

Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

# Renewable and Sustainable Energy Reviews

journal homepage: [www.elsevier.com/locate/rser](http://www.elsevier.com/locate/rser)

## Spatial multicriteria framework for sustainable wind-farm planning – Accounting for conflicts

D. Manolan Kandy<sup>a</sup>, U. Mörtberg<sup>a,\*</sup>, V. Wretling<sup>a</sup>, A. Kuhlefeld<sup>a</sup>, G. Byström<sup>a</sup>, H. Polatidis<sup>b</sup>, A. Barney<sup>b</sup>, B. Balfors<sup>a</sup>

<sup>a</sup> Dept. of Sustainable Development, Environmental Science and Engineering, KTH Royal Institute of Technology, Stockholm, Sweden

<sup>b</sup> Dept. of Earth Sciences, Uppsala University, Campus Gotland, Sweden

### ARTICLE INFO

#### Keywords:

Wind power planning  
Spatial multi-criteria analysis  
Conflict score  
Swedish wind power strategy

### ABSTRACT

Considerable pressure is placed on wind power in Sweden due to the country's goal of generating 100% of its electricity from fossil free resources. The aim was to develop the REWIND methodological framework to support wind power planning, built on spatial multi-criteria analysis (SMCA). In addition, the purpose was to develop a conflict score as a novel component of this framework, for handling goal conflicts. This framework includes the scoping, design and evaluation stages. It was applied in a case study of Västernorrland County with extensive involvement of stakeholders throughout the process.

The conflict score allows a separate analysis of trade-offs between factors, highlighting potential conflicts across the landscape to increase transparency. Thus, users are allowed to decide on a threshold on how much conflict among factors should be allowed for areas to qualify as planning alternatives. Critical issues that will need further attention concern quality and availability of data, creation of representative spatial indicators for the factors, weighting methods, and uncertainty analysis. The REWIND framework is open-ended and allows for further development to provide planning support that gives more control of factors and conflicts to be acceptable in real-world planning. Capacity building involving stakeholders in the design of planning alternatives are crucial. In Sweden, it can promote a more proactive planning process in the municipalities, supported by the regional actors, leading to a more predictable permitting process for developers. This will be useful for inclusive wind power planning in any country, since it is applicable on different scales.

### 1. Introduction

Climate change and its impacts has compelled the energy sector to look for renewable forms of energy generation with less greenhouse gas emissions. This has led to an increase in the share of renewables in global electricity generation to 28% in year 2021, largely due to the increase of wind power to 6.6% [1]. Ambitious climate policies and reduction in technology costs has further enhanced the growth of the wind sector. However, wind energy development also faces a multitude of ecological [2–4] and societal impacts [5,6], which affects the social acceptance of this technology [7,8]. Noise and visual impacts on residential areas [6,9,10], collision risks for birds and bats, and habitat fragmentation affecting biodiversity [3,4] are a few examples. Thus, on-shore wind power development comes with synergies and conflicts between sustainability goals, such as the United Nations Sustainable Development Goals on Climate action and Affordable and clean energy on one side,

and Good health and well-being as well as Life on land on the other side [11]. Therefore, it is important to understand the interlinkages among sustainability goals, interpret these based on the regional and local circumstances and integrate them into the planning process for the siting of wind farms. This can pave way for a sustainable expansion of wind power in the long term.

In Sweden, the share of renewable energy has been increasing in recent years, particularly wind energy, which contributed 27.5 TWh or about 17% of the total electricity production (160.9 TWh) in Sweden [12]. Furthermore, a Swedish energy and climate goal is to obtain 100% of the country's electricity production from fossil free sources by the year 2040. In this context, the Swedish Energy Agency (SEA) and the Swedish Environmental Protection Agency have developed a common national strategy for sustainable wind power development (NWS) within the framework of the Environmental Objectives Council [13]. The NWS estimates that to achieve the goal of 100% renewable electricity production by 2040, at least 100 TWh of wind power is required, of which

\* Corresponding author.

E-mail address: [mortberg@kth.se](mailto:mortberg@kth.se) (U. Mörtberg).

<https://doi.org/10.1016/j.rser.2023.113856>

Received 5 December 2022; Received in revised form 1 October 2023; Accepted 8 October 2023

Available online 21 October 2023

1364-0321/© 2023 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

## Nomenclature

### Abbreviations

AHP	Analytical hierarchy process
CAB	County Administrative Board
HS-HC areas	Areas with high suitability and high conflict
NWS	National strategy for sustainable wind power development
SEA	Swedish Energy Agency
SMCA	Spatial multi-criteria analysis
TWh	Terra Watt hours
WLC	Weighted linear combination

### Notations/Symbols

CS	conflict score
SFM	standardised factor map
#SFM	number of standardised factor maps

80 TWh would come from onshore production. In addition, a balanced assessment of what is a reasonable distribution for each county was estimated by the NWS, partly based on a spatial analysis to indicate where future onshore wind power could be located across Sweden, with varying degrees of expected conflict [14]. However, further analyses on regional and municipal levels were considered necessary to gain a more comprehensive understanding of potential suitable sites [13].

In Sweden, the municipalities play a key role in the wind power planning process, due to their planning monopoly. In addition, for a permit for a wind farm to be given, formal approval by the municipality is required [15]. According to Wretling et al., 2022 [16], there is a large heterogeneity within wind power planning practice concerning how trade-offs between wind power deployment and other sustainability aspects are handled, as well as a lack of coherence between planning and permitting. In addition, to gain a permit for wind power development has become increasingly more difficult. This highlights the need for additional support at the municipal level. Furthermore, in Sweden, the County Administrative Boards (CAB) represent the national interests at the regional level, and have a supporting role towards municipal planning [15]. Thus, there is a growing interest to develop critical competence and relevant knowledge to enable trade-offs between the different sustainability considerations in an informed and balanced manner. They could be guided by collaborative planning principles, where a wide range of actors are included to discuss the suitability of different planning alternatives [17]. This calls for the development of methods and tools to support the regional and municipal collaborative wind power planning processes in seek of sustainable planning outcomes.

### 1.1. Spatial multicriteria analysis for planning support

With this increased requirement for sustainable wind energy in Sweden, not only technical and economic aspects like good wind speed and accessibility need to be taken into account in wind power planning, but also the impacts. A useful tool for integrating all these aspects is spatial multi-criteria analysis (SMCA) that transforms the geographical data regarding multiple criteria and stakeholder's preferences into decision aiding output maps [18–20]. This systematic approach can assist decision makers in localising and quantifying the synergies and conflicts involved in site selection while also visually representing them [21].

To integrate the many disparate criteria, SMCA studies commonly use weighting methods to find a compromise solution. Weights are obtained from stakeholders based on their preferences and professional judgements, and are applied to find the most suitable sites to promote as planning alternatives. The most commonly used method to find weights is through the analytical hierarchy process (AHP) [22] and to aggregate

spatial indicators through weighted linear combination (WLC) [23]. However, when applying weights to the criteria and aggregating their spatial indicators, trade-offs are introduced [20] that may to some extent mask goal conflicts. Finally, SMCA methodology includes evaluation of the planning alternatives, for which several methods exist [24, 25]. The relations between the evaluation and the weights, suitability and conflicts need to be highlighted.

SMCA has been used in many wind power siting studies, however, the practicality of the methods as real-world planning tools has not been much highlighted [26,27]. Among studies applying SMCA for wind power planning during the last 20 years, many evaluate given planning alternatives (e.g. Refs. [28–30], and in the review of such studies by Ref. [24], 35 of the 58 studies only conducted evaluation. However, for proactive planning (as opposed to reactive planning) conducted on municipal or regional scales, it is important to also include the design of planning alternatives within the planning process.

Among studies that design planning alternatives by applying SMCA, many use AHP and WLC, while it is quite common that they are conducted without involvement of stakeholders (e.g. Refs. [31–33]. When stakeholders are involved in such studies, they are often involved in criteria weighting [34–36], sometimes also in choice of criteria [37,38], but rarely in structuring the decision problem [27], nor addressing goal conflicts that may be hidden by the AHP-WLC approach (but see Hanssen et al. [39]).

User-friendly and transparent methods that support incremental improvement of design options, rather than ranking given alternatives, have been recommended for participatory and politically sensitive stages of planning processes [26]. Apart from the challenge of addressing goal conflicts, other key challenges when applying SMCA for planning support, that may even affect the outcome, were summarised by Ferretti and Montibeller 2016 [40]. Among these challenges were, besides choice of SMCA methods; choice of sources of information, structuring the decision problem while ensuring that all relevant but only the fundamental objectives are included, how to shape the spatial standardization functions, how to elicit weights from the stakeholders, and how to efficiently perform spatial uncertainty analysis. These can be seen as critical steps that need further elicitation.

Thus, for sustainable wind power planning, we need an SMCA framework that is adapted to the planning process and stakeholder dialogue, while organising and integrating a multitude of data, knowledge and perspectives, that takes goal conflicts into account. The AHP-WLC methodology is interesting to test for this purpose, while it needs further development for a systematic handling of goal conflicts. Many studies applied SMCA on wind power planning, but few developed the SMCA framework in direct collaboration with stakeholders, while explicitly addressing the problem of goal conflicts that available methods may hide.

### 1.2. Aim

The overall aim of this study is to develop the REWIND methodological framework for providing support for real-world, onshore wind energy planning on regional and municipal levels in Sweden, in collaboration with stakeholders. The framework comprises of; *scoping*, identifying and organising criteria and decide on their treatment; *design*, using the criteria to create planning alternatives; and *evaluation*, where selected alternatives are ranked and evaluated. This approach revisits and further develops a selection of existing SMCA methods, while integrating a novel conflict mapping step into the framework for addressing the problem with hidden conflicts using the ordinary AHP-WLC method.

