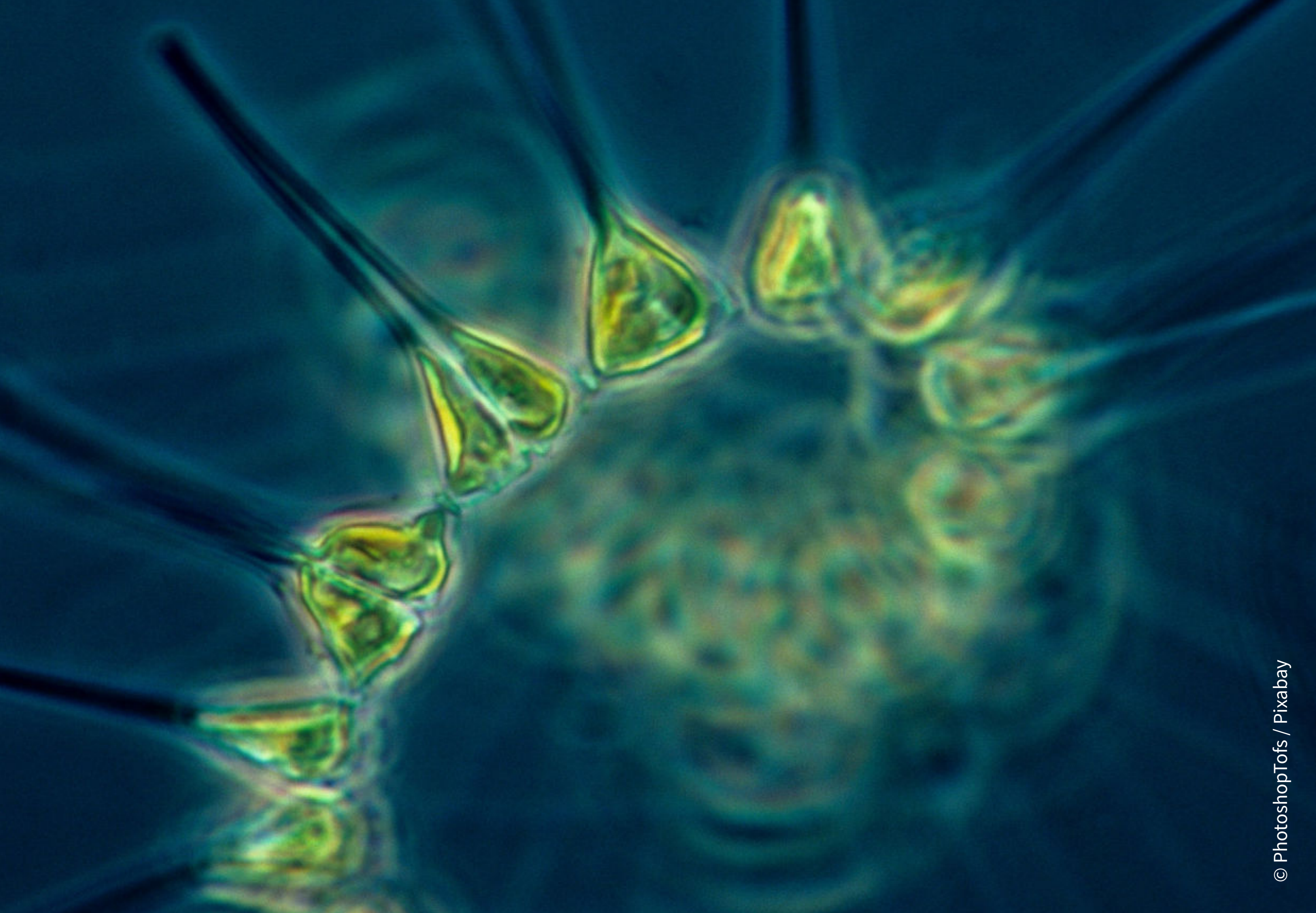
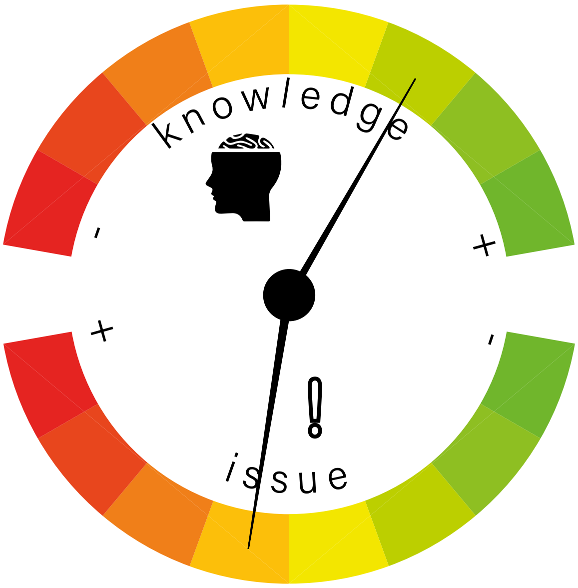


What effects can offshore wind farms and their grid connections have on primary producers?

Bulletin n°15

May 2026

COME3T



Question deemed to be "an issue of intermediate concern at the scale of offshore wind farms and for which there is good knowledge of primary producers but limited knowledge of the effects of anthropogenic pressures (including offshore wind farms)"

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Introduction

By capturing carbon dioxide (CO_2) from the atmosphere, photosynthetic organisms – of which phytoplankton make up a large share – play a crucial role in climate regulation. Located at the base of the marine food web, phytoplankton, and more broadly all primary producers, are a key compartment in marine ecosystems. However, these organisms are exposed to the effects of climate change and to pressures induced by human activities. Among these pressures, the development of offshore wind farms helps to mitigate climate change by producing carbon-free energy but leads to the construction of new structures at sea. **The interactions between the development of offshore wind farms and primary producers are explored in this bulletin**.

After presenting the main ecological concepts relating to primary producers and the first trophic levels, this bulletin investigates all the existing interactions between offshore wind farms and these communities. Taking into account their wide diversity, the main monitoring tools will be presented in the third and final part.

