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Is setback distance the best criteria for siting wind turbines under crowded conditions? An empirical analysis

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ABSTRACT

Wind power has emerged as the most dominant source of clean energy during the two first decades of the 21st century. As wind turbines became popular, complaints about annoyances from neighboring settlements has led to establishment of greater setback distances in some jurisdictions, due to noise, shadow flickers, and aesthetic considerations. The current study seeks to establish an objective basis for determining optimal setback distance from human settlements. It begins by characterizing the tradeoff between turbines' environmental externalities and energy potential across northern region of Israel, where proposed wind farms are now being considered. The analysis relies on GIS software, which allows for quantification of the energy potential along with impacts of noise and shadow flickers. Based on the geographical data, we compare six contrasting regulatory approaches to setback distance for limiting wind turbines, evaluating how they would be applied in Israel's northern region. The results reveal that at setback of 700–800 m, annoyance levels depend on site-specific conditions, which in some sites are marginal. Zoning restrictions of 1,000–1,200 m pose only negligible externalities to nearby settlements. Greater distancing decreases the number of potential turbine sites dramatically without significant reducing anticipated annoyance levels and can unnecessarily compromise natural areas.

1. Introduction

Five years after the Paris Agreement, more than ever, humanity seeks to reduce greenhouse gas emissions in order to mitigate climate change and keep global temperature increase below 2 °C higher than pre-industrial levels (UNFCCC, 2015). Worldwide efforts rely on electricity from renewable energy sources to replace conventional power plants. In 2019 for example, renewables installations represented 72% of total additional capacity (IRENA, 2020a). The growth of clean electricity is expected to continue in the future, as many countries set ambitious goals to achieve greater shares of renewable capacity (REN 21, 2020).

Wind power constitutes an important source of renewable energy. With 22% of the total renewable sources for electricity production today based on wind energy, it is second only to hydropower (REN21, 2020). Already wind turbines (WTs) are able to compete with fossil fuel prices (IRENA, 2020b), as technological improvements continue, reducing the minimal turbine cut-in speed. Moreover, recent advancements enable the installation of higher turbines, carrying longer blades that collect a greater velocity of wind at heights of 200 m (IRENA, 2019).

Yet, despite its advantages, WTs external effects have become increasingly controversial due to a range of negative environmental impacts. It is possible to divide these impacts into two main sub-groups (a) effects that harm ecological systems (i.e. flora, fauna, and habitats) (Marques et al., 2014; Wu et al., 2019); and (b) anthropogenic impacts which may affect public health or annoy nearby residents through noise, shadow flickers or visual impacts (Henningsson et al., 2013; Zerrahn, 2017; Freiberg et al., 2019).

Both scholars and the media have noted the rise of "green vs. green" conflicts when siting renewable energy infrastructure in sensitive landscapes. To help alleviate these conflicts and potential trade-offs, countries need to design strategies to increase public acceptance and develop solutions for the associated environmental impacts, ranging from technological improvements and planning to management protocols and appropriate zoning regulations.

Since noise is one of the most common concerns arising from the establishment of WTs (Langer and Wooliscroft, 2018; Peri et al., 2020), it is important to analyze the phenomenon in light of the potential for avoiding or reducing this impact. Noise can be defined *as unwanted sound or rapid fluctuations of air pressure which create a repeating cycle of compressed and expanding air*. Typically, noise energy is converted to a

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sound pressure level that can be measured in decibels (dB(A)) units for reporting purposes. The decibel scale is a logarithmic scale, based on the human threshold of hearing. In addition, noise can be measured according to different sound frequencies (dB(C) or dB(G)).

As part of its guidelines to protect public health, the World Health Organization set a target of 40 dB(A) as the maximal permissible noise level to which the people should be exposed at night. The standard is designed to protect society's most vulnerable groups (WHO, 2017). Indeed, a modern WT can constitute a source of noise with levels over 100 dB(A), even as the perceivable levels decrease to 35–40 dB(A) after hundreds of meters (Dai et al., 2015). This dramatic drop reflects the *"distance decay effect"*. Accordingly, those citizens most concerned about WTs are generally located in the first kilometer of dwellings from a turbine – with discomfort values dropping as proximity decreases (Wen et al., 2018). Noise propagation depends not only on distance, but also on site-specific details, such as background noise levels, topography, building materials, and wind velocity/direction (Alberts, 2006).

Wind farms tend to be located in rural areas with low background noise. As they frequently operate during the nighttime, turbines constitute a potential nuisance for neighboring residents during hours when the public is most sensitive to noise. Earlier studies have identified a long-term correlation between sleep disruption and exposure to WT noise (Onakpoya et al., 2015; Poulsen et al., 2019). At the same time, there is an absence of significant evidence confirming additional implications for public health (Ellenbogen et al., 2012; Poulsen et al., 2018a, 2018b).

It is interesting to note the correlation which exists between noise complaints and residents' attitude toward WTs, along with their satisfaction from the planning process (Pedersen et al., 2009; Firestone et al., 2018; Pohl et al., 2018; Hübner et al., 2019). This is why a "*nocebo effect*" sometimes plays a role in citizen concerns about WTs, with perceptions influenced by pre-existing perceptions and biases. As a result, nearby residents have reported annoyances or even symptoms of an illness which has been called: "*wind turbine syndrome*" (Crichton et al., 2014).

Shadow flickers is another potential disturbance that WTs can cause neighboring settlements. The rotation of the blades interrupts the sunlight, producing an unavoidable flicker. Flickers are measured according to daily or yearly frequencies, with the severity of shadow flickers based on specific geographic locations. Therefore, it is possible to resolve the effect on a specific dwelling by landscaping solutions or installing automatic sensors that send notification to the operator or the houseowner that monitor the flickers duration. To ameliorate the flickers' impacts, sensor alerts can shutdowns the turbine for several minutes or trigger automatic windows shades, if the houseowner agrees.

Much like noise, the shadow frequency tends to be correlated with distance. Several studies have assessed the impact of flickers, all corroborating the conclusion that shadow flickers do *not* pose a health hazard for humans. At the same time, a high frequency often creates a substantial annoyance for residents (Harding et al., 2008; Smedley et al., 2010; Voicescu et al., 2016) while flickers can also be dangerous for drivers, distracted while passing by turbines (Stojčetović and Velinov, 2014).

