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# The Impacts of Onshore Wind Power on Biodiversity

Knowledge Update

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## KNOWLEDGE UPDATE

According to the International Renewable Energy Agency, wind power is one of the most rapidly growing sources of energy in the world. In 2021, wind and solar power combined represented 88 % of the added renewable energy capacity. Moreover, the International Energy Agency estimates that in order reach net zero emissions by 2050, wind capacity needs to be more than doubled worldwide. In the coming years, most of the added wind power will still be generated on land, and wind turbines with taller towers and longer blades will be built in order to increase cost-effectiveness and adapt to low wind conditions. It has been estimated that more than 11 million hectares of natural land worldwide could be lost to wind and solar power, which would have an impact on more than 3.1 million hectares of key biodiversity areas and more than 1,500 threatened vertebrate species, especially in tropical areas. Even though increasing wind power capacity is crucial for attempting to mitigate climate change, its potential effects on biodiversity mean that there must be a compromise between climate change mitigation and the objectives of biodiversity conservation.

## WHAT DO WE KNOW OF THE IMPACTS OF ONSHORE WIND POWER ON BIODIVERSITY?

There is now evidence that onshore wind farms have an impact on biodiversity and ecosystems, altough there are still marked differences in terms of research into different taxa and biological groups, with flying vertebrates being the most studied group.

The FRB's review paper in 2020 (Niang & Goffaux, 2020) identified different types of impact. A summary is given below in point 1. In addition, Tolvanen *et al.* (2023) carried out a systematic review of the literature to try to quantify the displacement of species caused by wind power development, a topic previously identified as having important knowledge gaps (see point 2).

A recent study (Wood Hansen & van den Bergh, 2024) has since shown that climate change mitigation will trigger major changes (in human activity, energy systems and material use) that will potentially shift the pressure of climate change to other environmental problems (known as environmental problem shifting (EPS)), but that estimates of net EPS are still needed. A summary of their conclusions is given in point 3 of this chapter.

Thess and Lengsfeld (2022) investigated the social costs of wind power, focusing on three lesser studied side effects, namely: (1) the impact on insects, (2) the spatiotemporal distribution of air velocity, temperature, humidity and precipitation in the vicinity of wind parks, and (3) the impact of noise on people. A summary of their findings on insects is given below in point 4.

Lamhamedi and de Vries published a literature review in 2022 on three aspects of the land-wind energy nexus: (1) the conflict between different land-uses and renewable energy development, (2) the environmental impact of wind power installations, and (3) public opposition. These three aspects provide opposition to the dominant narratives that support renewables, and should be taken into account in order to not jeopardize the sustainability of the investment, and thus the common goal of reducing greenhouse gas emissions. A summary of the main conclusions of this review relative to the impacts on land and biodiversity is given below in point 5.

### 1. The impacts of onshore wind power on biodiversity (summary of the literature review published by the FRB in 2020)

Documentation of the negative impacts of onshore wind turbines on biodiversity is variable. There are many publications on flying vertebrates, *i.e.* bats and birds, but other groups of species are far less studied. However, it is difficult to draw general conclusions from the quantitative data presented in these papers to estimate the impact of the French wind park on birds, because these impacts also depend on the local biogeophysical context.

The impact of wind turbines on the components of biodiversity include: (1) direct mortality by collision, (2) indirect mortality from a decline in habitat quality and resource availability near wind turbines, and (3) avoidance or displacement due to the loss of roosting sites, food, or habitat, or due to ecological barriers. Less mobile species, such as reptiles, amphibians, invertebrates, and plants, are particularly impacted. Avoidance behaviours are far less documented (except for bats and birds) as they are difficult to study, than direct mortality by collision. Note that clearing woodland areas can have negative impacts (*e.g.* habitat loss for woodland species), but can also lead, in the mid- to long term, to the creation of other habitats such as clearings and woodland edges. It should also be noted that deforestation also affects the carbon balance.

In addition, we would like to point out here that, although this is less known and less documented, wind farms can also have a negative effect on local plant species diversity, a phenomenon that should be taken into account wherever rare, endemic and threatened species occur (Urziceanu *et al.*, 2021).