In short

Primary producers are organisms capable of producing their own organic matter through photosynthesis. They play a **fundamental role** in the **structure** and **functioning of ecosystems** as they create the initial flows of matter and energy within the **food web** (network of all the feeding relationships between living organisms). Like all human activities, offshore wind farms constitute a source of potential pressures. Two pressures exerted by offshore wind farms (**added artificial substrate** and **chemical pollution**) have been identified as potential sources of local impacts on productivity and biomass and are considered important to monitor. **However, the effects of wind farms on primary production are considered to be low with respect to the different forcings existing in the marine environment** (in particular climate change and anthropogenic inputs).

Definitions

Biofouling
Biological process which occurs whenever a medium is introduced into an aquatic environment or a surface already present in the environment becomes bare. This natural or man-made structure forms a new available surface where attached or mobile living organisms can develop (biofilm, then algae, invertebrates, etc.) (21).

Biomass
Quantity of living matter present at a given time within a given surface area or in a given volume (18).

Chlorophyll *a*
Pigment that is essential for photosynthesis thanks to its ability to absorb light energy to convert it into chemical energy and produce organic matter (18).

Clines
Water masses with different physico-chemical properties – salinity, temperature, etc. – forming layers at different depths (1).

Nutrients
All the elements required for organisms to grow and complete their life cycle. These nutrients are mainly composed of minerals – carbon, nitrogen (in its different forms as nitrate, nitrite and ammonium), phosphorus (in the form of phosphate), silica and trace elements (iron, copper, etc.) – and small organic molecules (1, 5, 18).

Circadian rhythm
A biological pattern or cycle that is dependent on the alternation between day and night (5).

Pelagic
Relating to the water column. A pelagic organism is an organism that spends all or part of its life cycle in the water column, either swimming (case of many fish) or passively drifting (case of plankton and many larvae of marine species) (5).

Phanerogam
Marine flowering plants such as ***Zostera*** (eelgrass) or ***Posidonia*** (seagrass). They can be distinguished from algae by their characteristics (presence of roots, stems or leaves) and their mode of reproduction (presence of seeds and flowers), which is similar to that of terrestrial plants (1).

Photosynthesis

Process by which certain organisms use solar energy to produce organic molecules from carbon dioxide (CO_2) and water. Through this process, light energy is converted to biochemical energy and results in the formation of simple sugars as well as the release of oxygen (O_2) (1).

Production

Quantity of organic matter produced by an ecosystem or by an ecosystem compartment per unit area per unit time. It is expressed as the biomass produced per unit area per unit time (e.g. $gC.m^{-2}.year^{-1}$) (1, 2).

Productivity

The production of biomass in relation to the biomass already present, i.e. the capacity of an ecosystem or organism to produce organic matter per unit biomass per unit time (1).

Trophic

Relating to the predator-prey relationships existing between different living organisms (1).

Key concepts

What are primary producers?

Primary producers or **autotrophs** (2) are organisms that produce their own food via two processes: **photosynthesis** or **chemosynthesis**. Photosynthesis uses light as a source of energy. This light energy is absorbed by a pigment called chlorophyll *a* to convert carbon dioxide (CO_2) and water (H_2O) into organic matter, with the release of oxygen (O_2) **(Fig. 1)**. Chemosynthesis is a process carried out by bacteria, which use chemical energy to convert carbon dioxide (CO_2), water (H_2O) and a chemical compound (hydrogen sulphide (H_2S), ammonia (NH_3), etc.) into organic matter (1).

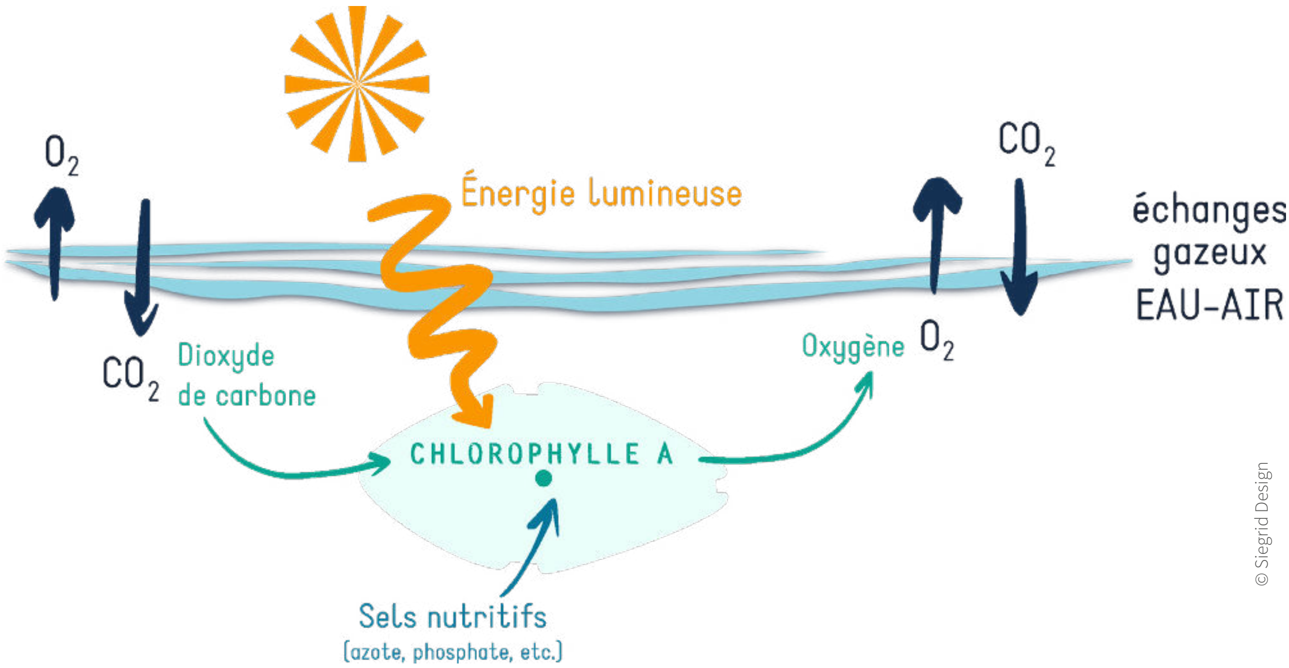


Fig. 1 *Diagram illustrating the process of photosynthesis in the marine environment.*

Primary production refers to the amount of organic matter produced by photosynthesis at a given point in time. A distinction can be made between primary production (i.e. the quantity of matter produced per unit area per unit time) and **primary productivity** which is the production per unit biomass. This production is heavily influenced by various environmental parameters (temperature, salinity, water residence time, light conditions, nutrient inputs, etc.) which vary in time and space (1).

