Wind turbines and health: a review with suggested recommendations

Jean Simos[1]
Nicola Cantoreggi[1]
Derek Christie[1]
Julien Forbat[2]

[1] Université de Genève
Institut de santé globale,
Campus Biotech,
9, chemin des Mines
1202 Genève
Suisse
<jean.simos@unige.ch>
<nicola.cantoreggi@unige.ch>
<derek.christie@unige.ch>

[2] Université de Genève
Faculté des sciences de la société
40, boulevard du Pont-d'Arve
1205 Genève
Suisse
<julien.forbat@unige.ch>

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J. Simos

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Abstract. Wind energy has considerable potential worldwide; however, several health concerns are associated with its development. Based on a structured search of the international scientific literature, this review investigates the main health concerns, grouped into the following categories: noise, infrasound and low-frequency sounds, wind turbine syndrome, stroboscopic effect and shadow flicker, safety, landscape impacts, and real estate prices. There is a geographical mismatch between the globally positive aspects of wind farm development and the possible health effects on the neighbourhood, which are the focus of this review. Health complaints are often difficult to link firmly to the activity of adjacent wind farms, with the exception of annoyance caused by noise pollution. Part of the negative health effects reported by local populations may be influenced by the so-called nocebo effect. However, discomfort and suffering should always be addressed and taken seriously into account by decision-makers and public health officials. The distribution of economic and health-related advantages and inconveniences should be perceived as being fair. This article concludes with a 9-point list of recommendations for the development of wind power in a context favourable to health.

Key words: renewable energy; wind; quality of life; environmental policy; health; noise.

Résumé

Éoliennes et santé : revue de littérature et recommandations pour les projets de parcs éoliens

L'énergie éolienne possède un potentiel considérable à travers le monde. Toutefois, des préoccupations concernant la santé accompagnent son développement. Se fondant sur une revue structurée de la littérature scientifique internationale, cette contribution examine ces préoccupations, regroupées selon les catégories suivantes : bruit, infrasons et sons à basse fréquence, syndrome éolien, effets stroboscopiques et ombres mouvantes, sécurité, impacts sur le paysage, et effets sur les prix du foncier. Il existe une disparité géographique entre les effets globalement positifs de l'éolien et les éventuels effets sur la santé des riverains, objet de cette revue. Les plaintes sanitaires sont le plus souvent difficiles à relier solidement à l'activité des parcs éoliens adjacents, à l'exception de la gêne provoquée par les nuisances sonores. Une partie des impacts négatifs rapportés par les populations riveraines peut être influencée par l'effet nocebo. Toutefois, le mal-être exprimé et les souffrances ressenties doivent toujours être pris en considération par les décideurs et les responsables sanitaires. La distribution des avantages économiques et des inconvénients sanitaires doit être perçue comme équitable. L'article conclut par des recommandations, sous la forme d'une liste en neuf points, visant un développement de l'énergie éolienne dans un contexte favorable à la santé.

Mots clés : *énergie renouvelable ; vent ; qualité de vie ; politique de l'environnement ; santé ; bruit.*

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Wind energy is widely considered to be a clean form of energy, because it does not directly emit CO_2 or particulates and is therefore climate-friendly. Wind is readily available, albeit intermittently, in all countries. In regions under continental or temperate climates, wind is often stronger during the winter, when the demand for electricity is higher. In Switzerland, according to the latest energy strategy of the Federal government, the proportion of wind energy in the total mix is set to reach 7% to 10% by 2050. This implies a very strong progression over the coming years. The wind energy infrastructure will have to be installed while taking into account other territorial interests such as landscape, the natural environment and biodiversity, the built environment, archaeology, noise protection, airspace security for civilian and military uses, and public health.

In order to evaluate the potential effect of any project, programme or policy on health, it is essential to construct a logical map [1] of the health determinants on which to base the analysis [2]. *Figure 1* indicates the main points of such a logical map, as well as the main challenges linked to the development of wind power farms. In a nutshell, wind power plants can influence health determinants either indirectly (these are mainly positive impacts) or directly (mainly negative impacts). The indirect impacts affect the entire population of a region or country, whereas the direct impacts tend to affect only people in close proximity to the new installations.

In this article, we concentrate on the potentially negative effects affecting local residents, such as:
– noise;
– low-frequency sounds;
– wind turbine syndrome;
– moving shadows induced by rotating pales and stroboscopic effects;
– safety;
– landscape impacts related to health;
– social aspects and real estate prices.

