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Noise pollution from wind turbines and its effects on wildlife: A cross-national analysis of current policies and planning regulations

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ABSTRACT

The quest for cleaner energy has caused governments to expand renewable energy infrastructure, including wind turbine farms. However, wind turbines (WTs) can also pose a risk to certain wildlife species, with wildlife-related research predominantly focusing on the potential harm caused to birds and bats from impact injuries. New evidence suggests that WT noise (WTN) impacts on wildlife can also be detrimental to wildlife, but rarely receive attention from planners. Potential types of WTN impact, including damage to wildlife physical wellbeing, vital survival mechanisms, social and reproductive processes, and habitat continuity. This article reviews the current literature on WTN effects on wildlife, and analyzes the planning guidelines relating to WTN and wildlife in three selected locales where WT infrastructure is being expanded: California, Germany, and Israel. Findings indicate that none of them have clear zoning limitations or obligatory environmental impact assessment (EIA) guidelines that require addressing the WTN effects on wildlife. However, some steps taken by planning authorities suggest potential for improvement. These include language in California planning recommendations addressing the potential effects of WTN on wildlife; a German survey of local bird species' sensitivity to noise (including a WTN section); and increasing non-obligatory recommendations that encourage distancing WTs from protected areas. The study concludes that WTN effects on wildlife could be mitigated by gathering additional scientific data on WTN impacts, mapping species presence and auditory sensitivity to provide information for planners and advisors, and mandating the use of better science-informed practices and technologies for WTN reduction, such as long-term monitoring, zoning, and micro-siting.

1. Introduction

Anthropogenic noise has dramatically increased in recent decades because of population growth, urbanization, expanding transportation networks and intensifying resource extraction [1], making it an intense, widespread disturbance. A growing body of evidence suggests that anthropogenic noise may detrimentally affect wildlife populations, communities, and ecosystems. The current, substantial development of renewable energy infrastructure, specifically wind turbines (WTs), has created a relatively new concern that wind turbine noise (WTN) might adversely affect wildlife. This requires the attention of scientists and planners alike. While impact injuries that WT blades cause to birds and bats have received much attention in the literature (e.g. Refs. [2–4], the effects of WTN on wildlife remains insufficiently explored [5,6].

While wind energy is considered a cleaner alternative to fossil fuels and plays an important role in the mitigation of climate change, WTs often meet resistance on local and national levels. They have been criticized for alleged direct and indirect impacts on multiple counts, including the wellbeing of neighboring residents, landscape aesthetics, and real-estate value. Today, allegations regarding WTN's potentially harmful repercussions for humans are examined, becoming another reason for communities, governments, and other organizations to object to erecting windfarms in certain areas. In many cases, this has led to establishing specific planning and zoning regulations regarding the siting of wind turbines near residential areas [7]. The effects of WTN on animals are considered in several studies pertaining to WTN effects on farm animals (e.g. pigs and geese) [8,9], and some attention has also been given to regulatory attitudes towards potential WTN effects on

Abbreviations: WT, Wind Turbine; WTN, Wind Turbine Noise.

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farms and farm animals (e.g., Hansen and Hansen 2020 [10]), but not wildlife (except for Rabin, 2006 [36]).

The effect of WTN on people has been studied increasingly in recent years, with a wide range of findings and conflicting conclusions regarding its impact on human health and wellbeing. Some studies consider WTN an annoyance similar to or even greater than other forms of industrial noise or traffic noise [11]. Other studies differ greatly in their findings and suggest that some alleged physiological effects of WTN on humans, especially in locations more than 500 m from WT farms, are minimal, partial, or highly affected by psychological factors, with literature reviews finding that direct correlation existed only with general annoyance and sleep disturbance (e.g., Refs. [11–14]). Low Frequency Noise (LFN) (<20 Hz) has been addressed in these general WTN studies, but has also received specific attention by some researchers, who found direct correlation only between LFN emitted from WTs and sleep disturbance in residential areas in proximity to WT farm [15–17]. Nevertheless, recent work on WTN effects on humans in relation to planning has suggested that WTN disturbance for humans should be considered in planning and legislation, and asserts the need to set a noise limit for WTN, similar to other noises [18].

In terms of WTN effects on wildlife, the focus of this study, there is evidence that WTN could have negative impacts on habitat quality and wildlife [2]; Dooling et al., 2002; Dai et al., 2015). As onshore windfarms are often located in rural or other non-urban areas [19], the impact of WTN on the natural acoustic environment is particularly important. However, as shown below, while the potentially adverse effects of WTN on humans are being studied and regulated by planning and building laws, the same scrutiny has not been applied to examining or reducing potentially adverse effects of WTN on wildlife. The impact of noise pollution on wildlife is still largely ignored in environmental impact assessments (EIAs) during planning processes, and there is insufficient mapping of wildlife species and their noise sensitivity, even in areas considered biodiversity hotspots [2].

In this paper, we first review the current literature on the potential effects of WTN on wildlife, and the various factors that could contribute to these effects. We then examine and analyze the current planning solutions and regulations put in place to reduce harmful WTN effects, using three case studies of places where environmental planning regulations address WTN with respect to humans: US (California), Germany, and Israel. Lastly, we discuss whether these adequately address the short and long-term negative effects of WTN on natural ecosystems and wildlife species, or if additional measures should be taken.

