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A sustainable way forward for wind power: Assessing turbines' environmental impacts using a holistic GIS analysis

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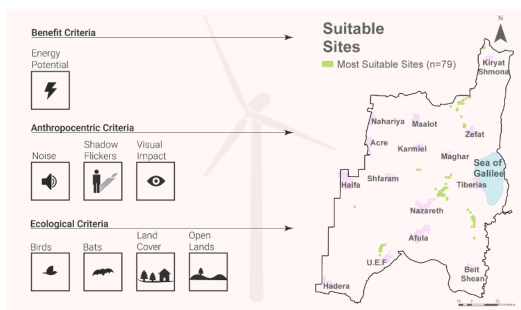
HIGHLIGHTS

- A GIS MCDA model was conducted to expedite optimal wind turbine site selection.
- A full characterization of turbines' impacts is critical for holistic planning.
- The model allows for integrated calculation of myriad environmental criteria.
- Environmentally suitable sites with significant energy potential are identified.
- Negative effects of turbine proximity to homes begin dissipating after 750 m.

GRAPHICAL ABSTRACT



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ABSTRACT

Wind power development is an increasingly vital source of renewable electricity that significantly contributes globally to reduced greenhouse gas emissions and the combatting of climate change. The environmental impacts of wind turbines have emerged as a dominant consideration in the planning process in order to increase public acceptance, protect the surrounding environment and to conserve pristine ecosystems. Hence, ensuring holistic planning and community participation are key factors if wind-generated electricity is to be expanded. Existing macro-planning methods lack quantifiable models for assessing wind turbines' full environmental implications. The current study uses a holistic and quantitative methodology to identify suitable sites for wind turbines in the north of Israel using available GIS software. By evaluating a broad range of local environmental and spatial conditions, the research improves on existing GIS modeling. The spatial criteria that affect zoning optimization are then applied using a Multi Criteria Decision Analysis (MCDA). The results indicate that 0.5% of possible sites in the study area are suitable for wind turbine development according to the strictest environmental constraints. Anthropocentric environmental impacts from turbines were found to be significant whenever sites were located less than 750 m from settlements. Ecological impacts, however, were not found to be correlated with the distance from natural protected areas. The study's novel, holistic approach enables decision-makers to identify sustainable locations with maximum energy benefits and minimal negative impacts as they seek to meet renewable energy goals.

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1. Introduction

These are the both the best of times and worst of times for wind power. On the one hand, wind power constitutes an increasingly large component of many country's preferred renewable energy portfolio. Wind energy enables the production of electricity without air pollution or greenhouse gas emissions. As early as 2011, a special report of the United Nations International Panel on Climate Change (IPCC) on wind energy envisioned a critical role for wind turbines (WTs) in future renewable portfolios, anticipating that the world's wind power capacity should reach 20% by 2050. While acknowledging that average wind speeds vary considerably by location, the scientists concluded that ample potential exists throughout most regions of the world to have turbines to meaningfully contribute to electricity supply [1]. In the decade which has ensued the cost of electricity from wind has dropped by between 44% and 78% from their peaks between 2007 and 2010 [2].

Many countries have responded to this precipitous decline in prices to base their renewable energy strategies on the use of WTs [3]. The growth rate in the usage of turbines has been dramatic during the past decade, with the world's installed capacity multiplying by a factor of 3.5 [4]. Technological advancements enabled the installation of taller turbines that can carry longer blades and collect a higher velocity of wind at heights of 150–200 m [5]. As a result, WT is critical to the global strategy for combatting the climate crisis.

Yet, despite its advantages, WTs' external effects have become increasingly controversial due to a range of negative environmental impacts. These externalities serve to decrease public acceptance and increase citizens' reluctance about the transition to wind energy [6,7]. Moreover, citizens in certain countries appear to have reached a sense of exhaustion towards onshore facilities, which is reflected in the recent prioritization of offshore installations [4,8]. Concerns about onshore WTs' environmental impacts are grounded in empirical experience and involve noise pollution [9,10], shadow flickers [9,11] and visual impact, due to their great height [12,13]. Moreover, potential adverse effects on nature reserves [9,14] and possible damage to biodiversity [15,16] create a conflict between the desire for renewable energy and preservation of pristine, ecological spaces. The discussion creates a "green versus green" dynamic, as advocates and opponents of WT both espouse legitimate environmental positions. The fundamental question is how to attain an optimal balance between the environment we want, and the energy we need. In this article, it is argued that the answer is to be found in a more holistic and integrative application of geographic information system (GIS) mapping software. By transparently and precisely characterizing the associated environmental tradeoffs, better decisions can be made for selecting appropriate sites for wind turbines in the vicinity of human settlements as well as near protected natural habitats. This approach is particularly valuable in areas characterized by high population density or ecological sensitivity.

There is a scientific consensus that high quality planning facilitates public acceptance of renewable facilities, especially when it is based on community participation and transparently presents potential environmental tradeoffs [17-20]. Accordingly, mapping potential sites using holistic criteria has great importance for optimal social welfare. Experience suggests that it can lead to a reduced number and intensity of objections by the public, a more efficient planning process and expeditious achievement of the country's wind energy targets. In other words, a holistic analysis based on transparent calculations of environmental impacts can contribute to the continuation of WT development. But if the full suite of environmental considerations is not part of the evaluation process, countries can expect to encounter mounting concerns and opposition to proposed WT installations.

In the Israeli case, the government set a modest goal of 17% renewable energy by 2030, of which 730 MW is designated for wind power [21]. If this target is met, the wind sector capacity should generate 14% of total anticipated renewables but only 2.5% of the country's energy production. Even so, at the start of 2020, only 27 MW (3.7% of the allocation) are installed in three small farms. It appears that three additional larger facilities in the north region will be activated within the next few years, adding another 390 MW, meeting more than half the 730 MW allotment by 2025. Several other projects exist in various stages of planning, all but one designated for the northern region of Israel. Their implementation remains far from certain. In fact, all the proposed plans for new WT installations were either already cancelled, or currently face opposition from the public and environmental NGOs.

The Israel planning system is designed so that, proposed WT plans' locations are selected solely by the private sector, with entrepreneurs submitting their plans to the relevant planning commission. No areas have been officially designated as appropriate for wind energy. Additionally, Israel is a small country with a high population density, leading to an acute scarcity of land appropriate for renewable energy in general. The characteristics of the area, together with lack of local experience with WT technologies, create a unique situation which hinders the expansion of wind capacity.

Admittedly, in Israel the environmental risks associated with WTs appear during early stages of the planning process. But such challenges are becoming more commonly globally as well. The present study offers a method for multilevel mapping to assess the feasibility of WT installations that can be used universally. We applied the approach to northern Israel with the goal of identifying optimal locations for new facilities. The ability to quantify geographical units and characterize hypothetical WT impacts on the human and the natural environment can assist in the setting of more precise renewable energy goals. Additionally, the utilization of optimal polygons produces an objective basis for the establishing new wind farms and increasing public faith in the legitimacy of associated plans proposed in their vicinity.

The study was conducted systematically using GIS-MCDA (multi criteria decision analysis). This allows for the combining of several criteria into a single holistic model. The proposed model promotes the integration of the full range of relevant environmental criteria in WT site-selection. This constitutes an alternative to the conventional, existing regulatory approach to turbine zoning which relies mainly on buffer zones and minimal distances to sensitive areas. Indeed, our literature reveals that existing GIS-MCDA studies about WT siting lack a holistic approach in which all relevant environmental, ecological and energy-related parameters are integrated in planning decisions. The study shows the benefits of quantifying project impacts for a comprehensive range of environmental criteria characterizing their actual environmental impacts. The environmental "price" calculated can then be weighed against any benefits associated with WT installations. These primarily reflect the potential energy production as expressed in MWh per year.

The mapping of the environmental impacts of WTs is based on wind farm planning tools that utilize methodologies from studies in the field of planning, that heretofore have not taken advantage of the full analytical capabilities of GIS-MCDA for WT siting. The proposed alternative approach enables decision-makers to use the model to better understand the associated tradeoffs of different potential turbine locations, to establish goals and to formulate plans that expand sustainable energy with minimal public and environmental impacts. As mentioned, such tradeoffs are far more complex in densely populated areas or in areas with particularly sensitive ecological dynamics. Public resistance to WTs has become an increasingly salient obstacle to their installation and to meeting renewable energy objectives. The GIS-MCDA methodology we present offers a transparent, replicable and holistic way for planners and renewable energy advocates to address these concerns.

The paper is organized according to the following sections: *Section 2* provides a literature review of GIS-MCDA studies in the area of wind energy planning. This section emphasizes the gap between previous approaches and the growing need to assess environmental impacts from WTs with an eye to fully characterizing anthropocentric and ecological implications. *Section 3* presents the study area and data collection sources. *Section 4* describes the methodological framework of the GIS-

MCDA procedure step-by-step, including the criteria analysis and their integration. *Section 5* reports the results of the model as applied in northern Israel, while *Section 6* discusses the results and their implications. Lastly, *section 7* presents our conclusions and lays out potential avenues for further research.