**Birds** are impacted by direct collisions, the modification of their habitats, and noise and light emissions from wind turbines. The most frequently killed species are those whose flight path coincides with the turbines' rotor swept area. They include certain species (threatened or not) with large populations, such as larks (*Eremophila alpestris*, *Alauda arvensis*, and *Chersophilus duponti*), but also protected species, especially migratory birds and raptors. Bird populations are also impacted by the disturbance caused by the construction of wind turbines, displaying more or less pronounced avoidance behaviours depending on the species. For diurnal raptors, which are mainly affected during their nesting period, their populations are often very small (sometimes only a few dozen nesting pairs): the cumulated impact of collisions with wind turbines further worsens their conservation status.

→ A French study by the LPO (Bird Protection League) (2017) stressed that:
  - 81 % of bird carcasses found belong to protected species or species whose conservation status is of major concern.
  - 60 % of bird carcasses found belong to migratory birds.

→ A Swiss study (Aschwanden *et al.*, 2018) showed that:
  - 55 % of fatalities were kinglets (*Regulus* sp.) and nocturnal migratory birds (due to limited visibility at night or in poor weather conditions).

→ Two studies in the United States (Smallwood, 2013 ; Walston *et al.*, 2018) estimated that:
  - 573,000 bird deaths each year are due to wind turbines,
  - Of which 83,000 are raptors.

→ Multiple studies have shown that the move to more suitable habitats leads to a reduction in breeding performance in raptors, and thus to a fall in numbers.

→ Can turbines be perceived as a predation risk and trigger avoidance/escape strategies in species such as Dupont's lark?

→ Species respond differently to the construction of wind farms: by comparing data from 12 wind farms in the U.K., Pearce-Higgins *et al.* (2012) found that red grouse (*Lagopus lagopus scoticus*), snipe (*Gallinago gallinago*) and curlew (*Numenius arquata*) densities had decreased, whereas skylark (*Alauda arvensis*) and stonechat (*Saxicola torquata*) densities had increased. Moreover, golden plovers (*Pluvialis apricaria*) and common snipes (*Gallinago gallinago*) showed avoidance of turbines and access roads.

→ Devereux *et al.* (2008) indicated that most wintering farmland birds in the U.K. are probably not affected by wind turbines in operation.

→ Montagu's harrier (*Circus pygargus*) exhibited a turbine avoidance rate of 93.5 % (Schaub *et al.*, 2020).

→ Avoidance behaviours can depend on the wind farm's stage of development (observed in wedge-tailed eagles (*Aquila audax*) and white-bellied sea-eagles (*Haliaeetus leucogaster*)) (Schuster *et al.*, 2015).

→ Jenkins *et al.* (2018) recorded a high volume of movement of great white pelicans through a coastal wind farm, coincident with the breeding cycle and associated with flights to alternative feeding grounds *ca.* 50 km away.

→ Migratory species such as geese, waders, common cranes (*Grus grus*) and black storks (*Ciconia nigra*) are the most affected by the barrier effect (Schuster *et al.*, 2015).

→ Turbine noise also affects birds by deafening them, which reduces their ability to communicate and impacts the defence of their territory, their youngs' call for help and the search for sexual partners and thus their reproductive success.

→ Some birds change their songs (*e.g.* a change in frequency was observed in skylarks); this may be a relatively early indicator of the significant deterioration of the acoustic environment as a consequence of wind farm start-up (Szymanski et al., 2017).

→ Nighttime lighting systems associated with turbines may have negative impacts on species' behaviour or may increase exhaustion and the likelihood of collision at night (Gómez-Catasús *et al.*, 2018).

Technical solutions exist to reduce the mortality of raptors, such as having cameras integrated into systems that activate audio deterrents or stop wind turbines, although their effectiveness is unclear. The most effective measures remain the restoration of habitats and keeping areas free of infrastructure. In France, the wind turbines that kill the most birds are often the oldest, installed without considerations for biodiversity richness (protected natural areas, Natura 2000 network) (LPO 2017).