To ensure development of WTs without significant environmental impacts, standards for sound and flicker tend to include frequency levels. These standards vary according to site-specific characteristic, taking into account the sensitivity of different areas. Such a flexible approach also facilitates the application of operational practices and mitigation options for compliance (Stanton, 2012). In practice, countries have adopted maximal noise values that vary from 35 to 60 dBA (Dai et al., 2015).

As decibel standards are based on a logarithmic scale, this represents a very significant range. Moreover, the standards normally change between day and night and integrate background noise level, wind speeds, character of the location (e.g. rural versus urban area) as well as seasons (Koppen and Fowler, 2015; Nieuwenhuizen and Köhl, 2015). Shadow flickers guidelines are more consistent between countries. A common regulatory approach seeks to ensure that flickers not exceed 30 minutes per day or 30 hours per year in any neighboring building (Stanton, 2012; Koppen et al., 2017).

Regulation based solely on micro-siting measurements of noise and shadow flickers requires detailed monitoring and enforcement before and after installation. Therefore, many regulatory strategies rely on establishing setback distances policy for reducing WT's externalities. These require that WT's be sited at a minimal distance from sensitive areas, such as settlements and residential areas. This approach not only provides protection for the nearest (and most highly exposed) dwellings, but it also offers a normative framework that is much easier to implement and enforce compared to site-specific estimates of sound-threshold values or shadow duration. In addition, minimal distance from settlements can contribute to more transparent macro-planning, expediting the identification of suitable sites for WT construction or estimation of large areas' wind potential.

As might be expected, greater setback distance tends to influence the public's acceptance of wind energy: earlier studies report, for example, that a 2,000 m buffer zone reduces annoyance among neighboring residents with opposition declining significantly (Langer et al., 2016; Wen et al., 2018). However, as Stede and May, 2020 reveal in a case study conducted in Bavaria, such inflexible constraints may influence the total potential area available for wind-generated electricity and contribute to a decrease in the number of permits of WTs.

Additionally, greater setback distances can lead to higher production costs as WTs will be located further from electricity demands center (Hoppock and Patiño-Echeverri, 2010) requiring increased costs associated with service roads and support infrastructure. Moreover, high setback distances can unnecessarily push development into natural, undisturbed, ecologically sensitive lands, far from urban surroundings (Picchi et al., 2019; Wu et al., 2019). For optimal sustainable energy planning, it is important to investigate how decision makers can balance this trade-off and promote guidelines that reduce external effects to a minimum while providing maximum appropriate land options for WTs.

Various studies examine optimal site-selection with GIS-MCDA-Geographical Information System-Multi Criteria Decision Analysis (Peri and Tal, 2020; Konstantinos et al., 2019; Höfer et al., 2016; Sliz-Szkliniarz and Vogt, 2011). In most GIS-MCDA studies, buffer zones from settlements and other points of interest are created as a constraint to WT development. Some methods integrate the distance from residential area as a category of weighting analysis, where greater distance produces a higher score (Gigović et al., 2017; Latinopoulos and Kechagia, 2015; Aydin et al., 2010). Extension of such an approach, to possible legislated scenarios that establish different setback distances, appears in several case studies that characterize the impact of regulation on the total potential sites that might be available for WT development (Masurowski et al., 2016; Harper et al., 2019; Sliz-Szkliniarz et al., 2019).

The question of the optimal distance from settlements, however, remains controversial. Studies that adopt different ranges of buffer zones with an automatic 'further is better' approach do *not* take into account the "*decay effect*". This primarily reflects citizens' concerns about WTs located in the first kilometer from dwellings – with subsequent discomfort values dropping as proximity decreases (Wen et al., 2018). Recently, important research was published by Salomon et al. (2020), in order to evaluate the impact of distance regulations and spatial distribution on social costs, based on the approach of Drechsler et al. (2011). The study assesses policy scenarios related to setback distances from residents as well as from bird habitat.

Perhaps the most important basis for comparison between different distance scenarios is *actual* environmental impacts. For example, if a hypothetical regulation increases the distance of WTs from settlements by 500 m, we should expect to identify a meaningful reduction in the noise emissions and in the shadow flickers frequency. Any benefits associated with new setback levels should be quantified with an eye towards establishing an optimal regulatory solution. In other words, exclusion of potential WT sites needs to be fully cognizant of any additional environmental and economic disadvantages caused by the more stringent rules while justifying the opportunity costs of foregone clean energy.

The present research considers the effect of different countries' regulatory strategies for zoning of wind turbine and the implications of applying them in Israel. Based on extensive GIS analysis, the study's model examines the reduction of intensity in noise emission and shadow flickers frequency at various distances from settlements. Conducting a macro-level estimation at a regional scale is preferable for better understanding the potential impact of alternative policies on neighboring residents – compared to the loss of potential sites for WT development.

The study relies on a comprehensive analysis conducted in Israel's northern region (Peri and Tal, 2020), where debates about the severity of externalities and optimal regulation have become highly relevant these days. The Israeli government set a modest goal of 730 MW by 2030 for wind power. This constitutes only 2.5% of the country's energy production. Even so, at the start of 2021, only 27 MW (3.7% of this allocation) has been installed. As might be expected in a very crowded country, many proposed projects face resistance by the public that expresses legitimate concerns about the WT site-specific implications.

At the same time, many renewable energy advocates support dramatic expansion of wind farms, especially given the intermittency of solar power electricity generation, the predominant renewable energy option in Israel. Because the local electricity from wind is typically generated in the late afternoon hours and at night, expanded wind capacity may contribute to a moderate reduction in the magnitude of backup, fossil fuel-powered electricity facilities (e.g., natural gas or coal-powered) presently required to support solar-generated electricity. Nonetheless, the high population density of Israel leads to an acute scarcity of land for all forms of renewable energy generation that are needed as part of a national climate change mitigation strategy (Tal, 2016).