The REWIND framework was applied in a case study in Västernorrland County in Sweden, where high expectations on wind power development is stated in the NWS, while simultaneously, potential conflicts arise in relation to impacts on the scattered residential areas, areas important for outdoor recreation, biodiversity values,

reindeer husbandry, military defence areas and the complicated issue of matching with the separate planning process of the electricity grids on different levels. The targeted stakeholders from CAB Västernorrland were prepared to make regional analyses in line with the NWS, while building capacity to fulfil a stronger supporting role for the municipal planning. This will in turn provide insights into how SMCA can evolve into a tool that is more transparent and supportive of real-world planning processes.

The scientific contribution of this research paper is a critical test of existing SMCA methods, with AHP-WLC at the core, in collaboration with dedicated stakeholders, while developing systematic conflict mapping solution to the problem of hidden trade-offs. A more user-friendly and transparent SMCA framework has potential to support real-world planning processes and policy making, thereby enable reaching climate goals while minimizing conflicts with other sustainability goals.

## 2. Methodology

An overview of the REWIND methodological framework developed for regional wind power planning in Sweden is shown in Fig. 1. This framework consists of three stages: **scoping**, where the criteria are identified and organised and their treatment decided on; **design**, where the criteria are used to create planning alternatives; and **evaluation**, where the selected alternatives are ranked and evaluated. ArcGIS 10.8 was used for the spatial analyses [41].

The **scoping stage** is comprised of the identification and structuring of relevant criteria, as well as defining constraints, factors and the value functions of their spatial indicators that are expressed in factor maps. After relevant criteria are identified, they are grouped into a hierarchical structure – a planning tree – where criteria addressing similar issues are grouped into main clusters. The planning tree is useful for weight determination when there are large numbers and a wide variety of

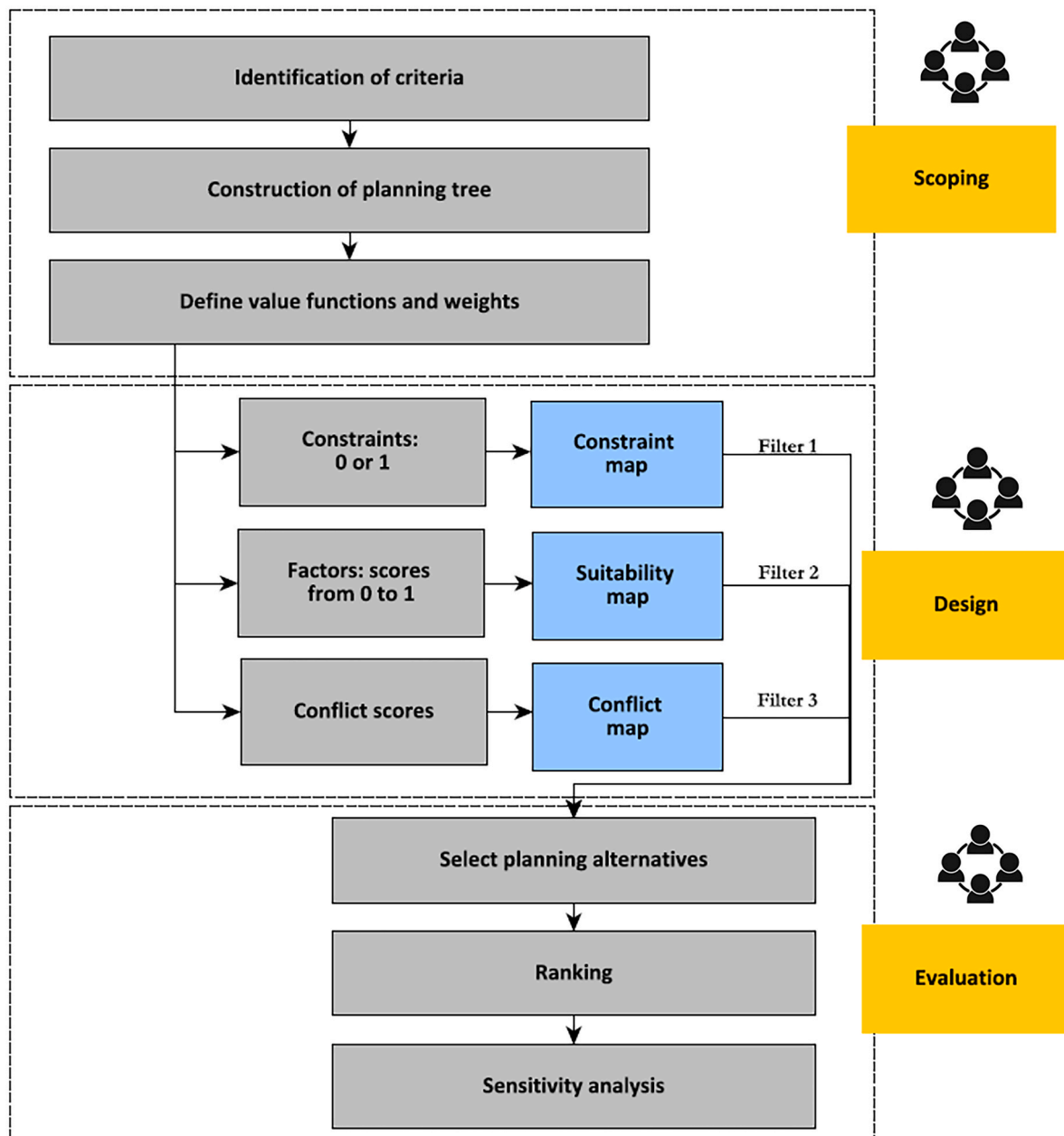


Fig. 1. Overview of the REWIND methodological framework, comprising of a stage wise process of scoping, and designing and evaluating planning alternatives. In the study, stakeholders were involved in all three stages, as illustrated by the symbols (adapted from Ref. [42]).

criteria. Spatial indicators for the criteria are then specified with scores based on scientific literature, legal requirements and policy, and/or expert judgements. Constraints are areas considered explicitly unsuitable for wind farm development, and a Boolean logic of either 0 or 1 is applied for these spatial indicators. For factors, the suitability scores vary in fuzzy continuous and/or discrete scales, standardised from 0 to 1 to be comparable. The factors express the degree of suitability, where the value 0 indicates an entirely unsuitable location and 1 indicates a location which is ideally suited for wind farm installation in terms of that particular criterion [20].

In the **design stage**, the most suitable locations for wind power development are sought. For this, a three-step filtering process is applied, as illustrated in Fig. 1. In the first filtering step, all constrained areas are aggregated into a constraint map that is used for eliminating all completely unsuitable areas from the process. In the next filtering step, a suitability map is created and applied to the study area, by combining the factor maps using weights. For deriving the weights of the criteria within the planning tree, AHP was applied. AHP is based on pair-wise comparisons of criteria and the importance of one criterion over the other is marked in a scale from 1 to 9 in a comparison matrix. In addition, a consistency check where a consistency ratio of less than 10% was considered acceptable was also conducted during the weight determination [22,43]. In the suitability map, each pixel got a suitability score based on WLC of factor scores and weights [20].

For the final filtering step in the design stage, a novelty was the

conflict maps, developed to enable exclusion of areas with high conflict. In this process, pixels with big differences between the factor scores were highlighted and eliminated. The conflict maps are based on inverse factor maps using Equation (1):

$$CS = \sqrt{\sum \frac{(1 - SFM)^2}{\#SFM}} \tag{1}$$

where CS = conflict score, SFM = standardised factor map, and #SFM = number of standardised factor maps. The conflict score highlights pixels where there are one or more factors with very low factor scores through magnifying their impacts by squaring. A conflict cut-off score is then assigned to conduct the third step of filtering, where pixels above the conflict cut-off score are eliminated from the site selection process. The conflict cut-off score can either be set in advance, or more arbitrary while iteratively targeting a certain area to be available for the next step. In this way, areas with conflicting factors can be eliminated to avoid subjecting them to weights, which can bring heavy trade-off based on the preferences of stakeholders. From the final suitability map, without high-conflict areas, large areas with high suitability can be outlined as potential planning alternatives.

In the **evaluation stage**, planning alternatives with sufficient size are selected, which also fulfil high suitability score and low conflict score thresholds. Then these alternatives are compared with one another by selected methods, such as comparing the factor scores, as well as the