**Bats** can be killed either by collision or barotrauma (a sudden drop in air pressure in the vicinity of blades in motion). They can also be impacted by the loss and degradation of their habitat and by noise. Many studies have shown that mortality by collision alone could threaten the viability of populations and lead to an increased risk of extinction. While most studies have focused on bat mortality by collision, very few studies have quantified the loss of habitat use resulting from the potential negative impact of wind turbines. Differences in the results of the studies we looked at suggest that wind turbines have two contrasted effects: avoidance at the scale of the wind farm, and attraction at the scale of the wind turbine.

***Collisions*** happen because bats may not detect the blades due to the extremely high speed of the rotor (up to 300 km/h at the tip of the blades), they may fly in the rotor swept area during migration or while foraging (well documented), or they may be attracted to wind turbines (see below).

***The attraction of bats*** to wind turbines varies depending on the species, the sex and age of the individual, the time of year and the location of the turbines (Reimer *et al.*, 2018). This attraction may be due to the high number of insects congregating near turbines, attracted by the turbines' colour and the heat they emit (most carcasses of eastern red bats (*Lasiurus borealis*) and hoary bats (*Lasiurus cinereus*) had a full stomach indicating that the individuals probably died while foraging). It may also be due to the presence of potential mates or roosting sites, particularly for tree-bats that perceive turbines as trees (Cryan *et al.*, 2014 ; Cryan & Barclay, 2009).

- → In Germany, bat fatalities weres estimated at over 250,000 individuals per year (FRB, 2017).

- → A study in the United States estimates that 888,000 bats die each year at wind energy sites (Smallwood, 2013).

- → Multiple studies show that:
    - Mortality is higher at the end of the summer and in the autumn, coinciding with bat migrations.
    - Species most likely to collide with wind turbines are those that use echolocation adapted to open habitats (the genera *Lasiurus*, *Lasionycteris*, *Perimyotis*, *Nyctalus*, *Pipistrellus*, *Vespertilio*, *Eptesicus* and *Chalinolobus*).

- → Avoidance, in particular of the lights and noise emitted by turbines, could greatly affect European bat species by reducing habitat availability (Barré *et al.*, 2018):
    - Thus, 2,400 km of hedgerows could be lost to bats, according to land surveys in Bretagne and Pays de Loire (FRB, 2017).
    - Most species of bats are impacted within 1,000 m of wind turbines, including gleaners and other species that are not generally considered collision prone (Barré *et al.*, 2018).

- → The barrier effect of large wind farms causes habitat loss, constrains daily commuting routes and disconnects potential feeding and roosting sites (Roeleke *et al.*, 2016).

- → Published after the FRB review, the study by Leroux *et al.* (2023) on the effects of wind turbine size, density and average rotation speed on European bats suggests that high turbine densities and large rotor sizes should be avoided, and turbines should be placed as far away as possible from optimal habitats such as forest edges, and not between these optimal habitats and the source of the prevailing winds.

- → Noise from construction activity can harm the hearing of certain species that regularly use passive listening for foraging (greater mouse-eared bats or long-eared bats), thus impacting their search for food (DREAL, 2017).

Comparative studies on wind farms have established that turbines could be even more harmful to bats than birds (Cryan & Barclay, 2009 ; Smallwood, 2013).

### 2. Onshore wind power and the displacement of wildlife (review of the article by Tolvanen *et al.*, 2023)

Disturbance caused by rotor movement, noise, vibration, flickering lights and increased human presence may lead to behavioural changes such as avoidance and changes in flight paths particularly in migratory species (Drewitt & Langston, 2006; Marques *et al.*, 2019 ; Schuster *et al.*, 2015 ; Santos *et al.*, 2021). Avoidance can occur at different scales, at the level of the entire wind farm (macro-scale), within the wind farm (meso-scale) or in the immediate vicinity of wind turbines (micro-scale) (Marques *et al.*, 2021). Information about displacement can be used to determine the distance thresholds beyond which wind energy development is expected to have a limited impact on biodiversity. This improves the possibilities of mitigating the negative effects of wind power on wildlife.

