Comparing suitability analysis methods for wind farms: weighing economic and environmental criteria

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1. Introduction

Energy consumption has been increasing dramatically in recent decades with the rapid growth of technology. However, conventional energy sources have been exploited to such an extent that demand now outstrips supply, leading to high and volatile prices. In addition, the burning of fossil fuels emits large amount of greenhouse gases, especially carbon dioxide, contributing to global warming. Renewable energy, such as wind, solar, hydroelectric, and geothermal power, has been introduced as an alternative to cope with these problems. Wind power in particular is one of the fastest-growing sources of renewable energy, and aside from its environmental benefits, it also contributes significantly to the domestic energy supply, creating job opportunities and economic growth (IEA Wind TCP 2017). The Global Wind Energy Council (2018) reports that wind energy supported over 260,000 jobs and brought €36.1 billion in investments in 2017.

Wind power plays a leading role among all types of renewable energy source around the globe, contributing around 4 percent of global electricity demand in 2016 (IEA Wind TCP 2017), and 11.6 percent of European electricity demand in 2017 (Global Wind Energy Council 2018). In the European market, wind energy ranked second, only behind gas, in terms of power capacity in 2017 (Global Wind Energy Council 2018). Wind energy is a mature and economically competitive technology compared to most renewable energy sources. According to the IEA Wind TCP (2017), wind power is becoming the least expensive method of generating new power capacity in many markets. It is now transitioning into a fully commercialized and unsubsidized energy source (Global Wind Energy Council 2018). According to Villacreses et al. (2017), reasons for the rapid growth of wind power including the following: (1) the urgency of stopping the depletion of fossil fuels and developing sustainable sources of energy; (2) the vast potential of wind sources globally; (3) considerable technical progress in the development of efficient wind turbines; and (4) supportive policies for the implementation of wind energy.

Nonetheless, a number of shortcomings in wind energy remain to be overcome. The main difficulty that all types of renewable energy share is the intermittent nature of their sources and production. Wind farms must be built where there is sufficient wind, and site selection is therefore crucial. Economic, social, and environmental facets must be included as well as technical considerations. For example, wind turbines have negative impacts on nature in terms of bird and bat mortality, as well as causing ecosystem disturbance, noise pollution, and soil erosion (Dai et al. 2015). However, there are often conflicts between these factors, especially between economic and environmental criteria. Suitability analysis is a method of simultaneously considering all factors, some of them conflicting. Various analysis methods exist to solve problems under different circumstances, including multi-criteria decision making (MCDM), which is one of the most commonly used and studied approaches and will be discussed in detail in this paper.

The aim of this paper is to answer the following question: how can the environmental impacts of wind farms be minimized while maximizing economic feasibility through suitability analysis and impact mitigation measures? We first give an overview of policies on wind energy implementation. We then conduct a review and analysis of multiple studies, which is divided into three parts. The first part introduces MCDM and its applications in other fields beyond wind energy. The second part discusses three alternative means for site selection: wildlife mapping, cost-benefit analysis, and life cycle assessment. The third part explores a variety of impact mitigation techniques for wind energy. Finally, we conclude our discoveries and provide some suggestions on future research.

2. Policy background

In this section, we discuss the impacts of both national and transnational government policies on the growth of wind energy globally. We first assess the role of the European Union in the development of the wind energy sector across the bloc, with a focus on offshore wind. This is followed by a discussion of the effects of domestic energy policies on wind energy in Canada, Japan, Germany, Turkey and China.

2.1 Transnational renewable energy policy in Europe and the role of the European Union

As part of its Renewable Energy Directive of 2009, the European Union (EU) set a series of binding national targets for the expansion of renewable energy in its member states, starting with an overall target of producing at least 20 percent of its consumed energy from renewable sources by 2020 (Fouquet 2012). Further goals have since been set, stipulating that this proportion must reach 27 percent by 2030, with the long-term aim of reaching up to 75 percent by 2050 (Long 2014). Member states have been required to develop national action plans for renewable energy that include interim targets, although these are non-binding. However, despite these targets, previous studies on the EU’s influence on the growth of wind energy have been inconclusive. Fitch-Roy (2016) finds substantial evidence of a convergence in government policy on offshore wind energy between five major EU member countries, namely the United Kingdom, Germany, Denmark, Belgium, and the Netherlands. He finds that the European Commission guidelines on state aid, which requires that renewable energy production be subject to auctioning or competitive bidding, has likely improved coordination between agencies and departments at the national level with regards to the approval of offshore wind projects. He also cites the liberalization of electricity networks and the Habitats and Birds Directive as potential contributors to regulatory convergence, although he emphasizes that their effects have been complex and cannot rule out other explanatory factors. In contrast, Long (2014) suggests that the development of a common energy policy has been limited by aspects of EU primary law that hinder the bloc's ability to intervene in national energy policy, such as the principles of subsidiarity and proportionality, as well as dependence on the votes of individual member states in the European Parliament. Moreover, he argues that the EU's regulatory approach to renewable energy has been complicated by the functioning of the internal market, as member states have been allowed to meet the targets set in the Renewable Energy Directive by transferring or buying guarantees of origin for renewable energy sources from each other. Similarly, the expansion of offshore wind farms in the absence of uniform rules on maritime spatial planning has also led to disputes between member states over their trans-boundary impacts.