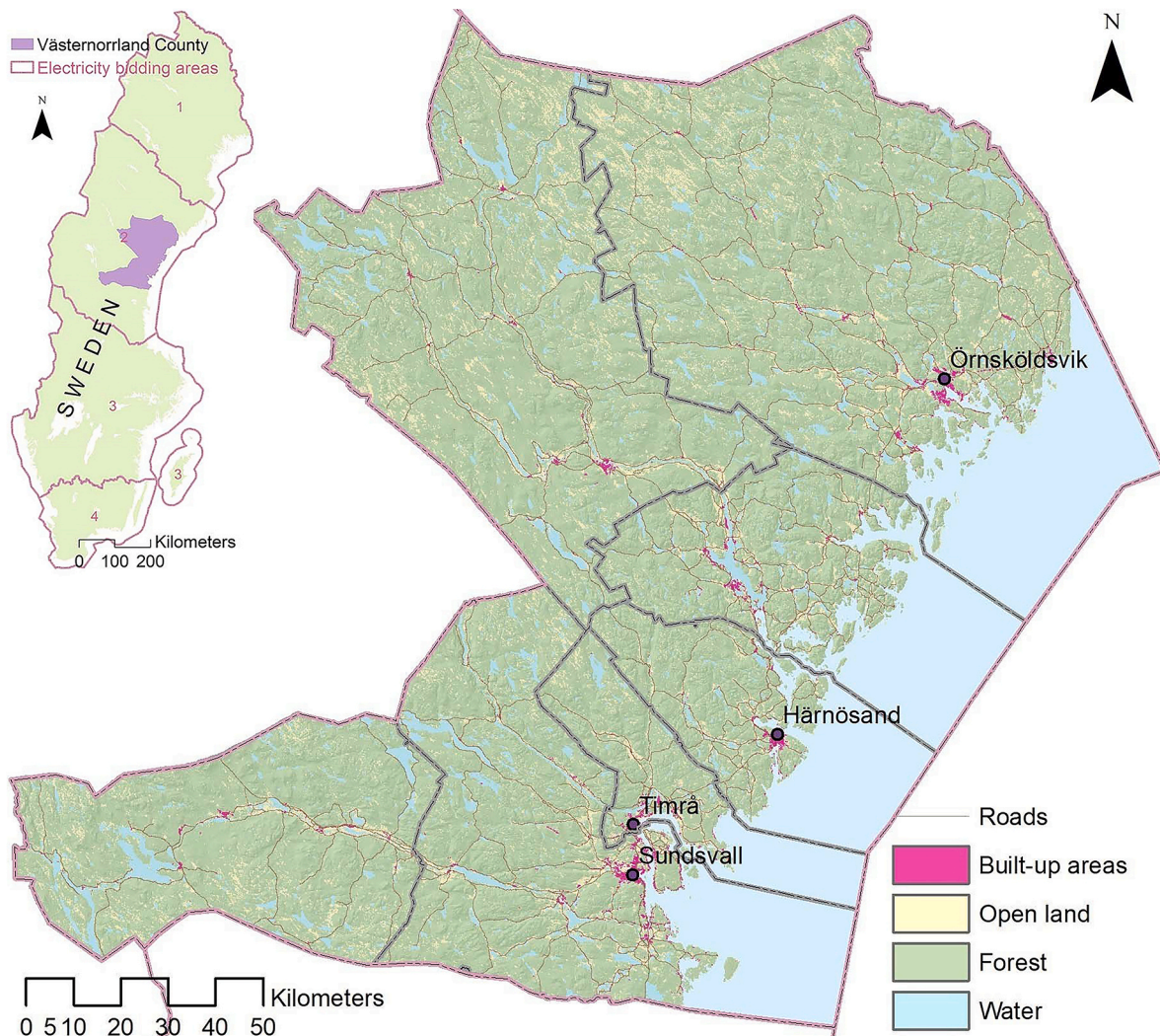


Fig. 2. The study area Västernorrland County in Sweden. Coordinate system Sweref99TM, spatial data © Lantmäteriet.

mean suitability scores and conflict scores, to decide the final rankings.

### 3. Application of the REWIND framework in Västernorrland County

The REWIND methodological framework was applied in a case study of Västernorrland County located in the north of Sweden, shown in Fig. 2. The study area include seven municipalities and has a total land area of 23,084 km<sup>2</sup> [44]. The county contains a variety of landscapes, with a long coast in the east as well as forested, mountainous terrain in the west, along with abundant lakes and rivers. Approximately 81% of the county’s land area is covered by forest, 2% by agricultural fields, 8% by other open land, 7% by water, and only 2% is urban and infrastructure [45]. Electricity production in the county is derived from a combination of hydropower (85%), windpower (7%), industrial back-pressure (7%) and solar energy (1%) [46]. The electricity production from wind power increased between 2015 and 2022 from 1.07 to 5.66 TWh within the county with an installed capacity of 2284 MW [47]. This production is expected to increase even more in the coming years and according to the NWS, it is estimated that the wind energy potential in Västernorrland County is roughly 7.5 TWh [13].

For testing the REWIND methodology in the study area, targeted areas should host wind farms with 25 MW of installed capacity, matching very roughly a size of 10 km<sup>2</sup>, and a connection to the regional grid. For comparability, a set of 10 equal-sized areas with a rectangular layout (5 × 2 km) were chosen. The wind-power calculations were based on the power curve from Gamesa G132–3.3 MW turbines at 7 m/s wind speed with 132 m rotor diameter [48]. The spacing between turbines was assumed to be eight times the rotor diameter in one direction and 5 times in the perpendicular direction, as a rule of thumb [49].

As illustrated in Fig. 1, stakeholders were engaged in all three stages. The stakeholders were selected from different departments of CAB Västernorrland as well as from SEA, listed in Table 1. They had a shared interest from regional and national perspectives to develop methods and tools for wind power planning, that could later on be used by themselves in dialogue and collaboration with municipalities. Prior to the workshops, all stakeholders obtained a “criteria catalogue” with information on possible factors from other studies (scientific and practical), possible data, and possible treatments of factors, which was updated continuously. Furthermore, they got instructions about the weighting procedure, and early versions of the results between and after workshops 3 and 4.

#### 3.1. Scoping stage: criteria and spatial indicators

In the scoping stage, criteria and spatial indicators were chosen and

decisions taken on their treatment (Suppl. Table S1, [42]. The stakeholders took part in identification of criteria and spatial indicators, treatment of the latter, and structuring the decision problem into a planning tree (workshops 1 and 2, e-mail conversation), illustrated in Fig. 3. The spatial indicators were standardised into a suitability scale, where they were subjected to either fuzzy or Boolean logic, or a combination thereof, to get the final criteria maps. The raster cell size used in the spatial analysis was 25 m × 25 m. Decisions regarding the treatment of the spatial indicators for the criteria, such as buffer distances and fuzzy functions, were based on scientific literature, legal requirements and policy, and/or expert judgements and were supported by recommendations from the stakeholders.

Since there are many factors that influence wind power planning with a corresponding large amount of input data, they were clustered into a hierarchical planning tree to simplify the weighting process. In consultation with the stakeholders, the factors were grouped in clusters aligned with the legislation and societal institutions. The clustering made the factors easier to compare with one another instead of with all the other factors in the planning tree. The planning tree was also used as a basis for creation of the factor maps. In total 40 datasets were used as inputs to the spatial indicators, each treated and standardised as shown in Suppl. Table S1 and expressed as sub-factor maps. We then combined the sub-factor maps that belonged to the same factor in the planning tree. This was done through mosaicking these maps into either the lowest suitability score for each pixel, to be conservative, or in case of proximity to roads and electricity grids, the highest suitability score was kept. In this way, 12 factors and 3 constraints were created for further analyses, as shown in Fig. 3.

For the cluster Wind power development, the factors Wind resource, Power grids and Roads were used. For Wind power development, the electricity grid should have sufficient voltage levels to handle the power generated. Therefore, the regional grid was considered in this study, generally with a voltage capacity of 40–130 kV, to match the needs for wind parks with around 25 MW of installed capacity.

The cluster Socio-cultural values included Residential areas, areas important for Outdoor recreation, as well as areas with Cultural values. Reindeer husbandry was considered as stand-alone to align with related legislation and institutions. Other land use and infrastructure included Defense, Infrastructure and Other land-use. Within the cluster Nature conservation, two selected bird species were included, that were not specifically tied to forest or wetland habitats but sensitive to wind power development and highly relevant for the study area. These were the Golden eagle (*Aquila chrysaetos*) and the Red-throated diver (*Gavia stellata*), both of which’s habitats were treated as criteria [50,51]. Both these birds are listed in Annex I of the EU Birds Directive, and classified as Near Threatened in the Swedish Red List [52].

**Table 1**

Stakeholders taking part in workshops (WS) of the study; practitioners from CAB of Västernorrland and SEA, and researchers and students from KTH and Stockholm University (SU).

Participant No.	Organisation	Role	WS 1 (31/01/2017)	WS 2 (25/09/2017)	WS 3 (12/06/2018)	WS 4 (26/10/2018)
1	CAB	Energy strategist				X
2	CAB	Environmental permit delegation	X	X	X	
3	CAB	Nature and rural areas	X	X	X	X
4	CAB	Nature and rural areas	X	X	X	X
5	CAB	Nature and rural areas	X		X	
6	CAB	Nature and rural areas	X	X		
7	CAB	Planning	X			X
8	CAB	Planning		X		X
9	SEA	Energy systems			X	X
10	SEA	Energy systems			X	X
11	KTH	Researcher	X	X	X	X
12	KTH	Researcher	X	X		
13	KTH	Researcher				X
14	KTH	MSc student			X	X
15	KTH	MSc student			X	
16	SU	MSc student	X	X	X	X

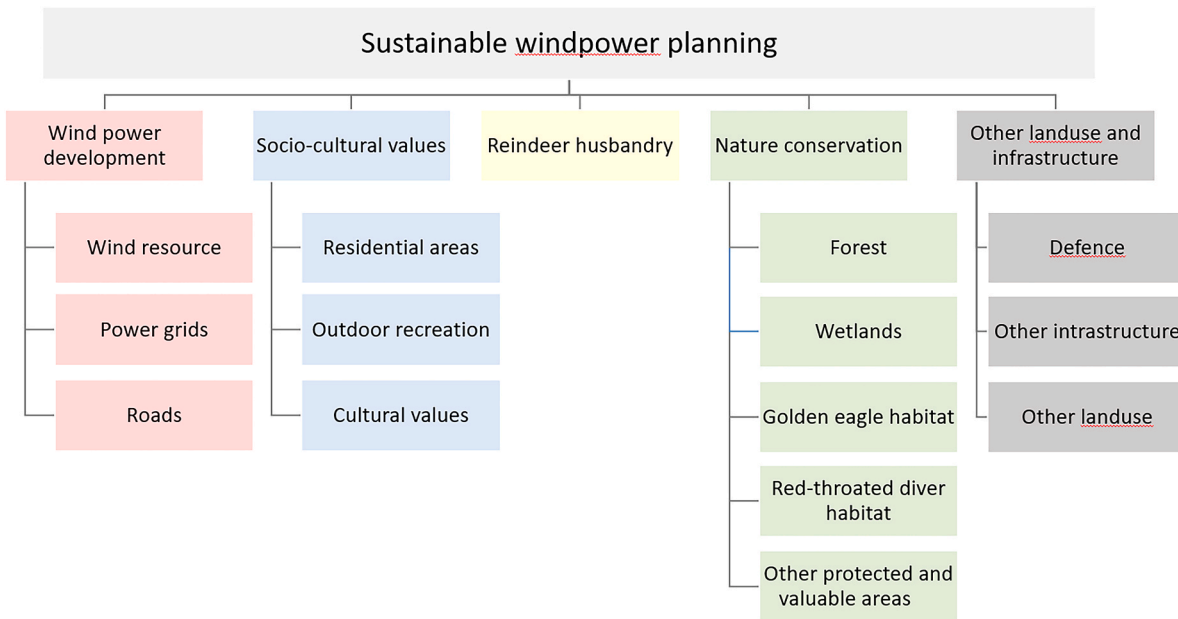


Fig. 3. Planning tree for Västernorrland County with clusters including factors and constraints for sustainable wind power planning.