To better understand the extent of displacement, the authors carried out a systematic review of the impact of onshore wind power on birds, bats and terrestrial mammals. Eighty-four peer-reviewed studies published between 1993 and 2023 provided 160 distinct displacement distances that were analysed by the authors. As expected, these studies where imbalanced, with 69 studies on birds (including three that also included terrestrial mammals and one that also included bats), 13 on terrestrial mammals, and 9 on bats. They were carried out mainly on < 100 m tall wind turbines; only four studies looked at wind turbines taller than 150 m, which is already a problem, as the number of these giant structures is increasing rapidly. These studies were carried out in 22 different countries, mostly in the United States (23 studies), Spain (10 studies), the U.K. (10 studies), and Norway (6 studies).

Their results show that 63 % of birds, 72 % of bats, and 67 % of mammals reported displacement to avoid wind turbines. Cranes, owls and semi-domestic reindeer showed consistent displacement of up to 5 km. Birds showed displacement of 5 km on average, but in some cases, "no displacement" was found. Bats were displaced by up to 1 km on average in 21 out of 29 cases. Waterfowl, raptors, passerines and waders were displaced on average by up to 500 m. These results suggest that these species suffered an important loss of functional habitat. For flying species such as raptors and bats, displacement and collisions create a double-edged sword that causes population decline regardless of whether displacement occurs or not. The information on displacement distances reported in this study can be used to mitigate the negative effects of wind power by avoiding high-quality areas that are important for threatened species, minimizing small-scale habitat loss and collisions, and restoring or creating high-quality habitats to compensate for functional habitat loss.

The vulnerability of bird populations to wind power development can be high, especially among species with long lifespans (long-lived species) and low reproduction rates. For example, owls and raptors have slow maturation and reproduction rates. Displacement influences their abundance during the breeding season, increases the abandonment of nests, and decreases breeding success. Combined with the effects of collisions, this can lead to a spiral of extinction for local populations. Habituation to wind turbines has not been observed in raptors, suggesting that population changes may be permanent.

Bats display a mixture of attraction and displacement. The maximum observed displacement distance was 1 km, but this is probably an underestimate as longer distances were not studied. Displacement seems to vary depending on the preferred foraging habitat (woodland, hedgerows or open habitats), echolocation range, and migratory pattern, but in general the mechanisms leading to displacement remain largely unknown. Many studies report negative effects on populations, and even extinctions have been anticipated if wind power development continues to increase. Despite initial population declines and changes in species diversity due to habitat loss and displacement, some bat populations can recover, as a study of 22 tropical bat species in Mexico has shown (Briones-Salas *et al.*, 2017).

There are still relatively few studies on the displacement of terrestrial mammals. Wind power development may induce changes in area use and the migration patterns of large mammals as a results of habitat fragmentation, decline in habitat quality, and disturbance. Almost half of the studies focused on semi-domestic reindeer in mountain areas in northern Scandinavia, which is a region with high potential for future wind power development. The long displacement distances indicate a further decrease in potential reindeer pasture areas, which have already been degraded due to forestry, mining, grazing, and climate change. Nevertheless, since semi-domestic reindeer are increasingly kept in enclosures and fed during the winter, their habituation to people may increase, and in the long run, they may also habituate to wind power development more than wild animals. By contrast, the abundance of large mammalian predators has been observed to increase in wind power development areas due to increased access through gravel-roads (Gómez-Catasús *et al.*, 2021).

Small mammals are sensitive to habitat loss and fragmentation due to their limited ability to move. Their displacement distance may therefore be linked to habitat specificity: if a species can use varying types of habitats, the displacement is weaker. The decline in biodiversity could be mitigated by situating wind power infrastructure in low-quality habitats, minimizing small-scale habitats loss and collisions, and by creating high-quality habitats to compensate for habitat loss.