2. Literature review

Diverse studies about planning and geographical mapping of wind power potential have been conducted in many countries. GIS tools serve to transform geodata into tabular data. Combining these data along with MCDA allows for the interpretation of geo-spatial variables, as well as for the ranking of potential sites based on the outcome of a chosen model [22]. Models utilizing WT methodologies have appeared in the literature since 2001 [42]. From that time on, numerous case studies involving wind power were conducted in different regions, examining spatial criteria from the fields of economics, environment and society. A recurring methodological process in these studies refers to three main phases: exclusion of unsuitable sites; selection of evaluation criteria for siting WT; and identifying the most suitable sites.

2.1. Exclusion unsuitable sites

The 'exclusion zones' usually are based on defined criteria, following a similar method in many studies. The selected categories and their actual values vary among case studies. In this phase, categories with certain threshold values are selected in order to exclude areas that are not considered worthwhile for the installation of WTs. Common exclusion categories are: minimal wind velocity, maximal slope of terrain, safety distances from settlements, electricity transmission lines, roads, railways and airports. Moreover, it is common to exclude turbines from nature reserves, water sources, quarries, military and historical sites [27–42].

2.2. Selection of evaluation criteria

In the next phase of the analysis, key criteria for finding optimal wind farm sites are defined for the remaining sites. Categories (evaluation criteria) are usually measured on a continuous scale and their aim is to enhance or to detract from the suitability of a specific alternative location. In general, there are two types of categories: benefit criteria, contributing positively to the site selection and cost criteria, contributing negatively to site selection (i.e. lower values are preferable than higher ones).

When using GIS-MCDA techniques to evaluate different sites potential for WTs, certain criteria emerge as particularly influential across previous studies. From a technical and economic perspective, studies tend to focus on wind velocity, slope, proximities to roads and transmission lines. Table 1 gives an overview of studies that considered anthropocentric criterion in past GIS-MCDA procedures. It is worth noting that studies addressing WT impacts with setback distance and weighting assume that the further the location of a turbine from human settlement, the smaller the environmental impact it creates.

The literature is filled with research that assesses different individual aspects of WTs, but rarely are they integrated. Many of the studies that express environmental effects separately, use insufficient tools as proxies for actual impacts. For example, noise propagation is assessed by distance or as a buffer zone from each WT site, after general assessment of decibel emissions [23,31,32]. Only *Kazak et al. 2017* [31] mapped out how a WT might create an area of shadow risks. There is, however, no

Table 1
Overview of anthropocentric criteria found in wind turbine GIS site-selection studies.

Study	Case Study Region	Description of the anthropocentric criteria			
		Noise Decibel	Shadow Flickers	Visual Impact	Residential Area
Konstantinos et al. 2019 [23]	Eastern Macedonia and Thrace region, Greece	Yes-Weighting between buffers	–	Yes- Weighting as a binary variable	Yes- Constraint with buffer and Weighting
Harper et al. 2019 [24]	UK	–	–	–	Yes- Constraint with buffer and Weighting
Ayodele et al. 2018 [25]	Nigeria	–	–	–	Yes-Constraint with buffer and Weighting
Pamučar et al. 2017 [26]	South Banat, Serbia	–	–	–	Yes- Constraint with buffer and Weighting
Manomaiphiboon et al. 2017 [27]	Thailand	–	–	–	Yes-Constraint with buffer
Gigović et al. 2017 [28]	Vojvodina, Serbia	–	–	–	Yes-Constraint with buffer and Weighting
Mentis et al. 2017 [29]	Africa	–	–	–	Yes- Constraint
Villacreses et al. 2017 [30]	Ecuador	–	–	–	Yes-Constraint with buffer and Weighting
Kazak et al. 2017 [31]	Wrocław, Poland	Yes- eighting between buffers	Yes-Weighting between buffers	Yes-Weighting	–
Höfer et al. 2016 [32]	Aachen, Germany	Yes- Distancing from settlements	–	Yes- Distancing from settlements	Yes-Constraint with buffer and Weighting
Noorollahi et al. 2016 [33]	Markazi, Iran	–	–	–	Yes- Constraint with buffer
Sánchez-Lozano et al. 2016 [34]	Murcia Region, Spain	–	–	–	Yes-Constraint and Weighting
Atici et al. 2015 [35]	Balıkesir and Çanakkale, Turkey	–	–	–	Yes-Constraint with buffer
Tsoutsos et al. 2015 [36]	Crete, Greece	–	–	–	Yes-Constraint with buffer
Latinopoulos and Kechagia 2015 [37]	Kozani, Greece	–	–	–	Yes-Constraint with buffer
Van Haaren and Fthenakis 2011 [38]	New-York, US	–	–	–	Yes-Constraint with buffer
Sliz-Szkliniarz and Vogt 2011 [39]	Kujawsko–Pomorskie Voivodeship, Poland	–	–	–	Yes-Constraint with buffer
Aydin et al. 2010 [40]	Western Turkey	–	–	–	Yes-Constraint with buffer and Weighting
Rodman and Meentemeyer 2006 [41]	Northern California, US	–	–	–	Yes- Constraint
Baban and Parry 2001 [42]	Lancashire, UK	–	–	–	Yes-Constraint with buffer and Weighting

explanation of whether angle calculations related to the study region are made generically or separately for different sites. As for the visual impact, *Höfer et al. 2016* [32] increase value scores gradually as distance increases. *Konstantinos et al. 2019* [23] conducted an important investigation of WT's visual impact. Yet, their examination remained at a binary level, assessing whether the turbine can be seen or not seen from several points. *Kazak et al. 2017* [31] also carried out visibility analysis. But there is little information about how their calculations were applied and where the turbine viewpoints took place.

From an ecological perspective, as a general rule it is considered preferable to zone WT as far away as possible from nature reserves, water source and avian habitats [26,27,30]. Additionally, land cover type received attention, with operational assumptions that certain land covers, like forest, woodlands, and wetlands are less suitable for siting a wind farm. Table 2 summarizes the criteria used for ecosystem impacts, such as wildlife, land cover type, nature reserve and undisturbed spaces. Once more, the common approach assesses the impacts using exclusion zones, buffering and distancing from relevant areas, especially for sensitive birds and bats habitat. Land cover type, in many studies is relegated to simply being a technical factor [29,31,34,35,36,37]. Based on ecosystem considerations, WTs should be installed in those areas which least interfere with existing land use and cause minimal distribution [28,41]. Therefore, studies should increase the score for siting facilities on disturbed or agriculture lands relative to natural shrub, herbaceous vegetation or woodlands.

The many nuances and the extreme diversity among individual and cultural sensitivities suggests that the analysis which informs decisions about optimal WT location should be holistic. If models merely focus on setback distance from settlement and other human facilities, the result will be that suitable sites will all be located on relatively remote open spaces. Ironically, the presence of rich ecosystem services in such locations should actually *increase* the value of these open spaces and the importance of avoiding human disturbance. The only GIS-MCDA study that takes this into account as a category was published by *Hofer et al. 2016*. [32] In this case, the value scores decreased gradually and only at distances of 500 m from human facilities.

Picchi et al. 2019 [14] conducted a comparative analysis of numerous studies assessing renewable energy potential that considered visual and ecosystem impacts. Their review article criticized the lack of efficient methods and comprehensive spatial reference systems that accommodate both cultural and regulating ecosystem services. Accordingly, research efforts should utilize a multi-level approach to optimally integrate the full environmental impacts of renewable energy. This claim has merit, especially with regards to evaluations of WT using GIS-MCDA methods. In short, the existing literature does not thoroughly address the full environmental and ecological impacts of WTs.

2.3. Identify the most suitable sites

In the final phase, a significant challenge arises when combining criteria from different domains. Several techniques are used to assess the overall suitability of different sites. Weighted Sum Method (WSM) is

Table 2
Overview of ecological criteria found in wind turbine GIS site-selection studies.