### 3.2. Design and evaluation of planning alternatives

The design stage is comprised of three filtering steps as shown in Fig. 1. First, constrained areas were excluded, so they were not part of the weighting in the subsequent process. All the criteria in the cluster Other land use and infrastructure consisted only of constrained areas and were therefore not part of the weighting process. Among the other criteria, many consisted of both constrained areas and areas with different factor scores (see Suppl. Table S1), and from these, the completely unsuitable areas were excluded in this first filtering step.

In the second filtering step, the remaining areas were subjected to weighting of the remaining 12 factors, through AHP. The planning tree was used for clustering the factors. Stakeholders contributed with weighting of factors (workshops 3 and 4), using an online AHP tool as a part of the workshops to obtain weights [53]. Firstly, weights according to their own expertise were asked for, and secondly according to their experience of supporting wind power planning dialogues, to represent stakeholder interests that were not present (such as wind power developers, reindeer owners, and residents), expressed as weight profiles as shown in Table 2.

A cut-off score of 0.85 was used to find areas of high suitability. Finally, the standardized factor maps were aggregated using WLC to get an overall suitability score for each pixel. In the third filtering step areas with high conflict scores were excluded. The conflict cut-off score was chosen to be 0.15 and this was decided based on the size of the remaining area. Based on the outcome of the three filtering steps, the 10 best sites were selected as planning alternatives. Stakeholders contributed in the selection of planning alternatives, where a standardized size of 10 km<sup>2</sup> was agreed upon for comparability, and discussed outputs including conflict mapping (workshop 4 and e-mail conversation).

To test the sensitivity of the methods to changes in weights, two scenarios were created. The first scenario applied the average of all weights to derive suitability maps. Since the weight profiles representing wind power developers was perceived as deviating most from the other, one of these single profiles was used for sensitivity test of consequences of changing weights (profile 1.8 in Table 2). Thus, both sets of weights were applied in the evaluation step, to evaluate the influence of the weights.

## 4. Results and discussion

### 4.1. The design stage

After all the constrained areas were excluded, 30.4% of the total county land area remained open for further analyses. This limited the site search area to 7012.4 km<sup>2</sup>, illustrated by Fig. 4. The municipality of Kramfors had the highest percentage of land eliminated after the application of constraints, 84.2%, and had only a remaining area of 284 km<sup>2</sup>. The municipality with the largest remaining land area after the constraints were eliminated was Örnsköldsvik, with 2138.6 km<sup>2</sup>. Based on the planning tree clusters, the major share of land elimination in the first filtering occurred due to the Socio-cultural criteria (45.8%), in particular due to residential areas and the constraint distance of 800 m around them. Other main reasons for excluding areas were due to criteria from the clusters Ecological values (37.7%), Wind-power development (30.3%) and Other land use (infrastructure, 5.0%), while it should be noted that there were overlaps between the constraints.

The average weight distribution related to the planning tree is shown in Table 2. As can be seen, the average weights for the factors wind resource and reindeer husbandry were highest, whereas the factors for wetlands and red-throated diver were lowest. The aggregated suitability scores ranged from 0 to 0.99 for the entire study area. The cut-off value for the suitability score of 0.85 and above, together with the constraints, lead to the elimination of 87.6% of the total area available for further consideration, as illustrated by Fig. 4. The remaining area after this step was 2854.8 km<sup>2</sup>.

In the final filtering step, areas that had a conflict score above 0.15 were eliminated. This together with the previous filtering steps removed 95.8% of the total area, leaving 963.4 km<sup>2</sup> for planning. As can be seen in Table 3, the municipalities Örnsköldsvik (270 km<sup>2</sup>), Sundsvall (189 km<sup>2</sup>), Sollefteå (186 km<sup>2</sup>) and Ånge (153 km<sup>2</sup>) had relatively large available area after the filtering steps. However Timrå (49 km<sup>2</sup>), Härnösand (53 km<sup>2</sup>) and Kramfors (63 km<sup>2</sup>) had smaller areas available. The lowest factor score obtained through the Filter 3 step (finding areas with high suitability and low conflict) were 0.3 for roads and 0.45 and above for the rest of the factors. Overall, areas with high conflict scores most often had low suitability scores, but in addition, some areas with relatively high suitability scores also had high conflict scores, as shown in Fig. 4.

**Table 2**  
Weights accomplished from workshops at CAB Västernorrland.

Factors Weight profiles	Wind resource	Power grids	Roads	Residential areas	Outdoor recreation	Cultural values	Reindeer husbandry	Forest	Wetlands	Golden eagle	Red-throated diver	Other protected/valuable nature areas
Workshop 3 (12 June 2018)												
1.1 Ecological expert botanist	0,17	0,08	0,07	0,05	0,17	0,04	0,18	0,07	0,07	0,03	0,03	0,06
1.2 Ecological expert general	0,02	0,02	0,02	0,04	0,04	0,04	0,12	0,09	0,09	0,09	0,09	0,34
1.3 Ecotourism developer	0,01	0,02	0,02	0,03	0,24	0,06	0,27	0,13	0,11	0,04	0,02	0,05
1.4 Reindeer owner	0,01	0,01	0,04	0,03	0,01	0,06	0,68	0,09	0,02	0,01	0,02	0,02
1.5 Energy-climate strategist	0,52	0,10	0,09	0,04	0,04	0,01	0,08	0,01	0,01	0,03	0,01	0,04
1.6 Outdoor recreation I	0,03	0,03	0,03	0,14	0,44	0,05	0,10	0,01	0,01	0,06	0,06	0,02
1.7 Landscape protection	0,05	0,05	0,04	0,11	0,11	0,11	0,17	0,09	0,03	0,09	0,09	0,06
1.8 Wind power developer I	0,49	0,15	0,07	0,05	0,03	0,03	0,07	0,02	0,02	0,02	0,02	0,05
1.9 Wind power developer II	0,31	0,20	0,05	0,07	0,04	0,03	0,05	0,07	0,07	0,03	0,03	0,04
1.10 Wind power developer III	0,37	0,24	0,11	0,03	0,03	0,06	0,06	0,02	0,02	0,02	0,02	0,05
Workshop 4 (26 October 2018)												
2.1 Outdoor recreation II	0,09	0,01	0,03	0,05	0,08	0,02	0,14	0,07	0,08	0,17	0,16	0,10
2.2 Municipal politician	0,01	0,01	0,03	0,44	0,13	0,05	0,21	0,02	0,01	0,01	0,01	0,06
2.3 Local residents	0,02	0,02	0,02	0,12	0,04	0,45	0,09	0,10	0,07	0,02	0,03	0,04
2.4 Wind power developer IV	0,40	0,12	0,05	0,09	0,01	0,03	0,05	0,01	0,01	0,03	0,01	0,21
Mean weights												
All profiles (mean)	0.18	0.07	0.05	0.09	0.10	0.07	0.16	0.06	0.04	0.05	0.04	0.08
Clusters (mean)	0.30			0.26			0.16	0.27				

In the last filtering step (Filter 3), about 1890 km<sup>2</sup> were identified as places with high suitability score but also with relatively high conflict scores (HS-HC areas). These areas had high factor scores for factors with high weights, which lead to compensation of other factors. The two highest weighted factors in our study were wind resource and reindeer husbandry. The aggregated factor weights from these factors contributed 24% of the total weight in this case, and their minimum factor scores were 0.30 and 0.67 respectively in the HS-HC areas. However, most of the other factors in these areas had factor scores lower than 0.1. For example, several HS-HC areas located in Örnsköldsvik municipality (orange areas in Fig. 4) had low factor scores ranging down to 0.10 (wetlands), 0.20 (grids) and 0.30 (roads), whereas it had high scores for other factors. The provided weights were the reason for this trade-off. Thus, the degree of compensation could be high in these areas, based on how much the stakeholders emphasised a given factor.

Lastly, after the final filtering step using the average of all weights, the remaining land area available for planning in Västernorrland County (963.4 km<sup>2</sup>) was scattered across the study area, and ten planning alternatives were selected based on visual examination to find large cohesive areas. These alternatives were distributed across all the municipalities except Härnösand, as shown in Fig. 4. All the selected sites occupied a total area of about 11–16 km<sup>2</sup>. However after elimination of constraints from inside these sites, the final available area of each alternative was about 10 km<sup>2</sup>.

#### 4.2. Sensitivity test

To test the sensitivity of the model, one specific weight profile was selected that used a wind developer’s perspective (weight profile 1.8 in Table 2). With this profile, which emphasised the wind resource by a factor weight of 0.49 followed by power grids with weight 0.15, the filter 2 step resulted in a total suitable area of 2282.8 km<sup>2</sup>. The lowest factor score for wind resource was 0.65 among the suitable sites. For instance, the municipality Sundsvall had an additional suitable area of 29.1 km<sup>2</sup> when compared to the average of weight profiles. All these areas were concentrated in areas with higher wind speeds. By contrast, in the municipality Örnsköldsvik there was reduction of suitable area of 261.5 km<sup>2</sup> in comparison to the average of weight profiles. Most of this reduced area had a factor score lower than 0.65 for the factor wind resource.