2.2 Domestic renewable energy policy

The main support mechanism used by national governments to foster the growth of the renewable energy sector has been feed-in tariffs. These function on the basis that entities that generate renewable energy are entitled to sell their electricity to the grid at a fixed tariff for a defined time period, with the goal of ensuring economic viability (Fouquet 2012). There is considerable empirical evidence that feed-in tariffs have contributed to the growth of wind energy in multiple institutional contexts. Dursun and Gokcol (2014) observe that wind energy capacity in Turkey, which had been negligible prior to the passing of a renewable energy law in 2005, quadrupled within a year of the introduction of tariff support. Further policies to promote wind energy, including the raising of tariffs in 2010 and the targeting of producing 30 percent of electricity from renewable sources by 2023, led to continued growth, with capacity increasing by a factor of almost 100 between 2005 and 2012. Zhao et al. (2016) similarly find that a piece of 2009 legislation establishing a feed-in tariff scheme had "significant positive impacts" on wind power capacity in China. Moreover, Mudasser et al. (2015) determine that a community feed-in tariff paid for the sale of surplus wind power to the grid is essential to ensuring the economic feasibility of wind-biogas hybrid energy systems applied in a farm setting in Nova Scotia, Canada. However, Nordensvärd and Urban (2015) caution that an entrenched system of feed-in tariffs in Germany, which first introduced the incentives in 1991, has led to a technological lock-in effect that encourages continuous upscaling and the pursuit of financially risky offshore projects. They argue that this has resulted in higher energy prices for consumers as well as underinvestment in the modernization of an outdated electrical grid, the provision of long-distance energy transport from north to south to meet demand, and the development of small-scale wind farms.

The literature also presents evidence that other forms of government support for renewable energy have generally been less effective than the aforementioned financial incentives. In Japan, government funding for wind energy prior to the late 2000s consisted primarily of support for technological research and development, with a focus on building wind databases and promoting grid stabilization (Mizuno 2014). This support was vastly expanded in 2007-09, when capital subsidies for wind energy technology was broadened to encompass the upscaling of turbines, the development of composite materials, wind power generation forecasting, and fixed and floating foundations for offshore wind turbines. Despite these significant capital investments, Japanese wind energy remained virtually negligible, providing only 0.01 percent of electricity in 2010. A feed-in tariff system was only introduced in 2012 as the Japanese government sought to remedy energy shortages and an increased dependence on imports after the shutdown of 50 nuclear plants nationwide in the wake of the Fukushima disaster. However, its effects had not yet been observed as of 2014 due to the long lead times of wind energy projects in Japan. Zhao et al. (2016) make similar observations on the effects of “non-price policy” in China, which consists primarily of targets, bidding systems, quotas, energy legislation, and fiscal and tax incentives. They find that these policies have had less of an impact on wind energy capacity than “price policy” (primarily feed-in tariffs), although their impact has been greater in areas with considerable wind resources, where the government’s efforts to promote wind energy development has helped to stimulate investment.

3. Methodology

This paper analyzes a range of studies including reviews on the use of MCDM, case studies illustrating the use of wildlife mapping, cost-benefit analysis, and life cycle assessment in wind energy applications, and various methods of impact mitigation. The case studies have been selected due to their wide geographic range, spanning from Brazil to Germany to South Korea, and different research focuses, with some geared towards site selection while others aim to compare available technologies. We focus on assessing and evaluating the methodologies of the studies on suitability analysis, with the goal of identifying their respective strengths and weaknesses to determine the most suitable method in each context. In contrast, our evaluation of the studies on impact mitigation focuses on their results, aiming to evaluate the merits of the options covered. Our analysis is therefore structured in three parts. First, we explain the concept of MCDM and examine its applications in various fields beyond wind energy. We then evaluate the respective advantages and disadvantages of wildlife mapping, cost-benefit analysis, and life cycle assessment and compare them to those of MCDM with the help of the aforementioned case studies. Finally, we discussed mitigation techniques to mitigate adverse effect caused by wind farms on local bird species.

4. Results and discussion

4.1 MCDM and its applications

4.1.1 MCDM

Unlike solving textbook exercises, real-life problems involve a wide range of uncertainties that cannot be controlled, and many variables must be taken into consideration when tackling them. This is where multi-criteria decision making (MCDM) methods come into play. MCDM methods enable decision makers to determine the best alternative out of several given alternatives based on given set of criteria (Triantaphyllou 2000). Alternatives refer to all possible scenarios to be chosen from, and criteria are rules that help evaluate the suitability of each alternative. It is important to bear in mind, however, that no single optimal outcome is determined by each method. Instead, the optimal result depends on the preferences of decision makers.

In a general context, MCDM covers two branches: multi-objective decision making (MODM) and multi-attribute decision making (MADM). MCDM more commonly refers to the latter and will be in the rest of this paper. MODM is applicable when decision spaces are continuous, while MADM/MCDM is used when decision spaces are discrete (Triantaphyllou 2000). A solution can be computed from a mathematical model in an MODM problem. In contrast, MADM/MCDM methods produce solutions by ranking alternatives. A decision can then be made based on this ranking.

Various MCDM methods exist to handle different problems, and these methods can be classified according to a range of criteria. For example, they can be classified as deterministic, stochastic, crisp, or fuzzy methods based on the data types used. They can also be hybrid, i.e. combining methods in more than one category. Some commonly used methods are AHP (analytic hierarchy process), ANP (analytic network process), TOPSIS (technique for order of preference by similarity to ideal solution), ELECTRE (elimination et choix traduisant la realité), and WSM (weighted sum model) (Triantaphyllou 2000; Mardani et al. 2017).