Primary producers can be divided into two groups based on their habitat:

- **planktonic primary producers** for organisms present in the water column,
- **benthic primary producers** for **microalgae** (microphytobenthos), **macro-algae** (seaweed) and **marine phanerogams** which develop in or interact directly with the substrate or sediment (26).

• Planktonic primary producers

From the Greek "plankton" meaning "wandering", **plankton** refers to all small organisms which drift with the currents and water movements (5, 18). Most plankton species have limited mobility, although some planktonic organisms can migrate over large distances (up to 1,000 metres deep) between day and night (for instance the diel vertical migration of copepods) (5). Plankton can be divided into two main categories: **phytoplankton** and zooplankton (18).

As primary producers, phytoplankton include all organisms capable of producing their own organic matter through photosynthesis, including microalgae (diatoms, dinoflagellates, chlorophyceae, etc.), cyanobacteria (18) and **mixotrophs**, organisms that can carry out photosynthesis and consume living organisms (1). Zooplankton are not primary producers as they are exclusively **heterotrophic** (i.e. they obtain organic matter by consuming living organisms) (1).

• Benthic primary producers

From the Greek word "benthos" meaning "depth", **benthic organisms** spend the majority of their life cycle (or even their entire life cycle) on or near the bottom or in the sediment. Such organisms can be sessile (like corals, mussels, etc.) or motile like certain crustaceans (brown crabs, spider crabs, etc.) or flatfish (sole, plaice, etc.) (1).

Microphytobenthos refers to all photosynthetic microalgae and cyanobacteria that grow on different benthic substrates (seaweed, rocks, etc.). Like phytoplankton, some microalgae have the ability to move through the sediment. Macroalgae (seaweed) generally grow on rocky seabeds, as illustrated by kelp, while marine phanerogams, such as eelgrass, tend to grow on sandy seabeds. Together they make up the **macrophytobenthos** (1).

In coastal environments, the interactions between pelagic organisms (living in the water column) and benthic organisms (living on or near the bottom) and their habitats play an important role in the functioning of the ecosystem. The relationships (flows of organic matter and nutrients) between pelagic and benthic habitats are referred to as **benthic-pelagic coupling** (15).

What are the first trophic levels and what is their role?

The relationship between a predator and prey is referred to as a **trophic relationship**. Phytoplankton are consumed by zooplankton, which in turn are consumed by other zooplankton species, such as jellyfish, or by larger predators (small pelagic fish, such as sardines or anchovies, for example). These are consumed in turn and the process continues until reaching the top predators (such as marine mammals) which have few (if any) natural predators. The structure and trophic relationships between the different species in the water column make up the **pelagic food web**. Meanwhile, the **benthic food web** is formed by primary producers on the seabed (micro- and macro-algae), which are consumed by herbivorous species (grazers such as sea urchins and abalones, herbivorous fish which consume algal and plant debris), which are in turn consumed by larger predators (starfish, predatory fish such as groupers and sea bream). As previously, these are consumed in turn and the process continues until reaching the top predators.

These two food webs are closely interlinked, firstly because certain species belong to both food webs for all or part of their life cycle, and secondly because the organic matter produced by the pelagic food web becomes a major component of the benthic food web through sedimentation.

The different primary producers are located at the base of these food webs and make up the **first trophic levels** (1) **(Fig. 2)**.