2. Wind turbine noise

2.1. Potential effects of noise pollution and wind turbine noise on wildlife

Noise pollution influences the acoustic environment even far from anthropogenic centers, in remote areas that include critical habitats for endangered species [20]. Noise pollution negatively impacts wildlife by disrupting mechanisms that are crucial for their survival [5,21,22]. In particular, noise can: 1) cause physiological damage such as chronic, high levels of stress hormones [23], or actual hearing loss [24]; 2) be directly perceived by animals as a threat, causing them to increase costly anti-predatory behaviors at the expense of foraging, or flee the affected area altogether, leading to functional habitat loss [25]; 3) distract foragers, reducing their efficiency of finding and handling food (Dominoni et al., 2021); 4) hinder animal communication by reducing the distance at which a signal can be detected [26], limiting the ability of the signal to reach its intended recipient, and decreasing the amount of information that can be extracted from a signal, such as the sound of an approaching predator or potential prey [27,28]. These mechanisms are not mutually exclusive, and the role that each plays in determining the impact of noise pollution varies by species. Not all species react to noise in the same way, due to differing sensitivities to noise, context, and life-history [1,5]. Overall, noise pollution alters animals' communities, reduces their overall survival and fitness, and contributes to the decline of global biodiversity [22].

While the number of studies on the impact of noise pollution on wildlife is increasing [29], very few focus on WTN [30]. Nonetheless, dedicated studies on WTN are important given that properties of sound, location of its source, and spatial propagation have all been found to vary greatly between land uses, and be crucially significant for determining the type and extent of anthropogenic noise effects on wildlife [1,31]. Traffic is the most widely studied source of anthropogenic noise [29]. [32] compared the spectral properties of WTN and traffic noise, and suggested that a combination of highway noise and WTN might create a greater, more complex disturbance, rather than one masking the other. Specifically, WTN alters the natural acoustic environment by inducing airborne loud broadband sound [33] which is within the hearing range of many animals [34], including most bird species [35]. A few other studies have also looked at the effects of WTN on other wildlife with mixed results. For example [36], found that WTN affects the California ground squirrel's antipredator behavior, causing a higher level of alertness attributed to loss of auditory capacities.

Despite the dearth of studies concerning the effects of WTN on wildlife, they have generated some insights that could contribute to understanding the ecological impact of WTN. In general, it has been shown that noise pollution affects species demography (i.e., community composition, population density) and promotes habitat avoidance (e.g. Refs. [1,29], because noise alters animals' habitat selection. Several studies have demonstrated the impact of WT on demography and habitat avoidance, mostly in birds (e.g. Refs. [37,38], but also in other taxa such as mammals [39]. Very few studies have been able isolate and connect habitat avoidance specifically to WTN (e.g. Ref. [40], but Lehnardt et al. (in review) recently teased apart the effects of WTN on songbirds experimentally, by broadcasting the sound of a wind turbine in the field and showing that this significantly reduced the number of birds present. Furthermore, the existing literature implies that WTN alters birds' vocal communication, with possible implications for reproductive success [30,41,42].

Buxton and colleagues [20] argue that protected areas experiencing high levels of noise pollution must be identified and managed appropriately, and that noise pollution merits consideration as a serious threat to biodiversity. Moreover, Francis and Barber [5] suggest that noise pollution must be addressed using a combination of tools, technologies, and techniques, many of which are already available. They also advocate to include considerations pertaining to noise pollution in the planning and management of protected areas, adding that different types of noise can affect wildlife in various ways. Despite the current dearth of studies examining the direct effects of WTN on wildlife, there is already sufficient knowledge accumulated on the impacts of noise pollution, and the effects of WT on avoidance behavior in birds and mammals in response to the spectral properties of WTN. Therefore, WTN should concern planners and policy makers who seek effective guidelines for the sustainable planning of wind farms.

2.2. Factors influencing the acoustic effect of WTN

WTN can be divided into two types, according to the origin: *mechanical and aerodynamic*. Mechanical WTN is produced by the turbine's moving components (gear box, generator and bearings). The normal deterioration of these parts over time, the use of substandard parts and inadequate maintenance contribute to increased noise production. Mechanical noise can be decreased by appropriate design (e.g., adding insulation), proper and regular maintenance, and using high-quality parts [7,43]. Aerodynamic WTN is the noise produced when the wind passes the turbine blades. It increases in correlation with the speed of the rotor, and can be influenced by several other factors, such as atmospheric turbulence that can create a "whooshing" sound [44], wind direction and wind speed [45]. Aerodynamic WTN can be somewhat reduced by changing the design of the turbine blades prior to manufacture [7].

The direction in which WTN is emitted has also been found to be an important variable for its effect on the acoustic landscape. The pattern of sound radiation or "*directivity of sound*" can vary, and the angle of the acoustic range around the noise source can be more or less acute or obtuse [46] although the average noise angle for WTN is approximately 120° (calculation based on Friman, 2011). Several variables can influence the directivity of the "whooshing" aerodynamic sound of WTs, which is the dominant source of WTN. They include the angle of attack (i.e., the angle in which the wind meets the blade), wind velocity, blade shape, blade tip velocity, and turbulence in the air. Additional variables, including weather conditions such as temperature or cloudiness, as well as background noise, might also influence sound directivity and mapping measurements [46]. Furthermore, WTN levels depend on environmental conditions and can greatly differ between nighttime and daytime. Increased levels of WTN at night may be attributed to the stable night-time atmosphere that causes high wind shear [11,47].