Despite the distinctions between these methods, they share the same fundamental principles. The process of all MCDM methods can be generalized into five steps (Triantaphyllou 2000):

1. Determine the goals to be achieved by solving the problem.
2. Determine possible alternatives and the criteria to be applied.
3. Quantify the impact each alternative has on each criterion, and weight criteria.
4. Calculate the aforementioned values to rank alternatives.
5. Decision makers make the final choice based on the ranking of alternatives.

4.1.2 MCDM for wind farm site selection

Many studies use MCDM to select locations for wind farms in order to reconcile the various and often conflicting criteria involved. Since site selection is a spatial problem, a geographic information system (GIS) is usually combined with MCDM. GIS has the advantage of allowing large quantities of spatial information from various sources to be analyzed (Gigović et al. 2017). In addition, AHP is often applied for wind farm siting to rank and weight criteria.

Wind farm site selection through MCDM can be generalized into five steps (Latinopoulos and Kechagia 2015; Gigović et al. 2017; Mahdy and Bahaj 2018): (1) identify constraints, (2) exclude infeasible sites based on constraints, (3) identify and weight criteria, (4) standardize the suitability of locations based on each constraint and criterion, (5) calculate the total suitability of each location. Protected areas, buffered zones from infrastructure, urban areas, military facilities, and threshold values of wind speed are some frequently adopted constraints. Similarly, wind speed, slope, distance to infrastructure, distance to protected areas, and land use are commonly adopted criteria. Finally, a suitability map is generated with which decision makers decide where to construct wind farms.

4.1.3 Other applications of MCDM

MCDM is a broadly and increasingly used decision-making method applied in numerous fields that involve multiple criteria. Energy management (Mardani et al. 2017), service quality enhancement (Mardani et al. 2015), the tourism and hospitality industry (Mardani et al. 2016), green supply chain management (Govindan et al. 2015), and civil engineering and construction technology (Zavadskas et al. 2018) are a few examples. Studies on MCDM have been increasing rapidly in recent years and are likely to continue.

In the field of energy management, MCDM is applied not only in site selection for renewable energy but also in environmental impact assessments, waste management, water resource management, and land management, among other applications. Mardani et al. (2017) find that environmental impact assessments were the most common application of MCDM of all subfields in energy management in terms of papers published.

In the realm of business, service quality is an important factor for enhancing a company's competitiveness. It is especially critical in the following ten areas categorized by Mardani et al. (2015): the airline industry, websites and internet services, the tourism and hospitality industry, the healthcare industry, other transportation industries, the manufacturing industry, the banking sector, service organizations, and other areas. The use of MCDM in the airline industry accounted for the most frequently studied area. Aside from service quality, studies on the tourism and hospitality industry cover five further aspects: tourism destination, location selection, marketing, ecotourism, and other areas (Mardani et al. 2016). Location selection ranked first in terms of the distribution of papers in the aforementioned six aspects.

Likewise, supplier selection is crucial as a means of controlling product quality, costs, and corporate image, the last of which is particularly relevant as green supply chain management has become increasingly common due to growing concern for the environment. MCDM is a highly appropriate approach since numerous economic, social, and environmental criteria must be included when evaluating suppliers. According to Govindan et al. (2015), environmental management systems are the most widely adopted criterion in green supplier selection.

As in supply chain management, sustainability has become a vital element in civil engineering and construction. Zavadskas et al. (2018) suggest seven MCDM application domains in these fields: building structures and systems, location selection problems, construction technology, sustainable construction, construction management, building maintenance, and retrofitting. They show that sustainable construction and construction technology have been the most important fields in the last three years.

As previously mentioned, a considerable number of MCDM methods exist. We have selected seven groups of frequently used MCDM techniques to demonstrate the research distribution of these techniques in the fields discussed above: (1) AHP and fuzzy AHP, (2) ANP and fuzzy ANP, (3) DEMATEL and fuzzy DEMATEL, (4) TOPSIS and fuzzy TOPSIS, (5) VIKOR and fuzzy VIKOR, (6) integrated techniques, and (7) other techniques. The results are shown in **Figure 1**. Due to the range of different evaluation approaches, it should be noted that the results are not complete and precise. Nevertheless, they are capable of illustrating the distribution trend of MCDM techniques. It is obvious that integrated techniques and AHP and fuzzy AHP are the two most common techniques. Multiple techniques can also be combined to overcome the limitations of individual techniques, explaining the high ranking of integrated techniques in the distribution. Similarly, AHP and fuzzy AHP are often chosen due to their ability to address both qualitative and quantitative criteria. More importantly, these two techniques are highly regarded due to their comprehensibility and convenience for decision makers (Govindan et al. 2015).