Methods

An online literature search on PubMed and ScienceDirect was carried out between January and March 2015, and updated in August 2017, using the following keywords:
– *Wind turbines + Health + Noise;*
– *Wind turbines + Health + Infrasound;*
– *Low frequency noise;*
– *Turbines + Health + Shadow flicker;*
– *Wind turbines + Health + Safety;*
– *Wind turbines + Health + Landscape;*
– *Wind turbines + Health + Social;*
– *Wind turbines + Land value;*
– *Wind turbines + Syndrome.*

The terms *Technique*, *Technics* OR *Technology* were added to each search.

Furthermore, grey literature was actively sought after by writing to recent authors and experts in the field, and by consulting web sites in countries considered to be leaders in research on interactions between wind turbines and health, such as those hosted by the health ministries of Switzerland, Australia and Canada. Finally, the Google Scholar search engine was used with the same keywords as above, in order to verify that no important articles had been omitted.

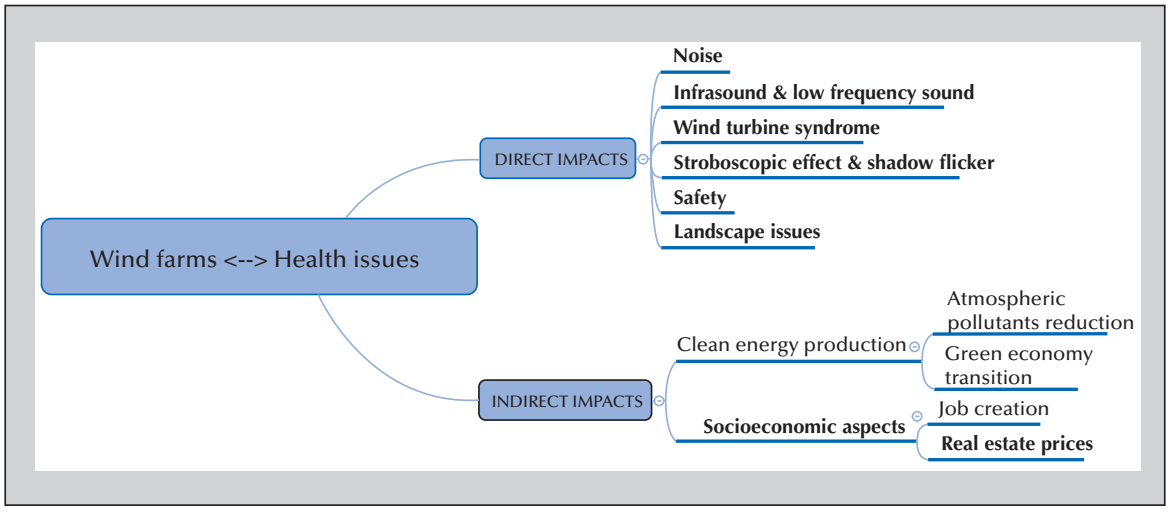

Figure 1. Health issues related to wind farms (items in bold are those presented in this paper).

Figure 1. Questions liées à la santé que posent les parcs éoliens (les éléments en gras sont ceux présentés dans l'article).

Several references identified using these strategies were not included in the analysis because they did not treat health as such but only political and/or social acceptability of wind turbine projects.

Altogether, 67 articles published between 2012 and 2017 were included in our review. They were sorted according to study type, time period, statistical strength and their inclusion in other literature reviews on similar topics [3-6]. The review also uses the results of a literature review carried out in 2012 by the NGO *equiterre* for the local government of Swiss canton Jura [7] and of a review conducted by a working group of the French National Academy of Medicine [8]. These reviews were mainly based on articles published before 2012. This is why our review focused on articles published from 2012, and why it should be considered as a complement and not a replacement for these earlier reviews. Eventually, 104 publications were taken under consideration for our analysis.

Results

Noise

There is no physical distinction between sound and noise. Sound is a sensory perception, whereas complex arrays of sound waves can be described as music, speech, etc. Noise can also be described as undesirable sound [9]. In this literature review, we use the words *sound* or *noise* according to their use by the authors whose work is cited.

Wind turbines generate two types of noise, known as mechanical or aerodynamic. Thanks to technological progress in materials and design, mechanical noise has been considerably reduced over the past few years [7, 10]. The main noise produced by modern wind turbines is therefore aerodynamic in nature. It is emitted by the movement of air between the blades and is determined by many factors including wind speed, rotor size, the shape and surface area of the blades and the angle at which the wind affects the turbine. In general, vertical wind turbines emit less noise than horizontal turbines, but they tend to be less efficient and therefore produce electricity at a higher cost.

