manufacturing
Recycling	Physical environment	Operation, decommissioning
Reduce material requirements	Physical environment	Source materials
Siting	Animals, humans, physical environment	Construction
Sustainable ('green') materials	Physical environment	Manufacturing
Turbine design	Animals	Operation

Source: GAO analysis. | GAO-24-106687

Artificial reefs. Offshore turbines could enhance animal habitats for some species, but negative effects are possible.[19] Some turbine structures could become artificial reefs that support biodiversity (see fig. 5). Multiple approaches could further enhance habitats, including foundations designed to mimic native species' habitats. However, these approaches could attract and expand the geographic range of invasive species. In addition, artificial reef formation may lead to displacement, reduced habitat availability, or higher predation rates for some species. One expert told us coordination is important to ensure feasible designs. Other countries have implemented habitat enhancement approaches. Studies are underway in the U.S. to better understand potential effects of turbines on habitats.

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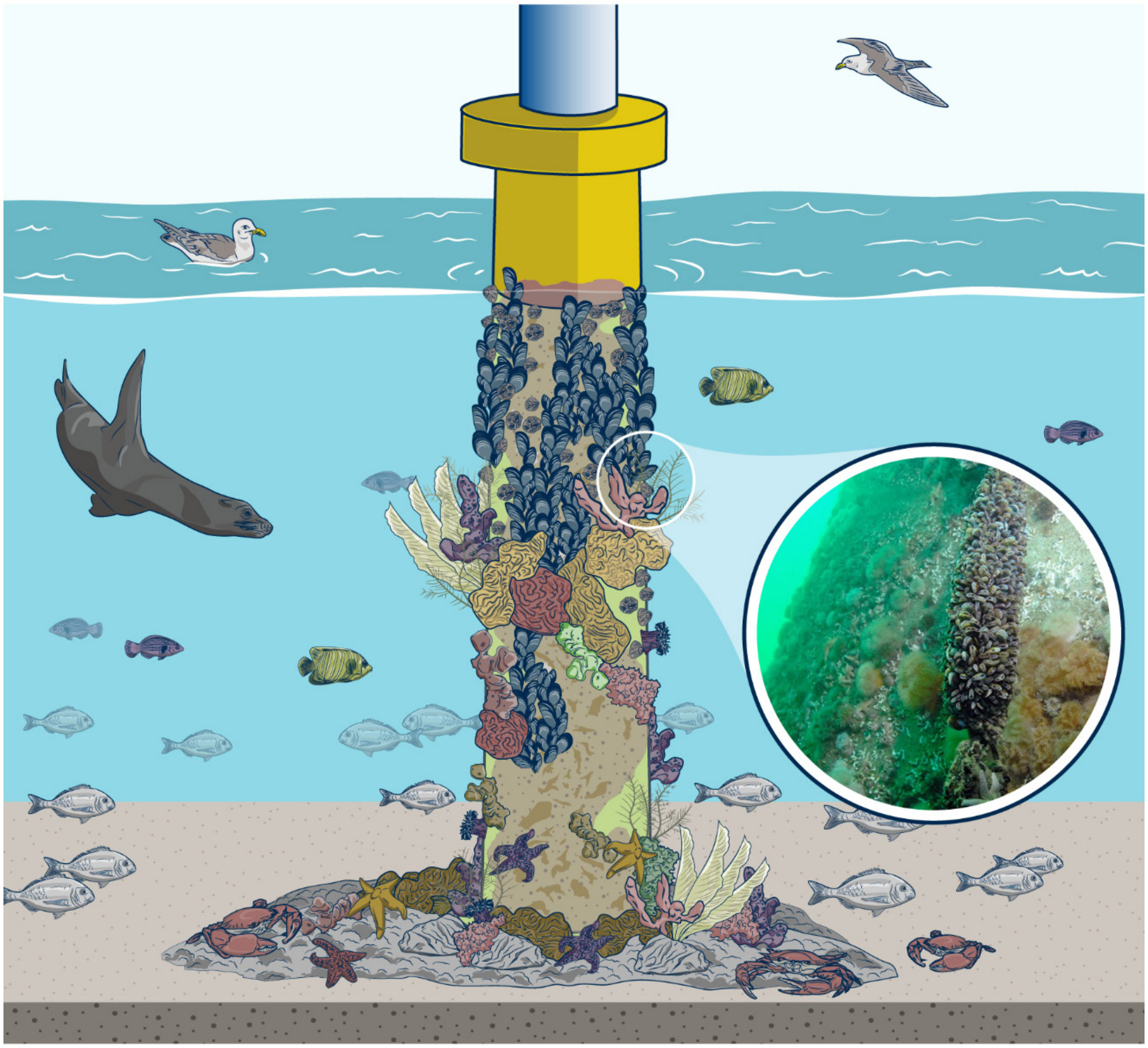
[19] For example, one study on the Block Island Wind Farm in Rhode Island found changes in seafloor habitat, which hosted numerous indigenous fish species. Hutchison et al., "Offshore Wind Energy and Benthic Habitat Changes: Lessons from Block Island Wind Farm," *Oceanography*, vol. 33 no. 4 (2020), https://doi.org/10.5670/oceanog.2020.406.

Figure 5: An artificial reef on a turbine structure



Source: Steven Degraer, Drew A. Carey, Joop W.P. Coolen, Zoë L. Hutchison, Francis Kerckhof, Bob Rumes, and Jan Vanaverbeke, Oceanography, Vol. 33, No. 4, pages 48-57, figure 1 and cover image, https://doi.org/10.5670/oceanog.2020.405 as adapted under CC BY 4.0, https://creativecommons.org/licenses/by/4.0. | GAO-24-106687

Construction noise reduction. Reducing underwater noise during the construction of offshore turbines could reduce potential effects to marine life.[20] Multiple technologies and approaches could help reduce offshore wind-related construction noise.

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[20] According to an NREL and Pacific Northwest National Laboratory report, noise levels that can cause auditory injury generally occur in relatively close range to pile driving. At greater distances, the intensity of noise is reduced and is less likely to cause injury, but may still affect the behavior of some marine species. The level of information available related to the effects of offshore wind-related noise varies by species. A number of approaches have been developed to reduce noise and minimize effects to wildlife. NREL and Pacific Northwest National Laboratory, *Environmental Effects of U.S. Offshore Wind Energy Development: Compilation of Educational Research Briefs* (2022).