Sound can be considered as either *sound power* or *sound pressure*. Sound power is the total acoustic power emitted by a source and can be used to predict how far the sound will travel and what the sound levels could be at various distances from the source. It is measured at the source, making it independent of the dB level where it is received. Conversely, sound pressure reflects the sound level received and perceived by the listener. For observers distant from the source, the sound pressure decreases, as the sound moves farther from the source. This distinction is important, because WTN measurement and solutions could focus on either reducing the noise at the source (i.e., lowering the level of noise emitted by the turbine), which would require the development and implementation of new technologies; or on reducing the level of noise experienced by the receiving side, which might be achieved using acoustic barriers, zoning, or micro-siting.

The amplitude, frequency, and sequence (i.e., temporal pattern) of WTN can differ widely, and dramatically change the type and level of WTN impact on humans and wildlife. Most studies of the effects of WTN on people pertain to low-frequency noise, between 20 and 200 Hz. Outdoor WTN levels upwards of around 40 Hz normally exceed the hearing thresholds of indoor areas, although this might vary depending on noise insulation standards [48]. Sound frequency is also important when addressing WTN effects on wildlife, since WTN is usually characterized by a broad band range, with changes in the WTN spectrum observed in the frequency range of 200–5000 Hz [49], which overlaps with the hearing range of many wildlife species [34], particularly birds [35]. Wind turbines also emit a low frequency noise that is out of most people's hearing range, including very low frequency noise (<20 Hz) that some refer to as "infrasound" or "infrasound and low frequency noise" (IFLN). It is still unclear whether IFLN has any influence on human health or wellbeing in situations where turbines are too distant for audible noise to be detected. However, a few states have decided to take the precautionary approach and address resident claims in some cases [14,15]. While the perception of IFLN has been documented in several mammal and bird species [16], the extent to which the infrasound component in WTN impacts wildlife is yet to be thoroughly examined.

Size, particularly diameter, is key to turbines' capacity to produce energy. Turbine technology has developed exponentially in the past few decades, with capacity now reaching up to several megawatts (MW) per turbine [50]. A growing trend is using larger turbines, with larger blades, which produce more electricity, because they can harness higher winds, even in areas where there is little wind close to the ground. For instance, US Department of Energy data show that the average height of wind turbines (from ground to blade tip at 12:00 position) increased from 95 m in 2000 to 140 m in 2016, with 50% of the turbines having blades longer than 110 m [51]. However, turbine size does not correlate with noise level, as smaller turbines are actually noisier for their size, because the rotational speed of the blade tips is faster, and because more research and resources have been invested in reducing noise from large turbines [52].

Available technology and best practices offer solutions for decreasing the damage caused by WTN, either by lowering noise levels at the source, so WTs emit less noise or by creating noise buffers between WTs and residential areas or other areas of interest. The first category includes solutions such as blade design [7] and turbine insulation [48], as well as using high-quality parts and ensuring good maintenance [7,43]. The second category includes physical barriers such as noise attenuation walls [53].

In addition to factors inherent to WTN, the traits of various animal species are also central to determining the impact of WTN on wildlife. Different species respond differently to noise pollution, and this variability is dependent on the species ecology, life-history, and physiology e.g., frequency hearing sensitivity, including ability to hear low-frequencies. Future development of WT, which is predicted to include increases in height, rotor diameter and speed, might further complicate our ability to predict the impacts of WTN. These changes may lead to an additional or altogether different set of species being impacted by turbines [53]. As wind energy is further applied and developed in coming years, unknown long-term effects could change WTN impact. Assessing its cumulative effects will become even more crucial and pose yet another challenge for impact assessment. While long-term WT operation could result in increased habituation to noise in some species, it could also create large-scale habitat fragmentation, while also interacting with other anthropogenic disturbances (e.g., light pollution) and lead to reduced population viability for reasons that are difficult to understand or measure [5,53].

3. Findings from three case studies: planning regulations for mitigating WTN impacts and protecting wildlife

The current study includes an in-depth analysis of WTN-related policies and planning documents of three case studies: California, Germany, and Israel. Like many others, these three states are attempting to slow global climate change by reducing GHG emissions and increasing the amount of energy produced using renewable sources, mainly wind and solar. These installations require developing new and better regulatory procedures to mitigate their impacts on the landscape, environment and humanity [54]. Other than Germany, most OECD states regulate the effects of WTN only with respect to residential areas, and do not relate to wildlife in protected or sensitive areas. Koppen and Fowler's [55] overview of WTN regulations in Belgium, Denmark, Finland, France, Germany, Sweden, Australia, Canada, and various US states, shows that Germany is the only country where permitted noise levels for certain rural areas are lower than those of residential areas, indicating that only Germany has enacted additional WTN safeguards for protected natural areas (which are almost exclusively situated in rural areas).

After a preliminary review of various WTN-related documents from OECD countries, we chose these case studies because they offer variety in terms of geographic location, size, the number and size of current and proposed WT farms, and planning guidelines and regulations that pertain to WTs, noise, wildlife, and zoning (see Table 1). However, there are some similarities between the cases: they are all in OECD member-states that have access to advanced scientific data and technologies, are currently promoting policies that support the development of renewable energy and its related infrastructure; they generally have advanced guidelines for WT planning that include multiple environmental aspects; and have some regulatory guidelines and recommendations already in place that address both the general effects of WTN (focusing mostly on humans), and specific guidelines to protect wildlife and habitat. A preliminary review of OECD states' planning guidelines was used to select the case studies, and revealed that in these three states there is some response related to the issue of WTN effects on wildlife, albeit limited. Preliminary interviews with environmental planners in these countries have indicated that there is a limited but growing

Table 1
Background data.