Exposure to noise produced by wind turbines is a result of a combination of factors, some of which are linked to the source of the noise (such as the number, power and position of the wind turbines) and others which are due to local conditions [7]. These can be subdivided into factors linked to the terrain (altitude, hilliness, type of soil), the weather (wind strength and direction, humidity) or the local environment (rural, urban or industrial setting; presence of roads, railways, rivers, lakes, trees, etc.).

Noise is an important self-declared stress factor for people living close to wind farms [11] and several studies have shown a link between noise generated by wind turbines and self-declared sleep disorders and psychological problems such as stress and anxiety of populations living nearby. In the Netherlands, a questionnaire based on prior work by Pedersen and Waye [12, 13] was sent by e-mail in April 2007 to a representative sample of people living close to wind turbines [11]. Other topics linked to environmental health were also covered, such as road traffic, in order to make the objective of the study less obvious. The study area was defined as a 2.5 km radius around a wind turbine with a power of at least 500 kW, as long as a second wind turbine (of at least 500 kW) stood within 500 metres of the first wind turbine. Out of the 725 respondents to this study, 199 lived in urban or suburban areas, 245 were in rural areas with a main road nearby (defined as within 500 metres from the closest wind turbine) and 281 in rural areas without a main road in the vicinity. Around 23% of the respondents said they were annoyed by noise from the wind turbines when they were out of doors; this figure fell to 14% when they were indoors. A dose-response relationship was found between sleep disturbances and noise, especially for values exceeding 45 dB(A) outdoors. Interestingly, sleep disturbances were more frequently reported in noisy areas than in calm areas, but wind turbines were more often mentioned as the source of sleep disturbances in calm areas. On the one hand, a positive correlation was established between wind turbine noise and psychological distress. On the other hand, for noise levels up to 46 dB (A), Michaud *et al*. [14] found no association between noise exposure and sleep disturbance and highlighted other factors influencing the quality of sleep, notably the use of sleep medication and the consumption of caffeine.

Van Renterghem *et al*. [15] carried out tests on the recognition of noise attributable to wind turbines. Fifty participants who had a positive attitude to renewable energy participated in their study, where a recording of a 1.8 MW wind turbine, turning at 22 rotations/minute, was superimposed on road traffic noise. The simulations were carried out in a studio with a total noise level of 40 dB(A). During the first phase of the test, participants were not informed about the objective of the study and it was found that a similar level of noise coming from a wind turbine combined with road traffic elicited significantly more distress than noise coming only from a wind turbine. In a second phase, participants were asked to identify the contribution of the wind turbine within a noise constellation including road traffic. It was found that they were able to do this as long as the noise level was lower than 23 dB(A). The authors conclude that there is no masking of wind turbine noise by road traffic noise, nor a synergistic effect between the two types of noise. Specifically, they found that wind turbine noise was no more annoying than highway noise at low indoor levels, but that people who easily recognized wind turbine noise were more annoyed by it.

The absence of masking of one sound by another and the greater annoyance experienced in the presence of

wind turbine noise compared to road traffic noise was confirmed by other studies. Schäffer *et al*. [16] found that wind farm noise was more annoying than road traffic noise, especially when amplitude modulation occurred.

In another study, Michaud *et al*. [17] showed that among 1,238 individuals living between 0.25 and 11.22 km of wind farms, tolerance to wind farm noise was between 11 and 26 dB lower compared to road transportation noise. Hansen *et al*. [18] found that outdoor to indoor noise reduction recommendations were usually based on traffic noise emissions and therefore less efficient in the case of wind farm noise because of its lower frequency. They showed that the A-weighted noise reduction for wind farm noise was approximately 10 dB lower than for traffic noise. Since A-weighted decibels (dB(A)) express the loudness perceived by the human ear, the implication is that humans are naturally less tolerant of wind farm noise compared to road traffic noise.

Health Canada [4] studied the impact of wind turbines on health using a 600-metre perimeter around wind farms in Ontario and Prince Edward Island. As well as a questionnaire, cortisol and blood pressure were measured. A control group was formed of households between 600 metres and 10 km from the wind turbines. There was a significant association between several self-declared medical problems (sleep deprivation, stress, etc.) and measured levels of cortisol and blood pressure. However, the researchers were unable to establish a significant association between these objective and subjective health problems and the proximity of the wind turbines. The study did establish that disturbance regarding noise from wind turbines began at a lower level than with other noise sources (road, rail), and increased more rapidly as the noise became louder.