To summarise, areas with very high wind factor scores combined with the high weights for the wind factor contributed to 49% of the suitability score in this “wind developer weight profile”. When these suitable sites were filtered through the conflict score threshold, further land was eliminated, leaving 760 km<sup>2</sup> for planning. This should be compared to the 963 km<sup>2</sup> available area applying the average of all weights, as shown in Table 3. This substantial difference in size occurred due to the stronger role of the wind resource factor, for which the relative lack of high-score areas became more emphasised in the

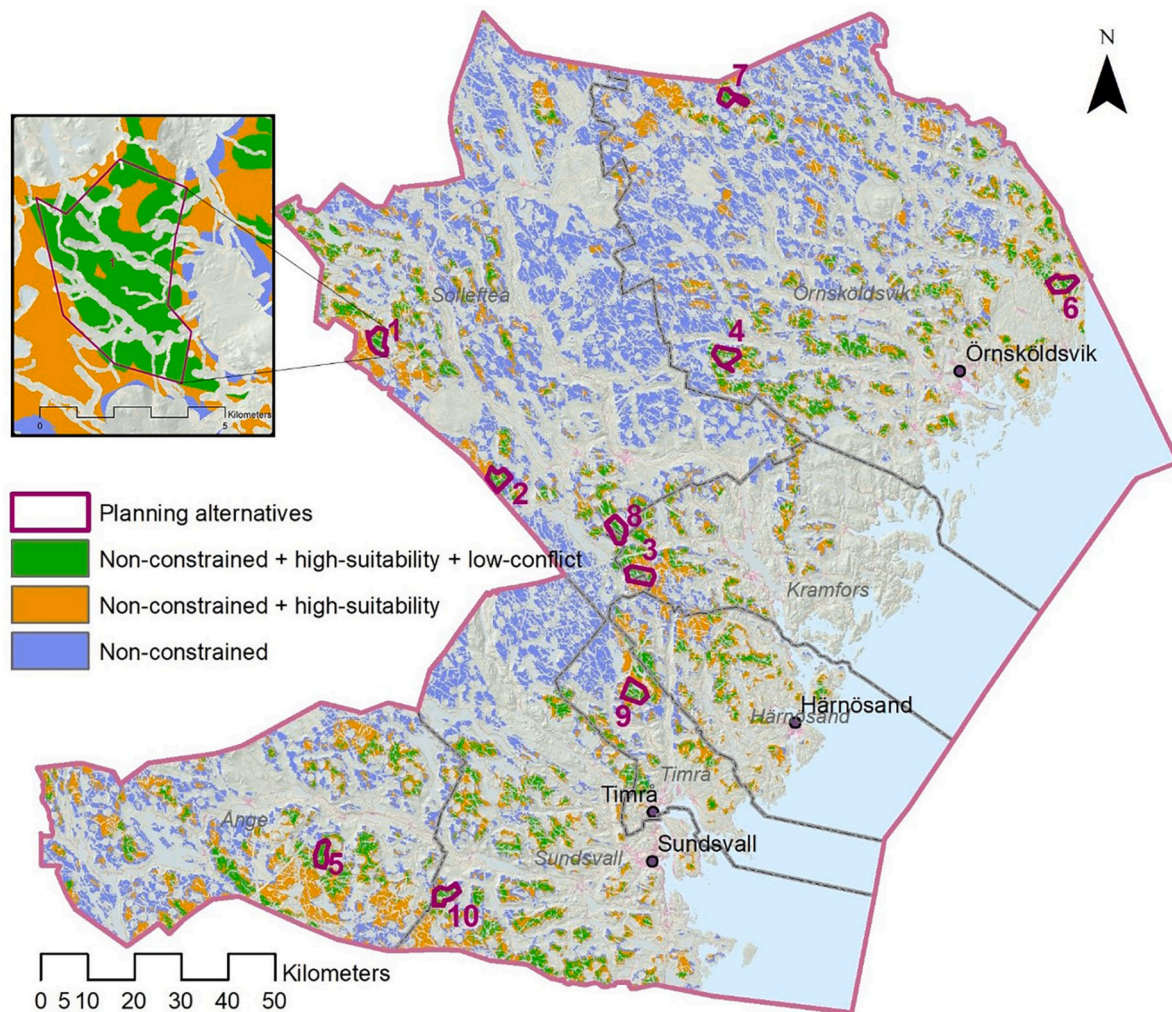


Fig. 4. Results from three filtering steps, with ten selected planning alternatives. Coordinate system SWEREF99 TM, spatial data © Lantmäteriet.

Table 3

Remaining area open for planning (km<sup>2</sup>) and amount of eliminated area (%) due to filtering, and for Västernorrland County and its municipalities. Areas are based on land-cover data excluding the Baltic Sea [45].

	Väster-norrland County	Sollefteå	Kramfors	Örnsköldsvik	Sundsvall	Timrå	Härnösand	Ånge
Total land area (km <sup>2</sup> )	23084	5798	1791	6774	3471	829	1106	3316
Land area (km <sup>2</sup> ) available after filter 1: constraints	7012	1992	284	2139	926	240	248	1184
% area reduction after filter 1: constraints	70	66	84	68	73	71	78	64
Land area (km <sup>2</sup> ) available after filter 1 + 2: suitability > 0.85	2855	538	181	768	473	133	185	578
% area reduction after filter 1 + 2: suitability > 0.85	88	91	90	89	86	84	83	83
Land area (km <sup>2</sup> ) available after filter 1 + 2+3: conflict score < 0.15	963	186	63	271	189	49	53	153
% area reduction after filter 1 + 2+3: conflict score < 0.15	96	97	96	96	95	94	95	95

suitability map.

#### 4.3. Results from evaluation of planning alternatives

From the areas of high suitability and low conflict after applying Filter 3, ten planning alternatives of about 10 km<sup>2</sup> were found through visual examination and digitized, targeting cohesive areas with high suitability and low conflict. The ten planning alternatives selected in the design stage were further investigated in the evaluation stage. For this, the suitability score obtained from the mean weight profile (average of all weights obtained from workshops) and conflict score were applied.

The resulting rankings are shown in Table 4. As can be seen, Alternative 6 ranked best and Alternative 8 ranked worst from both suitability score (mean weight profile) and conflict score evaluations.

The best and worst alternatives coincided with the overall mean factor scores evaluation. This implies that the deciding factors for the ranks in these alternatives were the factor scores and that the weights and aggregation approaches followed were not enough to bring trade-off to change their ranks. Similarly, the Alternatives 1, 7 and 10 also matched between the suitability score (mean weight profile) ranking and conflict score ranking. However the ranks were altered, with a change of three rank positions, in the cases of Alternatives 2 and 5,



**Table 4**

Evaluation of the planning alternatives, comparing the suitability scores (SS), and conflict scores (CS). SS was based on a) mean of weight profiles, and b) the selected wind developer profile as a sensitivity test.

Planning alternative	Municipality	Total area (km <sup>2</sup> )	Area without constraints (km <sup>2</sup> )	SS a) mean of weight profiles	Ranks based on SS a)	CS	Ranks based on CS	SS b) wind developer profile	Ranks based on SS b)
				SS evaluation	CS evaluation	SS evaluation – sensitivity test			
Alt 1	Sollefteå	16.1	10.8	0.96	2	0.09	2	0.98	1
Alt 2	Sollefteå	14.6	9.9	0.94	6	0.10	3	0.91	7
Alt 3	Kramfors	16.8	10.9	0.95	4	0.11	5	0.95	4
Alt 4	Örnsköldsvik	15.3	9.7	0.93	8	0.11	6	0.87	10
Alt 5	Ånge	11.9	9.8	0.94	5	0.11	8	0.91	6
Alt 6	Örnsköldsvik	15.6	10.3	0.96	1	0.09	1	0.98	2
Alt 7	Örnsköldsvik	11.6	9.2	0.94	7	0.11	7	0.93	5
Alt 8	Sollefteå and Kramfors	15.0	10.5	0.92	10	0.13	10	0.88	9
Alt 9	Timrå	16.8	10.6	0.95	3	0.11	4	0.96	3
Alt 10	Sundsvall	14.9	10.2	0.93	9	0.13	9	0.88	8

between the two methods. In the sensitivity analysis, the weight profile 1.8 (wind developer perspective) was applied and the resulting ranks are shown in Table 4. There were slight shifts in the ranks, but only with two positions in two cases with comparison to the mean weight profile.

## 5. Final discussion

As for any SMCA study, a multitude of decisions have to be taken concerning data, decision rules and stakeholder involvement, which need to be critically examined since they contribute to error and uncertainties, and can have implications for the outcome.

### 5.1. Selection of factors, input data and its treatment

In the scoping stage, the selection of criteria is a key step where it is necessary to integrate all relevant aspects of the planning problem. The selection was here based on literature studies and discussions with the stakeholders. In the selection of criteria, it is important to make sure that they are independent of each other, to avoid double counting [20]. This could be approached through methods for finding correlation among factors, developed by e.g. Lindén et al. [54]. However, if they are partly overlapping, either some of them has to be dropped, or a composite created. In the current study, this was approached through joining (mosaicking) several datasets into single spatial indicators. Still, remaining interdependencies could be possible, which needs to be addressed in the future.

Data to represent the criteria do however not always exist, or may not be entirely relevant. Still, from incomplete data, spatial indicators need to be created, that more or less well represent the criteria in factor maps. One example is the average wind speed data [55] and how representative it is of wind energy conditions in each specific site, over different terrain and scales, etc. Another example concerns the data representing reindeer husbandry [56], for which more detailed data exist, but is difficult to interpret and may be outdated. This leads to a data deficiency for this factor that needs further investigation.

Relevance of data regarding power grids is another difficulty that must be addressed during site selection, due to capacity problems. Power lines exhibit thermal, voltage and stability constraints which in turn limit their transmission capacity and ability to meet the demands [57]. Thus, a power line with insufficient transmission capacity cannot accommodate a new interconnection unless capacity-increasing measures are implemented. Currently, in Sweden, the transmission capacity in the north-south direction of the national grid is limited. The reason is foremost the electricity production being more concentrated to the north of Sweden while the electricity demand is high and increasing in the south [58]. Consequently, for Västernorrland county, it can be difficult to establish new wind farms until the transmission congestion in the national grid has been resolved, which also affects the regional grid

[58].