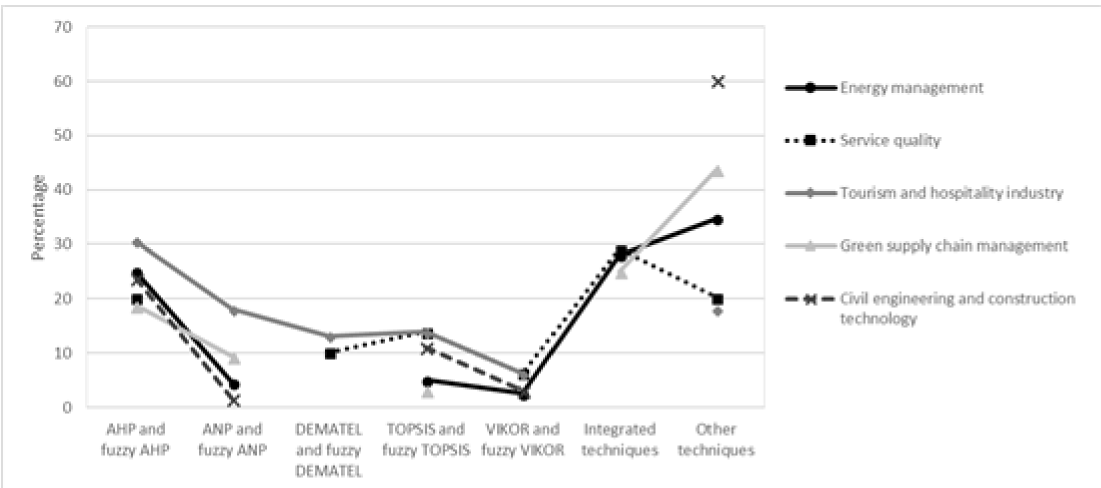

Figure 1. Research distribution of MCDM techniques utilized in different fields (Mardani et al. 2017; Mardani et al. 2015; Mardani et al. 2016; Govindan et al. 2015; Zavadskas et al. 2018).

4.2 Other methods of suitability analysis for wind farms

We now explore three other common methods of assessing site suitability for wind power, namely wildlife mapping, cost-benefit analysis, and life cycle assessment. Wildlife mapping consists of modelling the habitats of animals likely to share the same physical space as existing or proposed wind farms and then overlaying them with areas suited to wind energy generation to detect and prevent potential land-use conflicts. Cost-benefit analysis generally involves quantifying the financial costs and revenues generated by a wind farm to determine its economic viability, although it can also be expanded to include negative environmental externalities. Lastly, life cycle assessment entails modelling the long-term environmental impacts of a wind farm over the course of its service life, from the manufacturing of its components to its disposal.

4.2.1 Wildlife mapping

Despite their significant potential to mitigate climate change through reductions in greenhouse gas emissions, wind farms have been shown to have a range of adverse impacts on species whose habitats are located in their vicinity, including birds, fish, and marine and terrestrial mammals (Passoni et al. 2017; Snyder and Kaiser 2008). Habitat mapping can thus serve as an important tool to minimize conflicts between demands for renewable energy on the one hand and wildlife conservation on the other hand. For instance, areas known to be important stopover points for bird migration or close to nesting sites should be avoided, since although direct collisions with wind turbines remain rare, the presence of wind farms may reduce the amount of available habitat and force birds to fly longer distances to avoid them (Snyder and Kaiser 2008). This can in turn have a detrimental effect on their physical condition and potentially increase mortality rates, which can be critical in the case of endangered species (Belaire et al. 2014). Avoiding the habitats of such species can also be beneficial from the perspective of wind farm developers. Belaire et al. (2014) emphasize the Endangered Species Act in the United States, which requires developers of all potential wind energy projects located in the habitats of designated endangered species to apply for an incidental take permit and develop a habitat conservation plan. This process involves not only additional financial costs but also the risk of failing to receive a permit, leading to further financial losses (Snyder and Kaiser 2008).

In light of the increasing need for habitat mapping with the rapid global expansion of wind energy, Belaire et al. (2014) model the stopover habitats of the whooping crane, an endangered bird species residing in North America, and assess the potential wind resources along a 180-mile (290 km) migratory corridor in the U.S. state of Nebraska. Likewise, Passoni et al. (2017) examine the distribution of grey wolf habitats around planned wind energy sites in Croatia, with the aim of optimizing the location of these sites in order to meet policy targets while minimizing their potential impact on wolves. The two studies use highly similar methodologies, employing machine-learning techniques to predict whooping crane stopover sites and grey wolf reproduction sites respectively. The variables are predominantly related to geographical features. Belaire et al. (2014) divide their study area into 1 km^2 pixels and categorize each pixel based on land cover type, bearing (directional heading to the nearest stopover site) and proximity to other land cover types (distance to the nearest agricultural area and nearest wetlands). Passoni et al. (2017) use a higher spatial resolution of 250 m^2 pixels and do not categorize them by land cover type but instead measure their distance to the nearest settlement, farmland, roads and forest, as well as accounting for altitude and slope. Both studies thus score each pixel in terms of its suitability as a habitat. Belaire et al. (2014) additionally calculate an aggregate suitability score based on the probability of a pixel being highly suited to both whooping crane migration and wind energy generation, with a high probability indicating a high probability of a conflict and hence a low aggregate suitability score. Likewise, Passoni et al. (2017) calculate the ecological cost of each site and thus rank them based on their ecological suitability. Based on the generation capacity of each site, they then select an optimal combination of wind farms to meet the energy generation targets set in Croatian government’s renewable energy plan by 2020.