Study	Case Study Region	Description of the ecological criteria			
		Birds and Bats	Land Cover	Open Lands	Ecological Area
Konstantinos et al. 2019 [23]	Eastern Macedonia and Thrace region, Greece	Yes- Constraint habitat	Yes- Ranking and Weighting	–	Yes- Constraint
Harper et al. 2019 [24]	UK	–	–	–	Yes- Constraint with buffer and Weighting
Ayodele et al. 2018 [25]	Nigeria	Yes- Constraint IBA with buffer	Yes-Constraint for several types	–	Yes- Constraint with buffer
Pamučar et al. 2017 [26]	South Banat, Serbia	–	Yes-Constraint for several types	–	–
Manomaiphiboon et al. 2017 [27]	Thailand	Yes- Constraint wildlife area with buffer	–	–	Yes-Constraint with buffer
Gigović et al. 2017 [28]	Vojvodina, Serbia	–	Yes- Ranking and Weighting	–	Yes-Constraint with buffer and Weighting
Mentis et al. 2017 [29]	Africa	–	Yes-Constraint for several types	–	Yes- Constraint
Villacreses et al. 2017 [30]	Ecuador	–	Yes- Ranking and Weighting	–	Yes-Constraint with buffer
Kazak et al. 2017 [31]	Wrocław, Poland	Yes- Distancing from habitat (NATURA 2000)	Yes-Constraint agriculture	–	–
Höfer et al. 2016 [32]	Aachen, Germany	Yes- Constraint IBA with buffer and Distancing from habitat	Yes- Ranking and Weighting	Yes-Buffering several disturbed areas and weighting	Yes-Constraint and Weighting
Noorollahi et al. 2016 [33]	Markazi, Iran	–	–	–	Yes- Constraint with buffer
Sánchez-Lozano et al. 2016 [34]	Murcia Region, Spain	Yes- onstraint IBA	Yes- Weighting only agrological capacity	–	Yes-Constraint
Atici et al. 2015 [35]	Balıkesir and Çanakkale, Turkey	–	–	–	Yes-Constraint with buffer
Tsoutsos et al. 2015 [36]	Crete, Greece	Yes- Constraint IBA	Yes- Constraint for several type	–	Yes-Constraint with buffer
Latinopoulos and Kechagia 2015 [37]	Kozani, Greece	–	Yes-Constraint several types and Weighting	–	Yes-Constraint with buffer and Weighting
Van Haaren and Fthenakis 2011 [38]	New-York, US	Yes- Constraint IBA	–	–	–
Sliz-Szkliniarz and Vogt 2011 [39]	Kujawsko–Pomorskie Voivodeship, Poland	Yes-Constraint IBA with buffer	Yes- Constraint for several type	–	Yes-Constraint with buffer
Aydin et al. 2010 [40]	Western Turkey	Yes-Constraint IBA with buffer	–	–	Yes-Constraint with buffer and Weighting
Rodman and Meentemeyer 2006 [41]	Northern California, US	–	Yes-Constraint endangered species and Weighting	–	Yes- Constraint
Baban and Parry 2001 [42]	Lancashire, UK	–	Yes-Constraint with buffer to woodland and weighting agriculture lands.	–	Yes-Constraint with buffer and Weighting

most typically used as a method to combine the different layers into a single score. The results of such analyses, however, are highly influenced by the inherent subjectivity of the weighting parameters being used.

To address the weighting challenge, some studies use the Analytic Hierarchy Procedure (AHP) in their evaluation. This method assigns weighting categories based on expert opinion [23,25,28,30]. Other models focus on economic criteria [27,29,38,39], despite their drawback of overlooking critical social and environmental costs. Other studies used Fuzzy Analytic Hierarchy Process (FAHP) [25,26,34]. These assessments' aim is to address the issues of uncertainty, vagueness and inconsistency in WT site selection and associated decision making. Additional theories exist in the literature based on Order of Preference by Similarity to Ideal Solution (TOPSIS) [23,37], ELECTRE [35], methods of Benefits, Opportunities, Costs and Risk (BOCR) [43], and Best-Worst Method (BWM) [26].

Many GIS-MCDA studies confront the challenge of assigning category weighting, or comparing between planning scenarios and sensitivity analysis responding to the criteria scoring:

Rodman and Meentemeyer 2006 [41] use a rule-based GIS model to predict suitable sites for WT in the San Francisco Bay area. Their analysis relied on three models: a physical model, an environmental model, and a human impact model. All models are combined by ascribing the same weight to all layers. Each layer is subdivided into multiple classes, where each class gets value scores according to its suitability.

Latinopoulos and Kechagia 2015 [37], focused on the Kozani region of Western Greece. The study assessed the weights that could be assigned to three different policy scenarios. The first scenario assumed that all categories were of equal importance. In the other two scenarios, the weights were prioritized for a policy driven by environmental and social criteria, along with another alternative policy, where the focus relied entirely on technical and economic criteria.

Recently, *Harper et al. 2019* [24], highlights how the predicted overall energy capacity varies depending on the combination of three legislation-planning criteria including economic viability and site acceptability in the UK. Their research aims to provide an accurate tool for capturing the social, technical, and legislative restrictions together.

Such scenario methods allow for the integration of estimate criteria from different disciplines into a single model, without setting subjective weights. The disadvantage of assigning scenarios relates to the challenges of applying threshold values. This means that in some cases, the limits separating *suitable* and unsuitable site might be very unclear and seemingly arbitrary.

2.4. Literature review summary

In summary, the literature review reveals a significant need for a quantitative geographical examination of the environmental criteria (i.e. noise, shadow flickers, visual impact, birds and bats, open lands and land cover) in order to comprehensively integrate all meaningful parameters inside a single existing model. Examining each site based on its actual possible environmental impact affords the opportunity to explore more potential cells, instead of immediately excluding entire regions, which occurs when using the very broad strokes associated with buffer zone methods. This advantage is particularly salient in Israel where lands are limited. Moreover, such an approach permits greater objectivity, and allows for a richer consideration of the geo-spatial variables that influence these criteria. For example, spatial noise propagation is influenced not only by its distance from a WT, but also by background noise, topography, wind direction and velocity. Likewise, damage to birds also completely depends on WT location and species, while shadow flicker is a result of the actual angle of the sun in relation to the turbine and structures.

As *Resch et al. 2014* [44] claimed in their review of spatial planning and renewable energy, there is occasion for expanding upon existing models and bringing GIS analysis into a more traditional generic model. This study is consistent with these claims. The methodology is based on GIS-MCDA and adopts the standpoint that only excludes regions on the basis of clearly defined criteria, while simultaneously classifying suitable sites according to threshold values. Using this approach, we are able to overcome the "subjectivity disadvantages" associated with earlier methods. Rather, relying on threshold values while focusing on specific possible scenarios contributes to a richer estimate of the land available for feasible, wind-power development. The added flexibility gained is especially relevant in countries where the supply of land and potential sites are relatively low.

The present study's primary innovation involves the quantification and integration of the full range of environmental criteria (both anthropocentric and ecological), while presenting a more comprehensive model for WT site selection. Geo-spatial modeling for WT planning has not been conducted in Israel thus far. In contrast with other countries, Israel affords a modest number of potential WT locations and a high level of resolution in available information regarding key parameters (e.g., avian presence).

3. Study area and data collection

The study was conducted in two Israeli regions: the Haifa region and the Galilee region, both in the north of Israel. The Golan Heights were excluded from the analyses because the prior approval of three turbine projects in the area, encompassing about 390 MW, essentially exhausted the potential, available sites. The study area map and it is boundaries are featured in Fig. 1. The total examined area contains 4,208 square kilometers and is home to 2.43 million residents, reflecting a population density of 578 residents per square kilometre [45]. Population density in the north of Israel is higher than the national average, which is already among the highest in the OECD [46]. As Fig. 2 demonstrates, Israel's northern countryside is filled with settlements of varying sizes, religious affiliations, cultures and community characteristics. The overall designated area for human settlement is 789 square kilometers. Additionally, the study area includes nature reserves and national parks (669 square

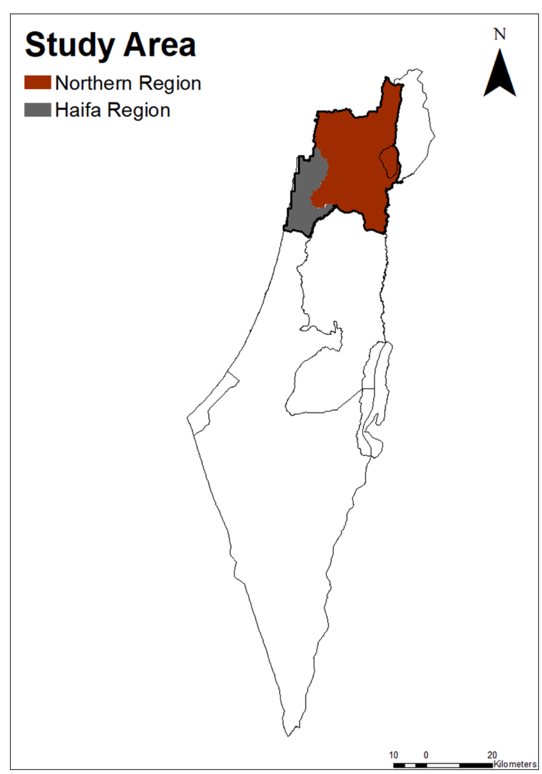

Fig. 1. The map of northern Israel and Haifa region where study was conducted.

kilometers), as well as military training zones (168 square kilometers). Together, these areas cover 40% of the region's territory, not even taking into account existing infrastructure, industrial areas, army camps, and other land designations.

The complex terrain of the "Galilee" creates a challenge for utilization of Israel's wind potential in its northern countryside. The data file format and the source from which they were taken are presented in table 3. The data were collected from various sources, all accessible for ArcGIS 10.7.1 and WindPro 3.2 software. During the analysis, comparison of the files was made with OpenStreetMap data as well.

4. Methodology

Fig. 3 presents the study's different stages. This section describes the study's methodological framework, carried out using GIS-MCDA techniques. In order to locate the most suitable WT locations, the regions' areas were divided into 500x500 meter cells (0.25 square kilometers).