How to treat the input data concerning scaling and standardisation, to derive spatial indicators that represent the factors, are important decisions where data and knowledge gaps become apparent. For many criteria, more detailed analyses are possible, such as the potential energy gain related to wind speed in different locations (e.g. Refs. [28,59]). However, this may not be feasible in planning over large areas, but may be more realistic to develop at more detailed scales. Another type of decision on criteria concerns constraints. These may not necessarily be areas explicitly forbidden to build wind farms within, but could also be areas that are interpreted as unsuitable based on current policy or economical implications. One example would be areas with wind speed of less than 5 m/s that were constrained since economic feasibility would be difficult there. This can definitely change over time due to advancements in technology, policy changes, etc.

This study used 12 site specific factors for which spatial indicators were constructed from 40 input datasets (Suppl. Table S1). To simplify the AHP weighting procedure, the factors were grouped into clusters in a planning tree. This is recommended by Saaty [60], based on the assumption that human memory and judgement has limitations when the number of comparisons are more than 7 (preferred) or 9 (maximum) [61]. However, many studies seem to carry out pair-wise comparison without clusters, even if the number of factors exceeds 7, while they basically use the same method [33,62–65]. In contrast to this, other studies applied a hierarchical clustering approach [35,66]. In both these studies, clusters that included a single factor received the highest weights. This could be a tendency also in the current study, where the cluster Reindeer husbandry had only one factor, that obtained the highest individual weight of all factors among the weight profiles. Therefore, impacts of the structure of the planning tree may need further investigation.

Furthermore, the planning tree limits pair-wise comparisons of factors from different branches, which may affect the weights. However, the link to sustainability and environmental quality goals becomes more obvious with the use of clusters, especially since they here were aligned with the legislation and societal institutions. Finally, it is also possible that the final distribution of weights will depend on which factor weighting method is applied. In this case the pair-wise comparison in the Saaty scale [60] was used, carried out by the stakeholders, but other methods (e.g. Ref. [67]) may give different results, which remains to be tested.

### 5.2. Suitability and conflicts

The second filtering step involved aggregating factor maps into suitability maps using weights. Through WLC, a single indicator is generated, representing the overall suitability for each pixel within the study area. This cause a certain amount of compensation of the factor

scores. When combined with weights, any value other than zero within a factor map would compensate in the site selection process, depending on other co-existing factors and constraints in the same location. So, after applying Filter 2, keeping only areas above a certain suitability threshold, areas with relatively high suitability may have some factors with low scores and low weights, compensated by other factors with high factor scores and high weights. Therefore, areas with conflicting factors may be included in the suitability map. Thus, it is always possible that the stakeholders involved will not realise the impact of different weights in the design stage and are unaware of the invisible trade-offs that occur in suitability maps.

To address this trade-off problem, the conflict score was developed. It is calculated without integrating weights and is set up to amplify low factor scores to find their corresponding areas. It was applied to further fine-tune the remaining areas after Filter 2, where areas of high suitability were outlined. Through the conflict score, a more transparent and controlled trade-off among factors was applied to these areas. Thus, areas with conflicting factors can be eliminated to avoid subjecting them to weights, which otherwise can bring strong trade-offs based on the preferences of stakeholders. In addition, there is potential to further develop the conflict score to understand the range of factor scores within a pixel in different ways. Other ways to reflect different degrees of trade-off and risk for conflict also exist, such as ordered weighted averaging [68]. However, this approach tends to be non-transparent and may be more difficult to communicate to stakeholders.

Applying WLC to the factor maps, the arithmetic mean of the weighting profiles was used, while to test the sensitivity to weights, a single diverging weight profile was selected, a “wind-developer” perspective. The arithmetic mean is however not a representation of a negotiated decision about the importance of factors in a multiple stakeholder setup, which would be necessary in a real world planning process. Sensitivity to weights can be further explored through creating multiple scenarios from different weighing profiles, or specifying a range of weights. It would also be eligible to incorporate a detailed sensitivity analysis to identify which factors are most sensitive to weight changes [69]. However, a multitude of uncertainty and sensitivity test may yield quite complicated results, and may be difficult to apply in real world planning practice which involve larger plans and diverse opinions. Still, it is highly desirable to develop such analysis and visualisation methods, where some areas with high suitability may shift in the landscape, while other, more robust ones, may not.

In the evaluation of planning alternatives listed in Table 4, the mean values of the suitability scores of each alternative were relatively high and the conflict scores relatively low. This was due to the high threshold value set for the suitability scores, low threshold value for the allowed conflict score, as well as availability of such areas within the study area (illustrated in Fig. 4). Comparing the planning alternatives, the ranking according to suitability score and conflict score followed each other relatively well, however there were still some changes in rank between them. Here, the information about conflict is important and will add to the evaluation. The ranking when using the wind developer weight profile for testing the sensitivity showed similar results. This can be interpreted as the planning alternatives were relatively robust when changing the weights between stakeholders or weight profiles, in this case. Furthermore, using separate methods for evaluation, on top of summarising suitability and conflicts scores, can be useful, where suitability mapping with WLC and conflict mapping are complementary methods. For evaluation, there are dedicated methods, such as ELECTRE, TOPSIS and PROMETHEE [70–72]. These methods do not demand the underlying assumptions of the WLC and are easy to apply when the number of alternatives are limited [20].

### 5.3. Application in planning and policy-making

Finally, in this case study, the REWIND framework was applied on the regional level within the County of Västernorrland. The stakeholders

from CAB Västernorrland were preparing to conduct regional analyses in line with the NWS, while building capacity to fulfil a stronger supporting role for the municipal planning. In Sweden, municipal planning plays an important role for wind power development, so the next step would be to apply the REWIND framework not only to other regional case studies, but also in stakeholder dialogues on a municipal level. There is a need for an overall strengthening of the institutional capacity of CAB:s and municipalities to plan for wind power. A well informed and proactive planning process can help bridge the current lack of coherence between planning and permitting in the Swedish wind power planning [16].

Methods that are user-friendly and transparent can support an incremental design of planning alternatives, rather than ranking given alternatives [26]. This can be crucial in participatory and politically sensitive stages of planning processes. Here, the conflict score and the possibility to set a threshold for how much conflict will be allowed is one way of increasing transparency. When changing scale to the municipal level, more information and stakeholder views would be present locally, so a re-run of the analyses in a more detailed manner would be necessary.

Thus, the REWIND framework can evolve into a tool that is more transparent and supportive of real-world planning processes. This can help increasing awareness among stakeholders on climate targets as well as other sustainability goals, and how they play out in different landscapes. When weights change, areas of high suitability and low conflict may change, but some areas will turn out more robust while other change completely. This should be part of a continuous learning process, while underlying assumptions can be scrutinized and results shared. Areas with goal conflicts can be localized, quantified and visualized. In particular, this methodology is relevant to planning, but could also address the mission of the NWS, on how much wind power can be developed in a region without compromising other sustainability goals. This allows for input to engineering design of new grids, and enables contribution also to policy making.

### 5.4. Limitations and further research

This study is a case study which means that it has limitations in the direct applicability of the detailed choices made, since other contexts and stakeholders will be different. In addition, all relevant stakeholders were not represented in person, but indirectly by planning experiences of the workshop participants. Nonetheless, the involvement of stakeholders in all steps of the SMCA framework, with their ambition to apply such processes themselves in a near future, implies a unique opportunity for capacity building, to test the applicability of selected methods and to find directions forward.

An inherent problem of SMCA studies is the limited availability of data and knowledge to form spatial indicators for the criteria [40]. Errors are introduced in many ways, concerning in-data accuracy, data relevance, decision rules, and lack of detailed knowledge on e.g. specific impacts and technical-economic preconditions, which are moving targets. Also the structuring of the decision problem is a challenge, while involving all relevant main goals. This can be done in many ways, but the alignment with legislation and institutional organisation turned out to be transparent when working with stakeholders. Another limitation concerns the sensitivity study, which ideally should be expanded to involve all factors and all sets of weights, which is a common SMCA problem [27], along with the problem to visualise the outcome [40]. Still, with recent developments in computer capacity, this type of method development would be an important and possible avenue of research.

Another issue could be the assumption that the stakeholders understood the AHP method and that the weights reflected the actual perceptions of the participants. Using a simpler and more straight forward weighting method with better visualisation of weights outputs can be a way to ensure that the final weights make sense to the participants. In this context, addressing goal conflicts increased the transparency

instead of hiding trade-offs, while the conflict score could be further developed, to even better serve its purpose.

Overall, the REWIND framework itself is flexible and can show the way to further implementation in other wind power planning contexts, in Sweden or abroad. The novel method to highlight high-conflict areas is useful in any SMCA context. Opening up around other main challenges on choice of criteria, data and its treatment, knowledge gaps, structuring the decision problem to make sense in planning, further developing methods for criteria weighting, and further developing spatial uncertainty analysis and visualisation would be crucial steps for implementation in sensitive planning processes. This case study could be repeated and refined elsewhere, and the capacity building would strengthen proactive planning which have the potential to pave way for sustainable wind power development.

## 6. Conclusions

For sustainable wind power planning, SMCA needs to be adapted to the planning process and stakeholder dialogue, while organising and integrating a multitude of data, knowledge and perspectives, considering goal conflicts, and designing and evaluating planning alternatives. Within this study the REWIND methodological framework was developed, including the scoping, design and evaluation stages. As parts of this methodology, a new component was developed, in the form of a novel method for conflict mapping.

The conflict score was developed to highlight potential conflicts across the landscape. It is applied without weights, to allow a separate analysis of the trade-offs between the factors. So, the conflict score can be seen as a type of veto threshold in the SMCA process, steering how much conflict among factors should be allowed within areas of overall high suitability that could otherwise be selected as planning alternatives. In the case study area of Västernorrland County, where the REWIND framework was applied, around 30% of the area was unconstrained, while only 4% could be considered as having both high suitability and low conflict levels.

