Frontiers for Young Minds

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HOW DO OFFSHORE WIND FARMS AFFECT THE OCEAN?

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YOUNG REVIEWERS:

BENJAMIN
AGE: 11

CELINE
AGE: 14

HELENA
AGE: 13

Wind has been used for centuries as a powerful source of energy. Today, it holds a central place in clean, renewable electricity production. Giant wind turbines are being installed in the ocean to harness the wind and generate more energy. Numbers of these turbines are growing worldwide, especially in Chinese and European seas. However, wind turbines can affect the environment by changing the conditions of the ocean and atmosphere. These changes have consequences for ocean life, which are not yet well understood. In this article, we explain some effects of offshore wind turbines on the marine environment. We show how wind turbines slow down the wind and disturb the seawater and the associated marine life. We also discuss why it is important that scientists work together with companies and policymakers to find ways to reduce potential negative impacts and maximize positive ones.

THE POWER OF WIND

Wind, a powerful element harnessed by humans, has been a source of energy for centuries. From drying clothes to powering windmills and navigating the seas, wind's uses are many. Today, wind has taken center stage as a clean, **renewable** source of electricity.

RENEWABLE

A natural resource that can grow back or refill, so it will not run out.

Trapping wind energy and converting it to electricity requires large towers called wind turbines, equipped with three long, rotating blades. The wind sets these blades in motion and, with the help of mechanical devices and a power generator, the blades convert the wind energy into electricity. Then, underground cables transport the electricity to the wall sockets in our homes.

Winds turbines can stand on land or out at sea. Wind turbines on the ocean are called offshore wind turbines. They are a remarkable sight, anchored deep into the seabed or floating on water, and when grouped in large number, they form wind farms. The space above the sea surface does not contain obstacles such as mountains, hills, trees, or cities that interrupt wind flow—so the ocean is an ideal place to install wind turbines. Over the seas, winds are stronger and more regular than over lands, allowing for a more efficient harvest of wind compared to onshore. For instance, wind speed can be 25% higher at 10 km offshore [1]. As a result, offshore wind turbines generate up to 2–3 times more energy than those on land.

Since the first wind farm installation in 1991, offshore wind farms have been growing fast around the world, with an increase of about 1,000% over the last 10 years. The top countries generating electricity from offshore wind turbines are China, the United Kingdom, and Germany (Figure 1A). Europe has a particularly large number of wind farms. The North Sea (Figure 1B), located in northeastern Europe, is one of the most-used seas for offshore wind energy, due to its shallow water depth and sea floor characteristics. The North Sea electricity production can power more than 750,000 homes each year.

Despite the valuable renewable energy they produce, the impact of offshore wind farms on the environment remains uncertain. What are the effects of these massive structures on the atmosphere and the oceans?

OCEAN CURRENTS ARE CRITICAL FOR MARINE LIFE

STRATIFICATION

A natural process that separates water into layers based on mass. Lighter water is generally warmer and less salty and floats on heavier water, which is cooler and saltier.

The oceans are constantly in motion, driven by the rotation of the Earth, the influence of the Moon and the Sun, and the drive of the wind. When the Sun heats up the water, it triggers a movement in which warmer water rises and colder water sinks. We often find warm, less-salty water overlying cold, salty water. This layering is called **stratification**. Wind pushes and stirs the surface waters, generating