Locale	Population (millions)	Size (km^2)	Density (inhabitants/ km^2)	Wind energy production in 2020 (GWh)
California	39.5	423,970	97.9	13,680[a]
Germany[b]	79.9	357,022	223.8	50,700[c]
Israel[d]	8.8	21,937	401.1	0.027 (27MW)[e] *(Goal: 0.5 GWh in 2025)*

[a] California Energy Commission, 2019 Total System Electric Generation. https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/2020-total-system-electric-generation/2019.
[b] CIA (Central Intelligence Agency), World Factbook: Germany: Introduction, Geography, https://www.cia.gov/the-world-factbook/countries/germany/#introduction.
[c] Frauhofer Institute for Renewable Energy Systems, https://www.ise.fraunhofer.de/en/press-media/news/2020/public-net-electricity-generation-in-germany-2020-share-from-renewables-exceeds-50-percent.html (Retrieved August 17, 2021).
[d] CIA, World Factbook: Israel: Geography July 2021. https://www.cia.gov/the-world-factbook/countries/israel/#geography. Numbers including the Golan Heights and East Jerusalem, excluding the Gaza Strip and West Bank.
[e] Israel's Electricity Authority, Report on the Status of the Energy Market: August 2020. https://www.gov.il/he/departments/general/dochmeshek.

awareness of the potentially harmful effects of WTN on wildlife.

In the case studies, we examined the statutory guidelines, regulations, and official requirements regarding wildlife, noise, and zoning applicable to developers who propose new wind energy farms, in order to better understand the current WT planning situation, and whether there might be some regulatory basis for addressing or mitigating WTN effects on wildlife. In each case, we addressed the general guidelines for the locale, including the differences between California counties and German states (*Bundesländern*), if any. For California, the documents examined included federal guidelines (i.e., U.S. Fish and Wildlife Service Land-Based Wind Energy Guidelines, 2012, expiring Nov. 30, 2021), the California Energy Commission and California Department of Fish and Game California Guidelines for Reducing Impacts to Birds and Bats from Wind Energy Development, 2007 [56], and county-level documents from the eight California counties where the largest WT energy producing projects in the state are currently located (CalWEA, 2021).[1] For Germany, the study examined national government documents, focusing mostly on official documents of the German Ministry of Economy and Energy (*Ausschreibungs-spezifische Regelungen für Windenergieanlagen an Land*, FWE 2021a) that address WT planning guidelines for developers and other documents dedicated to the issue of zoning for WT farms (*Zusammenstellung der Bund-Länder Initiative Windenergie*, FWE 2013; *Überblick zu den Abstandsempfehlungen zur Ausweisung von Windenergiegebieten in den Bundesländern*, FWE 2021b). These documents also detail the differences between the different states. For Israel, which is still at the preliminary stages of large-scale wind energy production, and has a centralized planning authority with a single set of national environmental regulations for wind energy, we reviewed the current planning guidelines and the requirements from wind energy developers, seeking approval under the Israeli national plans for wind turbines (NOP 10/d/12) and energy infrastructure (NOP 41).

As in many other developed countries, planning tools in California, Germany and Israel focus predominantly on zoning and restrictions pertaining to the minimal distance of WTs from residential areas, as well as maximal decibel (dB) noise levels that may relate specifically to WTN or to overall levels of noise pollution from any anthropogenic source. They require an environmental impact assessment (EIA) before approving a WT project, with some attention to WTN, including not just sound pressure levels but also distinction between daytime and nighttime levels, indoor and outdoor levels, and different land uses (e.g., parks and beaches as in Germany (. In several cases, rural areas and urban areas are also treated differently in terms of sound pressure levels allowed. In some places higher noise levels are allowed in rural areas and elsewhere the opposite is true, which already hints to the complexity and ambiguity that currently exist around noise pollution from WT. The following review covers the regulations, guidelines, and tools currently applicable in each jurisdiction, as they relate evaluating and mitigating of WTN in general (often only for population centers), and other potentially relevant tools and guidelines that address the impact of anthropogenic noise on wildlife, and which might be employed in the case of WTs.

3.1. California (USA)

3.1.1. Zoning

Zoning is heavily dependent on county regulations, with permits for wind projects issued on the county level. Guidelines for WT planning have also been published at the state and federal levels, although these are often outdated and are offered as voluntary steps or general recommendations, as opposed to obligatory regulations [57].[2] A report written by the California Energy Commission (CEC) and California Department of Fish and Game (CDFG) in 2007 [56] offers voluntary guidelines for reducing the impacts to birds and bats from wind energy development, and upholding California Environmental Quality Act (CEQA) recommendations, which are often necessary to procure a permit for wind energy projects. In terms of zoning, these guidelines suggest adhering to county or city ordinances, although they state that "Some county ordinances include language regarding assessment of impacts to birds and bats, but, currently, none provide specific guidance on studies necessary for assessing significance of impacts to bird and bat populations or provide direction for monitoring programs and feasible mitigation options" [56].