4.2.2 Cost-benefit analysis

Whereas habitat mapping is a tool to guide site selection that focuses on predicting and preventing land-use conflicts, cost-benefit analysis enables different wind turbines and potential wind energy sites to be directly compared in terms of economic feasibility. In their analysis of the costs and benefits of offshore versus onshore wind and conventional power, Snyder and Kaiser (2008) cite intermittent power generation and aesthetic issues as common criticisms of wind power in general, as well as concerns over navigational safety as a specific drawback of offshore wind farms. They juxtapose the significant fluctuations in wind energy generation with the need for the electrical grid to provide constant levels of power to consumers, which requires the additional expense of integration with fossil fuel-powered backup systems, particularly natural gas power plants. They also refer to surveys in both the United States and Denmark showing a willingness among respondents to pay for a wind turbine to either not be built or be moved further away from the coast, demonstrating a negative public perception of wind farms on both sides of the Atlantic. However, they find no evidence to suggest that wind turbines have any negative effect on property values. Moreover, they identify a number of advantages of offshore over onshore wind. These include physical proximity to major population centres in the case of the United States, which reduces the cost of high-voltage transmission, and the availability of stronger and more constant winds offshore, which allows offshore wind turbines to generate up to 50 percent more electricity than onshore turbines. Other benefits include the relative ease of transporting large turbines by ship and with marine cranes, allowing far larger turbines to be erected offshore, and the ability to employ new turbine designs to take advantage of reduced aesthetic and noise constraints at sea, such as downwind rotors, lattice towers, and two-bladed rather than three-bladed turbines.

Snyder and Kaiser (2008) stop short of offering a quantitative cost-benefit analysis comparing offshore and onshore wind power, instead emphasizing that both the costs and revenues of wind farms are highly site-specific. As such, Kim et al. (2013) examine variations in wind energy generation potential and capital and operating costs along the South Korean coastline, while Mudasser et al. (2015) compare the economic viability of wind-biogas hybrid energy systems employing different-sized turbines at three separate locations in Nova Scotia, Canada. Both studies account for similar financial expenses, including development (manufacturing, construction, and installation) and operational (electricity generation and maintenance) costs. Kim et al. (2013) further include corporate tax and project development costs in their model, while Mudasser et al. (2015) include penalties as well as the potential costs of purchasing additional energy from the utility grid to meet shortfalls. Kim et al. (2013) measure benefit simply by aggregating the value of the energy generated, whereas Mudasser et al. (2015) also include the end-of-life salvage value of the wind turbine and biomass digester. The two studies differ most starkly in their performance metrics, making their results difficult to directly compare. While Kim et al. (2013) compare potential wind energy sites through their benefit-cost ratio, Mudasser et al. (2015) use real interest rates to compute both the total net present value (NPV) and the NPV per kWh of power generated for each turbine and site. Mudasser et al. (2015) also employ financial payback periods as an additional indicator of economic performance.

4.2.3 Life cycle assessment

In contrast to the wide range of accounting approaches used in cost-benefit analysis, life cycle assessment (LCA) consists of a standardized methodology used to evaluate environmental performance. The steps of an LCA are defined in the international standards ISO 14040 and 14044 as follows (Wagner et al. 2011). First, the goal and scope of the study is defined, including the functional unit, system boundaries and assumptions made. The next stage is the inventory analysis, in which the life cycle of the system is broken into stages for investigation, with each stage containing material and energy flows. The impact assessment defines and categorizes the environmental impacts of these flows. Finally, the interpretation stage involves evaluating these impacts to reach conclusions.

LCAs can be performed on existing wind turbines, as in the case of Wagner et al. (2011), who examine the German offshore wind farm Alpha Ventus in the North Sea, or as projections for prospective or hypothetical turbines, as is carried out by Oebels and Pacca (2013), who investigate the potential environmental impact of a theoretical wind power station in Brazil. Bonou et al. (2016) deviate from this dichotomy by conducting a product-specific study of four wind turbines “in the applied setting of Siemens Wind Power.” Regardless, the functional unit in wind power studies is consistently defined as a current of 1 kWh generated by a wind turbine or farm delivered to the grid. There are minor variations in the phases into which the life cycle of a wind turbine is broken: whereas Bonou et al. (2016) treat the manufacturing and assembly processes as separate stages, and Oebels and Pacca (2013) further distinguish between the material processing stage and the manufacturing stage, Wagner et al. (2011) combine the three into one.

Crucially, however, Oebels and Pacca (2013) differ from the other studies in that they omit the end-of-life (disposal) stage on the basis that none of the actors in the Brazilian wind energy section have yet studied or proposed measures for the end-of-life treatment of a wind farm. This stage would thus have to rely on previous studies conducted in Europe, where the production of electricity generates far more carbon emissions than in Brazil due to a much smaller contribution of renewable sources to electricity generation. Similarly, Bonou et al. (2016) report that the end-of-life stage is commonly excluded from LCAs due to uncertainties over future treatment technologies and the economic market for them, as well as a lack of inventory data on existing technologies such as the recycling of metals. These uncertainties lead to considerable differences in estimations of the impact of this stage. While Wagner et al. (2011) find that it only has a “minor influence” compared to other stages, Bonou et al.

(2016) estimate that the recycling of materials could lead to environmental savings of up to 20 to 30 percent.

As with cost-benefit analysis, the range of indicators used to quantify the material flows over the useful life of a wind turbine lead to flexibility but also make it difficult to compare the results of different studies. Oebels and Pacca (2013) adopt a relatively narrow scope, quantifying only carbon dioxide emissions, while Wagner et al. (2011) also consider cumulative primary energy demand, energy payback period, and a range of midpoint environmental indicators, including effects on eutrophication, human toxicity, photochemical ozone creation, and acidification. Based on the ReCiPe impact assessment model, Bonou et al. (2016) further differentiate between midpoint indicators, which relate to individual environmental problems, such as those considered by Wagner et al. (2011), and endpoint indicators, which quantify environmental impact at higher aggregation levels in terms of human health, the natural environment, and natural resources.