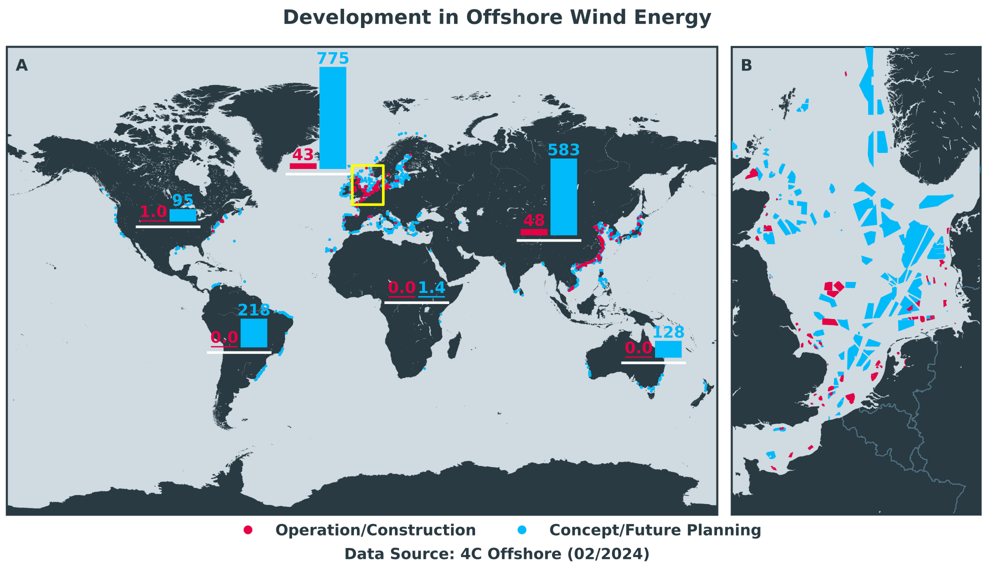

Figure 1

Figure 1

(A) World map showing global development in offshore wind energy. The bars compare the total offshore wind capacity (in gigawatts) for the current (red) and future (blue) development stages in different regions of the world. The yellow box indicates the North Sea region. **(B)** Close up of the North Sea region. Red areas represent offshore wind farms that are in operation or are under construction. Blue areas represent regions that are projected to be used for offshore wind energy in the future (Data used obtained from https://www.4coffshore.com/windfarms/).

horizontal and vertical water movements. The combination of all these factors, along with the tides, create powerful currents that flow around the globe like a huge conveyor belt—this is called the **global ocean circulation**.

Stratification and vertical water movement play a crucial role in the distribution of marine organisms and the accessibility of the nutrients they need. Water movement spreads the nutrients around, while stratification keeps most of the nutrients in the light-flooded surface waters. Therefore, ocean currents are critical for sustaining marine life. They support everything from the smallest **phytoplankton** to the whales at the top of the food chain. Offshore wind farms could influence atmosphere and ocean movements, natural rhythms, and the health of marine life.

GLOBAL OCEAN CIRCULATION

A global system of ocean currents driven by differences in temperature and salinity, influencing the global climate.

PHYTOPLANKTON

Tiny plant-like organisms living in aquatic ecosystems. They use sunlight energy to produce sugars and oxygen, which are crucial for aquatic food webs.

WINDS OF CHANGE—MODIFICATION OF OCEAN STRUCTURE

When wind passes through wind farms, the turbines generate electric energy and slow down the wind speed by up to 10–30%. However, in neighboring areas, the wind remains at its original speed. These local differences cause the wind field behind the turbines to become unstable, with lower wind speeds and more turbulence, known as "wakes". Since ocean currents are partly driven by wind, the wakes can affect not only the atmosphere but also at the ocean surface below [1].

With less wind speed in the atmosphere, less wind is pushing the ocean surface and therefore ocean currents decrease. This effect becomes more significant when there are multiple turbines in an area. As a result, extensive reductions in wind speed can influence the ocean circulation, mixing and stratification over large area [2].

But that is not all. The wind turbines themselves, which are firmly anchored to the sea floor, act as obstacles for ocean currents—the way a wooden stick in a creek disturbs and slows the water downstream. Within wind farms, ocean currents are slower behind the turbines and surface friction at the foundations causes increased turbulent mixing of the water so that natural stratification decreases. This affects the distribution of temperature, salt, and nutrients in the water around wind farms, with consequences for marine life [3] (Figure 2).