On the county level, several California counties require that proposed projects found to have significant potential environmental impact relate to CEQA recommendations and require an Environmental Impact Report (EIR) [58] [2] (see also California Energy Commission, 2019). Developers need to request a permit from the county, in accordance with expectations stipulated by the county for the specific project. The developers then hire private consultants to assist with preparation of the environmental review documents that they must submit to the county. In California, the US Fish and Wildlife Service also must be consulted regarding an "incidental take permit for eagles" [57].

There are differences in zoning regulations between counties within California when it comes to wind energy projects. For instance, in Imperial County [58], the WT regulations address not only permitted areas, but also a maximum permitted continuous sound level (CNEL 70 dB), "measured at the nearest human receptor site outside the parcel boundary," or 0.5 miles from the sound (whichever is greater) (p.2). In Solano County, the guidelines do not include a WTN distance caveat but do include requirements for spacing between the wind turbines, along roads, dwellings, and property lines California Wind Energy Collaborative, 2006 [59], a topic not addressed in the Imperial County

[1] There are eight main wind energy installations in California. In size order, they are Tehachapi Pass in Kern County (2925 MW), Solano County (1028 MW), San Gorgonio Pass in Riverside County (655 MW), Altamont Pass in Contra Costa, San Joaquin, and Alameda Counties (330 MW), Imperial County (264 MW), San Diego County (181 MW), Shasta County (101 MW), and Pacheco Pass in Santa Clara County (17 MW) (California Wind Energy Association, CalWEA, 2021).

[2] Shawn Smallwood, counseling ecologist for the Alameda County Scientific Review Committee (SRC), 2006–2011, previously counseling ecologist for the California Energy Commission (2004–2007), personal communication on renewable energy impacts, February 16, 2021.

guidelines (p.10).

Some counties in California also require a safety setback distance from adjacent properties and structures. In these guidelines, the distances differ for buffer zones and required distances between wind projects and other land uses. These distances are stated with varying degrees of clarity and specification, primarily addressing safety concerns such as prevention of damage or injury due to accidental blade-throw. For example, in Almeda County, required distances are 91 m from a property line, and 152 m from dwellings. In Contra Costa and Kern counties, the distances are 152 m from property lines and 305 m from dwellings. In Riverside County, the required distance is 152 m from a residential lot line. In Solano County, distances from both property lines and dwellings are 304 m. Each county also provides a variety of additional requirements and exceptions, such as Alameda County's adjustments for sloping terrains, with safety setback distances also pertaining to roads and highways, which are often adjusted for WT height and other factors. It should be noted that the reason for these safety setbacks is usually not WTN-related; rather they are precautions related to accidental blade throw (i.e., blade failures resulting in projectiles) [56,57].

3.1.2. Environment and wildlife

Generally, impact assessments are done in lieu of recommendations from agencies like the US Fish and Wildlife Service (USFWS). USFWS has posted guidelines intended to "encourage scientifically rigorous survey, monitoring, assessment, and research designs proportionate to the risk to species of concern", but these are not official requirements that wind project developers must uphold. As USFWS document itself states, the wind energy guidelines are voluntary recommendations [60]:11).

In California, state and local public agencies must comply with the California Environmental Quality Act (CEQA) before giving a project discretionary approval. A project is compliant if the proposing agency either 1) determines if a project is exempt from CEQA; or 2) if it prepares an environmental analysis which could be one of three types: (a) a negative declaration (ND); (b) a mitigated negative declaration (MND); or (c) an environmental impact report (EIR). Either an MND or an EIR analyzes a project's main environmental effects, address compliance with environmental laws, guidelines, and regulations, and suggest feasible measures to avoid or mitigate those effects. An EIR also offers alternatives to the project [61]. Some California counties include the need to comply with and address CEQA guidelines and submit an EIR for WT in the relevant county regulations and approval process, as for example, Imperial County [62], and Kern County [63].

Nevertheless, CEQA is self-proclaimed to be very broad, and developers are required to use feasible alternatives or mitigation measures to decrease environmental effects only if a site is determined to have a significant environmental impact. If there are no options that are easily applicable or economically viable, developers can usually get around the provisions of this act. They would then fall back on the recommendations made by agencies like the US Bureau of Land Management (BLM) (in the case of land managed by BLM), or the California Department of Fish and Wildlife [57].

Government regulations are similar regarding risks to bats and birds. In California, the CEC & CDFG 2007 government recommendations categorize potential wind sites into four categories based on the bat and bird fatality rates, with one being low risk to four being high risk to bats and birds [56]. However, an EIR is not required for each site. More specific recommendations are outlined, but again, none of them are legally mandated [59]. Nevertheless, developers who choose not to follow CEQA guidelines expose themselves to potential lawsuits, which in turn could slow project development, require additional changes to the project, or even stop the project entirely. Therefore, developers might choose to follow voluntary guidelines to avoid potential losses that could end up costing them much more than earlier compliance would have.

3.1.3. Noise

Noise regulations are solely concerned with humans, with standards for permitted WTN sound levels varying by county. However, the Fish and Wildlife Land Based Energy Guidelines (2012) do briefly address the issue of WTN on wildlife, and mention that there is scientific evidence that WTN can cause damaging effects on wildlife:

Turbine blades at normal operating speeds can generate levels of sound beyond ambient background levels. Construction and maintenance activities can also contribute to sound levels by affecting communication distance, an animal's ability to detect calls or danger, or to forage. Sound associated with developments can also cause behavioral and physiological effects, damage to hearing from acoustic overexposure, and masking of communication signals and other biologically relevant sounds (Dooling & Popper, 2007). Some birds are able to shift their vocalizations to reduce the masking effects of noise. However, when shifts don't occur or are insignificant, masking may prove detrimental to the health and survival of wildlife (Barber et al., 2010). Data suggest noise increases of 3 dB–10 dB correspond to 30% to 90% reductions in alerting distances for wildlife, respectively (Barber et al., 2010) (page 46).