While the national and regional planning system of Israel is responsible for overseeing the zoning of the country's new renewable energy facilities, the substantive standards according to which actual decisions are made are established by the relevant professional ministries. Accordingly, Israel's current regulations require that noise levels from wind turbines not exceed 40 dB at night or 50 dB at daytime (Israel Ministry of Environmental Protection, 1990). Local committees commonly limit a flicker duration to 30 min per day or 30 h per year. The Israeli setback standards are set by the country's health ministry, who stipulates 500 m as the minimal distance that WTs can be built away from residential areas (Israel Ministry of Health, 2016). Some voices call to increase this value and set regulations which are more consistent with European countries who have considerably more experience with wind power development. Others seek to discontinue additional WTs in Israel altogether, due to the generally high population density, the many iconic landscapes and concern for local avian and massive migratory populations (Gorodeisky, 2018; Israel Planning Authority, 2018).

Decision makers are supposed to strike a balance between annoyance levels, along with other externalities, and the lost renewable energy production caused by reduction of potential WT sites. The current study offers a new approach for estimating trade-offs between different regulatory approaches to zoning for WTs. Optimal setback distances based on detailed micro-siting data, can contribute to a more accurate estimate of potential for GIS-MCDA studies. A transparent, evidence-driven, micro-planning process, based on setback distance will increase the public faith and reduce the possibility of nocebo effects, allowing residents to better understanding the main implications of noise and shadow flicker reductions as a result of reasonable setbacks (Fast et al., 2016; Brennan et al., 2017; Rand and Hoen, 2017; Hübner et al., 2019).

The results suggest that WTs' externalities are still dominant when they are located only a few hundreds of meters away from human settlements. On the other hand, greater setback distances can significantly decrease the number of potential sites without adding a meaningful reduction in the environmental effects. Moderate distances of 1,000–1,200 m, therefore, reflect a prudent balance between concern for adverse environmental impacts and supporting clean wind power. Yet there are cases where such setback distances may be inefficient. We find that at distances of 700–800 m, annoyance levels depend on site-specific conditions, which in some sites are marginal.

We argue that a transparent, multi-dimensional approach to establishing setback distance can help increase the public acceptance for WTs and assist countries and communities in setting more precise criteria for optimizing renewable energy production. The ability to better characterize geographical units and quantify their actual impact on the human environment offers a possible solution for overcoming one of the main threats of WTs growth: mounting public concerns about wind energy's environmental effects.

2. Methods

If authorities were to adopt a flexible regulation which allowed for utilization of all relevant environmental parameters in practice, decisions would be much precise, and allow for maximal wind potential with minimal environmental consequences in the examined region. The assumption underlying the proposed methodology is that greater setback distance decreases both the energy potential and the environmental effects at the same time. Finding the appropriate, site-specific, balance between these two contrasting parameters is critical for maximizing social welfare. Integration and analysis of the GIS data allows for a systematic and replicable comparison of setback distances alternatives. The methodology applied in this study is divided into two separate parts: first, a selection process of different regulations for setback distance is applied (Section 2.1); second, a comprehensive *site-specific* GIS evaluation of the major environmental impacts, offers an alternative quantitative analysis that we use to compare between the effects of the different, setback distance approaches evaluated (Section 2.2).

2.1. Comparison between selected regulations

Table 1 summarizes European countries' disparate regulations for onshore WTs setback distances. It reflects the significant disparities in different jurisdictions' approaches and values for setback distance. In many cases there is a distinction made between large residential areas and isolated dwellings, while in other examples, the turbine's tip height, hub height and rotor diameter drive the actual setback distance. In some countries, guidelines are set at the regional or municipal level, and in some cases, like England, even by local citizens.

Countries such as Finland or Portugal do not apply setback distance thresholds at all, but rather establish *safety zones* from settlement, that are derived solely by noise limits. Minimal distance values for modern turbine (100–150 m hub height) can be found in the Flanders region of Belgium, France, and Romania. The distance tends to be around 500 m from settlements. In contrast, there are jurisdictions that require a distance *four times greater*, such as the rules promulgated in Poland, a few regions in western Estonia and in the federal state of Bavaria, Germany.

Based on Table 1, we assess regulations from six different countries: Israel, Denmark, Italy, Austria, Greece, and Poland. These OECD countries were selected because of the strike contrast found among their standards. Their WT regulatory strategy represents various distances from 500 m – which is the current distance presently allowed in Israel, to the maximum distance of Poland, which is more than three times greater. The other countries selected reflect a range of WT setback distances, with quantum increases of 150–350 m. The minimal WT setback distances from settlements located in these jurisdictions assessed in our WT module ranges (in meters) from 500, 672, 1,008, 1,200, 1,500, and 1,680, respectively. The following offers a brief description of the essence of these countries' WT zoning specifications.

In Denmark (Naturstyrelsen, Miljøministeriet, 2015), Poland

Table 1
Regulation of setback distance from WTs in European countries. RD-rotor diameter. TH- tip height. HH- hub height (Dalla Longa et al., 2018; Israel Ministry of Health, 2016).

Country	Setback Distance (meters)	Country	Setback Distance (meters)
Austria	800-1,200 (Set by regions)	**Israel**	500
Belgium	RD*3 (Flanders) TH*4 (Wallonia region)	**Ireland**	TH*4
Denmark	TH*4	**Italy**	200 (From single dwelling) TH*6 (From towns)
England	Local people have the final say on WTs applications: Minimal- 700. Maximal- 2,000 or TH*10	**Netherlands**	HH*4
Estonia	1,000–2,000 (Set by regions)	**Poland**	TH*10
Finland	None	**Portugal**	None
France	500	**Romania**	300 (1–3 buildings) 500 (More than three buildings)
Germany	Set by regions: Minimal- 300 (Hamburg). Maximal- TH*10 (Bavaria)	**Scotland**	2,000 (Governmental guide, final decision by local circumstances)
Greece	500-1,500 (By settlement type)	**Spain**	Set by regions: Minimal- 500 (isolated dwellings). Maximal- 1,000 (urban areas)
Hungary	1,000	**Sweden**	500 (From isolated dwellings) 1,000 (From urban areas)

(Council of Ministers, 2016) and Greece (MEECC, 2008) regulations establishing minimum setback distances are mandatory requirements across the entire country. The Danish guidelines prescribe setback distances four times the turbine tip height, while the Polish rules determine that turbines be set back at least ten times the distance of their total height. In the Greek case, a distance of 1,500 m is only required in “traditional settlements”. For settlements with population of over 2,000 inhabitants (or less than 2,000 that are characterized as touristic) the minimum setback distance is 1,000 m. A minimal distance of only 500 m is required for small settlements with small populations (less than 2,000 inhabitants).