From the experiences of the case study, we identified critical steps and issues within SMCA that need further attention to be applicable in real world planning contexts. Key findings: 1) Conflicts that are masked by suitability scores using ordinary AHP-WLC methods can be revealed by applying conflict mapping, which increases transparency. 2) Remaining issues that need development for creating a user-friendly and transparent framework are; the structuring of the decision problem, choice, quality and availability of input data, knowledge gaps, treatment of data to derive spatial indicators, weighting method, and how to efficiently perform spatial uncertainty analysis. 3) Capacity building involving stakeholders in the design of planning alternatives as well as their evaluation are crucial for a sustainable planning process. In Sweden, the REWIND framework has potential to promote a more proactive planning process in the municipalities, supported by the regional actors, leading to a more predictable permitting process for developers. This will be useful for inclusive wind power planning in any country, since it is applicable on different scales. The REWIND framework is open-ended and allows for further development to provide knowledge-based planning support that is transparent, understandable for the larger audience and give more control of the factors, weights and conflicts to stakeholders to improve the support and acceptance for use in real-world planning.

## CRedit authorship contribution statement

**D. Manolan Kandy:** Conceptualization, Methodology, Investigation, Software, Data curation, Writing – original draft, Visualization. **U. Mörtberg:** Conceptualization, Methodology, Investigation, Data curation, Writing – review & editing, Visualization, Supervision, Funding acquisition. **V. Wretling:** Writing – review & editing. **A. Kuhlefeldt:** Data curation, Investigation. **G. Byström:** Data curation, Investigation. **H.**

**Polatidis:** Methodology, Writing – review & editing. **A. Barney:** Methodology, Writing – review & editing. **B. Balfors:** 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.

## Data availability

Data will be made available on request.

## Acknowledgements

This research was supported by the Swedish Energy Agency, grant no. 47380–1, and the Swedish strategic research program StandUp for Energy. A Swedish version of Fig. 1 was published by Swedish Energy Agency and Swedish Environmental Protection Agency, in (Mörtberg et al., 2023); reused, translated and adapted with permission. We would like to thank the editor and three anonymous reviewers for valuable input on earlier versions of this paper.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.rser.2023.113856>.

## References

- [1] International Energy Agency. Global energy review 2021. Paris, [Online]. Available. 2021. <https://www.iea.org/reports/global-energy-review-2021>.
- [2] Skarin A, Sandström P, Alam M. Out of sight of wind turbines - reindeer response to wind farms in operation. *Ecol Evol* 2018;8(19):9906–19. <https://doi.org/10.1002/ece3.4476>.
- [3] Marques AT, Batalha H, Bernardino J. Bird displacement by wind turbines: assessing current knowledge and recommendations for future studies. *Birds (Lond)* 2021;2(4):460–75.
- [4] Rydell J, Ottvall R, Pettersson S, Green M. Vindkraftens påverkan på fåglar och fladdermöss: uppdaterad syntesrapport 2017. Bromma; 2017.
- [5] van Kamp I, van den Berg F. Health effects related to wind turbine sound, including low-frequency sound and infrasound. *Acoust Aust* 2018;04/01 2018;46(1):31–57. <https://doi.org/10.1007/s40857-017-0115-6>.
- [6] Freiberg A, Scheffer C, Girbig M, Murta VC, Seidler A. Health effects of wind turbines on humans in residential settings: results of a scoping review. *Environ Res* 2019;02/01/2019;169:446–63. <https://doi.org/10.1016/j.envres.2018.11.032>.
- [7] Bell D, Gray T, Haggatt C. The 'social gap' in wind farm siting decisions: explanations and policy responses. *Environ Polit* 2005;14(4):460–77. <https://doi.org/10.1080/09644010500175833>.
- [8] Petrova MA. From NIMBY to acceptance: toward a novel framework — VESPA — for organizing and interpreting community concerns. *Renew Energy* 2016;02/01/2016;86:1280–94. <https://doi.org/10.1016/j.renene.2015.09.047>.
- [9] Deshmukh S, Bhattacharya S, Jain A, Paul AR. Wind turbine noise and its mitigation techniques: a review. *Energy Proc* 2019;02/01/2019;160:633–40. <https://doi.org/10.1016/j.egypro.2019.02.215>.
- [10] Pedersen E, Larsman P. The impact of visual factors on noise annoyance among people living in the vicinity of wind turbines. *Journal of Environmental Psychology* 2008;28:379–89.
- [11] United Nations. A/RES/70/1 Resolution adopted by the General Assembly on 25 September 2015 70/1. Transforming our world: the 2030 Agenda for Sustainable Development 2015 2015;19:43. Accessed: 2021-05-17 09.
- [12] Statistics Sweden. "Electricity supply and use." Statistics Sweden., <https://www.scb.se/en/finding-statistics/statistics-by-subject-area/energy/energy-supply-and-use/annual-energy-statistics-electricity-gas-and-district-heating/pong/tables-and-graphs/electricity-supply-and-use-20012020-gwh/> (accessed 2022-February-17).
- [13] Swedish Energy Agency and Swedish Environmental Protection Agency. 2021 [Online]. Available: Nationell strategi för en hållbar vindkraft, vol. 2. Stockholm, ER: Swedish Energy Agency; 2021. <https://energimyndigheten.a-w2m.se/Home.mvc?ResourceId=183601>. [Accessed 12 February 2021].
- [14] Swedish Energy Agency and Swedish Environmental Protection Agency. "Beskrivning av det nationella kartunderlaget [in Swedish]" [Online]. Available: Underlag till den nationella strategin för en hållbar vindkraftsutbyggnad 2021. [http://www.energimyndigheten.se/globalassets/fornbart/strategi-for-hallbar-vindkraftsutbyggnad/beskrivning-av-det-nationella-kartunderlaget\\_rev\\_2021-04-09.pdf](http://www.energimyndigheten.se/globalassets/fornbart/strategi-for-hallbar-vindkraftsutbyggnad/beskrivning-av-det-nationella-kartunderlaget_rev_2021-04-09.pdf).
- [15] Larsson S, Emmelin L, Vindelstam S. Multi-level environmental governance: the case of wind power development in Sweden. *Soc Stud* 2014 2014;6(2):291–312.