4.2.4 Discussion of suitability analysis methods

Table 1. Types of criteria accounted for in each suitability analysis method.

Method	Technical criteria	Economic criteria	Environmental criteria
Multi-criteria decision analysis	Yes	Yes	Yes
Wildlife mapping	Yes	No	Yes

Cost-benefit analysis	Yes	Yes	Only in Snyder and Kaiser (2008)
Life cycle assessment	Only in Bonou et al. (2016) and Wagner et al. (2011)	No	Yes

The unique strength of MCDM is its applicability in weighing independent and potentially conflicting criteria against each other to generate a single measure of suitability. In this regard, the deficiencies of wildlife mapping, cost-benefit analysis and life cycle assessment are readily apparent. **Table 1** compares the criteria considered by the four methods. The primary focus of Latinopoulos and Kechagia (2015) is on assessing the suitability of prospective onshore wind farm sites in Greece by weighing economic criteria against technical criteria. However, none of the studies reviewed in this section manage as broad of a scope. Both wildlife mapping and cost-benefit analysis have been shown to be appropriate for identifying optimal locations for constructing wind turbines and farms based on either environmental or economic criteria, but not both. Passoni et al. (2017) and Belaire et al. (2014) attempt to identify areas of conflict between wind farms and the habitats of wolves and birds respectively, but the economic feasibility of the assessed sites is beyond the scope of both studies. Similarly, Kim et al. (2013) and Mudasser et al. (2015) aim to determine the profitability of wind and wind-biogas hybrid systems across their respective study areas, but they do not take ecological costs into consideration. Snyder and Kaiser (2008) account for ecological costs by including carbon offsets based on market prices, but they concede that the actual costs of offsetting carbon are difficult to determine. Life cycle assessments have an even narrower scope, with all three reviewed studies focusing on measuring the environmental impact of a single site with no spatial analysis, although Bonou et al. (2016) compare the performances of four different turbines. However, both Bonou et al. (2016) and Wagner et al. (2011) take technical criteria into consideration when calculating energy payback time.

Despite these limitations in scope, all three methods are nevertheless highly suited to examining individual components of a multi-criteria decision analysis in depth. The long-term scope and standardized methodology of life cycle assessments allow them to provide reliable indicators of environmental impact on the scale of decades. While it would be impractical to conduct multiple life cycle assessments to analyze spatial variations in environmental indicators, their use in comparing the performance of different turbines has been well demonstrated by Bonou et al. (2016). In contrast, cost-benefit analysis can serve to determine not only the economic performance of a wind turbine or farm at a given site but also inherently involves the consideration of technical performance, given that revenues depend entirely on the amount of electricity that can be generated and sold to the electrical grid. Finally, wildlife mapping enables the habitats and migration patterns of specific fauna to be analyzed and visualized while also assessing the generation potential of wind energy in the same areas. By determining the potential impacts of wind turbines on wildlife, this method adds an additional dimension to the aggregate environmental impacts determined by life cycle assessment and allows entire areas to be excluded from consideration for wind turbine construction on ecological grounds. Latinopoulos and Kechagia (2015) in fact draw on aspects of all three methods in their analysis, taking into account technical criteria such as wind speed and slope, which affect generation potential and are hence also economic criteria, as well as environmental criteria such as land use and protected areas.

4.3 Impact mitigation for wind farms

Natura 2000, a network of nature protection areas in the European Union, defines mitigation as a process involving “introducing measures into the plan or project to eliminate the potential negative effects on the conservation objectives of the Natura 2000 site or to reduce them to a level where they will no longer adversely affect the integrity of the site.” Based on this definition, it can be said that mitigation measures all negative effects and provide countermeasures to eliminate or minimize the threat for the future. Setting up and operating a wind farm not only poses risk to local ecology but can also have detrimental economic, social, technical effects. In this section, we focus on the effects of wind farms on bird species and explore methods to mitigate this problem.

4.3.1 Effects of wind farms on bird species

Drewitt and Langston (2006) list some potential threats posed by wind farms to bird species. These include the risk of collisions with infrastructure such as towers, rotors, and nacelles, as well as displacement due to disturbances such as noise, visual intrusion, and personal movement. Marques et al. (2014) and Martin (2011) consider not only external factors but also species-specific factors such as bird morphology and behaviour. On the other hand, Morinha et al. (2014) assess the mortality rate of the birds due to wind farms in northern Portugal, as is presented in Table 2.

Table 2. Factors affecting bird collisions with wind turbines (Marques et al. 2014; Martin 2011; Morinha et al. 2014).