The turbine module selected for our investigation is the Vestas V136-3.45 MW. This turbine holds a blade diameter of 136 m and reaches an overall height of 168 m, with its hub height setting at 100 m. The module was selected for two main reasons: First, it is widely utilized worldwide and produced by an industry leading manufacturer, with a full data base containing the forms and programs on which our study is based. Second, this turbine is in scale with the modules that will eventually be erected in Israel. Indeed, a single, maximum WT can be built within the scale of a selected cell and still maintain the WT distancing customarily used to prevent significant wake losses [48].

The common approach for optimizing wind power productions favors a single, large turbine over several smaller ones. In this way, minimal land is compromised and there is better opportunity for utilization of strong wind at higher elevations. It is of course possible that in certain locations, modules that are smaller or larger than the one selected in our study will be preferred for a given site in order to benefit social welfare. As an initial evaluation, the current study offers a baseline for such comparisons in the future.

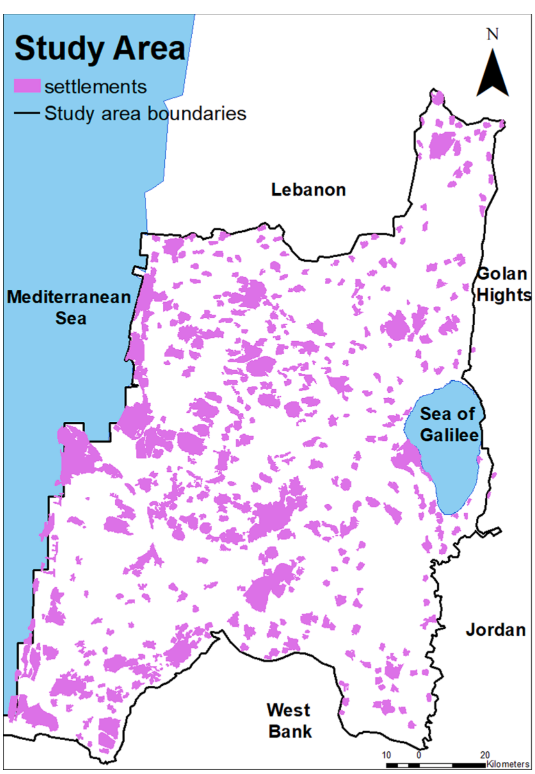

Fig. 2. Location of existing settlements in densely-settled northern Israel.

Table 3
Data collection and their source.

Data	File Format and Resolution	Source
Wind Velocity	Raster Map 100 m resolution	Israel Meteorological Service (2016). Israel's wind atlas, 100 m annual wind speed.
Slope	Raster Map 30 m resolution	DEM_Israel. HaMaarag – Israel's National Ecosystem Assessment Program.
Settlement, NPA, Fire Zones, Roads, Railways, Airports, Airstrips, Water Bodies, Quarries, Industry Areas	Vector Map	Israel Planning Authority, Haifa and Northern regions outline plan (TMM 2 and 6 respectively).
Transmission Lines	Vector Map	Israel Electric Corporation.
Birds and Bats	Raster Maps 5 km resolution	Israel WT sensitivity maps for birds and bats [47]
Land Cover	Raster Map 25 m resolution	HaMaarag – Israel's National Ecosystem Assessment Program.
Open Lands	Raster Map 50 m resolution	HaMaarag – Israel's National Ecosystem Assessment Program.
Topography	Raster Map 30 m resolution	Shuttle Radar Topography Mission (SRTM). https://www2.jpl.nasa.gov/srtm
Settlement Population	Table	Israel's Central Bureau of Statistics. Population by settlements (2018).
West Bank Settlements	Vector Map	Israel GovMap- https://www.govmap.gov.il.

In summary, *section 4.1* excludes unsuitable cells based on threshold values according to various criteria, while *section 4.2* optimizes the WT sites within cells. *Sections 4.3–4.5* describe the eight criteria defined for the model. These criteria are divided into three types of layers:

1) The benefit layer, reflecting the energy potential;
2) Anthropocentric layers, characterizing the environmental impact on neighboring residential areas, such as noise, shadow flickers and visual impact;
3) Ecological layers, expressing the impact on biodiversity and the ecosystems, such as the sensitivity of damage to birds and bats, land cover and estimation of continuity for open lands.

In *section 4.6* the assignment of value scores is described, together with the process of extracting the suitable sites and optimal locations based on environmental thresholds and energy production levels.

4.1. Exclusion zones

All told, 18,228 cells were created in the study area (Haifa region-3,796 and North region- 14,432). The first step of the study procedure was to exclude unsuitable cells from the database –i.e. to exclude zones in which the installation of WT, a priori, is not plausible or feasible. This includes areas with low wind potential, residential areas, NPA (protected natural areas of Israel's *Nature and Parks Authority*) and terrain with extreme slope. Table 4 presents the exclusion criteria and their threshold values. For some criteria, buffer zones were created around the respective features to ensure safety areas.

4.2. Siting turbines within cell

In order to quantify the criteria layers, it is first necessary to place a single turbine within each cell. At the outset, turbines were placed at the center of cells as a point feature. As different environmental impacts can take place within a 0.25 square kilometer cell, the goal of this step was to optimize hypothetical WT locations, in order to avoid misleading assessments. Therefore, we examined all possible WT locations to

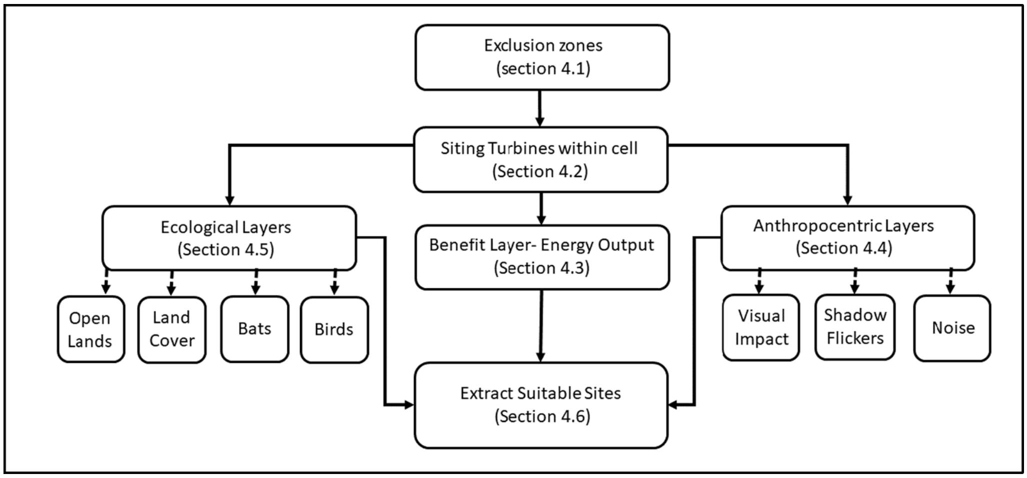

Fig. 3. Methodological framework reflecting the diverse environmental parameters integrated into GIS layers for model analysis.

Table 4
Exclusion parameters, indicating the specific criteria used for eliminating sites as potential wind turbine locations.

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

characterize the threshold values appearing in table 4 and determine the optimal conditions for installation. These include an underlying preference for maximal wind, minimal slope, maximal distance from settlements and NPA, as well as optimal land designations (e.g. agricultural lands as opposed to natural forest). For instance, if a cell contains both natural groves and agricultural fields, WT location would optimally be sited on the arable land. Another example involves cells in which some areas have a wind velocity of less than 5.5 m/s (which leads to exclusion due to the wind criteria described in *section 4.1*). In these cases, the WT location was moved to other areas within the cell, as it still had to fall within the threshold values of the wind velocity category.

Another constraint integrated at this stage involves the distancing between WTs in order to reduce wake loses. The typical WT spacing presently used in actual wind farms is ~6 − 10D, where D is the turbine diameter [49]. Nonetheless, there are cases where this distance can be lower at certain distributions, depending on the dominant wind direction.

To maximizes the number of examined cells, a minimal value of 400 m distance between WTs was selected during the optimization process of within-cell locations. It is possible that during the actual micro-planning of a site, this distance may increase. Yet, in the current study, we assumed that in general, it was unrealistic to have two WT modules operating in a proximity below 400 m.

The optimization process only allows for moving the points a few-hundred meters inside a cell polygon. Nonetheless, it brings to the model important site-specific insights, a clearer examination of the exclusion step and more realistic results in order to avoid specious assessments about a cell's potential. This within-cell localization process led to the elimination of more potential cells that did not meet threshold values, leaving us with a total of 1,017 remaining possible cells in which WT installation could then be evaluated. Fig. 4 presents these cell locations on a map of the study area.