It would also be desirable to increase the number of observations and conduct more research before installing a wind farm, or a set of wind farms, in a given area in order to precisely identify where wind turbines should not be located to reduce the impact on migratory species either during their flight or during their nocturnal stopovers (Cohen *et al.*, 2022). The production of risk maps for different sensitive species would improve spatial planning and define exclusion zones (May *et al.*, 2021 ; Morant *et al.*, 2024). It is also necessary to encourage before/after-control/impact (BACI) studies that are required for the approval and decisions associated with the development of wind power.

## 3. Environmental problem shifting: from climate change mitigation to biodiversity loss (review of the article by Wood Hansen and van den Bergh, 2024)

Wood Hansen and van den Bergh mapped the literature on environmental problem shifting (EPS) in the context of climate change mitigation. From over 10,000 scientific papers, the authors selected 311 relevant empirical studies. The literature on the subject is vast, but scattered around terms whose conceptual boundaries tend to be blurred, such as "trade-off", "side effects", and "spillover". The authors identified 506 relevant studies on EPS, of which 311 were empirical, 47 were conceptual or theoretical, and 148 were research syntheses or reviews of a mitigation option. They identified 128 distinct shifts, 22 categories of mitigation options and 10 environmental impacts. This literature does not cover all mitigation options identified by the IPCC. Moreover, some studies systematically overestimate EPS by not accounting for the environmental benefits of mitigating climate change.

Their first result was the identification of 21 terms used to refer to EPS: trade-off, cobenefit, interact, displacement, unintended consequence, side effet, coupled effect, problem shift, feedback, burden shift, by-product, interlinkage, spillover, adverse side effect, linkage, cascade effect, ancillary, environmental side effect, interdependent, and coimpact.

The authors mapped 86 shifts from 13 categories of mitigation options to 10 environmental impact categories (Table 1). The most frequent environmental impacts in the scientific literature are "freshwater use" and "land use".

| Environmental impact category | Subtheme |
|---|---|
| Freshwater use | Quantity<br>Quality |
| Land use and degradation | Land use<br>Land degradation |
| Biodiversity loss & ecosystem functioning (incl. marine environment) | Terrestrial & freshwater<br>Marine environment |
| Eutrophication & biogeochemical flows | Nitrogen<br>Phosphorus |
| Human toxicity (incl. ionizing radiation) | Carcinogenic and noncarcinogenic toxicants<br>Ozone layer depletion<br>Ionizing radiation |
| Air pollution | Conventional air pollutants ($SO_x$, $NO_x$, $PM_{2.5}$, and $PM_{10}$)<br>Ozone formation |
| Mineral & metal depletion | |

| | |
|---|---|
| Ecotoxicity | Freshwater<br>Terrestrial<br>Marine |
| Acidification (mainly $SO_2$, $NO_2$, and $NH_3$) | |
| Environmental impacts of mining (unspecified) | |

***Table 1 :*** *The different environmental impacts of onshore wind power*

The authors identified 24 studies on EPS related to wind power. These studies show that the shifts from onshore wind power deployment compared to fossil fuels are:

- first, an increase of the impacts on biodiversity and ecosystem functioning (point 1),
- then, increased land-use pressure (point 4),
- tension over metals and minerals, air pollution, human toxicity, tension over freshwater usage, the impact of mining, and ecotoxicity.

Wind power shifts pressure to wildlife conservation due to the local disturbance of ecosystems, risk of collision with flying species, and cascading impacts through trophic levels.

The exact shifts of a mitigation option vary with the geographical context (*e.g.* prior land use or freshwater availability), specific implementation techniques (*e.g.* turbine size), and the upstream source of energy. It is important to disentangle these underlying mechanisms, as they can provide regulators with leverage points that can be exploited to minimize shifting. Complementary policies, such as financial measures, incentives or regulation, can also minimize shifting.