- Alternate foundations. Alternate foundations, such as gravity-based or floating foundations, could reduce construction noise compared to monopile foundations, but have not been widely used.[21] Gravity-based foundations have not captured a significant market share because of their large size, soil and seafloor condition requirements, and perceived higher cost.[22] Floating foundation turbines are planned for deeper waters, and they can be installed using a variety of low-noise methods. However, the potential for animal entanglement requires further evaluation.[23] Most U.S. projects built during the 2020s will use monopiles, although this may change beyond 2030 as the industry evolves, according to NREL.

- Alternate pile driving techniques. Alternate pile driving techniques could reduce construction noise compared to impact pile driving.[24] For example, vibratory pile driving involves using a vibratory hammer in place of an impact hammer. However, vibratory pile driving is geologically specific. Vibratory pile driving is commercially available for some industries, such as bridge construction, but methods for offshore wind energy are under development.

- Quieting technologies. Quieting technologies, such as bubble curtains, resonators, and hydro sound dampers, reduce offshore wind-related construction noise by creating physical barriers around pile driving.[25] However, these technologies do not eliminate noise and must be properly installed for effective use. In addition, sites may have specific challenges that require projects to conduct their own analysis to determine the most effective quieting technologies. Operators in Europe and the U.S. have used these technologies, and additional testing is being performed to better understand their effectiveness.

This section focused on offshore construction because sound travels faster and farther in water compared to air, contributing to the need for additional technologies and approaches to reduce noise during offshore wind construction. Limits on construction and speed are an approach to reduce construction-related effects to animals from onshore wind (ch. 2, see pg. 16).

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[21] Gravity-based foundations are structures with wide, heavy bases on the seafloor and support the central column that rises about the waterline. Monopile foundations are the most common foundation type for offshore wind turbines globally.

[22] Matt Shields et al., *A Supply Chain Road Map for Offshore Wind Energy in the United States*, NREL/TP-5000-84710 (Golden, CO: National Renewable Energy Laboratory, 2023).

[23] According to an NREL and Pacific Northwest National Laboratory report, current literature suggests that the risk of marine life becoming directly entangled with a floating offshore wind cable system is low (primary entanglement). However, marine debris may become snagged in floating foundation cable systems, which could potentially lead to marine life entanglement (secondary entanglement). The report found insufficient information to evaluate secondary entanglement. National Renewable Energy Laboratory and Pacific Northwest National Laboratory, *Environmental Effects of U.S. Offshore Wind Energy Development: Compilation of Educational Research Briefs* (2022).

[24] In impact pile driving, a common method, a hammer hits the top of a steel pile; that impact sends sound into the air, water, and sediment.

[25] National Renewable Energy Laboratory and Pacific Northwest National Laboratory, *Environmental Effects of U.S. Offshore Wind Energy Development: Compilation of Educational Research Briefs* (2022).

Curtailment. Curtailment is the change of turbine operations to slow blade rotation speed, which can reduce animal collisions in some locations.[26] It can be sensor-based, occurring when certain animals are detected, or timed to occur during animal migrations or at certain wind speeds. However, real-time detection of some animals, such as bats, can be challenging, and timed curtailment could unnecessarily reduce energy production when migrating animals are not actually in the area. In addition, site specific assessments may be needed to determine the potential effectiveness of curtailment.

Curtailment is currently in use, and improved understanding of how and when animals interact with turbine blades could inform this approach. In addition, combinations of technologies and approaches could enhance curtailment. For example, machine learning could rapidly analyze images from camera-based technologies and detect animals in real time, which could support curtailment when a protected species approaches an operating facility.[27] These systems can be continuously trained and improved over time, such as with additional data. This technology is commercially available and has been installed at some onshore wind energy facilities in the U.S. and other countries.

Deterrents. Deterrents could prevent animals from approaching facilities and reduce collisions, but show varying success.[28] For example, some animals may become accustomed to acoustic deterrents, and some visual deterrents may result in attraction or other behavioral changes.[29] For some deterrents, additional research is required to validate effectiveness.

Some deterrents are commercially available, such as deterrents that use sound to discourage bats from approaching facilities, and developers have installed deterrents at onshore facilities. Other deterrents, such as blade-mounted deterrents and those that can withstand offshore environments, are under development.

Domestic manufacturing. Increased domestic manufacturing could reduce transportation-related emissions that occur with international supply chains.[30] According to a 2017 U.S. Department of Commerce report, respondents to a request for information expressed that it may be expensive and

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[26] National Renewable Energy Laboratory and Pacific Northwest National Laboratory, *Environmental Effects of U.S. Offshore Wind Energy Development: Compilation of Educational Research Briefs* (2022).

[27] Machine learning systems are a subset of artificial intelligence trained using observational or simulated outcomes used to classify or understand the content of images. These systems could be used for multiple applications, such as identifying animals, and can analyze large volumes of data faster than humans.

[28] Deterrents include acoustic and visual deterrents. Acoustic deterrents emit sound, such as ultrasonic sound. Visual deterrents may involve emitting light, such as ultraviolet light.

[29] National Renewable Energy Laboratory and Pacific Northwest National Laboratory, *Environmental Effects of U.S. Offshore Wind Energy Development: Compilation of Educational Research Briefs* (2022).

[30] For facilities installed in 2022, over 85 percent of nacelle assembly and between 70 and 85 percent of tower manufacturing occurred in the U.S. However, blade domestic content was between 5 and 25 percent. Department of Energy Office of Energy Efficiency & Renewable Energy, *Land-Based Wind Market Report: 2023 Edition* (Washington, D.C.: August 2023).

challenging to obtain permits to construct and operate a manufacturing facility.[31]

Uncertainty in future demand could also pose a challenge to scaling up investments, and some domestic products may also be more expensive. For example, domestic steel prices are higher than those in other major markets.[32] Efforts to increase domestic manufacturing are in progress and support a range of industries, including wind energy.[33]

Limits on construction and speeds. Construction and speed limits could reduce potential effects to animals. For example, onshore construction activities could be scheduled to avoid important periods of wildlife breeding or nesting, and onshore construction vehicles must also adhere to speed limits. In addition, offshore seasonal construction limits have been implemented in certain locations due to the presence of North Atlantic right whales. Offshore wind vessels must comply with vessel speed requirements to reduce collisions with whales.[34] According to NOAA, there are no known links between whale deaths and ongoing offshore wind activities.[35] However, stringent limits can extend construction time frames, increasing costs and potentially exacerbating overall effects on animals.