Janssen *et al*. [19] also found that noise from wind turbines becomes an annoyance at a lower threshold than noise from other sources. Investigating results from studies in Sweden in 2000 (n = 341) and 2005 (n = 754) and in the Netherlands in 2007 (n = 725), they found a relationship between annoyance perceived indoors and outdoors. Whereas in Sweden reported annoyance was higher in rural areas, in the Netherlands it was higher in urban and suburban areas.

The Health Canada study [4] found a significant association between self-declared annoyance and measured noise levels produced by the wind turbines, as well as vibrations, light flickering, the so-called stroboscopic effect, and visual prominence. The increase in annoyance was particularly high when the noise induced by the turbines exceeded 35 dB(A), at night-time, during the summer and whenever people were outdoors. Annoyance was reduced when background noise at night-time was more than 10 dB(A) higher than the noise emitted by the wind turbines. Finally, it was found that annoyance began to decrease after a distance of 550 metres in one area, but only after a distance of 1 to 2 km in another setting. No explanation could be found for these discrepancies.

In Poland, a recent study on 44 participants in laboratory conditions (a studio equipped with a succession of auditory, visual or audio-visual renderings of wind turbines) found that the levels of wind farm noise emissions represent the main factor of annoyance, before the visual aspects or the type of noise they produce [20].

The association between wind farm noise and annoyance has been highlighted by several studies, but the relationship between wind farm noise and actual health issues is more elusive. Below 46 dB(A), no correlation has been found between wind farm noise and health problems, quality of life or stress levels declared by residents living in the vicinity of wind farms [14, 21-23]. What is more, even the level of annoyance reported by residents might be influenced by subjective factors. In a study conducted in Auckland among 60 participants, Crichton *et al*. [24] found that people provided with positive information on wind farms tended to be less annoyed by wind farm noise than people having received negative "expectations".

More recently, studies have shown that health impacts might not be related to noise exposure itself but to noise sensitivity and visual disturbance as expressed by local residents. In Japan, Kageyama *et al*. [25] studied 1,079 adult residents and found that poor health, as measured by the Total Health Index, was not significantly related to noise exposure but to noise sensitivity and visual annoyance. In Ontario, Canada, Jalali *et al*. [26, 27] analyzed pre- and post-exposure of respectively 31 and 37 individuals to wind turbine noise and concluded that health status of participants significantly worsened for those expressing negative attitude towards wind farms, visual annoyance or concerns about property devaluation.

In summary, there is a slight correlation between noise produced by wind turbines and community annoyance. However, the various subjective and objective health complaints of local residents are not statistically associated with the presence or absence of wind turbines in their vicinity. The results published by Health Canada [4] underwent a critical review in 2014 by McCunney *et al*. [28], who also conclude that there is no consistent relationship between health complaints and wind turbines in that study. However, the review pinpoints certain aspects of the noise generated by wind turbines that may increase annoyance, such as intermittency and rhythm. The review mentions that self-declared sleep disturbances increase when the noise generated by wind turbines exceeds 40 to 45 dB(A). However, it criticizes the *coarseness* of some indicators, including sleep disturbance, which are complex phenomena that should be evaluated using more than one question.

A systematic review published in 2015 by Merlin *et al*. [29] covered publications between 1981 and October 2012. At the methodological level, the authors have a word of caution for studies investigating associations between health complaints and exposure where no baseline data

were collected (*i.e.* before the exposure took place). Other methodological issues include participants being informed of the objectives of the study beforehand, potential confounding factors, and the non-generalizability of many of the reviewed studies. According to this review, no significant association between health and exposure to wind turbines has ever been demonstrated.

In Denmark, Blanes-Vidal and Schwartz [30] found no significant correlation between residential proximity to wind farms and health impacts after controlling for other environmental co-exposures. In their review of eight studies including 2,433 participants in total, Onakpoya *et al*. [31] showed that individual attitude could influence responses to wind farm noise. In northern Germany, Yu *et al*. [32] drew a similar conclusion from a study of 20 participants in laboratory conditions: they found that personal attitude towards wind farms was a better predictor of expressed annoyance than wind farm noise.

Infrasound and low frequency sound

Infrasound is usually described as having a frequency below 20 Hz, while low frequency is between 20 and 200 Hz. These two types of sound are very common in natural and man-made environments, typical sources being respectively wind in vegetation, and road traffic. The 20 Hz limit is often considered to be the threshold of human perception. Infrasound can have a physical effect on humans, but it requires a pressure (dB) much higher than what is needed at higher frequencies. Sound between 20 and 60 Hz is perceived as weaker than sounds with similar strength but higher frequencies.