However, they add that there is still a need for more data to achieve an adequate understanding of WTN impacts:

The National Park Service has been investigating potential impacts to wildlife due to alterations in sound level and type. However, further research is needed to better understand this potential impact. Research may include: how wind facilities affect background sound levels; whether masking, disturbance, and acoustical fragmentation occur; and how turbine, construction, and maintenance sound levels can vary by topographic area." (Fish and Wildlife, 2012, p. 46).

Finally, studies of potential or existing WTN effects on wildlife, as per the USFWS guidelines, belong to a category "Tier 5 studies," which the guidelines state are usually conducted only in cases of substantial current or foreseen fatalities of a proposed project. The USFWS guidelines also clearly state that for most projects Tier 5 studies will not be required or conducted (Fish and Wildlife, 2012, p. 46; Smallwood, 2021).

3.2. Germany

3.2.1. Zoning

German regulations for wind energy planning differ between states (*Bundesland*), with some also including multiple zoning criteria for wind farms, in order to address distances from land uses related to wildlife or nature-related, protected areas. In 2021, the German Agency for Wind Energy on Land (*Fachagentur Windenergie An Land*) published a report summarizing the zoning guidelines for different size WTs in each state. Despite the great variation between states, it is nonetheless evident that at least some have enacted zoning measures to reduce the effects of WTs on valuable natural habitats, areas of natural landscape and heritage, and nature recreation sites.

The report first describes the suitability of each region for WT farms, and then outlines the regulations in each state for each type of land use. The required distance of WTs from residential areas varies from 400 m to 1100 m, with most requiring a minimum distance of 1000 m. In some states, sparsely populated areas require a smaller distance and some set distances based on WT rotor size, or locally permitted noise levels. In Baden-Württemberg, all distances are determined on a per-case basis. (*Fachagentur Windenergie An Land,* 2021 pp. 5–6*)*.

3.2.2. Environment and wildlife

A range of distances, from 300 m to 1000 m or set on a per-case basis, are prescribed for wildlife and habitat-relevant zoning, including open space with special rights for protected/open space networks, priority nature and landscapes, nature reserves, national parks, nature parks, landscape protection areas, protected forests/recreational forests, slopes and knolls that are characteristic of a particular landscape and distinctive landscape horizons (lines of sight) (*Fachagentur Windenergie An Land*, 2021, pp. 5–6). Zoning distances, between 50m and 500 m, but up to 1000 m for officially protected areas, from WT are also set for legally protected biotopes; bat habitats; bird breeding, nesting, feeding, and resting areas; sensitive or protected areas for local, endangered, and migrating bird species; and any areas protected under federal or EU regulations, including under the EU Bird Habitat Directive (*Fachagentur Windenergie An Land*, 2021, pp. 6–7). Some zoning restrictions (distancing by 50m–1000 m or per-case), apply other potentially relevant areas including protected, sensitive, and large bodies of water on land (rivers and lakes), water sources, and flood plains (*Fachagentur Windenergie An Land*, 2021, pp. 7–8).

3.2.3. Noise

Germany has taken one more step than other countries when addressing the effects of noise on wildlife, particularly birds. The Kieler Institute for Landscape Ecology (*Kieler Institut für Landschaftsökologie*) published a special report after conducting an extensive survey of local birds' sensitivity to traffic-related noise (including noise emitted by trains), in cooperation with the German Federal Ministry of Transportation, Construction and Urban Development (*Vorhaben des Bundesministeriums für Verkehr, Bau und Stadtentwicklung*). The report includes a general description of noise thresholds for local species and common migrating species in Germany, suggesting that traffic noise can disturb birds' attentiveness to predators and other dangers, disrupt their communications with each other and have other negative effects. The influence on each species varies according to time of day, the birds' specific reproductive cycle and breeding status (Garniel et al., 2007).

The Kieler Report (2007) observes that the flight patterns of some species, including geese, ducks, cranes, and gulls, tend to have wider radii of spatial avoidance around large WTs than around highways and local roads. Although their data suggest that the visual disturbance caused by WTs is likely the main reason for this finding, they also suggest that some birds, especially geese, are more sensitive to WTN than to noise originating on roads and railroads [64](p. 213). In addition to injuries and deaths from collisions, the report considers it highly probable that WTs have a combined audio-visual effect on birds. In conclusion, the Kieler Institute authors claim that data and knowledge about WTN and its effects on bird populations and habitats remain insufficient, while still contending that birds' sensitivity to noise means that WTN should be minimized, without suggesting specific measures [64]. That said, the report notes that acoustic walls would be insufficient for minimizing the effects of WTN on birds, because they often fly higher that the walls.