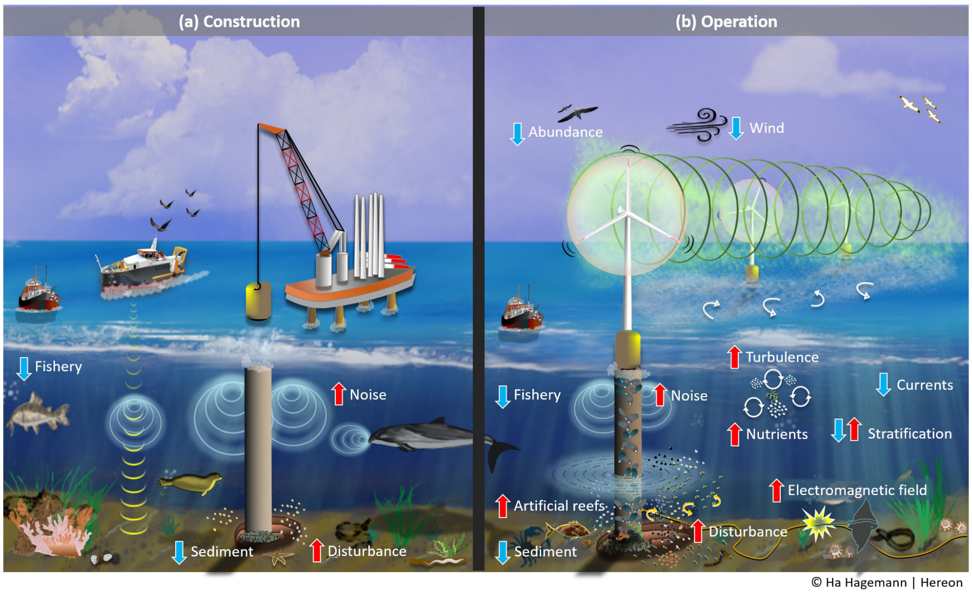

Figure 2

Figure 2

Offshore wind turbines have effects on the environment and ecosystems during **(a)** their construction, and **(b)** when they are in operation. Blue arrows represent a decrease in a specific process and red arrows indicate an increase.

MARINE LIFE BENEATH THE TURBINES

The effects of offshore wind farms on marine ecosystems are complex and not yet well understood. Their effects on air and water currents can change the seawater structure, which affects light and nutrient availability—essential elements for phytoplankton growth. Phytoplankton form the foundation of marine food webs, and they are eaten by zooplankton (tiny animals transported by currents), which in turn feed larger organisms, such as fish, leading up to top predators like whales.

Recent studies suggest that offshore wind farms can disrupt water mixing and change nutrient and light balance (Figure 3A). In turn, this affects the timing and strength of phytoplankton growth, which is crucial for the survival of other ocean species [4, 5]. For example, in the North Sea, wind wakes from installed wind farms influence conditions over large areas, causing up to a 20% change in phyto- and

CASCADE EFFECT

A chain reaction in which a change in one part of an ecosystem causes a series of changes in other parts.

zooplankton distributions (Figure 3B). This can affect the entire marine food web, including fish (Figure 3C), seals, whales, and seabirds, and it can even impact human activities like fisheries (Figure 3D). This is called a food chain **cascade effect**, in which a change in one group in the ecosystem affects all the other groups, like falling dominoes.

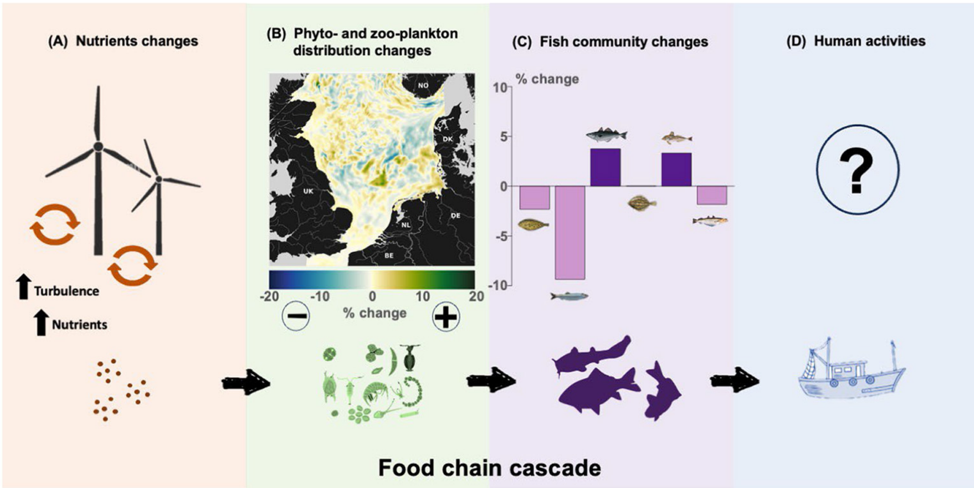

Figure 3

Figure 3

(A) Offshore wind farms increase turbulence and nutrients. **(B)** This can change the distribution of phytoplankton and zooplankton, as seen in the North Sea. **(C)** Changes in fish species can result from changes in plankton levels. **(D)** The effect on human activities like fishing is currently unknown. Black arrows indicate the cascade effect through the food chain. **(B, C)** Used ecosystem model data described in Daewel et al. [4] and fish model described in van de Wolfshaar et al. [7].