There is much uncertainty regarding the possible health effects of infrasound and low frequency sound generated by wind turbines. Salt and Kaltenbach [33] believe that, given what is known about ear function, it is probable that some effects may be generated by exposure to wind turbines. However, Jakobsen [34] and Leventhall [35] consider that health effects are unlikely, given that the infrasound produced by theses turbines lies below the threshold of perception. Accordingly, it seems difficult to demonstrate a potential health effect if the stimulus being investigated cannot be detected [36].

Published in 2013, an Iranian study [37] tested the mental performance of 90 University students, with an exposure respectively to silence and to low frequency sound (defined in this case to be 10-250 Hz) generated by a computer program based on common sources of low frequency sound: air conditioning or ventilation systems, compressors, car engines, etc. The students working in silence performed better – and faster – on a written test than those submitted to the low frequency sound. However, there was no difference between a sub-group exposed to 50 dB(A) and another exposed to 70 dB(A).

Health Canada [4] tried to tease apart the effects of low frequency sound by using dB(C) measures as well as dB(A) measures. However, the sound levels in dB(A) and dB(C) being strongly correlated with each other, this approach did not enable the study to demonstrate any association between the sound used and the health complaints listed in the questionnaire or the subclinical signs which were observed. The reviews by McCunney *et al*. [28] and Merlin *et al*. [29] both concluded that wind turbines had no demonstrated effect on health through low frequency sound. Published in 2015, a Canadian study [38] also showed that current audible noise-based guidelines were sufficient to protect human health from infrasound and low frequency sound effects.

In their review of seven studies published between 2000 and 2015, Baliatsas *et al*. [39] found only limited evidence of associations between low frequency noise and several health effects including annoyance, sleep-related problems, concentration difficulties and headache among adults living in the vicinity of wind farms. Furthermore, an exposure experiment in laboratory conditions in New Zealand [40] showed that participants provided with nocebo explanations were less likely to report health problems due to infrasound exposure than participants provided with biological explanations.

Wind turbine syndrome

In a review article, Farboud *et al*. [41] analysed various health complaints listed under the umbrella term "wind turbine syndrome" and which include vertigo, migraine and sleep disorders. They conclude that there is substantial evidence that such complaints do exist at significant levels in areas close to wind turbines. It is possible that such problems are secondary to stress, which in turn may be generated or worsened by the presence of wind turbines. The main conclusion of this review is that there is insufficient evidence to prove or disprove a significant effect of wind turbines on health.

At the biological level, Harrison [42] investigated whether it was plausible for low frequency sounds generated by wind turbines to stimulate the vestibular system in the inner ear, which would help explain the appearance of symptoms such as vertigo, nausea or nystagmus believed to be central to the wind turbine syndrome. The investigation concluded that it was unlikely that the inner ear would react to sound below 100 dB, except in the case of subjects with rare pathologies of the inner ear. Although both Farboud *et al*. [41] and Harrison [42] write that there is insufficient evidence to support an effect of wind turbines on health, the former says that an effect cannot be disproven while the latter emphasizes that no effect can be demonstrated.

Strobe effect and moving shadows

The so-called strobe effect or stroboscopic effect is sometimes referred to as the moving shadow (of the blades). The basic problem is that, depending on local

conditions, sunlight as it is reflected or diffracted by the moving blades makes the light impounding on the environment flicker [43]. According to the systematic review by Merlin *et al.* [29], the intensity of this phenomenon is influenced by the number, type and size of the blades, the weather, and other local factors; but a distinction should be drawn between health effects and self-reported discomfort. There are reports that gazing into rotating blades, such as those of a helicopter, may induce health effects in susceptible individuals: drowsiness or vertigo, or even seizures in people prone to epilepsy. As for self-reported discomfort, it increases with proximity to wind turbines and is probably due to *moving shadows* projected onto the local environment. However, confounding and methodological bias may explain some of the results.

According to the National Health and Medical Research Council in Australia, there is insufficient evidence to prove a link between moving shadows produced by wind turbines and an effect on health [3]. In Canada, a study conducted on 1238 participants living in the vicinity of wind farms [44] found that high annoyance to wind turbine shadow flicker was only moderately related to shadow flicker itself, representing around 10% in regression models when controlling for confounding factors. Nevertheless, as a rule of thumb, the area within which such effects may be considered is usually ten times the diameter of the rotor. In their review, Merlin *et al.* [29] note that any provision of extra space between wind turbines and houses based on the desired avoidance of the strobe effect or moving shadows effect should take into account the presence of trees and other large objects in the intervening space, which may reduce such effects.