Offshore limits could occur in real time. To better apply offshore construction or speed limits in real time when animals are present, acoustic and camera-based monitoring technologies can support human observers to help identify animals and support limits, although each of these monitoring systems has limitations.[36] For example, passive acoustic monitoring technologies detect sound and can identify animals in real time that are challenging to otherwise observe, such as underwater marine mammals. However, passive acoustic monitoring will not detect animals that are not vocalizing (see vignette, pg. 19). In addition, camera-based technologies capture images, and some are under development to detect animals at night, which could expand offshore construction windows by confirming when it is safe to do so.

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[31] U.S. Department of Commerce, *Streamlining Permitting and Reducing Regulatory Burdens for Domestic Manufacturing* (Washington, D.C.: October 6, 2017), https://www.commerce.gov/data-and-reports/reports/streamlining-permitting-and-reducing-regulatory-burdens-domestic-manufacturing.

[32] Congressional Research Service, *Domestic Steel Manufacturing: Overview and Prospects*, R47017 (Washington D.C.: 2022).

[33] The Inflation Reduction Act includes an advanced manufacturing production tax credit that incentivizes the domestic production of clean energy technologies, such as wind energy, and critical minerals. Eligible components for wind energy include blades, nacelles, and towers. Pub. Law. No. 117-169, tit.I, subt. D, pt.5, § 13502, 136 Stat. 1818, 1971-81, codified at 26 U.S.C. § 45X.

[34] For example, the Biological Opinion for the Coastal Virginia Offshore Wind Commercial Project describes multiple vessel speed restrictions. National Marine Fisheries Service, *Biological Opinion and Conference for the Construction, Operation, Maintenance, and Decommissioning of the Coastal Virginia Offshore Wind Commercial Project (Lease OCS-A 0483)*, https://www.boem.gov/renewable-energy/state-activities/nmfs-esa-consultations.

[35] National Oceanic and Atmospheric Administration, "Frequent Questions—Offshore Wind and Whales," https://www.fisheries.noaa.gov/new-england-mid-atlantic/marine-life-distress/frequent-questions-offshore-wind-and-whales.

[36] The Pacific Northwest National Laboratory is developing a thermal camera. Pacific Northwest National Laboratory, *ThermalTracker-3D: A Stereo-Vision Solution for Tracking Wildlife Behavior Around Remote Wind Turbines, Technology Overview*, https://www.pnnl.gov/available-technologies/thermaltracker-3d.

Manufacturing regulations and control technologies. The Environmental Protection Agency (EPA) implements federal environmental laws through writing, implementing, and enforcing regulations for air, water, and waste. This includes regulating pollution resulting from manufacturing wind energy components in accordance with applicable EPA permitting programs as part of implementation of federal environmental laws. For example, under the Clean Air Act, when applicable, operating permits require a specific set of emissions limits for industrial facilities.[37] These regulations apply to many types of manufacturing facilities, including those supporting wind energy, and help control pollution. However, according to a 2023 NREL report, domestically manufactured wind energy components compete with international facilities that have less stringent environmental regulations, which can affect cost competitiveness.[38] Many manufacturing pollution control technologies are in use to meet regulations.[39]

Recycling. According to DOE, between 85 and 90 percent of turbine materials, by weight, are recyclable.[40] However, blade recycling is challenging because blades are difficult to break down, increasing life cycle costs. In addition, one stakeholder told us the demand for blade recycling is uncertain because of the increased cost and the lack of regulations requiring recycling.

Some blade recycling technologies, such as cement kiln co-processing, are in use.[41] International and domestic entities are conducting research to advance blade recycling, including NREL, which has researched methods to develop materials that are more recyclable.[42]

Reducing material requirements. Improved turbine component design can reduce material requirements, such as steel or rare earth elements, by substituting materials or reducing weight.[43] For example, rare earth elements could be substituted with other materials in generators. In addition, manufacturers could reduce steel requirements for towers by using more concrete. This could reduce potential environmental effects related to obtaining source materials. However, turbines are designed to have long service lifetimes and withstand harsh conditions. As a result, new component designs must be performance

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[37] Operating permits issued to facilities that are considered major sources are required to include enforceable emissions limitations and standards. 42 U.S.C. § 7661c(1). In addition, the preconstruction permitting program under the Clean Air Act may be applicable to new facilities or those making major modifications. Other environmental laws and programs, including the Clean Water Act, could also be relevant to manufacturing facilities.

[38] Matt Shields et al., *A Supply Chain Road Map for Offshore Wind Energy in the United States*, NREL/TP-5000-84710, (Golden, CO: National Renewable Energy Laboratory, 2023).

[39] For example, fabric filters, sometimes referred to as baghouses, could reduce air pollution. In addition, membrane bioreactors could reduce water pollution.

[40] Department of Energy Office of Energy Efficiency & Renewable Energy, *Offshore Wind Market Report: 2023 Edition* (Washington, D.C.: August 2023).

[41] In cement kiln co-processing, blades are shredded and used as a replacement for coal, sand, and clay at cement manufacturing facilities across the U.S.

[42] National Renewable Energy Laboratory, *Recyclable, Plant-Based Material Could Take a Spin on Next Generation of Wind Turbines*, (Dec. 11, 2023), https://www.nrel.gov/news/program/2023/a-recyclable-plant-based-material.html.

[43] National Renewable Energy Laboratory, *Materials Used in U.S. Wind Energy Technologies: Quantities and Availability for Two Future Scenarios*, NREL/TP-6A20-81483 (Golden, CO: August 2023).

tested. In addition, the cost of material changes could affect project economics. Efforts are in progress to reduce material requirements. For example, DOE's Wind Energy Technologies Office has programs evaluating methods to reduce critical materials use.

Siting. Siting can help avoid potential environmental effects and create multi-use spaces. For example, siting can avoid construction on existing animal habitats or co-locate facilities with other industries, among other benefits. Siting is one of the most important approaches to reduce potential environmental effects and to identify and potentially reduce or address effects on existing ocean users. However, data availability can pose challenges to site selection. Multiple technologies and approaches can generate data to inform siting, such as acoustic monitoring and marine spatial planning models (see vignette, pg. 20).

Sustainable ("green") materials. Green materials, such as green concrete and steel, are produced with fewer emissions than traditional materials. For example, green steel could be produced using alternate fuels, such as hydrogen, or be paired with carbon capture, utilization, and storage to offset emissions.[44] However, green materials are typically more expensive than traditional materials and must be performance tested, which can take considerable time. Efforts are in progress to develop and promote green materials for wind energy.