In Austria, the guidelines are defined according to regional recommendations (Dalla Longa et al., 2018). The range of the regions’ allowable setback distance falls between 800 and 1,200 m. In the present analysis, we selected the greater distance which has been applied in the Lower-Austria region (1,200 m). The Italian national recommendations hold that a minimum distance of 200 m from a single dwelling, or alternatively a distance six times the tip height from towns (Dalla Longa et al., 2018). Yet, in practice substantial variability can be found in Italy depending on region. For the comparative regulatory analysis, we selected the Italian minimal distance of six time the tip heights from the entire settlements. If applied to our WT module, it allows setback distance of 1,008 m. The current Israeli WT regulation is not statutory-based and only appears as a recommendation by the (Israel Ministry of Health, 2016).

2.2. GIS framework

In order to characterize the impact of different setback standards and identify the preferred regulatory approach to addressing their externalities, we conducted a preliminary GIS analysis in the northern region of Israel, a district traditionally called “the Galilee”. It holds great historic and religious significance for Christianity and Judaism. The area contains 4,208 square kilometers and is characterized by scattered settlements and dense population with 578 residents per square kilometer (Israel’s Central Bureau of Statistics, 2019). In recent years, this area has been the target of considerable attention for installing wind farms, due to the generally good wind conditions and proximity to electricity demands. Therefore, the study area offers a very good example of a high-density region where it is important to find an appropriate balance between WTs and the human environment.

We assessed a range of possible WT sites using ArcGIS 10.7.1 and WindPro 3.2 software. The regions’ areas were divided into cells of 500 m resolution (0.25 square kilometers). After an exclusion of unsuitable areas based on the categories presented in Table 2, 1,017 locations of hypothetical WTs remained for the advanced calculations. Fig. 1 presents these cell locations on a map of the study area.

The exclusion stage applied minimal values as constraints in order to evaluate the maximum of number potential sites. For example, annual wind speeds of 5.5 m/s in many cases are inadequate to achieve satisfactory capacity. This analysis, however, seeks to assess even those sites with low energy potential. These locations may indicate a positive environmental score, allowing their consideration if future development increase the achievable energy from low-wind velocity. Although the energy calculations and capacity are not the main focus of this paper, they are important to note in this context.

In the next step, we evaluated a hypothetical turbine module within the each one of the remaining cells. The selected turbine for our investigation was Vestas V136–3.45 MW. It holds a blade diameter of 136 m; with an overall height of 168 m, its hub height was set at 100 m. The Vestas V136 is considered to be a particularly popular turbine model, with a full database containing the forms and specifications on which our study is based. Subsequently, we evaluated four variables for each turbine’s location separately, without assessing the cumulative impact of multiple WTs.

The following are the primary variables utilized in our comparison:

1) Distance to settlements-measured by meters from the WT location to the closest residential polygon, using NEAR function with ArcGIS software.
2) Annual energy output-measures in units of MWh, based on the wind distribution charted in the Israeli meteorological service’s wind atlas (Israel Meteorological Service, 2016). We used WindPro software for the energy calculations.
3) Noise emissions-measures in dB(A) with WindPro. The maximum noise level that might be propagated in the surrounding settlement was selected. Below 30 dB(A), we assumed that noise levels are completely negligible and could be assigned a value of “zero noise level”. We used the sound code ‘ISO 9613-2 general’, which defines a propagation model for WT noise. In addition, no background noise was added to the model, expect of background wind speed of 8 m/s that affect the propagation.
4) Shadow flickers frequency-measures according to maximal hours per year in a residential area using WindPro. The data evaluated a

Table 2
Exclusion parameters.

Criteria	Value
Annual Wind Speed	Min 5.5 m/s
Settlements Distance	500 m buffer zone
Industry Areas	Not intersect
NPAs	Not intersect
National Parks	Not intersect
Roads and Railways	150 m buffer zone
Airports	5 km buffer zone
Airstrips	One km buffer zone
Slope	20% Max
Water Reserves	Not intersect
Quarries	Not intersect