Safety

Safety issues cover the construction, operation and decommissioning phases of a wind farm [7]. A research team in Brazil [45] investigated the database of the *Caithness Windfarm Information Forum,* containing data from incidents linked to wind farms from the 1970s to October 2011. Among the events listed in the database, the most frequent were a broken blade (20%), fire (15%) and accidents with human injuries (15%). Among the latter category, more than half were fatal (8% of all listed events). Workers associated with the windfarm industry incurred most of the fatalities and injuries, however 28% of the non-fatal accidents and 18% of the fatal accidents occurred to local residents or passers-by. The most dangerous event is when a blade, a blade fragment or a lump of ice (during wintertime) falls off the mast. Documented cases show that such fragments can be projected at distances of several hundred metres: up to 800 metres in one case, but usually no further than 370 metres according to this review.

According to the Brazilian study [45], the risk of a person being hit by such an object is vanishingly small at around 10^{-7} (1/10'000'000) per year. However, the authors caution that the low number of accidents recorded so far may be due to the newness of the technology. Thanks to recent technological progress, safety has widely ceased to be an issue for neighbours although it may remain a problem for wind energy personnel.

Landscape effects

Landscape quality has been consistently associated with quality of life in many countries. Proximity to nature and to green spaces is associated with the strength of social networks and with several measures of mental health [7]. According to Maffei *et al.* [46], a key aspect of wind turbines is their visual impact, which is determined by their number, size and degree of integration into the local environment. These researchers investigated 46 individuals living in rural and urban areas, in Italy, who were immersed in *virtual reality scenarios* with wind turbines varying in number, size, distance, and even colour. Unsurprisingly, the turbines lowest in number and furthest away from the observer were considered most pleasant. White or green masts were considered more acceptable than red or brown masts. Interestingly, the participants drew no significant difference between a scenario with only one turbine and another with three turbines. Both these scenarios were considered more acceptable than one with six turbines. In the Czech Republic, a study on University students [47] suggested that visual annoyance of wind farms diminishes with distance, disappearing after 5 km for less attractive landscapes and after 10 km for highly aesthetically valued landscapes. According to a survey on 604 American hikers in Maine, USA, even when the visual annoyance provoked by wind farms is high, its impact on the enjoyment of activities tends to be limited [48].

The visual aspect of wind turbines was considered by McCunney *et al.* [28] in their critical review, where they found that seeing the turbines increased noise-associated annoyance. A host of individual factors were also linked to annoyance, such as personality factors, economic benefits linked to living close to wind turbines or the time that had elapsed since the turbines had been erected. And it can even be said that annoyance is linked to whether local residents find the turbines *beautiful* or *ugly* [29]. Furthermore, a study on 90 participants in Norway [49] found that visual annoyance was negatively correlated to considering wind farms as a desirable source of renewable energy. A recent study in rural South Dakota, USA, found that local residents considered moving wind turbines more beautiful than static ones, highlighting a possible relationship between economic expectations and visual annoyance [50].

In Ontario, Canada, Baxter *et al.* [51] compared two similar communities, one of which lived close to a wind

farm. They observed that people living close to wind turbines found them more beautiful than people living without that experience. However, McCunney *et al*. [28] caution that the visual and auditory components of the wind turbine experience are so closely correlated that it is not possible to demonstrate a separate effect for each component. They also mention the so-called nocebo effect, by which a negative feeling can be induced by negative expectations. The nocebo effect is well established in medical practice [52, 53] and has been associated with exposure to technological hazards such as electromagnetic fields [54, 55].

Social aspects and real estate prices

When new infrastructure impacts a neighbourhood, it is likely to have a range of social effects. Some of these effects are mediated through civil society organizations that are created to support or oppose wind energy in general as well as specific projects linked to wind energy. Social networks, risk perception and social acceptability are some of the dimensions that have been found to be important when analysing the social aspects of wind farm development [56]. Community participation beginning during the planning stage is important and can help reduce negative perceptions associated with wind energy projects [7].