To estimate shifts accurately, the authors suggest considering the environmental impacts that would occur in the absence of mitigation, but not all studies do so, which makes comparisons difficult. Three terms were introduced to describe the types of estimates that were carried out:

- gross shifting, which captures the environmental impact of a mitigation option without comparing it to the impact of unmitigated climate change;
- net shifting, which compares the environmental impact of mitigation with a reference scenario without mitigation (accounting for the impacts avoided by mitigation—including damages from climate change and impacts from continued production and use of fossil fuels);
- relative shifting, which circumvents the need for baselines by comparing the impacts of mitigation options relative to a common functional unit, such as kWh produced. For example, to estimate bird mortality from wind power (*i.e.* gross shifting), the impact should ideally be compared to the impact on birds of energy production by fossil fuel combustion and the impact of unmitigated climate change (*i.e.* net shifting).

Gross shifting can still be relevant if the negative environmental impacts of mitigation are felt locally and if the benefits of mitigation accumulate globally. Therefore, we must understand the equity problems posed if environmental problem shifting mitigates a problem on a global scale (*e.g.* climate change) but intensifies the pressures on the environment locally (*e.g.* pollination decline).

The ubiquity of EPS indicates a need for sustainable climate policy that effectively ensures that mitigation does not aggravate other environmental problems unnecessarily. EPS can be minimized by regulating the implementation of mitigation (*e.g.* technology type, geographic placement (avoiding natural areas with high environmental value, including protected areas)) and through complementary environmental policies.

## 4. The impacts of onshore wind power on insects, a less studied group (review of the article by Thess and Lengsfeld, 2022)

Insects dislike turbulence. They use strong, uniform winds for travelling but select calm areas for habitat; in particular many insect populations (including butterflies, moths, hoverflies, Hemiptera and dragonflies) make seasonal migrations to different parts of the world (Satterfield *et al.*, 2020).

A research synthesis and modelling study from the German Aerospace Center (Trieb, 2018) showed that, although the quotidian flight of most insect species occurs between 0 and 30 m above ground level, *i.e.* below the critical rotor height (between 20 and 750 GW), migration takes place at higher elevations (between 40 and 100 m) where strong, directional, undisturbed winds reduce the insects' energy expenditure and optimize their flight. For these exact same reasons, wind turbine developers placed wind turbine rotors just above the turbulent surface layer. And, to maximize efficiency and benefit from favourable wind conditions (much like animals), wind farms often, not to say always, coincide with the migration routes of birds and insects. In the United States, a study on monarch butterflies showed the obvious coincidence between the migration routes of these flying insects and wind farms.

But is this impact significant? The scientific literature is divided. Although there is consensus to say that there are dead insects at the foot of wind turbines and more generally that wind turbines have a physical impact on flying insects (like cars, trains,...), the extent of insect loss due to wind power compared to other factors on the one hand, and the ability of traps to correctly catch insects and their swarms in the turbulence zone near the blades on the other hand, are still unclear.

The authors estimated the insect density in the air in Germany to be 3 kg of insect biomass per cubic kilometer of air (this estimate takes into account the 75 % decline in insect biomass in the past 30 years (Hallemann *et al.*, in 2017)). Moreover, air flow through 30,000 German wind rotors was estimated to be 8 million cubic kilometers, which gives a total insect biomass of 24,000 tons, or 24,000 billion insects, flying through German wind rotors in operation in a year. If only 5% of insects are killed while flying through the rotor swept area, this represents a loss of 1,200 tons, or 1,200 billion insects each year.

Extrapolating these numbers to the global level, the authors estimate that the total global damage could be 100 times higher, corresponding to a potential wind power-induced loss of 120,000 tons of insect biomass, or 120,000 billion individuals each year. As insect impingement takes place during migration (see above), shortly before the annual reproduction process, it might eventually propagate to following generations and affect species' survival. Despite this evidence, and although the global decline in insect biomass has been reported in numerous studies, wind power is still seldom seen as a possible cause of this decline.

Quite the opposite in fact: during the past 30 years, considerable scientific and industrial efforts have been dedicated to the development of rotor blade surfaces that resist erosion from airborne particles (ice, sand, flying insects) and the adherence of residues from such impacts. Indeed, erosion of the blade's leading edge reduces the economic lifespan of a wind farm, and residues sticking to the blade surface reduce the efficiency of power generation.