3.3. Israel

3.3.1. Zoning for WT

Israel's National Outline Plan (NOP) includes Appendix 3: *Guidelines for Promoting WT Plans*, which states that WTs must be placed at least 500 m from any settlement or planned area that includes a residential area. Moreover, special (increased) attention should be given to the potential impacts of erecting WTs up to 1000 m from residential use, without specifying that the reason for this is noise (NOP 41, Appendix 3 §A). Appendix 3 §3.3.D adds that damage to "nature and environmental values" should be minimized, and that WTs should be distanced from heritage and tourism sites, without specifying distances (p. 26). However, the NOP and its appendices do not specifically address ecologically valuable or sensitive areas nor does it include any guidelines regarding the location of WT farms in or near designated protected areas. Some regions, including the Center and Tel Aviv districts, prohibit erecting WTs in undisturbed (natural) areas; although this is allowed in other districts, including the South and Haifa and North districts where most WT projects are planned (NOP 41, §3.2, p. 26).

3.3.2. Environmental and wildlife impact surveys or assessments

In Israel, an EIA is always required for WTs taller than 40 m, but demands vary for medium (18m–40 m), small (4m–18 m) or micro WTs (up to 4 m), depending on the level of environmental/landscape sensitivity and the number of WTs in each wind farm. In some cases, developers must also submit a landscape-environmental addendum (LEA), which is reviewed by the Ministry of Environmental Protection (MEP), and the Israel Nature and Parks Authority (INPA) (NOP 41 draft, 2019, §3.7.1.- §3.7.3). When assessing the effects of WT on wildlife, Israeli regulations focus predominantly on birds and bats, which are the subject of entire sections in the Appendix. The developer must submit a report that examines the primary potential for impact on birds and bats for medium and large WTs, based on existing data, rather than new surveys or active observations. After the report is reviewed by INPA and MEP, the relevant planning authority decides whether there is need for a full bird and bat survey. If so, the survey is done in consultation with the environmental authorities (NOP 41 draft, 2019:28).

NOP Appendix 3 refers to a non-statutory map of areas where birds and bats are vulnerable and developers are asked to consult it, if they wish to promote a WT plan. However, this map does not contain information regarding bird migration, and therefore provides only partial information for assessing potential WT impacts on bird populations. Additionally, if a field survey is done in accordance with the INPA guidelines, it is considered instead of the data on the vulnerability (Appendix 3, §B). NOP Appendix 3 further states that a year-long survey of local and migratory species must be conducted, and a monitoring plan made before the plan is approved. NOP Appendix 4 includes guidelines for direct (collision) and indirect effects, including "nesting sites and different habitats," but does provide further details. The effects of noise or vibration on bird, bats, and other species are not specifically addressed in this appendix or elsewhere in the new national spatial plan for siting guidelines.

As a rule, the LEA and EIA must include a section examining potential impacts on vulnerable fauna and flora, as well as connectivity (NOP 41: §2.1, p. 51), as in the older NOP 10, which was in effect until early 2021. The fact that the spatial outline plan requires particular information regarding birds and bats suggests that collision risk is the main wildlife-related aspect considered, as it is NOP 10, Appendix 3 (NOP 10 §3 and §5.2).

3.3.3. Noise

NOP 10 and NOP 41 include adverse environmental effects on humans, including noise and other environmental factors and ecosystem services as subjects that require preliminary surveys for large and medium WTs in ecologically vulnerable areas (NOP 41, Subsection 4; NOP 10, §3.7). In terms of noise, the minimal distances of WTs from certain areas are determined by adhering to the noise regulations for residential, business, industrial, or rural areas in place since 1990 (§3.9). NOP 41 Appendix 3 states that WTN shall not increase the existing background noise from other permitted activities by more than 5 dB, and that monitoring of loud noise must be conducted with the WT operators.

The level of infra-sound must be measured before the WTs are operational and monitored after the operation has begun. The noise level should not exceed 75 dB (G-scale), or any other maximum stated by regulations. NOP 10 requires developers specify, in the EIA, the measures to be taken for reducing or limiting the effects of WTN (although permitted noise levels are not specified in the spatial plan). If needed, a detailed account must be provided of the "acoustic shielding types which will be used, their technical characteristics and their effectiveness in reducing the predicted noise" (NOP 10, §5.7). According to the latest version of the guidelines, developers must submit a predictive WT noise-level map for all WT models (NOP 41 §6.6.6.a.2), and this is used to ascertain the minimal distance of WTs from any structure (NOP 41, §3.9).

3.4. Discussion: knowledge, tools, and potential planning trajectories

While there is growing evidence indicating that wildlife are at risk from anthropogenic noise (e.g. Refs. [2,33,35], including WTN, only initial steps have been taken to acknowledge, address or mitigate this impact through planning guidelines and regulations, as well as other planning-support tools. There are several measures that could be adopted by countries wanting to support renewable energy development by promoting the use of WT, but who are interested in reducing its adverse environmental effects. Wind farms are often placed in open habitats that are otherwise minimally affected by anthropogenic noise pollution, ones that are more likely to be occupied by noise sensitive species that cannot inhabit more disturbed and noisy areas. Therefore, special consideration must be given to WTN at these sites, with emphasis on its impact on wildlife.

The current study of WTN-related planning regulations in California, Germany and Israel did not find any obligatory planning regulations focused on addressing WTN effects on wildlife. Standards and zoning restrictions currently focus on noise disturbance in residential areas or on mitigating other types of potential WT-related environmental threats, e.g., impact injuries to bats and birds, visual disturbances, blade throw. Nevertheless, there are relevant guidelines and official documents addressing zoning, environmental concerns including wildlife, or WTN in general that offer voluntary guidelines and could be a useful starting point for further thinking about how the effects of WTN on wildlife could be mitigated by environmental planning efforts.