Types of Factors	Factors
Species-specific factors	Bird morphology (wingspan, wing height, tail length, etc.) influences the likelihood of collisions. High-wing species collide more frequently.
	Limited perception also contributes to collisions. This particularly affects birds with narrow fields of view as well as bats.
	Seasonal effects also apply, with greater mortality in some months than with others.
	Avoidance capabilities have a limiting effect on mortality. Species without avoidance

	capabilities tend to have high mortality rates.
Site-specific factors	Some landscape features such as steep slopes and shorelines can attract birds and can cause collisions if located near wind turbines.
	Weather conditions such as wind speed and low clouds can contribute to collisions.
	Flight paths also affect the collision rate. Migratory paths and nesting sites can be located near wind turbines, resulting in collisions.
Wind-farm specific factors	Turbine height and mortality are expected to be positively correlated, although this has not been empirically demonstrated.
	High blade speeds contribute to mortality.
	The positioning lights of wind turbines are likely to attract more birds, although their effect on mortality also have not been empirically demonstrated.
	Wind turbines are always oriented perpendicular to flight paths, which contributes to mortality.

4.3.2 Impact-mitigation hierarchy

Figure 2 shows a simple version of a mitigation technique mostly used in Germany, based on the work of Drewitt & Langston (2006), Marques et al. (2014), Darbi et al. (2009) and Conway et al. (2013). This method follows three basic steps: (a) avoidance, (b) minimization, and (c) compensation. Pre-planning steps are not elaborated on but are instead distributed across all three steps. **Figure 3** describes an alternative methodology to develop a mitigation plan developed by Gartman et al. (2016). However, one problem with this system is that it barely considers the compensation process. Of the two processes, **Figure 3** provides a much more detailed view of the mitigation system in a wind farm.

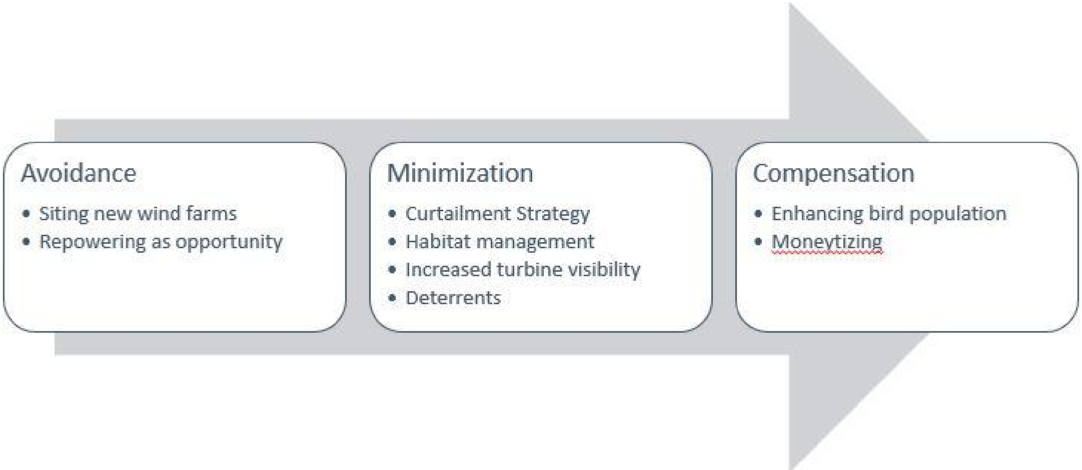

Figure 2. Impact-mitigation hierarchy (Drewitt and Langston 2006; Marques et al. 2014; Darbi et al. 2009; Conway et al. 2013)

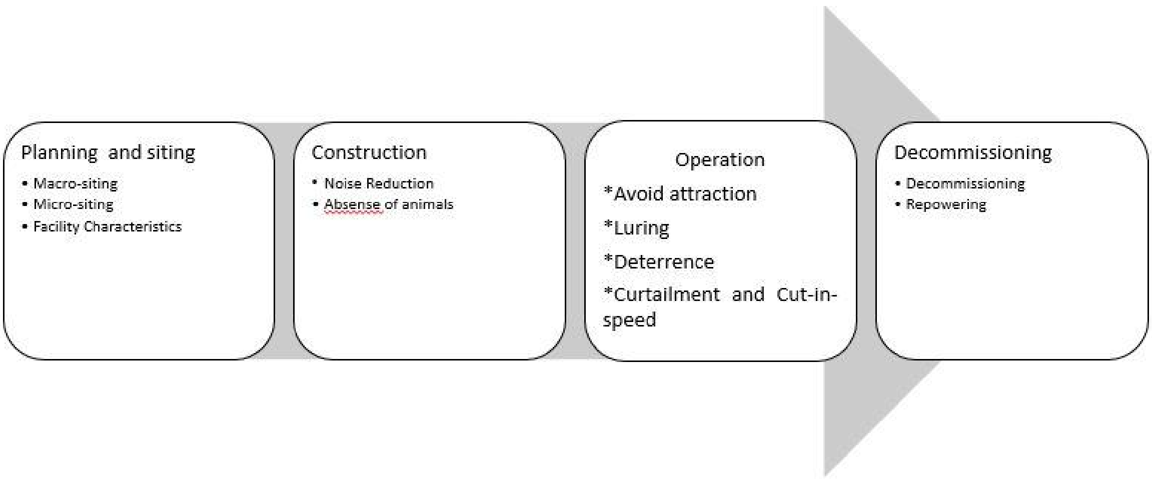

Figure 3. Impact-mitigation hierarchy (Gartman et al. 2016)

4.3.3 Classification of Mitigation

Gartman et al. (2016) focus on avoidance and minimization measures used in wind energy development. They do not discuss in-lieu fees or any monetary reparations, nor policies allowing the risk of species collision to exceed a given threshold under certain conditions, but they categorize eleven types of mitigation. A brief description of the types is given below.