Fig. 5 presents cell distances from the proximate settlements and NPAs sites (including national parks). Only 25% cells are located at two kilometer-distances from settlements while 27% of the cells are located at two kilometers-distances from NPAs. At the same time, 40% and 50% are located at distance of less than one kilometer away from a settlement or an NPA respectively. The cells' proximity to settlements or NPAs shows the complexity of WT development given Israel's dense conditions. Nonetheless, a large reservoir of cells remains for examination, significantly higher than the requisite area needed to obtain the governments' renewable energy goals.

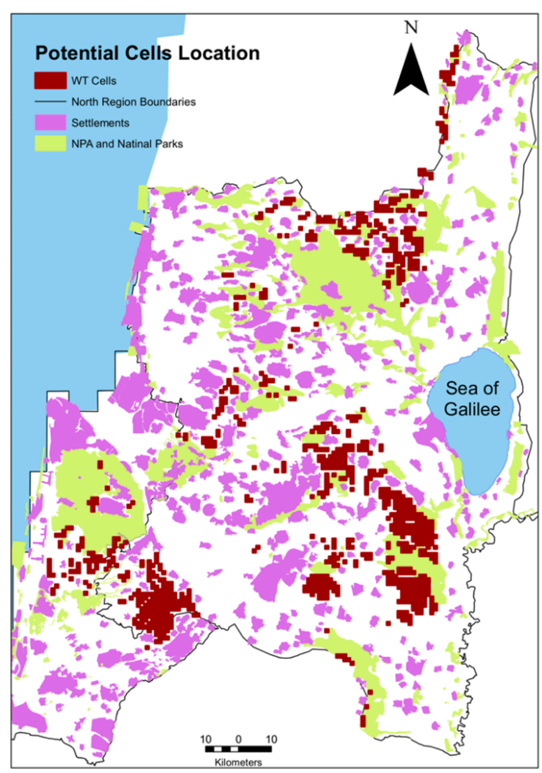

Fig. 4. Examined cell locations which were considered as potential turbine sites (N = 1,017).

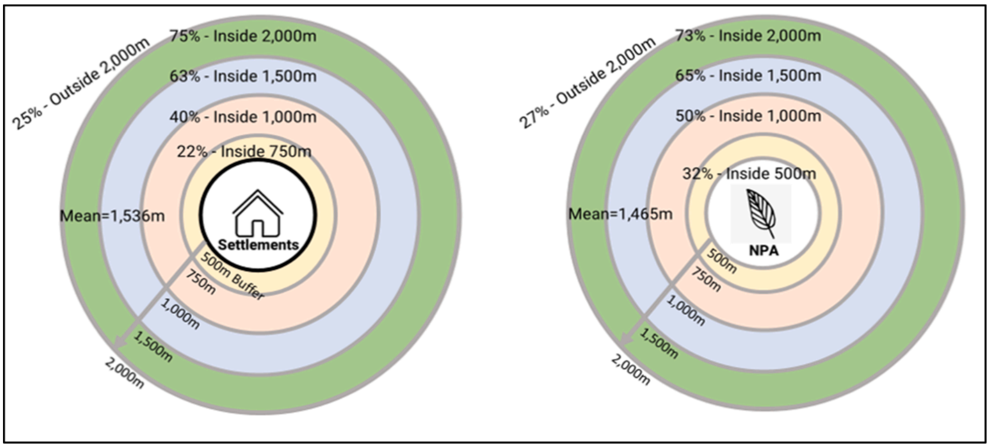

Fig. 5. Cell distances from settlements to protected natural areas (N = 1,017).

4.3. Energy output layer

One of the study's novelties is the use of geographical data software for wind farm planning. Several commercial companies provide such services, including Windpro, OpenWind, WindFarm, and WindFarmer. In this study, WindPro 3.2 was utilized, enabling energy calculations and replicable characterization of environmental impacts. The software's main advantages involve its capacity for assessing the geographical implications for various WT modules and the ability to integrate with additional GIS programs [48]. The software has yet to be used in GIS-MCDA studies, although, it has previously been used to measure the results of energy potential [50,51] and noise propagation [52].

The energy potential for each individual turbine was then calculated in terms of MWh per year, based on the wind distribution charted in the Israeli Meteorological Service's wind atlas. The model allows for the capturing of the greatest spatial efficacy for all locations. Once a value is measured by energy units (and not by installed power) the estimate for spatial planning is more accurate, facilitating more reliable cost-effective measures.

Although proximity to transmission lines and roads are a favored criterion in many GIS-MCDA studies, they are absent in the current model due to insignificant differences between locations. This a function of the ubiquitousness of infrastructure in the study area. To offer some perspective, the maximal distance to transmission lines in Israel's northern regions tends to be three kilometers, a negligible value compared to other areas in the world.

4.4. Anthropocentric layers

4.4.1. Noise

Noise is a sound produced by a certain source through sound waves. Oscillations in sound waves are characterized by frequency (Measured in hertz; Hz) and volume (measured in decibels; dB). The dominant source of noise from WT results from the aerodynamic friction that is created by the interaction between blades and the air. The noise moves in different frequencies and its propagation through space is affected by several factors: distance, number of WT operating, frequency, wind velocity and direction, background noise as well as others geographical factors [15,53]. The World Health Organization's (WHO) recommends limiting noise exposure to a nightly annual average of 40 dB outside of living rooms, in order to achieve quality sleep [54], while standard wind farms generate noise averaging around 40 dB threshold at distances of hundreds of meters [15].

WTs create a continuous and monotonous sound, distinctive from other noise sources (i.e. roads). In fact, many citizens are exposed to background noises louder than those produced by turbines [54]. Other noise sources, however, are mostly present during the daytime. Hence, WT noise can often be heard, especially during the nighttime in rural areas. Nocturnal turbine noise emissions can definitely affect neighboring residents' sleep quality [9,10,55]. In the literature there is no certain confirmation of adverse health impacts from WT noise, aside from sleep disturbances which are attributed to annoyance [10,56,57,58,59]. Studies show that annoyance statements are frequently influenced by the planning process and public participation [18]. When the public is engaged, WT noise appears to be less offensive [60].

Using the WindPro software, noise levels propagating from the WT to the neighboring settlements were measured through the standard noise code ISO 9613–2 General. Noise circuits took topographic lines into account and background noises from main roads. Three dB were reduced from WTs located at a distance lower than 300 m from a road; two dB were reduced for 300–500 m distances; and one dB was reduced for 500–700 m distances. These adjustments convey an advantage to locations bordering roads, which already emit noise pollution.

Finally, cells ranging lower than 30 dB were defined as "no-noise cells" (score of zero environmental impact). Noises ranging between 30 and 35 dB are also considered to be negligible as they meet the established standards throughout many countries [15,61] and Israel as well [62]. As the model is based on a single WT, the assumption is that the propagation of cumulative noise from several WTs within a wind farm increases the overall decibels emitted. Hence, in many cases, acoustically it makes sense to consider cells in which a single turbine produces noise at the 30–35 dB level. In cases where noise propagation reached more than one residential polygon, the measured values were added together.

4.4.2. Shadow flickers

Rotating blades interrupt the sunlight, producing an unavoidable flicker. The occurrence of shadow flickers is determined by a specific set of variables that include the distance from the WT, geographical location, time of season and day, weather patterns and the turbine height and rotor diameter [63]. Several studies assess the impact of flickers and all confirm that shadow flickers do not pose a health hazard for humans. At the same time, the phenomenon often creates a substantial annoyance for residents [11,63,64].

In order to quantify the impact of shadow flickers, we used WindPro software to calculate the maximal hours of flickers per year in a 'worst case scenario' (i.e. the turbines operate throughout the entire year without being blocked by disturbances, such as treetops). The topographic terrain was integrated into the calculations, while no limitations of range were defined. The maximal value of flicker hours per year in one settlement were multiplied by the shadow flickers risk area. These conservative assumptions lead to a very stringent calculation of the potential magnitude of flicker hazards, so that each settlement was assigned the most extreme possible value of flicker times and ranges. In the scenario of shadow flickers casting on more than one residential polygon, the measured values were added to each other. This calculation estimates which cells carry no flicker concerns (a score of zero environmental impact due to favorable location). It also allows for comparisons between other cells with varying flicker levels.

4.4.3. Visual impact

WT installations can produce a dominant visual impact as the WT object can be viewed tens of kilometers away. The nature of this impact is subjective: for some people, a view of the WT represents innovation and sustainability, while for others it reflects damage to the existing natural landscape. The contrasting nature of this impact highlights the importance of maximizing community participation in the planning process. Several studies suggest that *involuntary* exposure to WTs among neighboring residents is associated with adverse psychological and physiological effects [9,60]. Hence, it is important to quantify the factors that increase the visibility of WT.

There are two main approaches to quantifying the visual impact factors of WT. The first is through public questionnaires and visual illustrations [12,65–70]. The second approach investigates the visual impact through GIS tools [71–75]. According to the studies cited, there are several parameters that might increase the potential for adverse visual impact: distance from the turbines; the size and color of the turbine; the size of the wind farm; weather visibility conditions; the amount of citizens with exposure from observation points; the population's demographic characteristics; as well as the number and the size of the observation points.