Offshore wind farms can have many other effects on ecosystem structure and function (Figure 2) [6]. Construction is a massive industrial process, in which huge hammers drive each pile into the seabed. During both construction and operation of wind farms, increased noise levels and disturbance of the natural environment can affect birds, marine mammals, fish, and bottom-dwelling organisms such as crabs, mussels, or sea worms. Whales, for example, need their hearing for **echolocation**. Further, the newly installed turbines and the rocks that anchor them to the seafloor alter the environment and can serve as **artificial reefs**. In the air, sea birds can collide with the rotor blades or avoid the wind farms, changing their habitats. Consequently, offshore wind farms can modify the **biodiversity** of the whole area where they are installed.

ECHOLOCATION

A sensory system that certain animals (e.g., bats and dolphins) use to locate objects and prey in a dark environment by producing sound waves and listening to the echoes that return.

ARTIFICIAL REEF

A man-made underwater structure that mimics a natural reef and provides habitat for marine plants and animals.

BIODIVERSITY

All living things, such as plants, animals and micro-organisms, in a specific environment and their interactions.

WHERE DO WE GO FROM HERE?

Offshore wind energy can have both advantages and disadvantages for marine ecosystems. It is important to manage the rapid expansion of offshore wind farms carefully to minimize negative impacts while maximizing positive ones. While we have described some of the immediate impacts, long-term effects of offshore wind farms remain even more uncertain. More studies are needed to understand the effects of wind farms on marine life. This effort will require collaboration between companies, politicians, scientists, and sea users like fishers. Data from such research will be important to achieve the right balance, establishing rules that support construction and renewable electricity production while also protecting our precious environments.

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

BENJAMIN, AGE: 11

My name is Benjamin, and I am 11 years old. I like to play electric guitar and read manga. Some after school activities I do are playing pickleball and swimming on our local swim team.

CELINE, AGE: 14

Hi, my name is Celine and I am a high school student from Vancouver BC. I really enjoy studying chemistry and biology on my own time. Also, I like to play sports outside with my friends for fun. My other hobbies are reading, drawing, and scrolling on the internet.

HELENA, AGE: 13

My name is Helena and I just finished 7th grade. Some hobbies of mine are crocheting and reading. I enjoy traveling and learning to speak new languages. My after-school activities include playing the violin and swimming on our local swim team. I have three pets: two cats and one leopard gecko.

AUTHORS

DÉBORAH BENKORT

I am a scientist at Institut des Sciences de la Mer de Rimouski (Canada), working on modeling the chemistry and biology in the Arctic and Nordic Seas. I am interested in the interactions that exist between the physics of the ocean and the living organisms in the food web. In general, I study the ecosystem's response to global warming and human-caused pressures, to identify long-term ecosystem changes. *deborah_benkort@uqar.ca

NILS CHRISTIANSEN

I am a scientist at the Helmholtz-Zentrum Hereon (Germany). I am curious about how offshore wind energy and its infrastructure affect ocean physics and related ecosystem processes. I am trying to understand the human-caused pressures of offshore wind farms, to determine how we can reduce negative effects or even create opportunities for the marine environment. My current research focuses on offshore renewable energy in the North Sea and its impact on the ocean.

HA THI MINH HO-HAGEMANN

I am a scientist working on regional Earth system models at the Helmholtz-Zentrum Hereon (Germany). Computer models can be used to represent interactions and feedback between the major components of the climate system such as the atmosphere, ocean, sea ice, rivers, and marine biogeochemistry. I am interested in the impact of wind farms on the atmosphere and the ocean as well as the occurrence of extreme weather events of the past and future, as Earth's climate changes.

UTE DAEWEL

I love the ocean and everything in and around it. That is why I am working as an ocean scientist at the Helmholtz-Zentrum Hereon (Germany). In my work, I hope to unravel at least a few secrets of how ocean physics, chemistry, and biology interact. I do this with the help of mathematical computer models, in which we can, for example, project how the ecosystem might respond to impacts like climate change, fisheries, and offshore wind farms.

ANITA GILLES

I am a marine biologist working as a scientist at the University of Veterinary Medicine Hannover (Germany). I am fascinated by marine mammals and how well adapted they are to life in the ocean. I investigate the effects of human activities on their world. For instance, I determine the size of whale's populations and the drivers of their distribution. I also work on habitat models that predict how the increase of wind farms might change habitat use of marine mammals.