In order to understand the phenomenon and to identify mitigating measures, part of the literature is dedicated to the quantification of "insect collection efficiency" of airfoils and the "rupture velocity" of insects as a function of their size and the airfoil design. Another major part of the technical literature on wind power design is dedicated to measures for protecting rotor blades against insect impingement. Finally, a third category of technical literature is dedicated to the cleaning of rotor blades in order to maintain high efficiency.

We are in a situation where minimal effort has been made avoid impacts, but considerable effort has been dedicated to the avoidance of its consequences, resulting in sturdier and antiadhesive blade surfaces and more effective cleaning products. This probably aggravates the lethal consequences for insects. Today, insect collisions no longer pose a serious problem for wind farms in terms of efficiency and lifespan.

Another factor that must be taken into account before concluding that wind farms have no significant impact on insects is the parallel decline in insect biomass. Assuming that the calculated 1,200 billion insects lost during one season in Germany would leave about 10% of their body weight as residues on the blades, this would amount to 15 g per square meter of rotor blade per year. This means that the tremendous growth of the German wind park over the past 30 years, together with the massive parallel loss of insects, has made insect impingement practically invisible. The authors conclude that the relative reduction in visible insect residues on rotor blades since 1990 has been interpreted erroneously as a consequence of increasing turbine height, which was assumed to bring rotors outside the range of the insect flight boundary layer, and that these installations might still represent a problem for migrating insect populations.

Measures to limit the impacts on flying insects do exist. In particular, LIDAR can detect airborne particles approaching wind farms, predict wind speed, and track insect swarms at rotor height. It can stop turbines when densities at rotor height become critical, thus reducing the damage to insects without considerably losses in energy yield, in addition to improving efficiency and reducing maintenance cost by keeping the rotor blades clean.

The side effects of wind power on all potentially impacted fauna should be part of the development and site selection criteria discussions. This is the case for birds and bats but not insects.

## 5. The land-energy nexus

For an equivalent amount of energy produced, renewables require the use of vastly more land than fossil fuels or nuclear power. Consequently, the energy transition is facing critical roadblocks from competing land uses (natural, agricultural, urban and energy).

Planning systems and siting processes that have struggled to deal with the complexities of both fundamental and procedural issues related to land rights and biodiversity are set to face growing tension and conflicts as a direct consequence of their efforts to appropriate land. To the extent that land availability and accessibility, an increasingly scarce ressource, are considered to be a pertinent biophysical, social and societal constraint that might restrict the achievability of this transition within the current socioeconomic framework, thus asserting the need for more innovative land management and more efficient planning. A major impact of this renewable energy expansion is a broader access to clean and affordable energy, which removes a considerable impediment to socioeconomic and human development. Costs of renewable energy have dropped distinctly over the past decade, motivated by technological advancement, economies of scale, competitive supply chains, and better developer experience. This has resulted in the rapid deployment of many renewable energy technologies, especially solar and wind power. Supported by economic incentives, solar and wind technologies dominated the market in the last decade, and their implementation is still expanding rapidly. The International Renewable Energy Agency has established an optimistic plan, according to which clean electricity generation from renewable energy is expected to grow from 25 % in 2017 to 85 % in 2050. In developing countries in particular, these incentives and the positive image of renewable energy has led to large scale and long term land acquisition processes by public authorities or private investors, leading to major changes in land uses and land rights. These land acquisitions are directly causing the loss of access rights to pastures and water points for this land's primary users, such as subsistence farmers, pastoralists, or indigenous populations, thus denying them access to ressources that sustain their livelihoods and foster their cultural identities. This phenomenon is accompanied by biodiversity loss, due to landscape homogenization associated with the development of large wind farms for example.

In their latest report, the IPCC recognized that land use was a "nexus" (*i.e.* the intersection between key factors) for the survival of biodiversity and human livelihoods (*i.e.* for human well-being, and the supply of food, water and energy). In a joint report with IPBES, they stated that human activity directly affects

70 % of the global ice-free land surface. Thus, there is tension between those who support the rapid development of renewable energy projects and those who oppose certain projects because of concerns over land use, and its social and environmental consequences.