A visibility analysis for the turbine module selected for the current study was carried out individually for each WT cell using WindPro ZVI calculations. A quantitative model was built based on the key factors presented in the literature. This facilitated a comparison of turbine visibility levels in nearby settlements. Due to the ambiguity as to whether individual spatial perception is negative or positive, it was decided *not* to take into account roads, as well as riding or walking routes as visibility points. Rather, only the visibility effect on the neighboring settlements that are continually exposed to the turbines was characterized. The negative scoring for the visibility impact on cells was calculated by a summation of the values received from all the settlements exposed to the turbine, based on the work by *Hurtado et al. 2004* [75].

Table 5 summarizes the parameter values used for each affected settlement in the model. The scoring is based on three parameters, with their values normalized into discrete quantities in order to create a simple scoring method, which efficiently quantifies turbine visibility:

1) *The size of the vertical angle*: this parameter refers to the WT object, as visualized from the settlements. It addresses the components of distance and topographical influence.

2) *The size of the population in the settlements*: based on data from Israel's *Central Bureau of Statistics*, large and small settlements in different formations were characterized. A residential area with a larger population requires more attention with regards to visibility concerns, as it affects a greater number of people.

3) *Observation points within the settlements*: as visibility of the WT does not affect every point in the settlement polygon, consideration was given to the total area of the settlement exposed to the WT. Given an identical visibility area in two different settlements, a larger settlement polygon will receive a lower score than a smaller polygon. This consideration provides a quantifying measure for the observation points from the entire polygon and prioritizes settlements in which most of the landscape includes a WT in the visible panorama. The model was defined so that turbine visibility would be as low as possible for as many residents as possible. Through this method, the visibility issue can be fully considered, and different planning scenarios compared.

In the next step, the normalization values were connected to a negative scoring of the visual impact inside the affected settlements. The final scoring of the visual impact is represented by:

$$S_{vi} = \sum_{i=1}^{n} \frac{(a+p)O_b}{12} \quad (1)$$

Where a is the normalization value of the vertical angle, p is the normalization value of the population size, O_b is the observation area rates and an examined settlement represents by $i = 1, 2, 3, \ldots, n$. Dividing the equation by 12 allows for a single settlement to achieve a scoring value between zero and one. In this manner we quantify the visual impact using a method which is comparable among various of cells.

4.5. Ecological layers

4.5.1. Avian sensitivity (birds and bats)

WT damage to birds and bats can be brought about directly through avian collisions during blade rotations, or indirectly, through impacts on habitats. The potential damage to migrating and nesting species depends on three main factors: [76]

1. *Species characteristics*: the prevalence of the species in the area, migrating seasons, and morphological characteristics;

2. *Spatial characteristics*: weather and landscape conditions, feeding availability, and aviation routes; and

3. *Wind farm characteristics*: the number of turbines and their height, along with the planned locations of the turbines.

A single turbine on average produces a mortality of 2.3 birds and 2.9 bats a year [16]. However, a large deviation exists between turbines (between 0 and 60 for birds and 0–70 for bats). These high ranges are primarily caused by turbine placements amidst areas with vast avian activity, causing more significant damage to the avian population. The effective way to reduce avian impact is through more precise planning of turbine locations, which should be based on habitat location and migration routes, along with adjustments based on specific species behavior and flight risks [16,76]. For instance, placing a turbine close to the shoreline or on the edge of a hill can be especially hazardous to various types of bats [76], while the hazard to birds seems to be lower on spatial plains [77].

The avian and WT correlation is highly relevant in the Israeli case. Dozens of endangered nesting species still survive in the country. Moreover, Israel is located along a prime migration route for many species who move between Europe and Africa. Due to the acute ecological risks, a mapping study for avian sensitivity across the full range of Israel's geography was published by a local team of leading ornithology experts [47]. During the sensitivity mapping phase, cells were given scorings with regards to the risk of collisions in the area. In total, 59 species with various endangerment risks were entered into the model. Based on the species' characteristic analysis, a measure for risk of flight and habitat risk was assigned. Afterward, data from surveillance, surveys and transmitters were used to construct the final sensitivity map. The sensitivity mapping process was further applied to 26 types of

Table 5
Values assigned to visual impact parameters.

	1 low	2	3	4	5	6	7	8 High
Vertical angle (degrees)	1–2	2–4	4–6	6–8	8–10	10<	–	–
Settlement population (thousands)	1>	1–5	5–15	15–50	50–150	150<	–	–
Visibility area (in percentage)	12.5	25	37.5	50	62.5	75	87.5	100

bats. These sensitivity maps are used as a raster data source for the bird layer and the bat layer in the current study.

4.5.2. Land cover

There are profound environmental implications associated with the designation of certain areas for electricity generating facilities such as WTs. From an ecological aspect, it is preferable to establish WTs within ecologically disturbed areas, rather than placing them in the heart of open spaces. Many ecological systems require large, continuous and representative open areas. Understanding the cell's land cover within the study model allows for the prioritization of open space protection, with the goal of minimizing human footprint. In order to quantify this layer, a GIS database for Israeli land coverage was utilized. For each turbine location in the study, the land unit was defined. Disturbed land received the highest-ranking level for WT development, followed by agriculture or arable land, and then shrubland, herbaceous vegetation, planted forests and lastly, natural groves.

4.5.3. Open lands

If we only strive to locate turbines as far as possible from anthropogenic, built environments, the result will be a prioritization of WT in open lands. In order for the ecological layer to be accounted for within the model, open lands must be integrated within it. Conservation commitments favor an objective function of maintaining and maximizing proper, continuous stretches for biodiversity and for the ecosystem as a whole [14,76]. More than defining whether it is on disturbed or natural land, it is also important to account for how proximate each cell is to disturbed areas. A scoring model by the *Israel's National Ecosystem Assessment Program* was utilized to quantify the continuity of open land in the study area. This model investigates how close each spatial unit is to a disturbed object, with consideration of the magnitude of disturbance. There is significance to whether the proximity is to a fence, a road, a settlement or to a large power plant. In the general model of the current study, prioritization was given to siting WT in locations that scored a low value in the open land continuity measure.

4.6. Extract suitable sites

The final phase of the model involves the integration of the different GIS layers in order to identify the most suitable area for WT siting. The model therefore assigns value scores for each location based on an integrated analysis for each cell. The data, which make up seven different layers, serve as a continuous variable, while *land cover* is expressed as a discrete variable, divided according to five optional land types. Hence, all layers are classified into 10 scoring value classes (except for the land cover layer which is broken into 5 classes) where class 1 represent the most suitable cells for a WT and 10 the least. A class of 'zero' exists only with the *noise* and *shadow flickers* criteria, as we identified many sites without risk of noise annoyance (less than 30 dB) or shadow flickers. Based on these criteria, the rest of the examined cells were classified according to their ten-scoring value as well. This classification is made by the Jenks Natural Breaks algorithm [78].

After assigning a value score for the criteria, in the next step we select a planning scenario that integrates the definition of threshold values for the environmental criteria, based on their classification. Thus, a cell that was found to contain a 'highly suitable scenario' is deemed optimal according to the strictest environmental threshold values: below class 6 for the continuous variables *(noise, shadow flickers, visual impact, birds, bats, open lands)*, and not containing *land cover* with class 4 or 5 (planted forest or natural groves).

In addition, the anthropocentric criteria scoring is cumulative and reflects the total effect of several settlements. In some cases we avoid defining impacts of more than 35 dB and over 30 h per year of flickers inside a single settlement within the 'highly suitable scenario', based on an approach that is defined by existing minimal regulations [9,16]. The extra threshold values of noise and shadow flickers are possible due to the model specific measurements of these phenomena.

Afterwards, the model joins additional cells that are defined only as anthropocentric or ecological friendly, with a stipulation that they do not have any other criteria with significant environmental sensitivity. Table 6 describes the specific environmental scenarios defined by the study methodology.

Lastly, after the environmentally suitable sites are identified, the model calculates the annual potential energy that can be produced according to each location. Adding a benefit layer of "energy potential" to the selection criteria is frequently considered the most important category in GIS-MCDA studies. A site with high energy potential is important not solely because of economic consideration, but also from the perspective of sustainability. That's because a highly productive, single WT can reduce the total number of facilities needed and therefore minimize the associated environmental footprint.

The model divides environmentally suitable cells according to their energy value score. As a result, we identify locations with high or medium energy potential (above energy class 4) from the environmental "highly suitable cells". Additional sites that only meet "anthropocentric or ecological criteria" were joined, only if they were defined as having high energy potential (above energy class 7). These extractions provide maximal energy output along with minimal environmental impact and were deemed to the most suitable cells based on our proposed holistic orientation. Fig. 6 summarizes the extraction process in order to identify the most suitable sites based on threshold scenarios.

5. Results

The GIS model classified the eight layers based on the value scores of the criteria. As the Fig. 7 heat map shows, cells that were classified with a higher score reflect greater environmental impacts. The energy layer was the only criteria where increases in value score correlates with benefit, as we strive to maximize wind energy potential.