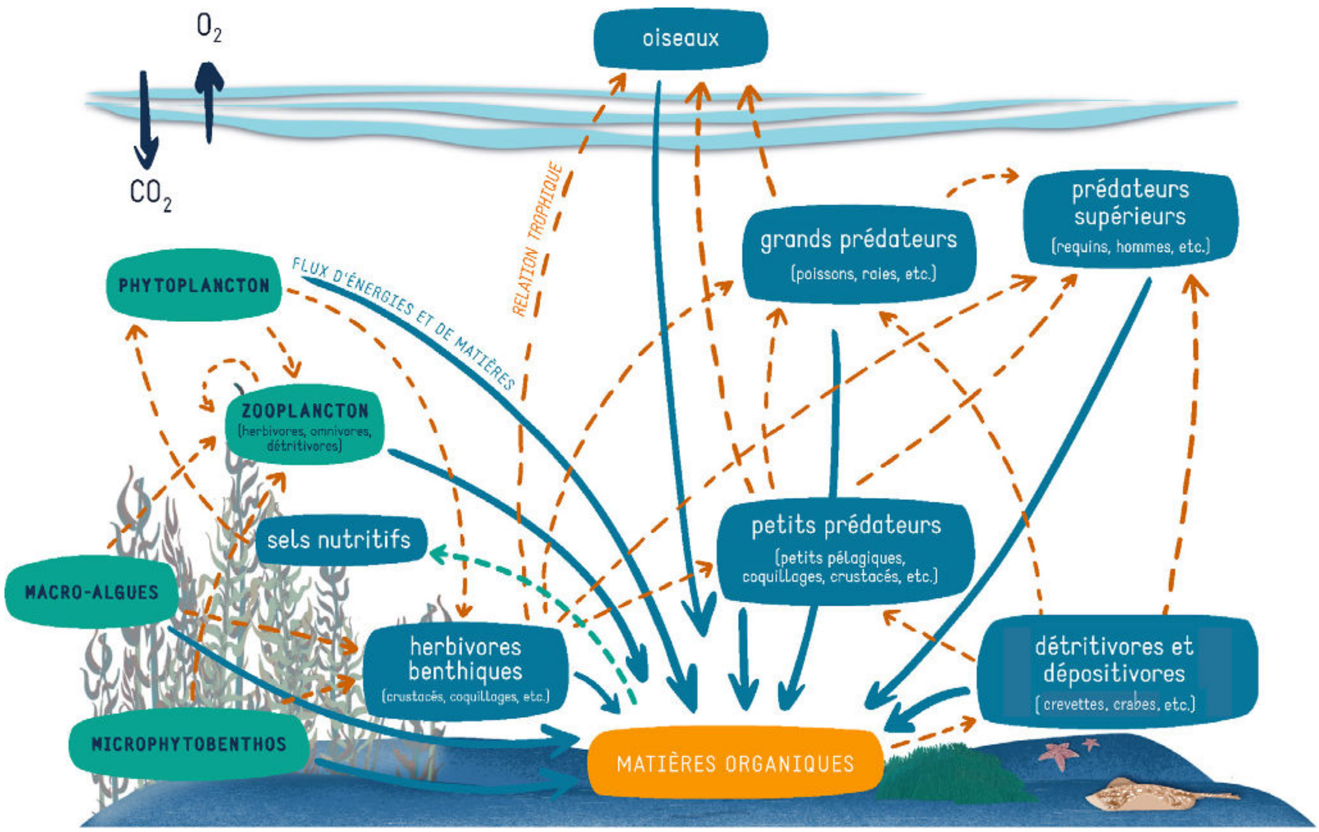


Fig. 2 *Marine food web. In green, the primary producers. In blue, the main trophic groups in the marine environment. In orange, organic matter. The blue arrows represent flows of energy and matter. The orange arrows represent trophic relationships. The green arrow represents the remineralisation of organic matter.*

Offshore wind farms and primary producers

What characterises primary producers and what should be considered to assess their potential interactions with offshore wind farms?

The marine environment harbours a wide variety of primary producers, with a broad range of origins and characteristics (genetic, functional, metabolic, morphological, etc.) (1).

The life spans of these organisms vary considerably (ranging from a few days to a few months for plankton or microphytobenthos; and from a few months to a few years for seaweed and seagrasses). Very specific approaches are required to study these organisms (1). At community level, a disturbance in the environment that exceeds their tolerance range and their adaptation capacity can lead to a **regime shift**. This results in a reorganisation of the structure of communities and, consequently, changes to the interactions between first trophic level organisms, as well as consequences for the structure and functioning of the rest of the food web (5).

In order to assess the potential interactions between an anthropogenic pressure and an ecosystem compartment, it is important first to identify all the characteristics of the environment and the specific pressure. In the case of offshore wind farms, there are several important factors to consider: **structure type** (fixed/floating), **foundation** (monopile, gravity-based, mooring system, etc.), **cable** (power, current, etc.), **cable-laying process** (burial, protection, etc.), **foundation installation process** (ballasting, pile-driving, etc.), **materials** (concrete, steel, synthetic fibres, etc.); as well as the **environmental parameters** which characterise the site: type of substrate, water depth, tidal range, local hydrodynamics, etc.

What are the potential effects of offshore wind farms on primary producers?

The potential effects outlined and described below are not specific to the development of offshore wind farms but result from the expected and/or observed effects on primary producers caused by the different pressures identified. Each ecosystem must be studied on a case-by-case basis so as to consider the pressures that could alter the ecosystem's productivity and affect the food web as a whole.

In the case of offshore wind farms, six sources of pressure were identified, two of which were deemed important to monitor in relation to primary producers **(Fig. 3)**. Their potential effects on the environment and their consequences are outlined below.