The perceived equity or *fairness* of wind energy has rarely been investigated, which is surprising because it is unlikely that the population benefitting from a project is the same as the community enduring its negative effects. In their comparison of two communities in Ontario, Baxter *et al*. [51] found that around half of the people living close to wind farms supported them, but only one-third of the people who lived further away. Positive correlations were found between people who supported wind power and those who were convinced that renewable energy was an important policy objective for Ontario as a whole. People in both communities were worried about loss of property value due to the presence of wind farms and about potential inequities regarding the distribution of the advantages and disadvantages of this technology.

Bakker *et al*. [11] and Janssen *et al*. [19] have shown that support for wind energy was higher among people who had received financial compensation. It should be mentioned that revenue, as well as social recognition, are both key determinants of health. A mail survey carried out in 2013 among 1200 residents living in the vicinity of a wind farm in Delaware, USA, showed that the acceptance of wind farm projects depends on social and cultural acceptance. Specifically, people who believed wind energy to be the future of clean energy were more open to wind farms projects [57].

McCunney *et al*. [28] also found that financial compensation reduced the negative effect of wind turbine noise. In their comparative study, Baxter *et al*. [51] investigated potential emerging conflicts in the context of new wind farm projects. They found that the positive aspects linked to wind turbines were more obvious to the community living close to them than to the community living further away. However, the community living further away from the turbines was more concerned about their effect on health than the community living close to them. According to a study in Finland [58] people living in small municipalities are more prone to "nimbyism" (*not in my back yard*) than people living in larger urban areas. This might be related to the visual impact of wind farms in small rural settings. On the other hand, people living in poor communities tend to be more supportive of wind farm projects, because of their potentially favourable economic impacts.

For home owners, the impact of a wind power installation on real estate prices is an important issue, likely to have an effect on future earnings. And revenue is a recognized health determinant. The consequences on real estate values are a matter of concern for neighbours of wind farms, as well as for people living further away [51]. According to a working paper on the topic commissioned by a Swiss local bank, there is a negative correlation between concern about falling property prices linked to wind power schemes and support for such schemes [59].

Three types of impact on housing prices can be associated with wind farm projects. The local impact depends – indirectly – on the proximity of the turbines. If they are close, the area will be considered more industrial than rural and this will decrease the value of the property. The visual impact is the direct inconvenience of having one or more turbines within view of the property. The nuisance impact is linked to noise and to shadows, which might be projected onto the property. Using a hedonic model, Hoen *et al*. [60] analysed the sales of over 7400 properties in the USA, situated between 205 metres and 8 km from the nearest wind turbine. They found no correlation between proximity to a turbine and property prices. More detailed analysis showed that when a wind farm project was discussed or decided property prices tended to go down, but that prices went up again as soon as work on the project began, yielding a neutral effect by the time that the wind turbines were operational.

Studies carried out in the USA, Canada and Germany have not shown consistent positive or negative effects of wind farms on real estate prices. However, a German review on the topic concludes with a word of caution, since the effects of the next generation of wind turbines, with tower heights in the range of 100 to 150 metres, have not yet been investigated [61].

A study from the Netherlands suggests that the negative effect on prices tends to be greater in urban areas, when turbines are larger, and for the first turbine to be installed compared to later extensions [62]. In Portugal, a study showed that the presence of wind turbines was

associated with a cost for local residents, in terms of mitigation measures such as noise abatement strategies [63]. Furthermore, a study in Germany has shown that the value of real estate was strongly impacted by the construction of wind farms in their vicinity and went down by 9-14%, while the value of properties only marginally affected – with only a limited view onto the installations – were not affected [64]. Another study, in the UK, also noted a considerable drop in the value of properties close to wind farms [65].

Discussion

Indirect consequences linked to wind turbine operation can be very positive as regards several social determinants of health (see *figure 1*). However, they typically affect populations at a far greater scale than the neighbourhoods directly affected by wind energy projects. Regarding negative impacts, it is clear from our review that the most important aspects are mediated by noise, which can cause annoyance among people living or working close to wind turbines.

Noise from wind turbines is perceived as more serious in areas where background noise is low. When winds are very strong, background noise from the wind may even drown out the noise produced by the turbines. Therefore, areas with high levels of ambient noise may have a better potential for wind energy generation than quiet areas. These areas may be noisy for natural reasons (ocean coasts) or due to human activities (proximity of transportation infrastructure).

Two trends can be seen in the wind energy industry. The first is the considerable investment and effort put into improving the quality of mechanical systems and materials. This has led to less noise being produced for a given turbine strength. However, this evolution is partly offset by an increase in the size of wind turbines in most countries. In recent years, a four-fold increase in power has resulted in only a two-fold increase in noise.