When planning processes address the impact of WTN on wildlife, WTN should be kept in context and compared to other anthropogenic activities, especially noise and other types of pollution originating in fossil fuels and alternative energy sources [53]. Currently, however, this might prove unfeasible, due to the lack of scientific or operational data, without there being any governmental targets for obtaining such data. These data would be an important resource when calculating environmental trade-offs and policies for planning scenarios for WT and the development of alternative renewable energy sources. Indeed, the lack of ecological scientific data on the effects of WTN on wildlife constrains many environmental and spatial decisions. A key challenge when assessing the effects of WTN on wildlife is separating it from other potential disturbances, such as blade impact injuries, flickering, or changes to the natural landscape. This might be overcome at the pre-implementation phase by experimentally broadcasting recordings that accurately reproduce the acoustic properties of WTN, and then quantifying the effects of the noise on the surroundings.

The nation-wide Kieler Institute survey [64] of local and migratory birds in Germany attempted to assess the effects of noise on wildlife, including the general and species-specific noise impacts, vulnerabilities, and thresholds. Despite measuring sensitivity to traffic noise rather than WTN, it provides valuable information by identifying the species that are most affected by noise. Similar surveys, which could be based on knowledge and monitoring data already collected by diverse scientists and institutions could provide a much-needed source of information for WT planning, and potentially have significant influence on whether the issue is addressed at all. Translating the findings of these surveys into specific planning guidelines and regulations could then be a next step towards the practical application of the insights gleaned from their data. The time that has passed since first official report in Germany that mentions scientific evidence for the impact noise has on birds suggests that action lags behind scientific findings. This is unsurprising considering the challenge of taking into account all the potential adverse impacts of infrastructure, especially in land-scarce regions. In the case of wind turbines, there are competing values and targets because of the urgent need to advance renewable energy as a key strategy for mitigating climate change.

The negative impacts of WTN can be greatly reduced. One type of solution is technical or mechanical, namely using better technologies, materials, and maintenance to minimize the noise emitted from WTs at the source. A second type of solution is installing acoustic walls to limit the dispersion of WTN to sensitive areas, although these are deemed less useful for protecting birds [64] and could also create habitat fragmentation (see Ref. [65]. This paper focuses on the third type of solution, planning and regulatory tools, such as noise regulations, setback safety distances, environmental impact assessments (including acoustic assessments), and planning guidelines and zoning of wind turbine farms (see, e.g., Ref. [53]. While these tools were developed and applied for the benefit of humans, or to address non-noise related WT impacts on wildlife, they could potentially be used or adapted to address WTN implications for wildlife. For example, the current requirements for Environmental Impact Assessments, acoustic surveys, zoning regulations, and wildlife monitoring and protection measures already mandated by Israeli and German planning authorities could be expanded to include WTN effects on wildlife. In California, county regulations could also be expanded to follow the state and federal guidelines to include more wildlife-related considerations when considering the impact of WTN.

Zoning that specifies a minimal distance from protected, ecologically-sensitive or valuable habitats and corridors could be an important tool for planners, especially in places like California, where the population density is lower than in Germany, where similar zoning restrictions already apply, due to other conservation concerns such as habitat fragmentation, and bird and bat collisions with WT. However, developers, planners, and their consultants first need access to place-specific data and awareness of effective monitoring methods for the impact of WTN on wildlife needed for developers.

Some scholars have made general recommendations that address EIAs and might also be relevant for assessing and mitigating adverse WTN impacts on wildlife. For example, Conkling and colleagues [66] suggest that rigorous pre-construction risk assessments and post-construction wildlife monitoring could be an important part of the solution to decreasing WT-related ecological damage and improve siting decisions. These should consider a range of potential adverse effects that WT might have on wildlife, including collisions, habitat loss or fragmentation, and altered foraging, breeding, and migratory behaviors. However, studies have also found that the lack of survey standardization, pre-construction baseline determinations and post-construction monitoring efforts are obstacles to reducing the harmful effects of WTs operation on wildlife. Rigorous point counts, behavioral observations, nest searches and acoustic surveys, if done both pre- and post-application, would be useful tools for assessing adverse WT effects on surrounding wildlife and advising planning efforts to minimize them [66,67].

4. Conclusion

Planning regulations are yet to address the issue of WTN impact on wildlife, despite accumulated evidence to suggest that anthropogenic noise generally, and WTN particularly, are responsible for actual and potential harm to animals and consequently to ecosystem function. The current study found that California, Germany, and Israel lack regulations that mandate developers to include the impact of WTN on wildlife in zoning decisions or even in environmental plans and surveys, although planning regulations are already in place to decrease impact injuries to birds and bats, and German zoning regulations protect national parks, protected areas, and ecologically valuable habitats. These, and other tools intended to protect humans from WTN, such as acoustic surveys, could be used as a basis for addressing and minimizing detrimental effects of WTN on wildlife species.

Scientific advances in this field, including technologies that allow for long-term acoustic monitoring in the field, or studies that follow animal movement, behavior, and survival before and after broadcasting simulated WTN, would be another valuable asset for planners and environmental advisors. Surveys of local species' noise sensitivity make valuable contributions to the understanding of the impacts of anthropogenic noise, including WTN, and are already available in Germany, and have the potential to inform, and even change, planning processes for WT. Further research should take into account the local considerations of governments and planners who wish to include wildlife conservation in the planning process, as they transition to renewable means of energy production.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

This is a document analysis. All documents are available online as referenced in the source list or footnotes.

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Appendix A. Supplementary data

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