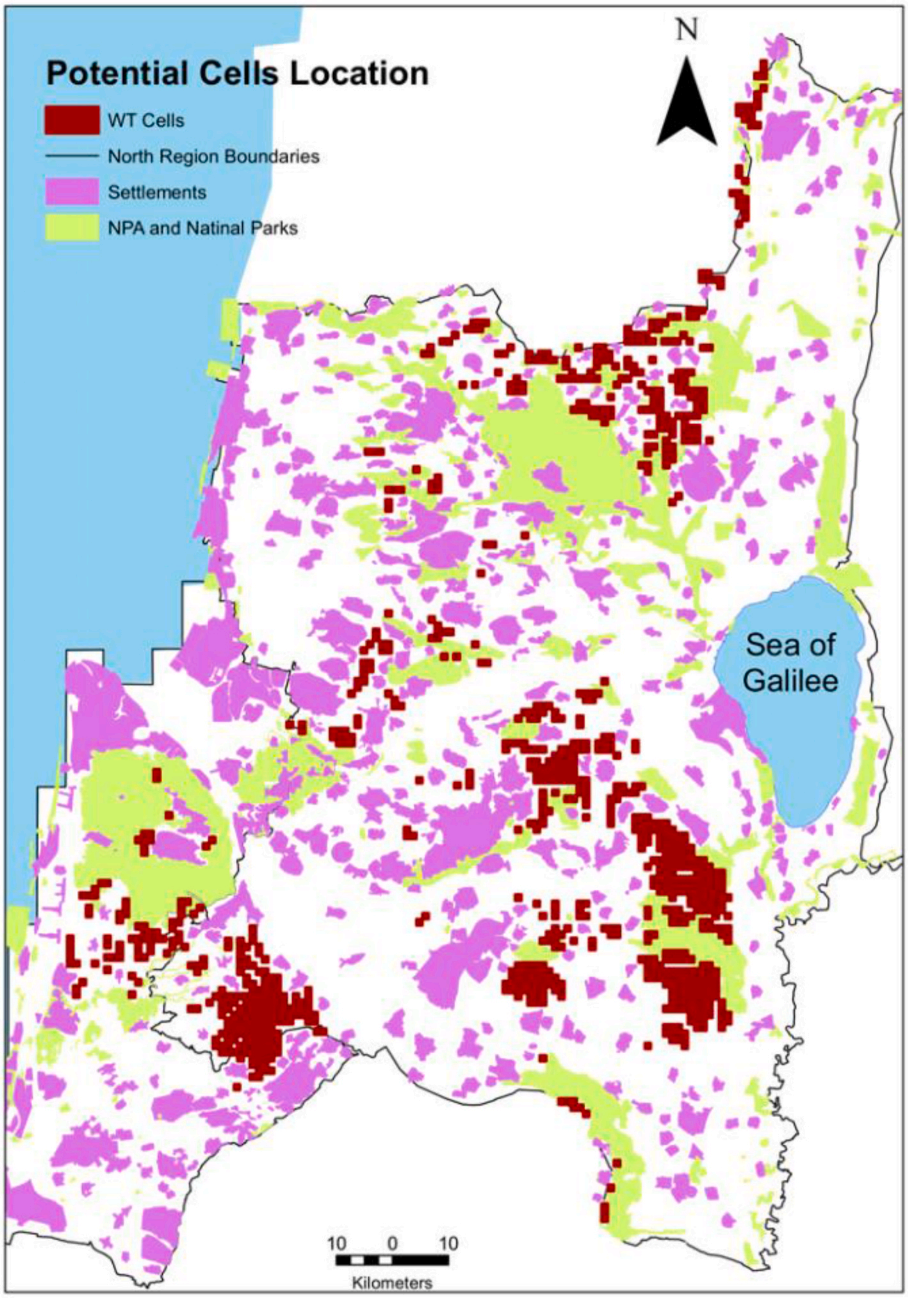


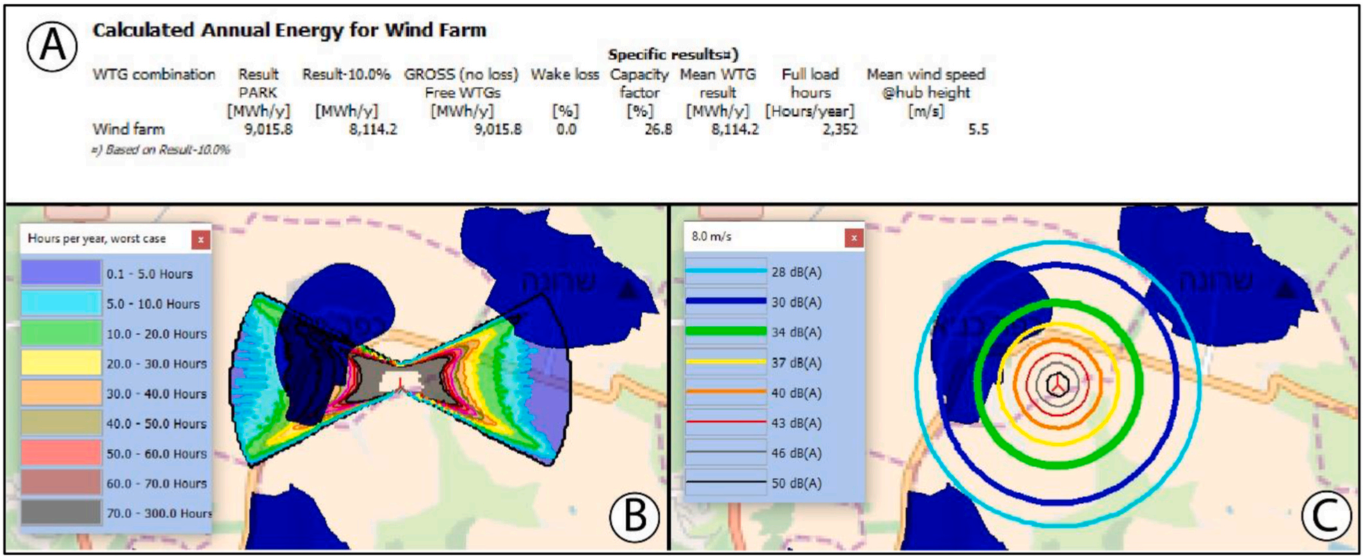
Fig. 1. The examined locations (brown cells) on a background map of the study area. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

worst-case scenario, which means that blades would rotate throughout the year without cloud interference.

Fig. 2 presents an example of a WindPro analysis from one specific site within the study area. The software algorithm, together with the geographic database, allows for evaluation of annual energy potential, noise decibel propagation from the WT and the maximal shadow flickers occurring in the surrounding settlements' polygons. The analysis relied on topography terrain as mapped by Shuttle Radar Topography Mission (SRTM), on a 30 m resolution raster map.

To ensure the validity of our assumption for a single WT module, in an early test, noise levels were examined for different modules as well (the largest was GE 5.3 MW-200 m total height). We found that noise propagation was relatively similar, as the source of sound remained between 105 and 108 dB(A) among these technologies according to the manufacturer details in the WindPro software.

After characterizing the actual environmental effect with acceptable wind potential scattered throughout Israel's northern region, we evaluated the implications of applying a given setback standard on the Galilee. The comparison between different regulatory approaches and the actual environmental effects resulting from WT installation in a given site provides new insights about the implications of resulting economic and environmental tradeoffs. This integration allows a clearer understanding of the consequences of adopting a given country's regulations for future renewable energy potential, as opposed to the actual reduction in annoyance attained for neighboring residents and reduced environmental impacts.