Turbine design. Turbine design choices could address potential environmental effects. For example, one study found that painting one turbine blade black reduced bird fatalities by 70 percent, but this study had a small sample size of four turbines.[45] Research is being conducted in the U.S. to determine the potential effectiveness of this approach. [46] In addition, as turbine height increases to increase electricity generation, fewer turbines may be needed to meet energy needs. However, new supply chains may be needed to support larger components. One expert also told us that, as turbine heights increase, concerns about negative aesthetic effects to the landscape are likely.

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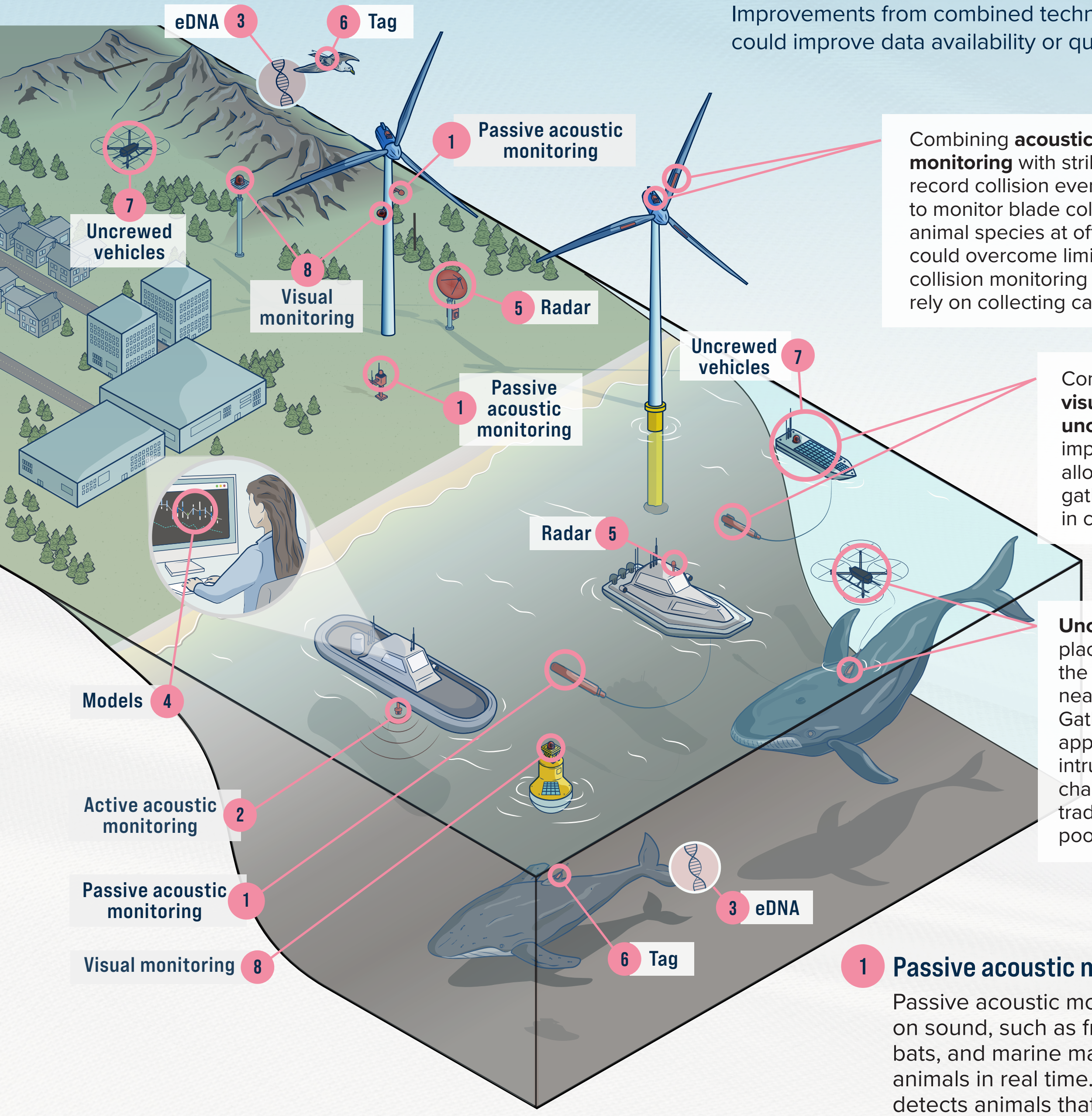
[44] We previously reported on carbon capture, utilization, and storage. GAO, *Decarbonization: Status, Challenges, and Policy Options for Carbon Capture, Utilization, and Storage*, GAO-22-105274 (Washington, D.C.: Sept. 29, 2022).

[45] This study was conducted in Norway. Roel May et al., "Paint it black: Efficacy of increased wind-turbine rotor blade visibility to reduce avian fatalities," *Ecol Evol*, vol. 10 no. 16 (2020), https://doi.org/10.1002/ece3.6592.

[46] According to Federal Aviation Administration (FAA) Advisory Circular AC 70/7460-1M, generally wind turbines should be painted either white or gray to ensure pilot visibility. For offshore wind turbines this circular applies to those turbines which extend from the coastline to 12 nautical miles offshore. See FAA Advisory Circular AC 70/7460-1M, Obstruction Marking and Lighting, Nov. 2020 at pp. 4, 51, 54.

Gathering data for wind energy

Technologies and approaches can be used independently or in combination to gather data to address potential wind energy-related environmental effects (see ch. 2). For example, some technologies and approaches can gather data to identify protected species or map the seafloor. This can inform siting to avoid protected species' habitats. Improvements from combined technologies and approaches could improve data availability or quality (see figure).



Combining **acoustic and visual monitoring** with strike indicators, which record collision events, could gather data to monitor blade collisions and identify animal species at offshore turbines. This could overcome limitations of traditional collision monitoring approaches, which rely on collecting carcasses.[47]

Combining **acoustic and visual monitoring** with **uncrewed vehicles** could improve data collection, allowing continuous data gathering and data gathering in challenging environments.

Uncrewed vehicles could place **tags** on animals, avoiding the need to deploy vessels near marine mammals.[48] Gathering data with this approach could be less intrusive and help overcome challenges that hinder traditional approaches, such as poor weather conditions.