- [16] Wretling V, Balfors B, Mörtberg U. Balancing wind power deployment and sustainability objectives in Swedish planning and permitting. *Energy, Sustainability and Society* 2022;12(48). <https://doi.org/10.1186/s13705-022-00376-y>. [Accessed 22 December 2022].
- [17] Wretling V, Balfors B. Building institutional capacity to plan for climate neutrality: the role of local Co-operation and inter-municipal networks at the regional level [Online]. Available: *Sustainability* 2021;13(4):2173. <https://www.mdpi.com/2071-1050/13/4/2173>.
- [18] Belton V, Stewart TJ. The multiple criteria problem. In: Belton V, Stewart TJ, editors. *Multiple criteria decision analysis: an integrated approach*. Boston, MA: Springer US; 2002. p. 13–33.
- [19] Malczewski J. *GIS and multicriteria decision analysis*. New York: Wiley; 1999.
- [20] Malczewski J, Rinner C. *Multicriteria decision analysis in geographic information science*. 1st. Berlin, Heidelberg: Springer Berlin Heidelberg; 2015. Imprint: Springer; 2015.
- [21] Murayama Y, Thapa RB. *Spatial analysis and modeling in geographical transformation process GIS-based applications*. first ed. Dordrecht: Springer Netherlands; 2011. Imprint: Springer; 2011.
- [22] Saaty TL, Vargas LG. *Models, methods, concepts & applications of the analytic hierarchy process*. New York: Springer; 2012.
- [23] Malczewski J. Local weighted linear combination. *Trans GIS* 2011;15(4):439–55. <https://doi.org/10.1111/j.1467-9671.2011.01275.x>.
- [24] Rediske G, Burin HP, Rigo PD, Rosa CB, Michels L, Siluk JCM. Wind power plant site selection: a systematic review. *Renew Sustain Energy Rev* 2021/09/01/2021; 148:111293. <https://doi.org/10.1016/j.rser.2021.111293>.
- [25] Malczewski J, Jankowski P. Emerging trends and research frontiers in spatial multicriteria analysis. *Int J Geogr Inf Sci* : IJGIS 2020;34(7):1257–82. <https://doi.org/10.1080/13658816.2020.1712403>.
- [26] te Boveldt G, Keseru I, Macharis C. How can multi-criteria analysis support deliberative spatial planning? A critical review of methods and participatory frameworks. *Evaluation* 2021;27(4):492–509. <https://doi.org/10.1177/13563890211020334>.
- [27] Adem Esmail B, Geneletti D. Multi-criteria decision analysis for nature conservation: a review of 20 years of applications. *Methods Ecol Evol* 2018/01/01 2018;9(1):42–53. <https://doi.org/10.1111/2041-210X.12899>.
- [28] Polatidis H, Morales JB. Increasing the applicability of wind power projects via a multi-criteria approach: methodology and case study. *Int J Sustain Energy* 2016/11/25 2014;35(10):1014–29. <https://doi.org/10.1080/14786451.2014.975130>.
- [29] Łaska G. Wind energy and multi-criteria analysis in making decisions on the location of wind farms. *Procedia Eng* 2017;182:418–24. <https://doi.org/10.1016/j.proeng.2017.03.126>.
- [30] A. Stoltmann, "Hybrid multi-criteria method of analyzing the location of distributed renewable energy sources," *Energies* vol. 13, no. 16, doi: 10.3390/en13164109..
- [31] Değirmenci S, Bingöl F, Sofuoğlu SC. MCDM analysis of wind energy in Turkey: decision making based on environmental impact. *Environ Sci Pollut Control Ser* 2018;25(20):19753–66. <https://doi.org/10.1007/s11356-018-2004-4>.
- [32] Latinopoulos D, Kechagia K. A GIS-based multi-criteria evaluation for wind farm site selection. A regional scale application in Greece. *Renew Energy* 2015;78: 550–60.
- [33] Szurek M, Blachowski J, Nowacka A. GIS-based method for wind farm location multi-criteria analysis. *Min Sci* 2014 2014;21:65–81. <https://doi.org/10.5277/ms142106>.
- [34] Díaz-Cuevas P. GIS-based methodology for evaluating the wind-energy potential of territories: a case study from andalusia (Spain). *Energies* 2018;11:10. <https://doi.org/10.3390/en11102789>.
- [35] Watson JJW, Hudson MD. Regional Scale wind farm and solar farm suitability assessment using GIS-assisted multi-criteria evaluation. *Landsc Urban Plann* 2015/06/01/2015;138(Supplement C):20–31. <https://doi.org/10.1016/j.landurbplan.2015.02.001>.
- [36] Sánchez-Lozano JM, García-Cascales MS, Lamata MT. GIS-based onshore wind farm site selection using Fuzzy Multi-Criteria Decision Making methods. Evaluating the case of Southeastern Spain. *Appl Energy* 2016;171:86–102. <https://doi.org/10.1016/j.apenergy.2016.03.030>.
- [37] Bili A, Vagiona DG. Use of multicriteria analysis and GIS for selecting sites for onshore wind farms: the case of Andros Island (Greece). *European Journal of Environmental Sciences* 2018;8(1):5–13. <https://doi.org/10.14712/23361964.2018.2>.
- [38] Díaz-Cuevas P, Biberacher M, Domínguez-Bravo J, Schardinger I. Developing a wind energy potential map on a regional scale using GIS and multi-criteria decision methods: the case of Cadiz (south of Spain). *Clean Technol Environ Policy* 2018;20(6):1167–83. <https://doi.org/10.1007/s10098-018-1539-x>.
- [39] Hanssen F, May R, van Dijk J, Rød JK. Spatial multi-criteria decision analysis tool suite for consensus-based siting of renewable energy structures. *J Environ Assess Pol Manag* 2018/09/01 2018;20(3):1840003. <https://doi.org/10.1142/S1464333218400033>.
- [40] Ferretti V, Montibeller G. Key challenges and meta-choices in designing and applying multi-criteria spatial decision support systems. *Decis Support Syst* 2016/04/01/2016;84:41–52. <https://doi.org/10.1016/j.dss.2016.01.005>.
- [41] ESRI. *ArcGIS 10, 8.1*; 2019. Redlands, CA.
- [42] Mörtberg U, Manolan Kandy D, Wretling V, Kuhlefeldt A, Balfors B [Online]. Available: Regionalt planeringsstöd för vindkraft 2023. <https://www.naturvardsverket.se/om-oss/publikationer/7000/978-91-620-7095-3/>. [Accessed 31 March 2023].
- [43] Saaty TL. Decision-making with the AHP: why is the principal eigenvector necessary. *Eur J Oper Res* 2003;145(1):85–91. [https://doi.org/10.1016/S0377-2217\(02\)00227-8](https://doi.org/10.1016/S0377-2217(02)00227-8) (in English).
- [44] Fastighetskartan Lantmäteriet [Property map]. [Online]. Available, <https://zeus.s.u.se/get/>.
- [45] Swedish Environmental Protection Agency. Nationella marktäckedata [National Land-cover Data]. [Online]. Available: <https://www.naturvardsverket.se/verktyg-och-tjanster/kartor-och-karttjanster/nationella-marktackedata/>.
- [46] Häll M, Helsing D. Energi- och klimatstrategi Västernorrland 2020-2030. Länsstyrelsen Västernorrland; 2019 (in Swedish).
- [47] Swedish Energy Agency. Swedish Energy Agency 2023. Vindkraftsstatistik [Wind power statistics], <https://pxexternal.energimyndigheten.se/pxweb/sv/Vindkraftsstatistik/-/EN0105.3.px/>. [Accessed 9 May 2023].
- [48] Baue L, Matysik S. Gamesa G132-3.3MW, <https://en.wind-turbine-models.com/turbines/1336-gamesa-g132-3.3mw>. [Accessed 14 September 2021].
- [49] Lawrence A, Short R, Williamson A. NSW wind energy handbook. Sydney: Sustainable Energy Development Authority of NSW; 2002.
- [50] Eriksson MOG. Storlommen och smålommen i sverige - populationsstatus, hotbild och förvaltning [the black-throated diver and red-throated diver in Sweden, 2010. in Swedish].
- [51] Johansson M. Modelling habitat suitability index for golden eagle. Master degree MSc thesis. Department of Physical Geography, Stockholm University; 2020 [Online]. Available: <http://urn.kb.se/resolve?urn=urn:nbn:se:su:diva-197086>.
- [52] Swedish Species Information Centre. "Rödlistade arter i Sverige 2020 [Red list species in Sweden. In: Swedish]; 2020. Uppsala, 2020.
- [53] Goepel KD. Implementation of an online software tool for the analytic hierarchy process (AHP-OS). *International Journal of the Analytic Hierarchy Process* 2018;10(3). <https://doi.org/10.13033/ijahp.v10i3.590>. 26 December 2018 2018.
- [54] Lindén D, Cinelli M, Spada M, Becker W, Gasser P, Burgherr P. A framework based on statistical analysis and stakeholders' preferences to inform weighting in composite indicators. *Environ Model Software* : with environment data news 2021; 145:105208. <https://doi.org/10.1016/j.envsoft.2021.105208>.
- [55] Bergström H, Söderberg S. Beräkning av vindklimatet i Sverige med 0,25 km<sup>2</sup> upplösning med hjälp av MIUU-modellen. In: Swedish]. Meteorological Institute Uppsala University model; 2012 [Online]. Available: <http://energimyndigheten.se/sv/Om-oss/Var-verksamhet/Framjande-av-vindkraft1/Vindkartering1/>.
- [56] Sametinget ST. Riksintresse rennängar. [Online]. Available: <https://ext-geodat akatalog.lansstyrelsen.se/GeodataKatalogen/>.
- [57] Yusoff N, Mohd Zin A, Khairuddin A. Congestion management in power system: a review. 2017. p. 22–7.
- [58] Kraftnät Svenska. Systemutvecklingsplan 2022-2031 [in Swedish] Sundbyberg: Svenska kraftnät 2021 [Swedish power grid operator].
- [59] Sijal SH, Mörtberg U, Mentis D, Welsch M, Babelon I, Howells M. Wind energy assessment considering geographic and environmental restrictions in Sweden: a GIS-based approach. *Energy* 4/1/2015;83:447–61. <https://doi.org/10.1016/j.energy.2015.02.044>.
- [60] Saaty TL. How to make a decision: the analytic hierarchy process. *Eur J Oper Res* 1990/09/05/1990;48(1):9–26. [https://doi.org/10.1016/0377-2217\(90\)90057-1](https://doi.org/10.1016/0377-2217(90)90057-1).
- [61] Miller GA. The magical number seven, plus or minus two: some limits on our capacity for processing information. *American Psychological Association*; 1956. *Psychological Review*.
- [62] Höfer T, Sunak Y, Siddique H, Madlener R. Wind farm siting using a spatial Analytic Hierarchy Process approach: a case study of the Städteregion Aachen. *Appl Energy* 2016;163:222–43. <https://doi.org/10.1016/j.apenergy.2015.10.138>.
- [63] Tegou L-I, Polatidis H, Haralambopoulos DA. Environmental management framework for wind farm siting: methodology and case study. *J Environ Manag* 2010/11/01/2010;91(11):2134–47. <https://doi.org/10.1016/j.jenvman.2010.05.010>.
- [64] Tegou LI, Polatidis H, Haralambopoulos DA. Wind turbines site selection on an isolated island. In: Presented at the management of natural resources. *Sustainable Development and Ecological Hazards II*; 2009.
- [65] J. Wańtrobski, P. Ziemia, J. Jankowski, and M. Ziolo, "Green energy for a green city—a multi-perspective model approach," *Sustainability*, vol. 8, p. 702, July/26 2016 doi: 10.3390/su8080702..
- [66] Vavatsikos AP, Arvanitidou A, Petsas D. Wind farm investments portfolio formation using GIS-based suitability analysis and simulation procedures. *J Environ Manag* Dec 15 2019;252:109670. <https://doi.org/10.1016/j.jenvman.2019.109670>.
- [67] Rezaei J. Best-worst multi-criteria decision-making method. *Omega (Oxford)* 2015; 53:49–57.
- [68] Malczewski J. Ordered weighted averaging with fuzzy quantifiers: GIS-based multicriteria evaluation for land-use suitability analysis. *Int J Appl Earth Obs Geoinf* 2006/12/01/2006;8(4):270–7. <https://doi.org/10.1016/j.jag.2006.01.003>.
- [69] Chen Y, Yu J, Khan S. Spatial sensitivity analysis of multi-criteria weights in GIS-based land suitability evaluation. *Environ Model Software* 2010/12/01/2010;25(12):1582–91. <https://doi.org/10.1016/j.envsoft.2010.06.001>.
- [70] Munda G. In: *Social multi-criteria evaluation for a sustainable economy*. 1st. Berlin, Heidelberg: Springer Berlin Heidelberg; 2008. 2008.
- [71] Bezerra PRS, Schramm F, Schramm VB. A multicriteria model, based on the PROMETHEE II, for assessing corporate sustainability. *Clean Technol Environ Policy* 2021/12/01 2021;23(10):2927–40. <https://doi.org/10.1007/s10098-021-02211-y>.
- [72] Hwang C-L. *Multiple attribute decision making methods and applications A state-of-the-art survey*. first ed. Berlin, Heidelberg: Springer Berlin Heidelberg; 1981. Imprint: Springer, 1981.