Calculated Annual Energy for Wind Farm

WTG combination	Result PARK [MWh/y]	Result-10.0% [MWh/y]	GROSS (no loss) Free WTGs [MWh/y]	Wake loss [%]	Specific results¤) Capacity factor [%]	Specific results¤) Mean WTG result [MWh/y]	Specific results¤) Full load hours [Hours/year]	Mean wind speed @hub height [m/s]
Wind farm	9,015.8	8,114.2	9,015.8	0.0	26.8	8,114.2	2,352	5.5

¤) Based on Result-10.0%

Fig. 2. An example of a single site evaluation for the three variables that examined in WindPro: A) Annual Energy output report. B) Shadow flickers frequency, hours per year. C) Noise propagation in decibels. * Blue polygons represent neighboring settlements. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3. Results and discussion

3.1. *Software analysis*

Prior to conducting the comparative regulatory analysis, we assessed the actual environmental effects of all potential sites in Israel's northern region for establishing WTs without setting constraints on setback distances. In total, 1,017 potential locations of WTs were examined. The geographical information of the variables converts into tabular data, which enables a clear, quantitative basis for zoning decisions.

Table 3 summarizes the analysis of the four salient variables for siting turbines. The WT sites are between 506 and 4,643 m from adjacent settlements with the average distance being only 1,536 m. Noise levels of more than 30 dB only occurred in 55% of the cells, while *shadow flickers* risk exists in 53% of the locations. Among the cells we found noise of 40 dB and 100 h of flickers to be the maximum impacts that a single WT can produce. The energy calculation reveals that the average output per year of a single turbine established in this region is 9,675 MWh, with electricity generational levels ranging between 7,620–13,919 with a standard deviation of 1,130 MWh.

Fig. 3 presents a scatter graph of the WT locations over the evaluated variables. As expected, the *energy output* decreases with distance, from a potential of 9,840 GWh with a minimal constraint of 500 m buffer zones from settlements to 25% of energy production (2,492 GWh) in a scenario where turbines are located 2,000 m away. As expected, the association between *noise* levels and the distance from nearby communities was relatively linear: at distances of 500 m, noise levels are between 38 and 40 dB; measurements of 35 dB are found at 700–800 m; and after 1,322 m there are no significant noise emissions (less than 30 dB) at all, according to our measurements.

The scatter plots of the *shadow flickers* are more varied, because flickers frequency is highly dependent on sundry geographical variables, such as the sun angle during the seasons or the site terrain. It explains why may be situations when there is no reason to limit shadow flickers on a settlement, even when WTs are located at relatively close distances. For instance, if the topographic terrain blocks the visibility of the turbine from dwellings or if the angle of the sun does not cast a turbine's shadows on nearby residential areas due to the geographic latitude. In Israel, because of the southern angle movement of the sun, there is no possibility for creating flickers when a settlement is located north of a WT site. Even so, a decrease in shadow flickers is correlated to the setback distance from the closest settlements. Accordingly, a shadow flickers frequency of more than 60 h per year can appear until reaching a distance of 700 m from settlements. At a distance of 1,500 m, however, a frequency as little as 20 h per year would not occur. The maximum distance for which we found evidence of any possible shadow flickers in northern Israel was at 1,803 m away.

A further analysis divides the data into four sub-groups according to the negative impacts of the WT (see Fig. 4). Limits between high and low values of noise and shadow flickers (35 dB and 30 h p/y) were selected according to standards found in the regulations of various countries (Dai

Table 3
Summary of the examined sites values (n = 1,017).

Variable	Mean	St. Dev	Min	Max	Null (no impact)
Distance (meters)	1,535.57	979.58	506	4,643	–
Noise (dB(A))	34.11	2.69	30	40	457 (44.94%)
Flickers (Hours p/y)	26.88	20.69	0.02	100.13	483 (47.49%)
Energy (MWh p/y)	9,675.39	1,129.58	7,620	13,919	–

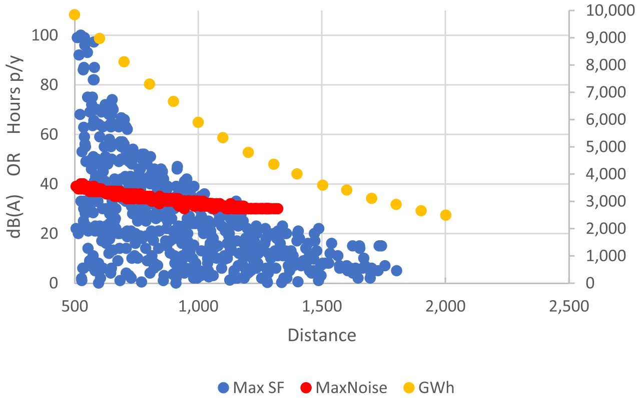


Fig. 3. Scatter plots of correlation between the total energy output (yellow), noise (red) and shadow flickers (blue) and distance from settlements. Note: Null locations of noise and shadow flickers excluded from the graph. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

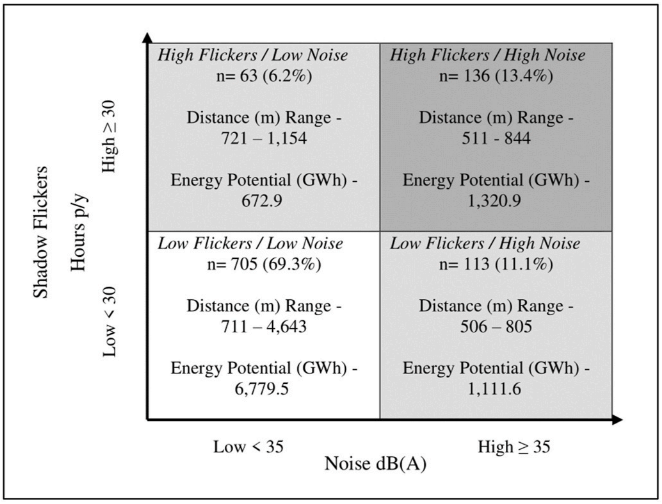


Fig. 4. Number of WT sites, their distance range and energy potential in the four sub-groups based on Noise and Shadow Flickers levels. High Noise/high Flickers (dark gray); High Noise/low Flickers and low Noise/high Flickers (light gray); Low Noise/low Flickers (white).

et al., 2015; Henningsson et al., 2013; Koppen and Fowler, 2015; Koppen et al., 2017).