Source: GAO (information and illustrations). | GAO-24-106687

1 Passive acoustic monitoring

Passive acoustic monitoring gathers data on sound, such as from vocalizing birds, bats, and marine mammals, and can identify animals in real time. This technology only detects animals that are vocalizing.

2 Active acoustic monitoring

Active acoustic monitoring gathers data from sound pulses echoing off underwater objects, such as seafloor terrain or fish. The data collected from this technology can effectively map the seafloor, among other uses, because sound, unlike the light used to map land above water, travels far in seawater. However, depending on the technology used, this approach introduces noise of varying scale and effect to marine animals.[49]

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[47] This technology has been field tested, and further development is in progress. Roberto Albertani and Matthew L. Johnston, *Advanced Collision Detection and Site Monitoring for Avian and Bat Species for Offshore Wind Energy (Final Technical Report)*, DOE-OSU-08733 (December 2022).

[48] Researchers have been testing the use of uncrewed vehicles to deploy tags on whales. For example, an uncrewed vehicle placed a tag on a North Atlantic right whale in 2023. NOAA Fisheries, *Short-Term Tagging of Rare Whale Takes A Step Forward* (July 21, 2023), https://www.fisheries.noaa.gov/feature-story/short-term-tagging-rare-whale-takes-step-forward.

[49] Carolyn D Ruppel et al., "Categorizing Active Marine Acoustic Sources Based on Their Potential to Affect Marine Mammals," *Journal of Marine Science and Engineering*, vol. 10, no. 1278 (2022), https://doi.org/10.3390/jmse10091278.

Gathering data for wind energy *(continued)*

3 Environmental DNA (eDNA)

eDNA methods examine environmental samples of water, soil, or air for animal genetic material from, for example, skin, feces, and urine. It can help gather data on animal presence in areas where they were previously unreported or poorly reported.[50] More studies are needed to understand how environmental factors, such as temperature and currents, affect detection.[51]

4 Models

Models are representations of real-world systems and can help improve understanding in the absence of other data. Models use data from current conditions to generate useful predictions of real-world systems and can be enhanced over time with additional or improved data. For example, a life cycle assessment model can systematically evaluate a product's environmental effects through all stages of its life cycle. In addition, marine spatial planning models can be used to obtain stakeholder input and identify sites for offshore wind energy development that help to avoid potential environmental effects.[52]

5 Radar

Radar can be used to gather data such as height, speed, and distribution of birds and bats. However, radar may not be able to gather data that can identify species or distinguish between birds and bats, and some systems may not detect smaller animals.

6 Tags

A tag is a device attached to an animal to collect data. Tags can collect multiple types of animal data, including their movement, heart rate, and breathing, as well as information about the environment, including sound and light. Tags can be limited by battery life and may detach from an animal, and certain tags may be too heavy to use on smaller animals.

7 Uncrewed vehicles

Uncrewed vehicles can include aerial, surface, and underwater technologies that can help gather data from locations that people cannot travel. Some may generate fewer emissions, less background noise, and be more cost effective compared to crewed vehicles. However, qualified personnel may be required to operate them. In addition, some may be limited by battery life and support vessel availability.

8 Visual monitoring

Camera-based technologies capture images ranging from turbine blades to entire landscapes, which can be used to gather data on animal presence and abundance. However, they may not be effective in all environmental conditions or with all animals.

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[50] For example, one study detected a Dwarf sperm whale in a location where it had not been previously detected. Jean-Baptiste Juhel et al., "Detection of the elusive Dwarf sperm whale (*Kogia sima*) using environmental DNA at Malpelo island (Eastern Pacific, Colombia)," *Ecology and Evolution*, vol. 11, no. 7 (2021), https://doi.org/10.1002/ece3.7057.

[51] Paula Suarez-Bregua et al., "Environmental DNA (eDNA) for monitoring marine mammals: Challenges and opportunities," *Frontiers in Marine Science*, vol. 9 (2022), https://doi.org/10.3389/fmars.2022.987774.

[52] National Centers for Coastal Ocean Science, *Spatial Planning*, https://coastalscience.noaa.gov/science-areas/offshore-wind-energy/spatial-planning/.

Source: GAO (illustrations).

3 Challenges May Limit the Use of Some Technologies and Approaches to Identify and Address Environmental Effects

We identified four challenges that may limit technologies and approaches to address potential environmental effects: cost, quality assurance, knowledge gaps, and data limitations. The challenges discussed in this chapter are applicable to both onshore and offshore; however, we may present examples that are specific to either onshore or offshore. These challenges may prevent the use of technologies and approaches or limit knowledge of their effectiveness or appropriate use.

3.1 Cost

Some technologies and approaches may incur additional direct costs for a wind energy operator, creating a potential barrier for use by making the facility's electricity less cost-competitive in the marketplace. For example, recycling turbine blades is currently more expensive than disposing of them in landfills. Recycling may produce materials of variable quality that lack a sufficient market, and it may be difficult to remove and transport blades to the few blade recycling centers in the U.S. Blades that can be recycled more efficiently exist but require additional testing and are not yet commercially viable.

Similarly, while domestic manufacturing can reduce potential environmental effects of wind turbine manufacturing, it is often more expensive than international manufacturing and low labor costs for overseas blade manufacturing can threaten U.S. supplier competitiveness. Experts and industry officials said some technologies and approaches require the purchase and installation of equipment, which incurs additional costs. In addition, installing equipment on offshore wind energy facilities can be more expensive than installing the same equipment onshore because offshore turbines are remote, and monitoring equipment must operate reliably in harsh ocean conditions.

Figure 6: Partially disassembled turbine blades for recycling

Source: Veolia North America. | GAO-24-106687

Some technologies and approaches have a continuing operational or extended construction cost. For example, curtailment reduces the operational time of turbines, reducing the amount of electricity that operators could sell. Limits on construction and vessel speeds for offshore facilities could extend the construction time for a facility, increasing costs.