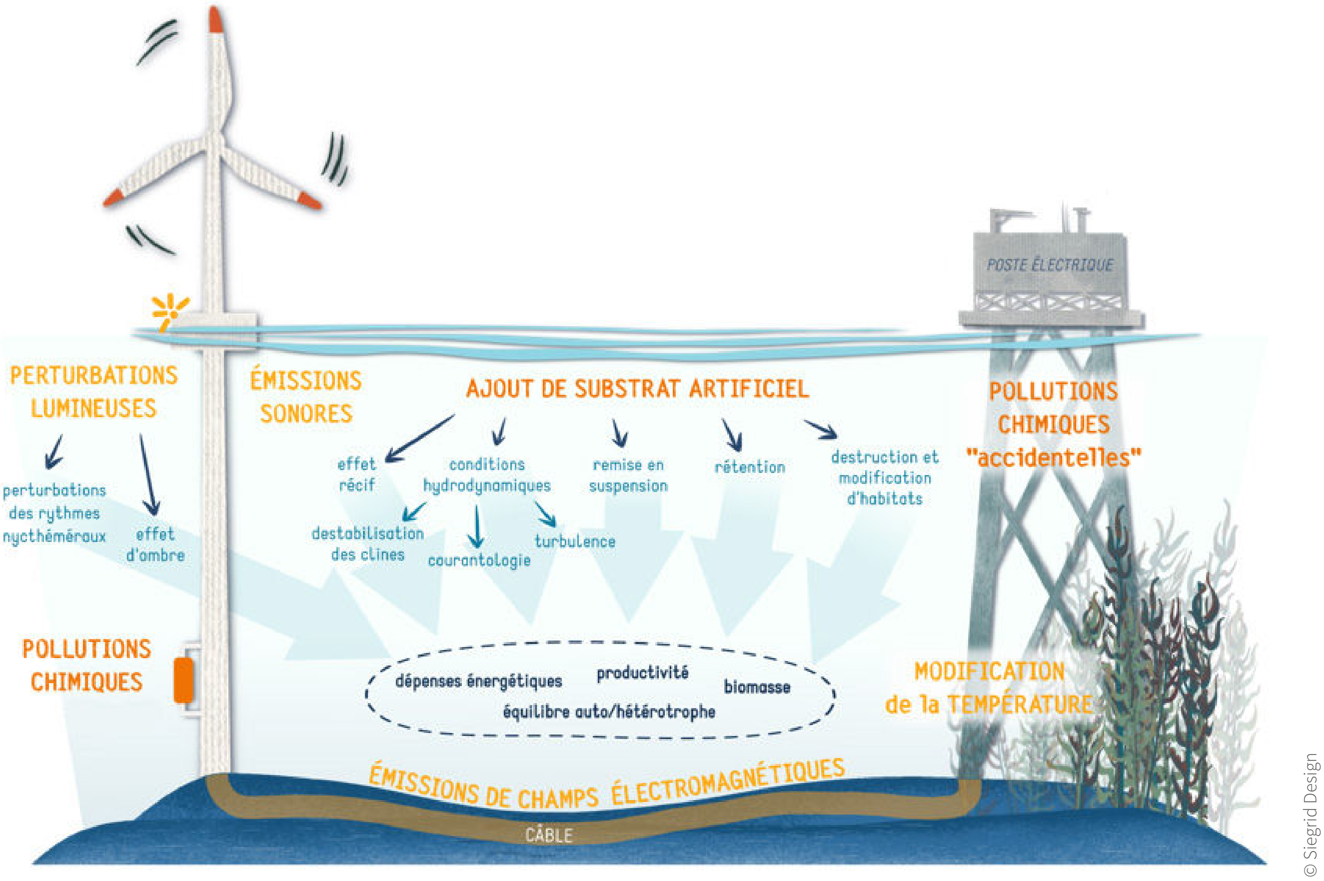


Fig. 3 *Overview of the pressures (in yellow) and main effects (in pale blue) of offshore wind farms on primary producers. Significant pressures are shown in orange and the consequences on the food web are indicated in dark blue.*

• Added artificial substrate

The introduction of any new structure at sea means the presence of new substrates in the marine environment. Whatever type of structure is added (wreck, wind turbine foundation, buoy, etc.), this addition can generate several potential effects on the environment:

- The **reef effect**. In naturally sandy areas, the presence of structures means the addition of a hard substrate offering an alternative habitat (7, 11). Regarded as one of the main effects of offshore wind farms (9), the reef effect can have two consequences on primary producers:
  - → **Changes in biomass** according to the capacity of filter-feeders and seaweed to grow on these new surfaces. An increase in the biomass of primary consumers can affect the biomass of phytoplankton communities, which will tend to decline.
  - → A change in matter recycling conditions. The organisms present can contribute to the transfer and recycling of organic matter (organisms that will feed and die there). This can lead to an organic matter recycling system specific to the wind farm ecosystem (1).

- **Changes to hydrodynamic conditions**, which are important to consider for planktonic organisms as they are particularly dependent on these conditions. These changes can consist in: **changes in turbulence** (wake effect caused by an obstacle to the natural water flow), **changes in currents** (disturbance to natural flows by a physical obstacle), **cline disruption** (disturbance to water mass stratification and exchange of existing nutrients), **resuspension** (mechanical action of machinery on the bottom during construction phase), **creation of a potential retention area** (creation of an obstacle to the natural flow of certain currents), **habitat destruction** (loss of benthic habitats) (1, 10, 12). The potential consequences for primary producers include:
  - → **changes in access to nutrients and light** (1) which can lead to (i) an increase in physiological stress and energy expenditure to maintain in the water column and find food (12), (ii) the reorganisation of plankton communities to foster the emergence of more tolerant species, (iii) an increase in the encounter rate between predators and prey up to a certain threshold and (iv) disturbance to the growth of benthic primary producers (1);
  - → The **formation of plankton patches** due to changes in productivity. This can lead to the emergence of certain planktonic groups and alter the structure and functioning of the ecosystem at the scale of the offshore wind farm (6, 24);
  - → The **modification/loss of benthic-pelagic interactions** according to the type of benthic habitat lost or modified (1);
  - → **Changes in nutrient availability and accessibility** due to the presence of structures in the water and their influence on local biogeochemical dynamics and the structure of the biological communities that are dependent on these nutrients. Locally, this can lead to changes to nutrient availability at the surface and either stimulate or reduce primary productivity (1).

• Chemical pollution

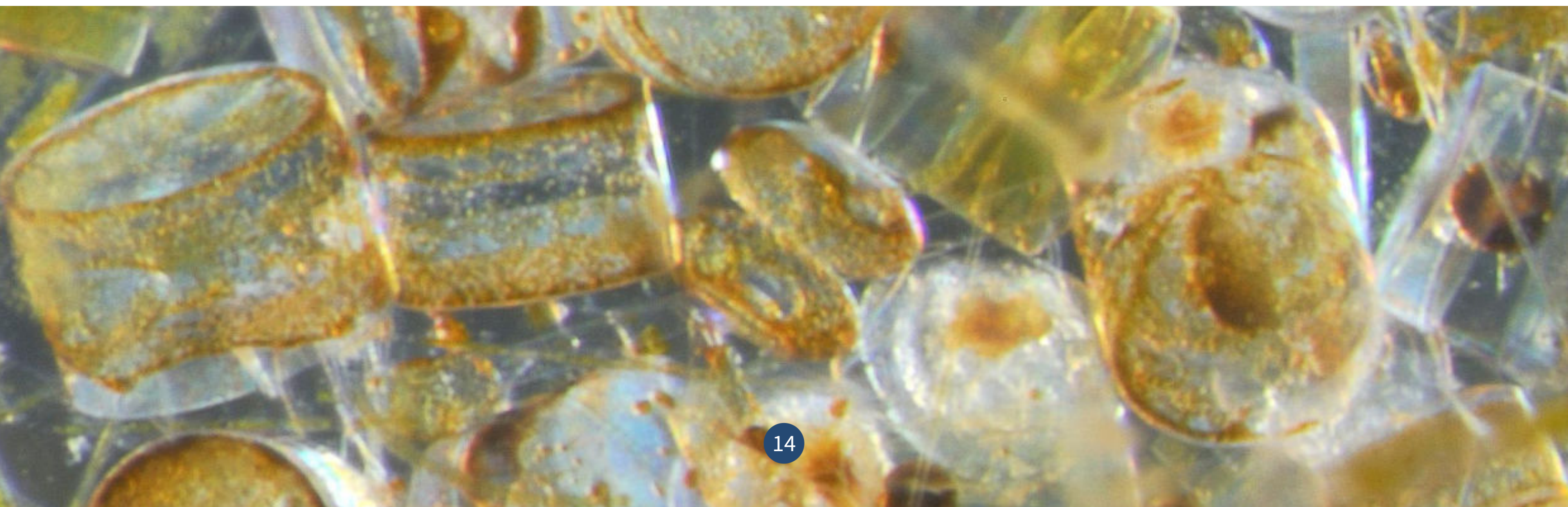
The main source of **pollution** in offshore wind farms results from corrosion protection systems (14, 16). According to current knowledge and monitoring carried out at offshore wind farms in France and Europe, chemical pollution caused by wind farms is low, particularly when compared with pollutant emissions from rivers (13), with concentrations generally falling within the range of natural variability (3). There is also a risk of **accidental pollution** due to spills results from maritime activities (maintenance, industrial tourism, etc.) within offshore wind farms (17): leaks of oil, hydraulic fluids, coolants, lubricants, etc. (9, 16). Such accidental pollution is not specific to offshore wind farms and is considered to be relatively low for this type of activity (1).