The results show a significant number of sites in the *Low/Low* sub-group (69.3%). This suggests that these locations emit less than 35 dB in nearby communities *and* no more than 30 h p/y of flickers in the worst case scenario. It is interesting that the *Low/Low* sub-group has locations that vary widely their distances from settlements (711–4,643 m), when compared to the remaining three sub-groups, which a much more narrow range of distances exists. In these three groups, the maximum distance, where any *high* impact of noise or flickers occurs, never exceeds 1,154 m. In other words, in only 31% of the hypothetical WTs is it there a possibility for creating an adverse impact from WTs on the neighboring residents. Such sites are only found at distances of 1,154 m or less.

3.2. *Regulatory comparison*

For the regulatory analysis, we evaluated the different setback distance guidelines from several countries in order to estimate these regulations' effects on the total energy potential and the environmental impacts affecting residents in the Galilee. Enjoying a rich data set of more than 1,000 cells scattered on a regional scale allowed for empirical comparison between different approaches, with the objective of identifying the optimal setback distance.

The results presented in Fig. 5 indicate that if Israel increases the setback distance to the Danish guidelines (672 m to our WT module), energy potential would decrease by 15%, while maximum noise exposure levels would never exceed 37 dB and the maximum frequency of flickers is 67 h per year. When using the Danish rules, around 40% of the cells have a possibility of producing noise or flickers annoyance, compared to 55% and 53% (respectively) when applying the Israeli recommendation of 500 m.

When evaluating the local application of the maximal setback distance required in Italy (1,008 m) and Austria (1,200 m) we found they would produce a significant reduction in the maximal noise levels (33 and 30 dB- respectively) as well in the frequency of the flickers (maximum 36 and 23 h p/y-respectively). Only a few cells, between 1,000–1,200 m are considered to have significant impacts.

According to Fig. 4, at these setback distances, only ten sites would have flickers for more than 30 h per year (2% of the suitable locations in these distances).

Although the acute environmental impacts between 1,000–1,200 m appear to be negligible, under the Italian guidelines there are 15% of sites where noise levels would be over 30 dB, as opposed to 4% when using the Austrian approach. The rates of cells with a possibility for shadow flickers, even if for a few hours per year, are 19% according to the Italian regulation and 11% when using the Austrian setback distance. As for the energy potential, the reduction does not appear to be as dominant as it is for the environmental effects. Nonetheless, 40% of the potential energy production was excluded when complying with the Italian setback distance, compared to the Israeli guidelines, with a full 51% decrease when applying the more stringent Austrian regulations.

The last two countries considered in our comparative analysis are Greece and Poland. These countries locate WTs at a minimum distance of 1,500 and 2,000 m from settlements, respectively. If Israel's northern region was to adopt one of these approaches, 36% (using the maximum Greek guidelines) or 32% (according to the Polish guidelines) of the wind energy potential would remain. According to these two types of regulation, all concerns about to noise annoyance are eliminated (0% of sites show noise levels higher than 30 dB). The number of locations with a possibility of flickers is also extremely low (less than 3%), and the maximal time that flickers that might exist is a mere 15–16 h p/y.

There is no doubt that setback distances of over 1,500 m significantly decrease the environmental effects for neighboring residents. At the same time, a reduction of two-thirds of energy potential will negatively affect the country's ability to meet its renewable energy targets. This presents a tradeoff between two environmental objectives (clean energy versus adverse environmental conditions for residents near WTs) which regulators will need to resolve based on their societal priorities.

4. Conclusions and policy implications

The purpose of setback distance is to balance between the need for wind energy and the annoyance that wind turbines might create within adjacent settlements. Our model reveals that in the northern Galilee region of Israel, distances of 1,000–1,200 m from the closest settlement are the most favorable for reaching optimal energy and environmental objectives. This ensures that nearby residents will be adequately protected from noise and visual intrusions. This finding correlates with the results of another recent study (Salomon et al., 2020). The Italian guideline of locating turbines six times the turbine tip height from towns is a good example of a reasonable and flexible approach for a prudent tradeoff. At these distances the turbines' noise levels and the shadow flickers' frequency are negligible. Nonetheless, around 60% of all potential energy is achievable. Distances over 1,500 m, such as the present regulations in Bavaria or Poland (with the total tip height multiplied by 10) significantly decrease the number of potential sites without adding to meaningful reductions in the adverse environmental effects.

Another interesting aspect of our finding involves the high number of locations in which a significant possibility (69%) for noise ***or*** flickers annoyance does not exist. It suggests that potential annoyance from WTs is highly site-specific and generic standards are not reliable in every location, especially in places characterized by density conditions. For crowded countries, setback distances of 700–800 m are recommended, such as the Danish approach. In that case, the standards of noise and flickers should be accurate and enforced because annoyance in these distances might be dominant in several locations but non-existent in others. For example, by measuring existing background noise or the shadows angle, planning authorities can decide whether a specific location is suitable for WT zoning, even at distances of 700–800 m. Therefore, in small, crowded countries flexible regulations based on actual noise/flickers measurements, offers a preferable strategy.

High setback distances of greater than 1,500 may "overserve" the purposes for which they are promulgated. In addition, exaggerated setback distances from human settlements for can push WTs into sensitive ecological zones. This is particularly problematic when pristine, open spaces are already rare in densely populated countries, such as Israel. Other disadvantages of exceedingly great setback distances are the requirement for longer road access and transmission lines, which