Wind farms and solar power plants drastically change the visual identity of rural landscapes by adding forms of industrial and artificial components to it. Such landscape alterations present a source of conflict with local communities who feel personally and socially affected in their landscape identification, and can exacerbate conflicts between towns (where most of the produced energy is consumed) and the countryside (where most renewable energy is produced). This generates an eventual conflict potential as energy production is made more visible, thus changing the common image of energy as an unthought-of commodity and suggesting an industrialization of rural space. Criteria such as environment conservation, environmental compatibility, cultural heritage, and preservation of biodiversity and natural ecosystems need to be integrated adequately within the energy transition through strong landscape and biodiversity protection policies to minimize the impacts of renewable powerplants. Renewable energy development is impacting land use at several stages of the project, including site preparation, on-site construction, and upcoming expansion. Electricity production from renewable resources also entails the construction of power-line corridors, roads, service buildings, and other infrastructure that are a part of any power development, extraction, or transmission project. Geometrically, these linear land-cover features fit more with industrial and urban land-use patterns, and are less compatible with rural land-use patterns, englobing agriculture, rangelands, and forest lands. Power-line corridors and roads may occupy only a relatively small area, but the cutting of vegetation and topographic reworking in these corridors cause fragmentation of ecosystems that can have large and cumulative effects on biodiversity, land use and land rights.

Thus, the development of solar and wind power perturbs models of land use, and particularly biodiversity conservation strategies (in France, the National Strategy for Protected Areas (*Stratégie nationale des aires protégées* – SNAP) and its regional versions). Green energy planning needs to be aligned with social and spatial justice concerns at the local level by simultaneously supporting sustainable land use, adequate rehabilitation and resettlement provisions, and proper compensatory mechanisms in the form of both environmental compensation for the impacts on biodiversity and environments as well as compensation for anyone who may be potentially affected, which can enhance trust in public institutions and promote social approval of the implemented projects.

Whatever the urgency of the energy transition, the development of renewables must comply with environmental regulations; more specifically, in France it must comply with “net zero land-take” (*zéro artificialisation nette* - ZAN) and respect the derogation procedures in place for protected species and habitats (avoid-reduce-compensate practices). Given the important financial flows associated with the development of renewables, tempting some to grab land for development, the regulatory role of government is essential here.

Land conflicts in relation to the deployment of renewable energy have divergent environmental and social outcomes, which may imperil the investment’s sustainability. In order to be sustainable, the investment should be socially responsible, environmentally conscious, and economically feasible. Additionally, it should ensure rural development opportunities, provide supporting poverty alleviation programmes, and thus generate economic prosperity and environmental protection in the long term.

# WHAT ARE THE CURRENT KNOWLEDGE GAPS?

In the prospective review published by the FRB in 2021 (Soubelet *et al.*, 2021), the following knowledge gaps were identified:

- → Better assess the quantitative importance and consequences on population dynamics of wildlife mortality from collision with wind turbines (by species, period, or ecophysiological status);
- → Evaluate technological innovations (*e.g.* acoustic deterrent devices) or operational changes for avoiding collisions (slow down/stop wind turbines during migration periods, or, for bats, during peak activity periods and certain weather conditions);
- → Assess habitat loss due to wind farms or individual wind turbines, and estimate the ecological consequences;
- → Take into account the cumulative effects on species and food chains of the growing number of wind farms in a given region;
- → Better characterize the effect of displacement/avoidance on populations, in relation to other effects such as habitat loss;
- → Characterize the impact on individuals and populations of the loss of hunting/foraging grounds and feeding areas caused by the presence of these installations;
- → Identify the sub-lethal and behavioural effects of noise and electromagnetic fields.

To this list can be added:

- o Quantify the impact of wind turbines on insects and publish recommendations for mitigation;
- o Characterize the effects of wind farms on local weather conditions and soil structure, in particular average air speed, temperature, humidity and rainfall, and the downstream effects on wildlife and agriculture;
- o Better understand the acute and chronic impacts of sonic and subsonic sounds emitted by wind turbines in operation on human health and biodiversity.

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