The energy output average value is 9675 MWh per year, and the range scale of the values is between 7,620–13,919MWh. Geographically, greater energy potential correlates with elevation, as the terrain's mountain peaks contain higher wind velocity. In general, locations in the eastern parts of Israel's northern district demonstrated better energy potential than in the west. Some northern sites also emerged as superior, especially those close to the border with Lebanon.

Noise and shadow flickers analyses indicate whether WTs in cells are likely to cause negative impacts to the residents. Accordingly, 49% of the total cells receive no negative value score for noise according to these criteria while 47% of the total cells receive no negative value score for flickers. As expected, the visual impact was most prominent in the center of the study area, which is home to large residential areas, such as the Western Galilee, close to the city of Karmiel and the Harod valley,

Table 6
Threshold values for three possible environmental scenarios.

Environmental Criteria	Scenario 1: Highly Sustainable Sites	Scenario 2: Additional Anthropocentric Sustainable Sites	Scenario 3: Additional Ecological Sustainable Sites
Noise	Below class 6 and maximum 35 dB in a settlement	Below class 6 and maximum 35 dB in a settlement	Below class 8 and maximum 35 dB in a settlement
Shadow Flickers	Below class 6 and maximum 30 h p/y in a settlement	Below class 6 and maximum 30 h p/y in a settlement	Below class 8 and maximum 30 h p/y in a settlement
Visual Impact	Below class 6	Below class 6	Below class 8
Birds	Below class 6	Below class 8	Below class 6
Bats	Below class 6	Below Class 8	Below class 6
Land Cover	Not contain category 4 or 5	Not contain category 5	Not contain category 4 or 5
Open Lands	Below class 6	Below class 8	Below class 6

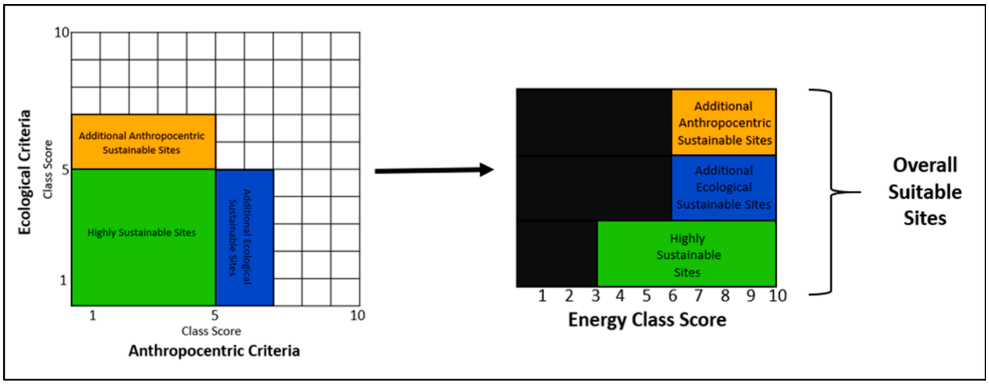

Fig. 6. The extraction procedure, based on the criteria's class score.

east of the city of Afula.

Preferable locations for birds and bats exist along the ridges nearby the city of Nazareth. As for optimal land cover, the major sites containing arable/agriculture land (45% of the cells) were primarily found in the south-east of the Galilee. Secondly, the highest concentration of herbaceous vegetation/shrubland (22%), are mostly located along the Ramot Menashe ridge, to the north of the city of Umm El Fahem (U.E.F). In general, planted forest were found in 19% of the samples, natural groves in 12%, and disturbed areas in only 2%, as many construction sites had already been excluded at the initial stages. Prioritized sites based on the open lands criteria in many cases run counter to the visual impact analysis. There is a rational explanation for this apparent incongruity: the dominance of visual impact dissipates the further the WT is sited from a disturbed area. There are, of course exceptions, like the Harod Valley: despite its high score in the open land layer, the area reveals significant visibility impacts due to its idiosyncratic geographic characteristics.

Maps charting the negative impacts of WTs were then overlaid with the 'environmentally suitable sites map,' based on the threshold values. The overlay map is depicted in Fig. 8.

The map reveals that 43 cells met the definition of "*highly suitable*". These locations represent the highest potential for WT development from an environmental point of view. Two-thirds of these cells are located around Nazareth and the rest scatter mainly along Israel's northern border. In the next step, additional potential cells entered the results as "*sufficiently suitable*" according to several criteria while only "*barely suitable*" in others.

Making the thresholds slightly more permissive allowed for identification of additional cells in which WTs would not have a significant impact on the neighboring residents and the ecological system. For instance, we identified several sites that met anthropocentric concerns, without significant effects of noise, shadow flickers, or visual impacts. The adjusted criteria still ensured that WTs would not produce ambient noise over 35 dB(A) within a nearby settlement, and that shadow flickers would not exceed 30 h per year. A parallel exercise was undertaken to add additional sites where critical ecological impact value thresholds were not exceeded. These locations do not present a high risk to avian populations nor did they contain any natural woodlands or sully continuous open spaces. The adjusted ecological and anthropocentric criteria provided an additional 178 cells. Together with the 'highly suitable cells', the model identified 221 environmentally suitable cells. This constitutes roughly 21.73% of the total investigated cells and 1.21% of the entire study area.

The results of the overall, *suitable* remaining cells, including those that meet energy considerations, are depicted in Fig. 9. All total, some 79 cells were identified as optimal sites for establishing WTs in northern Israel. All sites met the environmental and ecological criteria as well as the requisite energy feasibility demands. The overall suitable cells are predominately located in four main geographic areas: the northern Nazareth mountain ridge; the area of Yavniel and Tavor river, south of the Sea of Galilee; the mountains between the Galilee villages Yiron and Dishon, adjacent to Lebanon border; and the southern hills of Ramot Menashe, north to Umm El Fahem. The total land area in which overall suitable sites were identified constitutes 0.5% of the original study area.

Calculating the potential energy output which can expected by WT production in the overall suitable cells reveals that 846 GWh of energy per year can be produce from wind energy in the study area without violating relatively stringent environmental constraints. The value of an average cell's energy supply comes to 10,714MWh, 10% above the aggregate average of the total cells sampled. In terms of present zoning, suitable cells are primarily located on arable/agriculture lands (53%); 19% of the sites are found on herbaceous vegetation/shrublands; another 19%, would be sited in planted forests. Finally, disturbed areas constitute 9% of the overall suitable sites.

It is interesting to note some of the differences of sites which were deemed "overall suitable" relative to the original sample of 1,017 cells, according to the distances to settlements and NPAs (see Fig. 5). In the results appearing in table 7, proximity to settlements has a greater influence on the likelihood of a cell meeting the environmental criteria than the distance to NPAs. In fact, proximity to NPAs does not even correlate to suitable sites, as 35% of the suitable cells are located less than 500 m to NPAs and only 23% are more than 1500 m (in comparison to 35% of the original sample).

The impact of settlement distances was found to be significant between 500 and 750 m. In practice, only one cell that was assessed in the study falling inside this range was found to be suitable. There are, however, a large number of cells in the 750–2,000 m distance range, with the most common suitable distance from human settlement usually around 1,500 m. Farther than 2,000 m away from settlements, we found a decay effect, with the rate of acceptable cells starting to decrease.

6. Discussion

GIS-MCDA studies for WT site-selection commonly offer an efficient methodology for selecting optimal sites from a large geographical range, in efforts to increase the share of renewable energy and reduce greenhouse gas emissions. The procedure has the capacity to integrate economic, social, and environmental considerations into spatial analysis and indicate suitable sites for WT development. Among the environmental effects of wind facilities which can be assessed are noise, shadow flickers, visual impact, and impact on the ecosystem such as biodiversity (especially avian species) and conserved lands. The literature review of GIS-MCDA studies reveals a tendency to avoid quantification and contrasting of environmental impacts from renewable energy facilities, as many studies simply resort to buffer zones around settlements or NPAs in order to avoid WT's negative effects. In a country as small as Israel, this highly conservative strategy essentially means that WTs will never make a meaningful contribution to the country's renewable energy