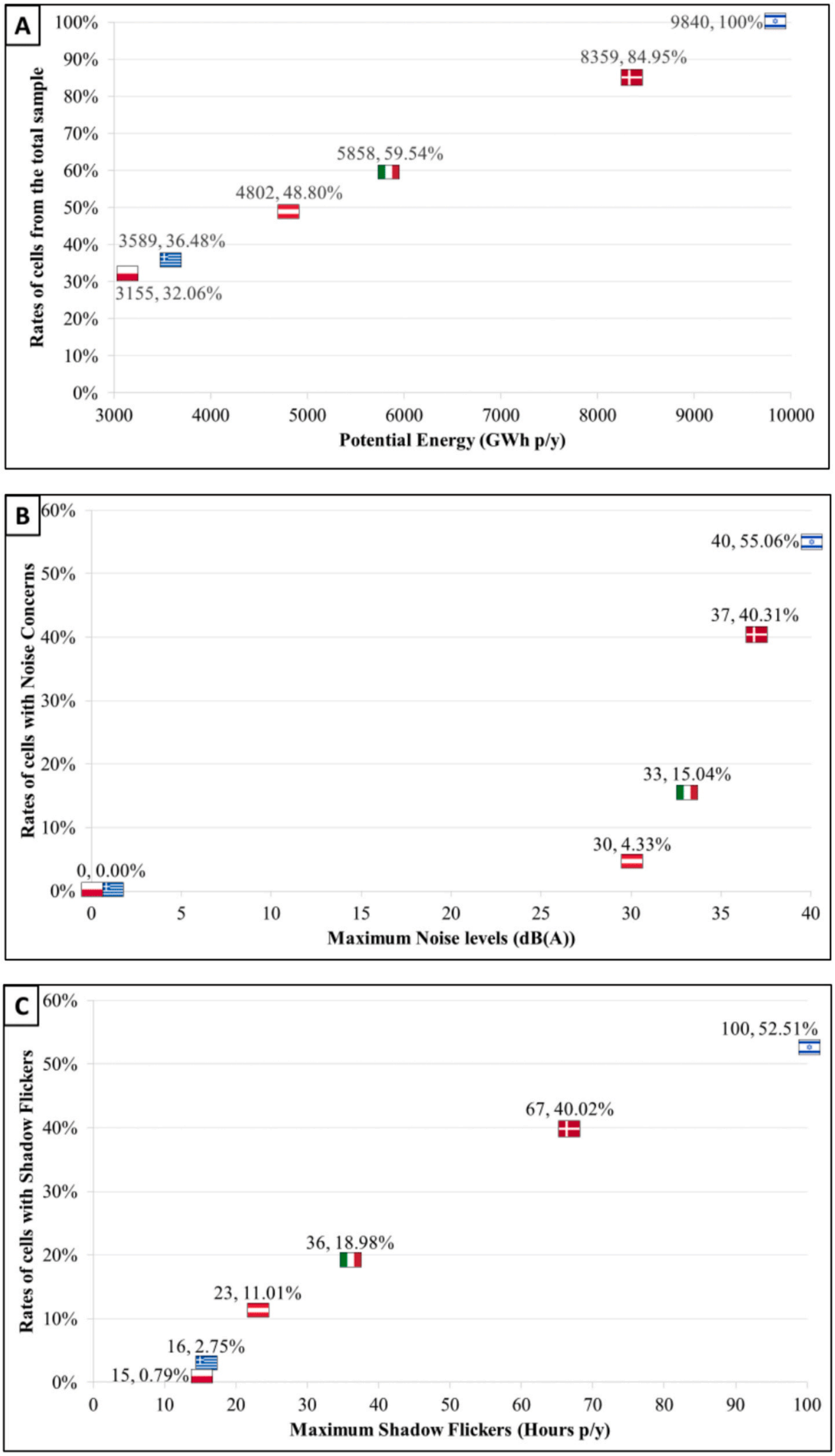


Fig. 5. The comparison graphs between six countries with different maximal setback distance: Israel, Denmark, Italy, Austria, Greece, and Poland. Fig. 5-A) shows energy potential and rates of remaining sites from the total sample. Fig. 5-B) displays maximum noise levels and rates of sites with noise above 30 dB. Fig. 5-C) graphs maximum shadow flickers and rates of sites with a possibility of flickers. (n = 1,017).

increase the ecological footprint of WT projects and create additional costs for support infrastructure.

The geospatial analysis of our study can help decision-makers in designing effective guidelines for wind power planning. It is especially relevant for small countries, where available lands for wind farms are scarce. The usage of *micro-planning* tools (GIS software) is essential to improve *macro-planning* regulations. Implementation of setback guidelines based on transparence data with conservative approach as applied in this study, should increase the public satisfaction from the planning process and their general acceptance toward wind power. These points found as a key evidence in early studies as well (Firestone et al., 2018; Pohl et al., 2018), as energy policy issues of concern to wind energy proponents also deserve some consideration in siting and zoning decisions (Stanton, 2012). Thus, produce a compelling balance between protecting residents and the identifying the necessary land resources for future wind farms is critical.

Our findings reflect the ease of implementing setback distances for WTs relative to more precise, regulatory programs based on site-specific conditions. This conclusion is consistent with regulatory dynamics that characterize other environmental media which are driven by stochastic, climatic factors (Fiorino and Ahluwalia, 2020). Setback standards are analogous to *design standards* for pollution that are set according to generic, physical, engineering specifications, whose adoption constitutes compliance, regardless of actual weather conditions. These are opposed to *performance standards*, where actual chemical concentrations of discharges or actual emissions need to be met (Besanko, 1987). For example, because of the variability of rain even, regulators and generators of nonpoint source water pollution found that implementation and oversight of design standards is far easier than the measurement and monitoring of runoff via performance standards (Tal, 1998). The same logic and logistical advantages of design standards are true for making zoning decisions about solar energy, where the number of installations that need to be reviewed and overseen is infinitely greater.

It is important, however, to note that our results refer to a single wind turbine module without integrating several site-specific considerations, such as background noise or shutdown effects on the shadow flickers frequency. The approach of the research was to apply a uniform methodology that allows for comparing the effects of different regulatory limits. This narrow context is also germane when applying our findings to real world conditions where a single WT is rarely installed as an individual unit. For example, even if a 35 dB level produces a seemingly quiet environment, which can be attained under particular guidelines, we do not consider this value as necessarily constituting a low level of noise. This conclusion is due to the possibility of greater, aggregate noise pollution in the case of several operational wind turbines within a given area. Future studies should focus on the environmental impacts of several wind farms located at a range of distances from settlements in order to assess their combined effect and how turbine interactions might affect our present findings.

CRediT authorship contribution statement

Erez Peri: Conceptualization, Software, Data curation, Formal analysis, Evaluation of results; Prepared, Writing – original draft, of the article. **Alon Tal:** Project administration, Conceptualization, Evaluation of results, Writing – review & editing.

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.

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