In this context, a position statement on wind energy issued by the Federation of German doctors in 2015 seems somewhat surprising. In this statement [66], there is a complaint about insufficient research being conducted as well as the assumption that because not everything is known, the technology may have negative health consequences that have not yet been described. In many ways, this position is close to the so-called precautionary principle.

In our view, the precautionary principle may be applied in another way: due to the known negative effects of fossil fuels and the problems associated with nuclear energy, it is necessary to pursue investment in renewable energy, including wind energy. Such investments should lead not only to higher energy efficiency, but also to lower environmental effects. As others before us have argued, it is not necessary to have formal proof of health effects to encourage technological innovation leading to a reduction in noise produced by new generations of wind turbines – especially since some of this emerging technology may also be applicable to existing wind farms, which could therefore be refurbished [8].

It can be seen from this review that people who experience wind turbines being erected in their neighbourhood may experience anxiety and distress. Among the various symptoms that have been examined by the scientific community, annoyance among some of the neighbours is the only one that is backed up by solid evidence. Whether this annoyance – or any other self-declared impacts – is actually experienced is strongly associated with the general attitude of the neighbour towards wind energy. The so-called nocebo effect can probably explain a substantial part of the link between a person's attitude and the annoyance that they feel. This would make wind turbine syndrome part of a wider category entitled "idiopathic environmental intolerance" and which includes electromagnetic hypersensitivity, multiple chemical sensitivity, sick building syndrome, etc. [67, 68].

Within the framework of idiopathic environmental intolerance, the experienced symptoms and the suffering are real, but it has not been scientifically established that they are a physical consequence of the exposure. To take into account the effect of information on risk perception and the appearance of symptoms, the concept of socio-cognitive exposure has been proposed [69]. Such a somatisation of anxiety-inducing information (or of information experienced as such) has been described for a range of environmental sensitivity conditions. Anxiety in turn is an important risk factor linked to cardiovascular diseases [70] and a range of mental health conditions [71].

Finally, the challenges facing the establishment of wind farms certainly also include forms of nimbyism; the loss of value of properties lying close to wind turbines confirms the fact that they generate push-back at local level. It is therefore essential to respect feelings of equity (or inequity) experienced by local residents. It is up to decision makers, including wind energy investors and politicians, to ensure a fair distribution of the economic and health-related advantages and inconveniencies of this form of energy. By placing the debate in the general context of public policy, it is possible to show that developing this form of renewable energy brings substantial health benefits – and even a reduction in healthcare costs. In the USA, a recent study estimated that around 90 billion USD had been saved in the field of public health between 2008 and 2015, thanks to wind energy [72].

Based on our review, we recommend the following checklist when developing wind farm projects:

– 1. It is important to recognise what local residents feel about the construction of wind turbines in their neighbourhood, even if they are not affected physically.

– 2. We suggest an open development process, including the participation of the resident population. This population should be associated with all decision making and their points of view should be taken into account. The empowerment of affected populations is a central tenet of health promotion. Its efficacy and usefulness have been demonstrated in many settings across the world. Empowerment also tends to increase the acceptability of projects.
– 3. Make the management of the wind farm local. By turning on or off, or by changing the operating speed according to the time of day, weather conditions, etc. a *modus vivendi* can be found between energy generation and healthy living conditions for the community.
– 4. Because the visibility of the turbines is a significant problem for their acceptability but is not necessary for their successful operation, they should be erected in areas visible from as few viewpoints as possible (or only at a distance). Institutions such as schools and hospitals require special consideration since it has been demonstrated that noise from wind turbines may reduce concentration and can be dangerous for mentally impaired individuals.
– 5. Use the rule-of-thumb exclusion zone: no housing should be within a radius equal to ten times the height of the mast. In addition, because of the risk of debris being projected from the summit of the mast, minimal recommended distances are 60 metres from a railway line, 90 metres from a dike, and between 40 and 90 metres from a water pipe or electric cable [according to Ref. 45].
– 6. In order to reduce the effect on the landscape, white or green colours can be chosen for the masts.
– 7. The number of wind turbines is important. Wind farms have better acceptability if they are relatively small.
– 8. The loss of property value is an important concern for local residents and has a high impact on the acceptability of projects. It is therefore important to monitor housing prices in affected areas before, during and after the implementation of wind energy projects.
– 9. We suggest carrying out rapid participatory health impact assessments for all sizeable wind energy projects. The aim of such assessments is not to undermine the acceptability of the project but, on the contrary, to increase its feasibility and acceptance by increasing the recognition of positive health effects related to the project. ■

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