The main consequences of chemical pollution for primary producers are changes to the **community structure and the associated flows of matter**. The impact of pollutants is often difficult to quantify, as studies on ecotoxicological effects are often carried out under controlled conditions, focusing on a specific organism and/or molecule. Depending on the nature and extent of the pollution, the consequences for communities will vary considerably. Although the presence of a layer of oil on the water's surface can have direct consequences for the productivity of primary producers (reduced light penetration, changes in surface flows and gas exchange, etc.), certain pollutants can cause physiological disturbances and affect the development and growth of communities (disturbance to photosynthesis, impaired growth, etc.) (1).

• Other potential pressures

Four additional potential pressures were identified for primary producers, although these are deemed to be of low significance compared to the "added artificial substrate" and "chemical pollution" pressures:

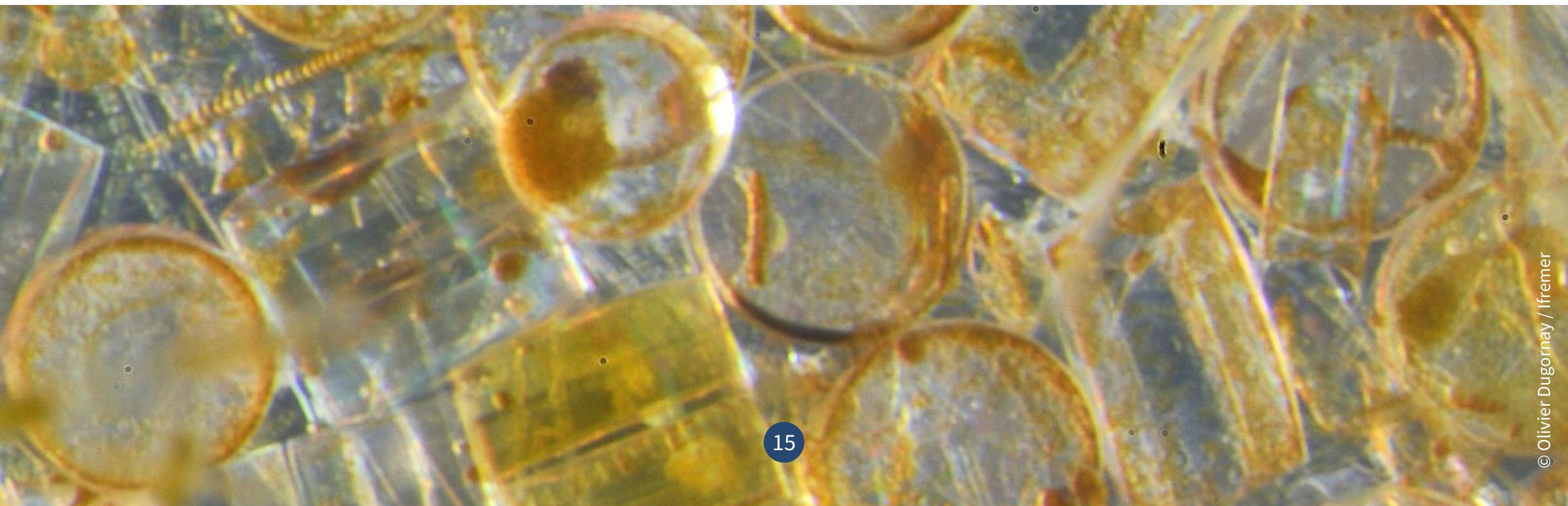
- **Light disturbance:** while the phenomenon of photo-attraction is well known, its impact on primary producer communities is less so. It is known, however, to lead to an accumulation of organisms near the source of the emission, making them more vulnerable to predation. Furthermore, certain plankton species are sensitive to light variation. Light emissions could therefore affect the circadian cycles of certain zooplankton species. (1, 17).
- **Noise emissions:** the effects of noise emissions on plankton communities are poorly known, and existing knowledge is mainly based on experimental laboratory studies. Although there appears to be an attraction effect on the larvae of certain species (particularly for the selection of a substrate of interest), there is little information on the effects of noise emissions on the first trophic levels (1).
- **Temperature changes:** within offshore wind farms, temperature changes are mainly induced by the cables and the substation's cooling systems. In both cases, the temperature variations are restricted to the vicinity of the cables and the electrical substation (4). Given the heat dissipation capacity of the water column, the temperature change is highly localised, and its impact is deemed negligible with regard to the ocean area under consideration. For sessile organisms, an increase in cable temperature could affect biofouling growth and accelerate certain metabolic processes,



thereby promoting the emergence of certain species with greater tolerance to temperature variations (1). However, very localised temperature changes within wind farms are deemed negligible with regard to the large-scale rise in ocean temperatures induced by climate change (18).

- **Electromagnetic field emissions:** within wind farms, only the power transmission cables are liable to generate artificial electromagnetic fields in the marine environment. Their effects on plankton communities are poorly known and are limited to the immediate vicinity of the the cables. In the case of organisms directly attached to the cables, the emission of electromagnetic fields can affect biofouling and potentially promote the emergence of certain species with greater tolerance to this type of disturbance (1).