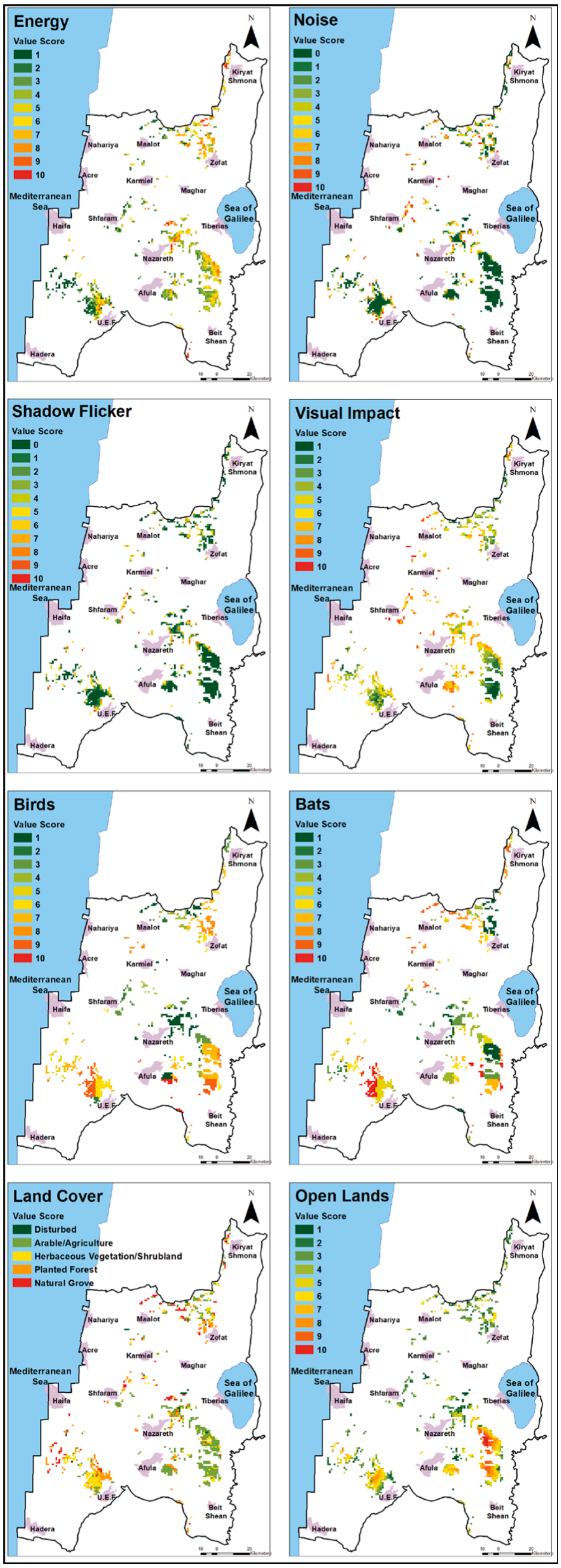

Fig. 7. Assignment of value scores based on the study criteria.

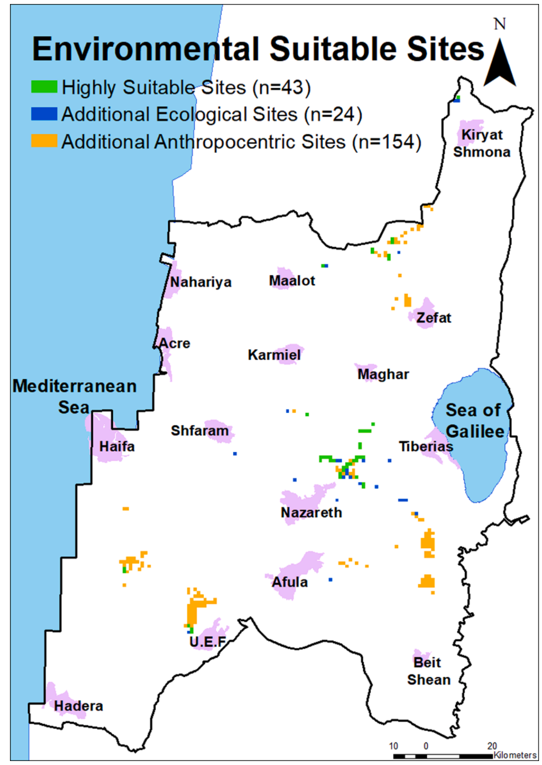

Fig. 8. Map containing sites for establishing wind turbines based on level of environmental suitability. (n = 221).

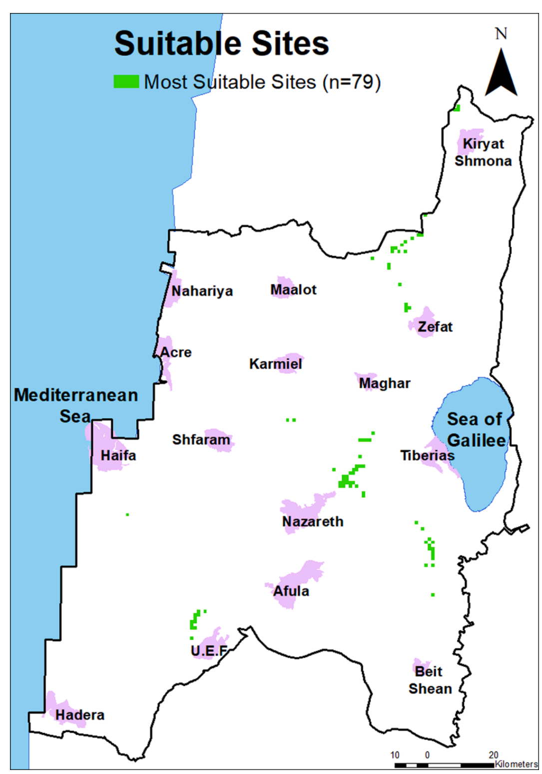

Fig. 9. Map containing overall environmental suitable sites for wind turbines in northern Israel.

portfolio.

The current study was conducted in the northern regions of Israel. Numerous projects are already in various stages of planning in the area

Table 7
Distance to settlements and naturally protected areas when contrasting the 79 overall suitable cells and the 1,017 possible wind turbine cells examined (in parenthesis).

Distance to Feature	Settlements	NPAs/ national parks
0–500	Buffer zone	35% (32%)
500–750	1% (22%)	10% (10%)
750–1000	16% (18%)	10% (8%)
1000–1500	41% (23%)	22% (15%)
1500–2000	22% (12%)	3% (8%)
less than2000	20% (25%)	20% (27%)
Mean	1,597 m (1,536 m)	1,344 m (1,465 m)

and the associated environmental controversies undoubtedly inform the process. The high population density throughout Israel and the complex conditions it creates pose a significant challenge to the exploitation of Israel's wind potential. In order to overcome biases, vested interests and suspicions among local residents, a clear, transparent methodology for modeling the actual site-specific impacts of a WT location is critical. In total, eight criteria defined our model, divided into three types of layers: the benefit layer (energy potential); the anthropocentric/ environmental layers (noise, shadow flickers, visual impact); and the ecological impact layers (birds, bats, land cover, open lands).

After collecting and organizing copious, site-specific data, the layers were assembled utilizing GIS software such as ArcGIS and WindPro. This allowed for efficient quantitative evaluations of the impacts for each potential WT module. While the analysis utilizes innovative criteria and calculations for integrating different GIS layers, ultimately, the methodology is designed to classify sites according to threshold values and scoring according to disparate criteria. The quantification of environmental impacts allows us to extract sites without developing WT in locations where ecological sensitivity is high or where WTs are likely to pose adverse environmental effects.

By integrating at the micro-level for every potential site, the study identified 221 cells of 0.25 km^2 that are environmentally suitable for WT development in the country's northern region. The number of cells decreased to 79 sites, however, when the energy potential was also considered, with only 0.5% of the total land area deemed appropriate for WTs. The 'overall suitable sites' locations concentrate in four main geographical areas. Aggregated, WTs established there have the potential to create an installed capacity of 273 MW and annual energy production of 846 GWh. Together with existing and approved wind farms in the region, this finding is almost sufficient to meet the country's goal of achieving 730 MW of wind power by 2030. The spatial calculations that emerge suggest that without a clear policy and aggressive planning efforts, it will be difficult to meet this goal based solely on renewable transmission in Israel's northern regions.

7. Conclusions

The study area contains a large number of settlements and ecologically sensitive NPAs. The result showed that the distance to an NPA does not affect WT site-selection. From an ecological perspective, location importance should be driven by *actual habitat sensitivity* and site-specific spatial characteristics rather than generic specifications. A generic setback distance from settlements is t a common constraint in GIS-MCDA studies and is at the heart of many countries' WT regulatory guidelines. The current study found some justification for this perspective. Specifically, when WTs are sited closer than 750 m from human settlements, the anthropocentric impact of WTs invariably is significant.

Accordingly, when environmental criteria are applied, it is extremely rare to find suitable sites at distances closer to human settlements. Many suitable sites, however, were found between 750 and 2,000 m from residential areas. If countries make the distance of WTs from residential areas and NPAs their paramount consideration in planning decision, establishing high setback distances as a precautionary measure it will lead to WT development on open spaces, exacerbating fragmentation and very likely causing deleterious ecological outcomes. To maximize wind energy potential, decision-makers should consider projects based on transparent environmental planning procedures with clear protocols for measurement and oversight, instead of setting extreme, inflexible guidelines with thresholds for setback distance. This is especially true in small or densely populated countries.

The site-selection methodology described in our study offers an accessible method for promoting environmentally optimal wind-power solutions that can be applied worldwide in efforts to expand renewable electricity. Future studies should combine the environmental impact results with other MCDA approaches such as Weighted Sum Methods and Analytic Hierarchy Procedures. Converting such analyses to monetary values can aid in a designing more holistic cost / benefit analyses for renewable energy that include the full external costs.

CRediT authorship contribution statement

Erez Peri: Conceptualization, Methodology, Software, Data curation. **Alon Tal:** Conceptualization, 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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