1. Planning and siting

A. Macro-siting

Mitigation begins with a planning phase using a mitigation environmental assessment (EA), environmental impact assessment (EIA), or strategic environmental assessment (SEA). The main goal is to use areas where spatial resistance is low and avoid sensitive areas such as nature protection areas.

B. Micro-siting

For birds and bats, flight corridors and spatial buffers away from these areas are established, or corridors are provided between clusters of turbines aligned with main flight trajectories of the species (Drewitt and Langston, 2006).

C. Facility characteristics

Several factors such as the design (i.e. tower type), size (i.e. vertical extent and height of the rotor swept area), and visibility (i.e. lighting and tower color) are considered when a wind turbine is designed. The two aforementioned factors (macro-siting and micro-siting) are also considered before the final design is confirmed.

2. Construction

These two variables must be considered carefully when constructing a wind farm:

A. Noise Reduction

Noise reduction is highly important not only for the local community and employees but also to wildlife.

B. Absence of animals

Effects on mammal species are usually prioritized both in onshore and offshore wind farms. The movements of bird species are rarely prioritized.

3. Operation

A. Avoid attraction

Avoidance means dissuading wildlife from wind turbines to reduce the risk of collision. It can be done through coordinated temporal and spatial land management, by minimizing food resources and food availability, and by adapting lighting in colour and intensity to avoid bringing wildlife within the rotor-swept area or the area directly below the turbine.

B. Luring

This entails habitat enhancement offsite or the replacement of lost habitat, such as compensation through the creation of ponds and forests, increasing prey or food availability outside the wind facility or potentially impacted area, establishing conservation easements on nearby private ranch lands, or planting to attract birds away from depredation sites.

C. Deterrence

The use of acoustic devices, electromagnetic (EM) fields, or visual deterrents can frighten wildlife away from turbines to reduce mortality.

D. Curtailment and cut-in-speed

Establishing curtailments (seasonal stoppages) can limit the amount of damage caused by a wind turbine to wildlife, especially migratory birds. Cut-in-speeds, which are threshold wind speeds for starting a turbine, are also important, as increasing cut-in speeds can reduce the mortality of bats, which can detect the spinning blades more easily as a result.

4. Decommissioning and repowering

Decommissioning and repowering are important in the dismantling phase of a wind farm operation. The decommissioning of older-generation turbines and other engines enables a wind farm to maintain effectiveness in the long run, which repowering facilities generate greater energy from lower wind speeds and reduce mortality rates for birds.

5. Conclusion

Our findings reveal that a number of suitability analysis methods can potentially be used to evaluate the economic and environmental performance of wind farms, each of which has its own respective focus, merits, and drawbacks. Multi-criteria decision making models are ideal for weighing multiple, often conflicting criteria against each other and calculating an indicator of overall suitability based on weighting assigned subjectively by the decision makers. The ease of comparing and analyzing variations in suitability by spatial location makes MCDM methods an invaluable tool to guide site selection for wind turbines. The flexibility afforded by the free setting of weighting and exclusion thresholds has contributed to the broad application of MCDM methods not only in a renewable energy context but also in fields as diverse as waste management, the airline industry, and civil engineering for purposes ranging from supplier selection to tourism marketing and building maintenance. On the other hand, wildlife mapping, cost-benefit analysis, and life cycle assessment are ideally suited to assessing fewer criteria in greater depth. While wildlife mapping and life cycle assessment typically only consider technical and environmental criteria, with the former specifically exploring areas of overlap between the two, cost-benefit analysis is generally restricted to evaluating economic feasibility based on a combination of technical and policy considerations. It may therefore be beneficial to integrate elements of these three analysis methods into an MCDM framework for an in-depth yet holistic assessment of site suitability.

We also find that impact-mitigation hierarchy models can be used to further mitigate the environmental impacts of a wind farm by integrating avoidance and minimization measures into planning considerations. Environmental impact assessments and life cycle assessments can provide detailed insight into long-term environmental effects, while wildlife mapping and other GIS-based spatial analysis techniques can be used to specifically detect and anticipate land-use conflicts between wind power generation and wildlife conservation. However, once a site has been selected, further measures can be made in the design and operation stages including material use, size, and visibility in the former and noise reduction, deterrence measures, and the tactical use of cut-in speeds in the latter to protect wildlife from the detrimental effects of wind turbines.

Despite the plethora of studies on MCDM and other suitability analysis methods, a number of gaps in the literature remain and warrant further examination. The vast majority of cost-benefit analyses of wind energy focus exclusively on economic feasibility with little to no consideration of environmental externalities. This is largely due to the controversial nature of accounting for them in economic terms, and incorporating the effects of wind turbines on wildlife thus remains a challenge. In contrast, life cycle assessments by definition are aimed at quantifying the lifetime environmental impacts of a wind turbine, and the question of economic feasibility lies beyond its scope. However, the inclusion of the end-of-life stage, which considerably affects results, remains a stumbling block due to a lack of inventory data and uncertainty over long-term technological trends. Further research into the reuse and recycling of disposed wind turbine plants is thus needed to improve the accuracy of LCAs.

Finally, the factors affecting the likelihood of bird collisions with wind turbines are not yet well understood, particularly given their relatively unlikely occurrence. As such, more intensive efforts to identify planning and design techniques that can effectively mitigate the impacts of wind farms on wildlife will become increasingly vital as wind energy continues to grow rapidly in the coming decades.

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