While changes in certain trophic interactions can be foreseen, identifying the consequences for the entire food web is a more complex task. This difficulty is largely due to the complexity of interactions and the specific characteristics of the ecosystem. These consequences also depend on the communities present, the extent of the pre-existing benthic-pelagic coupling, the local hydrodynamics, and the changes induced by the development of an offshore wind farm on these communities in terms of composition, abundance and/or biomass: increase/decrease in primary producers, development of filter-feeders/macroalgae consumers, attraction of mobile species (fish and apex predators), creation of new ecological niches, formation of patches, etc. (6, 24).



What monitoring solutions exist to...

... understand primary producers?

Depending on the type of habitat (benthic or pelagic), the monitoring actions implemented to improve our understanding will vary considerably. Plankton communities, for instance, are characterised by a daily growth cycle and therefore require monitoring tools suited to this specific pattern; benthic communities, on the other hand, are characterised by a wide diversity of organisms (from microphytobenthos to macroalgae) and are found at depths that make them difficult to observe. In both cases, data collection methods vary considerably and require contextual data relating to the species and the environment (in particular, the physico-chemical properties of the water).

Among the existing observation tools and techniques, **satellite imagery** has been used for a long time now to provide input for phytoplankton biomass indicators such as chlorophyll *a*. For greater accuracy, **samples** can be taken at sea (a,b,c,d). These samples can be analysed in the laboratory to identify and characterise the species present and the community composition, as well as to quantify abundance and biomass, using various identification techniques based on imagery, automated recognition and counting methods (compound or stereo microscope) (1). **Underwater videos and photos** are used to observe and map benthic communities, and in particular seaweed. Depending on the site's constraints and the required frequency, monitoring can be carried out by divers or underwater robots (ROVs and AUVs).

New methods based on **genetic analysis** are being developed and aim to (i) identify species by analysing part of their genome (barcoding) and/or (ii) assess plankton diversity based on the genetic sequences present in a sample (metabarcoding). The use of these **environmental DNA** techniques provides accurate insight into the local diversity.

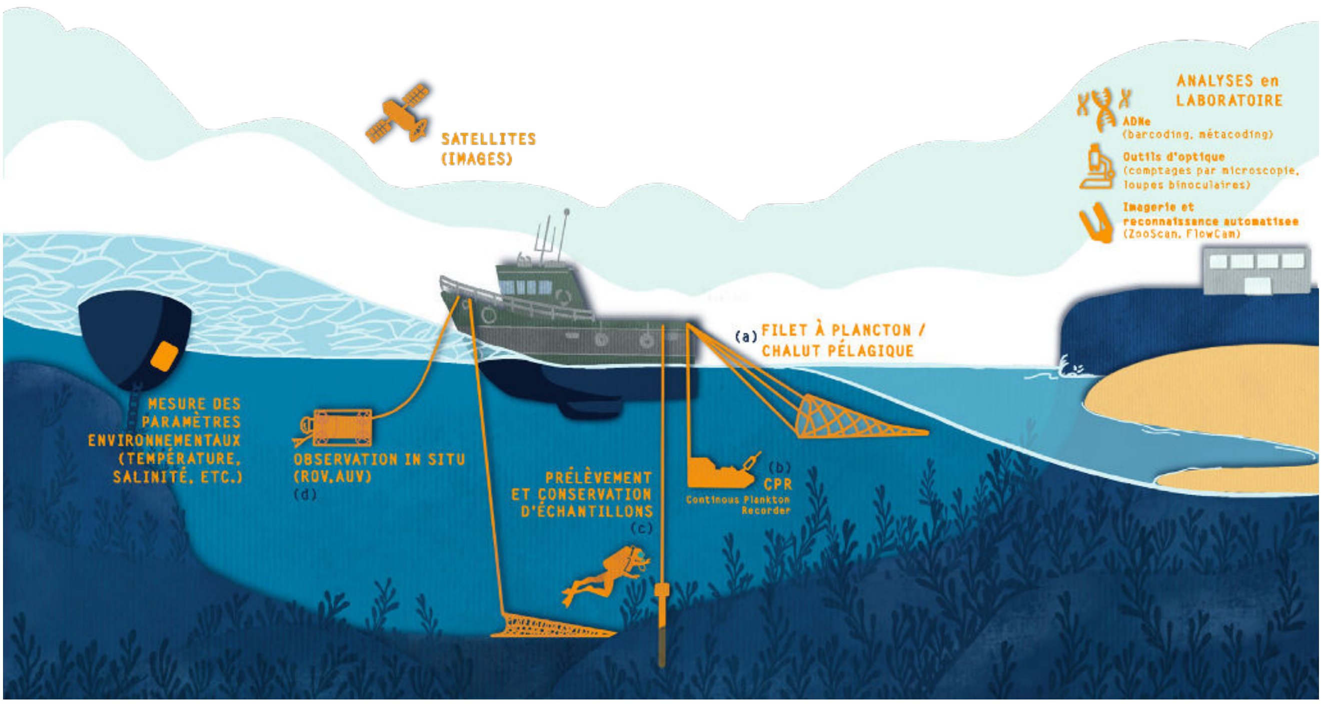


Fig. 4 *Overview of existing monitoring tools used to study primary producers*

… monitor the effects of offshore wind farms on these communities?

The development of offshore wind farms is not the only activity that generates pressures for primary producers. However, given that offshore wind farms have an average operational lifespan of 25 to 30 years, the regulatory environmental monitoring carried out by developers offers an opportunity to implement long-term monitoring programmes.

The majority of monitoring is currently based on occasional measurements. High-frequency measurements (at intervals of less than 20 minutes) carried out on a long-term basis would (i) provide insight into the complex dynamics of these communities (rapid growth, seasonal variability, etc.) and (ii) make it possible to characterise the communities (composition, species diversity, etc.) in order to better characterise the ecosystem. Existing time series collected at low frequencies (twice-weekly to monthly) remain useful for characterising communities prior to the construction of the wind farm. Additional, high-frequency monitoring would ensure a deeper understanding and more effective assessment of the effects, taking into account the environmental characteristics that have “shaped” the communities already present (25).