3.2 Quality Assurance

Wind energy facilities may be operational for decades and turbines need to maintain quality assurance during their lifetime. Therefore, technologies and approaches to address potential environmental effects need to operate for that time frame and not interfere with the turbine's operation or shorten its lifespan. Changes to the turbine—such as blade design, using green materials, and reducing material requirements—may require further testing to assess whether they introduce potential structural instabilities. For example, NREL is testing the mechanical stability of epoxies that could improve the recyclability of turbines.[53]

3.3 Knowledge gaps

Because wind energy development is ongoing, knowledge gaps make it unclear whether technologies and approaches to address potential environmental effects are

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[53] DOE offers component and system test facilities to validate a turbine component's design, performance, and adherence to safety standards.

needed and, if so, how to deploy and use some technologies and approaches or determine whether they will be effective. This may include, for example, technologies and approaches such as visual monitoring when human observation is not possible, or deterrents that may need additional research and design studies to demonstrate effectiveness. Other technologies and approaches, such as using satellite images to identify marine animals, applying tags to animals, and thermal cameras to detect animals, need additional testing or development to determine effectiveness and when they should be considered to address potential effects. The site-specific nature of environmental effects also hinders generalization to other locations. Proposed turbine sites—whether onshore or offshore—will need site-specific studies to inform what technologies and approaches would be most useful to address environmental effects.

The cumulative effects of a facility over time can also be difficult to understand. Researchers or operators may not consistently monitor onshore environmental effects among locations, making it difficult to know what, if any, technologies and approaches a wind facility may need. For example, bird deaths can occur due to collision with turbines but also with tall buildings, communication towers, or vehicles in the vicinity, which creates uncertainty as to the cause of bird deaths over time. Total mortality from onshore turbines may be underestimated if scavengers remove carcasses or deaths are otherwise not detected. There are also challenges with comparing the effects of wind turbines across species. Deaths of smaller birds may be harder to detect than larger birds, resulting in underreporting. Researchers often conduct fewer surveys before construction compared to after a facility is built, making it difficult to know the extent to which a facility changed the environment.

Compared to onshore turbines, the potential environmental effects of offshore turbines are not as well understood because there are fewer deployed in the U.S. As offshore deployment increases, wind energy operators may need to conduct additional research to better understand potential environmental effects of deploying some technologies and approaches and select the most appropriate ones. For example, there is limited knowledge about potential environmental effects after removing all or parts of offshore turbines during decommissioning because only a few offshore turbines have been decommissioned—and none in the U.S.

Remote offshore facilities may be challenging to monitor, such as observing how animals are affected by noise or tracking fatalities due to collision. Information on the effects of noise on animals and fatalities from collision with offshore facilities also varies by species. For marine mammals, more information is needed on how noise effects may accumulate through multiple exposures over time and how effects on individuals may affect the population. Studies on fish and invertebrates suggest noise effects are species-specific but further research could clarify animal hearing thresholds. Further, active acoustic monitoring, an approach to studying offshore animals, could introduce noise that affects animals. Similarly, additional information is needed on the risks marine animals could face from vessel collisions. It is known that vessel collisions are a cause of mortality for marine mammals, particularly large whales; however, uncertainty remains regarding the distribution of collision risk and mortality from offshore wind activities.[54]

Wind energy development and the siting of wind projects rely on public acceptance for the successful completion of wind energy projects. While stakeholders in wind energy have studied public opinions and attitudes toward wind energy projects, there are knowledge gaps in understanding the public's awareness of environmental effects. This could create misunderstanding and barriers to the development and deployment of wind energy.

3.4 Data limitations

Some technologies and approaches that may use machine learning—such as curtailment—require large amounts of data. Barriers to data access may limit the effectiveness of such technologies and approaches. While these systems could be used for multiple applications—such as identifying animals—and can analyze large volumes of data faster than humans, data may be unavailable, unverified, hard to access, or costly to collect. For example, collision risk models can estimate onshore or offshore bird collisions but need verified input data about bird behavior to provide accurate results. The data are not always readily available, and as a result estimates may not capture the full scope of risks for collisions.

Furthermore, researchers may collect data for specific purposes with no mechanism for public access, and industry data may be proprietary or only provided to regulatory agencies during the permitting process. While some public databases exist, it can be difficult to navigate and identify the relevant data for an approach. Researchers or organizations may not have the time, resources, or incentives to develop or contribute to a database.

Wind energy operators may collect data intended to meet immediate needs, without collecting data for long-term research. An official from the U.S. Fish and Wildlife Service said operator-provided data may be in operator-specific formats due to lack of uniformity in data collection. Additionally, operators may conduct studies, and data collected for these studies may not be compatible for other uses.

Data collection can be especially difficult for offshore wind facilities, limiting knowledge of the environmental effects and appropriate technologies and approaches. Visual monitoring by human observation faces data collection limitations when visibility or ocean conditions are poor. Factors such as temperature and water currents may affect data collection processes for the environmental DNA approach (see vignette, pg. 20). Passive acoustic monitoring technologies can only detect animals while they are vocalizing (see vignette, pg.19). Additionally, it can be difficult to install, maintain, and ensure performance reliability of monitoring equipment in offshore environments. Some approaches to data gathering for onshore facilities, such as visually observing and counting bird and bat carcasses, do not work for offshore facilities.

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[54] National Renewable Energy Laboratory and Pacific Northwest National Laboratory, *Environmental Effects of U.S. Offshore Wind Energy Development: Compilation of Educational Research Briefs.* 2022.

4 Policy Options to Help Enhance Benefits or Address Challenges

Policy options could help policymakers enhance the benefits of the data gathering and technologies and approaches to address environmental effects identified in chapter 2, or address the challenges identified in chapter 3. For the purposes of our report, policymakers include legislative bodies, government agencies, academic organizations, industry, and other groups. We identified five policy options through meeting with experts, our review of relevant literature, a site visit, and interviews with officials in the public and private sectors. This is not an exhaustive list of policy options.

Status quo

Policymakers could take no further intervention, allowing current activities to continue.

Potential implementation approaches

- Wind energy operators, federal agencies, and researchers continue to apply technologies and approaches that are already tested and commercially available.
- Government entities and academic institutions continue current and planned research efforts.
- Policymakers continue to rely on current data-sharing mechanisms, such as the Tethys database, for potential environmental effects.

Opportunities

Current efforts may address some of the challenges identified in this report without additional resources beyond those that have already been allocated. For example, current limits on construction and vessel speed could sufficiently reduce construction-related animal collisions. Incentives, such as those found in the Inflation Reduction Act, encourage further use of technologies and approaches to address environmental effects. Additional resources and time that may be required for other policy options could instead be used for other priorities.

Considerations

Some challenges may remain unresolved or may take longer to resolve than with intervention. Maintaining the status quo may not be responsive to the wind industry or executive and legislative priorities. For example, under current conditions, technologies and approaches to address environmental effects may incur additional costs that could make wind projects less competitive in the electricity markets, creating a barrier for the industry. In addition, with knowledge gaps, it may be unclear whether technologies and approaches are needed or how they should be used.

Encourage innovation and research

Policymakers could encourage research and development of technologies and approaches to address potential environmental effects.

May help address the quality assurance and knowledge gap challenges.

Potential implementation approaches

- Congress, academic institutions, industry, or other policymakers could encourage targeted studies to address gaps in knowledge, such as in the use of alternative materials and cumulative environmental effects.
- Government entities could consider supporting the research and development of technologies and approaches to address potential environmental effects. For example, they may consider prioritizing additional work to test recyclable turbine blades or reduce material requirements.

Opportunities

Additional research could help to better understand wind energy facility sites and inform appropriate technologies and approaches to address potential environmental effects. For example, although passive acoustic monitoring technologies are in use (vignette, pg. 19), some applications—such as acoustic sensors installed on fiber optic cables—are still under development. Additional research could increase confidence in those technologies and approaches and increase willingness to use them. Research in offshore environments, such as studying the effects of the removal of all or part of offshore wind turbines, may inform whether addressing potential environmental effects is appropriate in every case.

Communication between policymakers during research and development of new technologies and approaches can reduce costs and improve access to information and resources. One expert noted that academic institution and industry partnerships have successfully tested new technologies and approaches using demonstration wind turbines. Similar groups involving multiple policymakers may use resources more effectively to fill knowledge gaps.

Considerations

Innovation and research can require additional time, personnel, cost, and communication among policymakers. Industry, academic institutions, and other policymakers may not equally share this resource burden. In addition, policymakers may need to support additional communication to ensure that the timing of research meets decision-making needs.

Data sharing

Policymakers could facilitate improved data sharing about potential environmental effects, technologies, and approaches.

May help address data limitation challenges.

Potential implementation approaches

- Academic institutions, industry, or other research groups could establish or expand a centralized database to enable users to share and store data in a common location.

- Industry and other policymakers, such as researchers and government entities, could consider entering into agreements and trusted data-sharing mechanisms for proprietary or sensitive research.

Opportunities

Collected data could be more easily shared and used by different groups, which may encourage collaborative research efforts. For example, one official said sharing data about recyclable blade designs may allow researchers to anticipate new decommissioning challenges. Having data in a central database may encourage collaboration among policymakers who otherwise might not interact. Researchers in academic institutions and industry may have the opportunity to share information with the public and other policymakers during the planning process for wind energy facilities, which can encourage productive decision-making. Databases could also store other types of information about research alongside the raw data, such as the types and sources of the research, that may not otherwise be accessible.

Considerations

Establishing new or trusted data-sharing mechanisms may require additional maintenance, time, personnel, and other resources. Sharing research that includes proprietary or sensitive data may require investing in data security or removing the proprietary or sensitive information from the data. The agreements and mechanisms may not fully address wind energy operator concerns about proprietary or sensitive data being inappropriately shared or used.

Establish consistent methodologies

Policymakers could encourage the use of consistent methodologies to study wind energy facility sites and to address data and research limitations.

This may help address with the knowledge gaps and quality assurance challenges.

Potential implementation approaches

- Academic institutions, industry, or government entities, in collaboration with each other and permitting authorities, could encourage uniformity in data collection, research methodologies, and evaluation of technologies and approaches for addressing potential environmental effects.

- Academic institutions, industry, and other policymakers could consider using adaptive management, when appropriate and to the extent they are not already doing so, as a methodology for addressing potential environmental effects. Adaptive management is a process in which decisions—such as where and how to address environmental effects—can be adapted throughout a project’s lifetime, as decision-makers gain new information.

Opportunities

Consistent data collection methods could help establish uniformity in data, making research and knowledge more generalizable. Similarly, consistent methodologies for evaluating technologies and approaches to address environmental effects could speed adoption of new approaches. If researchers conduct site-specific research in a consistent way, research may be more easily compared and used in other locations and less time may be needed to reformat or translate data between uses.

The adaptive management process can encourage use of technologies and approaches to address potential environmental effects while researchers fill knowledge gaps. The Department of the Interior has established adaptive management application guidelines to provide a better understanding of how adaptive management can be implemented. Adaptive management may be useful in situations where there is uncertainty about the effects of current management. This framework, or similar methodologies, could be applied to offshore wind facilities to allow project construction and operation while researchers conduct studies.

Considerations

Communication among policymakers may be needed to encourage development and broad use of consistent methodologies. Establishing new data collection and strategic methodologies may require additional time, personnel, and other resources, and some policymakers may not easily accept voluntary methodologies that were developed by other groups. For example, we heard that uniform data collection may be more costly than individualized technologies and approaches; that uniform methodologies may discourage innovation and diversity of opinions; and that technologies under development may not fit under previously established methodologies.

Incentives

Policymakers could consider incentivizing the use of technologies and approaches to address potential environmental effects.

May help address the cost challenge.

Potential implementation approaches

- Government entities could consider providing incentives for the use of technologies and approaches to address potential environmental effects, such as providing incentives to develop turbine blade recycling methods or providing financial incentives for operators to recycle blades.

- Policymakers could encourage groups such as technology operators or electricity customers to accept and adopt technologies and approaches to address potential environmental effects.

Opportunities

Incentives can help operators and companies collaborate to develop and use technologies and approaches to address potential environmental effects that may not be economically viable otherwise. Direct financial incentives for developing and using domestic manufacturing or recyclable turbine blades may encourage current efforts. In addition, indirect incentives such as public approval and communication with wind energy operators may encourage adoption of technologies and approaches. For example, operators may differentiate from one another by using more sustainable materials.

This policy option may also help address considerations from other policy options, such as innovation and research or data sharing. Longer-term research, like exploring potential cumulative environmental effects, may benefit from financial and other incentives. Consistent funding for wildlife surveys throughout a wind energy facility’s lifetime may help fill knowledge gaps and allow for more informed decision-making regarding wildlife deaths.

Considerations

Incentives could lead to unintended outcomes. For example, incentivizing one strategy may adversely affect other possible options. One stakeholder told us data reporting requirements that may accompany federal funding may require disclosing proprietary or sensitive data. Environmental and social costs and benefits—for example, costs and benefits related to siting wind facilities on brownfields or co-located with other industries—could be difficult to quantify, making it challenging to set the appropriate level of incentives.