Recommendations

Although primary producers form the basis of the food web, their characteristics and specificities remain largely unknown. To overcome this knowledge gap, it appears necessary to:

- **Introduce a standardised monitoring system at national scale** through shared protocols (including environmental parameter measurements) implemented at a frequency suited to the life cycle of these communities, in order to better understand and characterise them. This monitoring system should be aligned with international standards, indicators (in particular biomass, abundance and diversity) and monitoring programmes already in place at national level, in order to ensure interoperability, data access and the comparability of results. Automated measurements to estimate primary production can be deployed on instrumented buoys or on board vessels (19, 20, 22, 23). In this respect, wind farm maintenance operations can provide an opportunity to acquire data by installing automated measurement systems on board maintenance vessels (1).
- **Develop innovative monitoring techniques** to monitor these communities and venture beyond the monitoring of species diversity (the number of different species in a sample). It appears necessary to move towards the monitoring of functional diversity (morphological characteristics such as size, physiological characteristics such as the mode of reproduction, and behavioural characteristics such as predation, photosynthesis and flows of matter) in order to more accurately characterise the community structure, in particular by identifying all the mechanisms linking "environment" and "ecosystem functioning".
- **Consider primary production mechanisms in more detail when designing modelling tools (biogeochemical and trophic)** in order to improve their representativeness and reduce uncertainties. Long-term monitoring actions could therefore provide a useful database for the validation and calibration of these tools.

Conclusion

Located at the base of the marine food web, plankton and all the different primary producers play a fundamental role in the structure and functioning of marine ecosystems. It is essential to study the effects of the different anthropogenic pressures on primary producers so as to understand and anticipate the changes that could occur in the short, medium and long term.

In the case of offshore wind farms, six sources of pressure were identified for these communities (added artificial substrate, chemical pollution, light disturbance, noise emissions, temperature changes, and electromagnetic field emissions). Two were deemed important to monitor: added artificial substrate and chemical pollution. The potential effects associated with these pressures must, however, be put into perspective against the backdrop of all existing marine forcings (climate change, pollutant inputs from rivers, human activities, etc.) and are deemed to be of low significance for primary producers. Beyond the existing monitoring actions and protocols, it is essential that monitoring and observation approaches be further developed to more effectively take into account the cumulative effects of the different anthropogenic pressures, particularly those associated with offshore wind energy and all human activities along the coastline.

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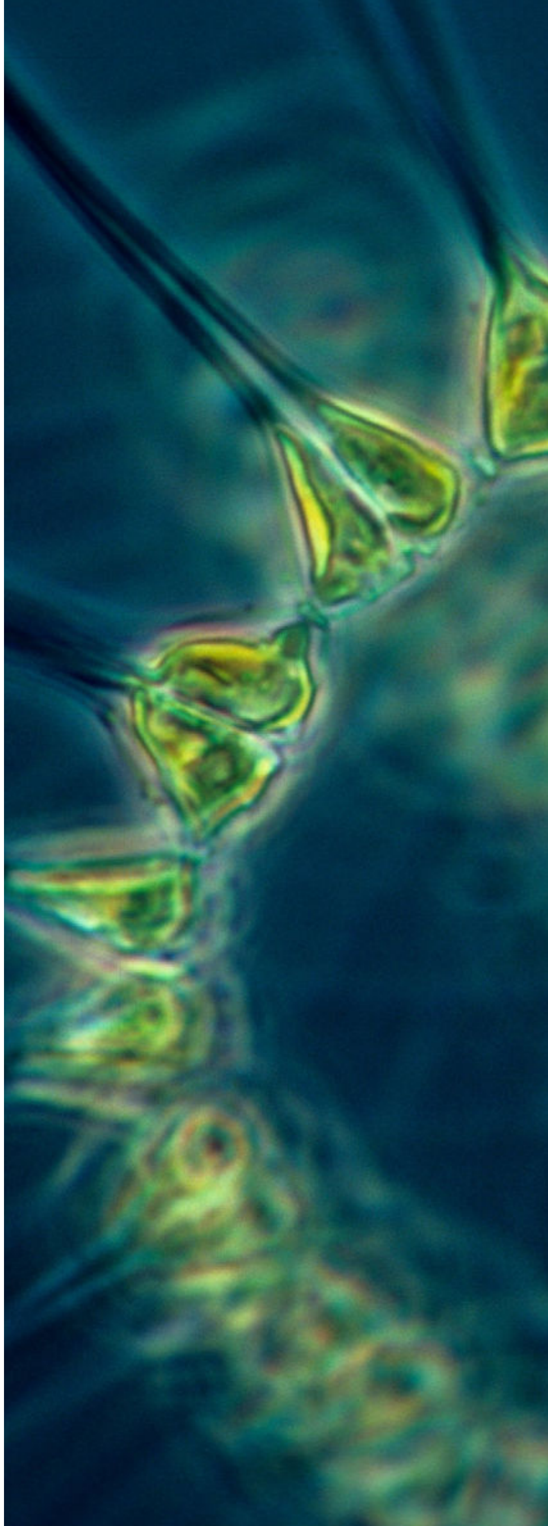

COME3T is an initiative that brings together a panel of national and regional stakeholders (universities, industrial firms, consultants, regions, State services, etc.) within a steering committee that puts forward questions, based on public concerns and key environmental and socio-economic issues identified by the stakeholders, to committees of neutral, independent experts. For each topic, a committee of experts is established following a call for applications and provides information, summaries and recommendations on the environmental and socio-economic issues associated with offshore renewable energy.

https://www.france-energies-marines.org/projets/come3t/

An initiative coordinated by France Energies Marines.

France Energies Marines is a research and innovation centre devoted to offshore wind energy with a recognised industrial, economic and societal impact in France and internationally. Its mission is to overcome the barriers facing the offshore wind sector. Supported by the French State, the Institute, driven by a 90-strong multi-disciplinary team and a network of international experts, underpinned by one-of-a-kind infrastructures, conducts excellence-oriented multi-partner research projects. The results of these projects are transferred to the sector in the form of research and expertise services, operating licences, know-how transfer and participation in expert committees and networks. One of its four key research programmes is devoted to the environmental and social integration of offshore wind farms.

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