5 Agency and Expert Comments

We provided a draft of this report to the Department of Energy, the Energy Information Administration, the Environmental Protection Agency, the Federal Energy Regulatory Commission, the Department of the Interior, the Marine Mammal Commission, and the National Oceanic and Atmospheric Administration with a request for technical comments. We incorporated agency comments into this report as appropriate.

We also offered our expert meeting participants the opportunity to review and comment on the draft of this report, consistent with previous technology assessment methodologies. We sent the report to 12 of those experts who volunteered to review and incorporated their comments as appropriate.

We are sending copies of this report to the appropriate congressional committees, the relevant federal agencies, and other interested parties. This report will be available at no charge on the GAO website at https://www.gao.gov.

If you or your staff members have any questions about this report, please contact Karen L. Howard at (202) 512-6888 or HowardK@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made key contributions to this report are listed in appendix III.

Karen L. Howard

Karen L. Howard, PhD
Director,
Science, Technology Assessment, and Analytics

Appendix I: Objectives, Scope, and Methodology

We prepared this report under the authority of the Comptroller General of the United States to assist Congress with its oversight responsibilities, in light of the increase in global wind energy usage. We examined: (1) What technologies or approaches might help address potential environmental effects related to the source materials, manufacture, construction, operation, and decommission of utility scale wind energy projects; (2) What challenges might hinder implementation of these technologies or approaches; and (3) What policy options might help address challenges to the implementation of the technologies or approaches, and what are the opportunities and considerations of these policy options?

To conduct our work, for all objectives, we:

- Interviewed officials from Department of Energy, Department of Interior, Energy Information Administration, Environmental Protection Agency, Federal Energy Regulatory Commission, National Oceanic and Atmospheric Administration, and Marine Mammal Commission. We identified and selected expert individuals or groups to interview with expertise in wind energy and approaches for addressing environmental effects, using a review of relevant documents and recommendations by those we interviewed over the course of our work.

- Identified and selected for interview nongovernmental individuals or groups with expertise in wind energy and technologies and approaches for addressing environmental effects, using a review of relevant documents and recommendations by those we interviewed over the course of our work.

- Reviewed databases, including Tethys, and online sources for literature relevant to potential environmental effects, technologies, and approaches. In addition to our literature and online searches, we received literature and documents from agency officials and experts we interviewed. We identified 394 articles, publications, and reports in the process of planning and conducting this work and selected the most relevant literature for further review based on our objectives. We also reviewed agency guidance and documents to inform our understanding of agencies’ processes and activities related to understanding and addressing the potential effects caused by wind energy.

- Visited a national laboratory and two companies to observe technologies and approaches to address potential environmental effects from wind energy.

- Conducted a virtual meeting with experts and stakeholders from government, non-governmental organizations (NGOs), academia, and industry to help examine the trade-offs between the technologies and approaches to address potential environmental effects of wind energy and inform policy options. In consultation with the National Academies of Sciences, Engineering, and Medicine (the National Academies), we also selected experts and stakeholders with technical, legal, or policy expertise representing a balanced and diverse set of views for participation in the set of panel discussions conducted over the course of 5 days. The meeting participants and their affiliations are listed in appendix II. Participants in this set of panel discussions provided documentation of any potential conflicts of interest, and upon review, we found the group of experts as a whole did not have any inappropriate bias. This meeting of experts was planned and convened with assistance from the National Academies to better ensure that a breadth of expertise was brought to bear in its preparation. However, all final decisions regarding meeting substance and expert participation are the responsibility of and were made by GAO. Consistent with GAO's Quality Assurance Framework, we provided the meeting participants an opportunity to review a draft of our report and provide technical comments. We incorporated expert comments in the report, as appropriate.

- For our first objective, we considered including technologies and approaches in the report if they were described by two or more sources and included those we found to be representative and not similar to or duplicative of other approaches we selected. The technologies and approaches included in the report are not a comprehensive list of every available technology or approach to address potential wind energy-related environmental effects.

- For our third objective, we identified policy ideas that appeared in the literature, or that we heard about or discussed in interviews or our expert meeting. We grouped the policy ideas into common challenges facing the development of technologies and approaches to address the environmental effects of wind energy and used this set of challenges to help identify policy options for addressing those challenges. As part of our analysis, we identified implementation technologies and approaches and potential opportunities and considerations for each policy option. The policy options are neither recommendations to federal agencies nor matters for congressional consideration. We did not conduct work to assess how effective the options may be and express no view regarding the extent to which legal changes would be needed to implement them. While we present options to address the common challenges we identified, the options are not inclusive of all potential policy options.

We conducted our work from February 2023 to July 2024 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

Appendix II: Expert Participation

With the assistance of the National Academies of Sciences, Engineering, and Medicine, we convened a meeting of experts to help examine the trade-offs between the technologies and approaches to address potential environmental effects of wind energy and inform policy options. The meeting was held virtually in November 2023.

The 15 experts who participated in this meeting are listed below, along with their titles at the time of the meeting. We sent the report to 12 of those experts who volunteered to review and incorporated their comments as appropriate.

Inês Azevedo

Associate Professor of Energy Science Engineering

Stanford University

Aubryn Cooperman

Researcher

National Renewable Energy Laboratory

Hayley Farr

Environmental Scientist

Pacific Northwest National Laboratory

Irene Gutierrez

Senior Attorney

Natural Resources Defense Council

Garvin Heath

Principal Environmental Engineer

National Renewable Energy Laboratory

Barbara Kates-Garnick

Professor of Practice

Tufts University

Brian Krevor

Senior Director

American Clean Power Association

Alicia Mahon

Wind Energy Program Manager

Pacific Northwest National Laboratory

Christopher Olson

Senior Vice President (retired)

3M

Claire Richer

Director

American Clean Power Association

Krish Thiagarajan Sharman

Professor of Mechanical and Industrial Engineering

University of Massachusetts Amherst

Alexander Slocum

Professor of Mechanical Engineering

Massachusetts Institute of Technology

Bethel Tarekegne

Systems Engineer

Pacific Northwest National Laboratory

Suzanne Tegen

Assistant Director

Center for the New Energy Economy

Elizabeth Wilson

Professor of Environmental Studies

Dartmouth College

Appendix III: GAO Contact and Staff Acknowledgments

GAO contact

Karen L. Howard, PhD, Director, Science, Technology Assessment, and Analytics (STAA), at (202) 512-6888 or HowardK@gao.gov

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In addition to the contact named above, the following STAA staff made key contributions to this report:

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These staff also contributed to this work:

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