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Wind energy assessment considering geographic and environmental restrictions in Sweden: A GIS-based approach

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ABSTRACT

The wind energy being a freely available and low-carbon energy source has got the focus of decision makers around the world, because wind energy systems can reduce the dependence of a nation on fossil fuels and can contribute to a sustainable development of both climate and energy. However, wind power comes with certain environmental impacts and land use constraints that should be taken into account, in order to reach main sustainability goals concerning biodiversity and ecosystem services. The Swedish national goal regarding wind energy development has been set to 30 TWh by the year 2020, of which 20 TWh should come from the on-shore wind energy resource. Therefore, wind energy development in Sweden could play an important role in achieving the future energy and environmental targets. In this regard, we assessed the wind energy potential available in Sweden using a GIS-based approach. We aimed to estimate the technical onshore wind energy potential available in Sweden by considering system performance, topographic limitations, environmental, and land use constraints in the form of two restriction scenarios. The results of this paper can draw the attention of decision makers to reach a sustainable wind energy development in Sweden. The results achieved in this paper suggest that Sweden possesses sufficient wind energy potential and land area available for wind energy installations, which can be used to meet the future renewable energy targets in Sweden.

1. Introduction

1.1. Energy perspectives on wind energy

Issues like climate change, energy security and increase in oil prices have drawn global attention to promote renewable energies and especially wind energy. Being a freely available and low carbon energy source, wind energy has drawn the attention of decision makers around the world, because wind energy systems can reduce the dependence of nations on fossil fuels and can contribute to a sustainable development of both climate and energy. Nowadays in the European Union (EU) as well as in other parts of the world, possible reasons to promote wind energy systems are energy security, climate and environmental threats, saving of foreign exchange and socio-economic well-being of nations [1]. Simultaneously, wind power comes with certain social and environmental impacts that need to be balanced for a sustainable implementation on large scales. Furthermore, wind speed is of stochastic nature and it can take place at any time of the day [2,3]. Consequently, power output of wind power plants is always stochastic. Therefore, the stochastic nature of wind power must be treated with special care while considering its large-scale integration into the national electricity system. According to the new "Climate-Energy Legislative Package" of the EU, by the year 2020 each member country should achieve the minimum national target of 20% renewable energies share in overall energy consumption [4]. As a proven source of low-carbon and free energy with comparatively lower environmental impacts than many other available energy systems [5,6,7], wind energy can perform a fundamental role in achieving the future targets of climate and energy policy in the EU. In line with this, the wind power sector has shown decent growth during the recent past in the world and especially in the EU. Till the end of the year 2012, 105 GW installed capacity of wind power was achieved in the EU, which can meet 7% of the electricity need of the EU [8]. According to the estimates of the European Wind Energy Association [9,10], in Europe 230 GW capacity of wind power will be installed by year 2020. This will meet up to 14–17% of the electricity demand of the EU, and will reduce 333

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million tons of CO_2 per year and will also save 28 billion Euros a year by avoiding fuel costs [11].

In Sweden the total installed wind power capacity was 3745 MW by the end of year 2012 and this capacity was far behind compared to some other European countries like Germany, Spain, UK, Italy and France, Fig. 1 [12]. In Fig. 1, it also can be observed that Sweden was at number eight in the wind power penetration percentage as compared to other wind energy leading countries [12]. The Swedish national goal for wind power development has been set to 30 TWh in the year 2020, of which 20 TWh onshore [13,14]. By the end of year 2013, the Swedish wind power capacity reached up to 4469 MW, which is equal to 10.7 TWh yearly average production, showing that 7.7% of the total electricity consumption in Sweden was generated by wind energy [9,15].

1.2. Environmental perspectives on wind energy

Wind power, like any energy system, has complex technical requirements as well as environmental and social consequences; concerning infrastructure and safety, biodiversity, ecosystem services and other social issues. Technical requirements for the deployment of wind power concern, among other, availability of the wind resource and the feasibility of connecting to electricity transmission grids and access roads [10,16]. Other practical issues include safety requirements in the form of minimum distances from other infrastructure, such as airports, roads, railroads, etc., as well as from residential areas and other places of activity [17,18].

In addition, wind power is considered to have non-negligible impacts on biodiversity, including the collision of birds with wind turbine blades as well as habitat loss and fragmentation due to the new infrastructure. Vulnerable species groups include birds and bats, among other [19–22]. Wind farms also have a number of important consequences for cultural ecosystem services, related to landscape aesthetics, recreation and noise [23–26]. Furthermore, social acceptance of wind power can be related to socioeconomic issues such as ownership and benefit-sharing [27–30].

In the Swedish planning system on a national level, biodiversity and ecosystem services can be seen as represented by protected areas as well as by areas of national interest for nature, culture and recreation values. The areas of national interest have a weaker protection and entail no strict prohibition against land use changes [31,32]. The values associated with the areas of national interest are supposed to be protected against major damage but the values will be compared to other interests in case of a suggested land use change. Therefore, they are treated differently by different plans and the weighting between diverse societal interests is not trivial, and leaves room for interpretation [33–35]. Furthermore, policy and planning in Sweden should take the national environmental quality objectives (Govt. prop. 1997/98:145 and 2004/05:150) into account, according to which goals for e.g. climate, biodiversity and landscapes are to be promoted. An issue that adds to the complexity of wind power planning is that areas with high wind speed often coincide with areas of high values for biodiversity and ecosystem services, protected or not, e.g. along the coastline and large lakes, as well as in the mountains. In addition, residential houses in Sweden are very scattered in the countryside, with the multiple agrarian land reforms of the 19th century as the historical origin [36], leading to increased risk for the spatial overlap with sites that are suitable for wind power. On the other hand, a special feature of wind power plants is that the physical land surface occupied by the masts also allows for different non-conflicting land uses [16]. Therefore, sustainable wind energy resource harvesting needs to be built on a solid knowledge about the availability of the wind resource, as well as on the consequences for the environment and for local communities.

1.3. Wind energy assessment by GIS-based approaches

In Sweden, strategies for the expansion of wind energy are guided by renewable energy goals and by areas of national interest for wind energy [13]. Therefore, municipalities are strongly recommended to take these issues into account in their energy planning. In order to strengthen this planning, the Swedish National Board of Housing, Building and Planning (SNBH) launched a project for helping the municipalities with their wind energy planning [37]. Therefore, to support such efforts, the knowledge of the availability of the wind resource, possible land use restrictions and the electricity generation potential are of main importance. The restrictions to wind energy installation can be of different kinds, mainly related to safety and to environmental impacts, as described in section 1.2.

In Sweden, large scale wind energy integration may be accelerated by properly quantifying, visualizing and identifying favorable areas with different assumptions. For wind energy resource assessment as well as for its planning, the consequences of many planning principles and restrictions can be explored by using GIS-based approaches. Such kind of approaches has been developed both for wind resource mapping as well as for investigating trade-offs between different interests. GIS-based wind energy assessment approaches have been used by for example [38,39]. GIS-based studies also have produced spatial models to identify optimal distances to both settlements and natural habitats with endangered species, so as to offer the best available trade-offs between ecological impact and energy production output [40]. A related study investigated trade-offs between ecological impacts of wind energy production [41]. Other GIS-based studies focused on finding suitable areas in terms of visual impacts

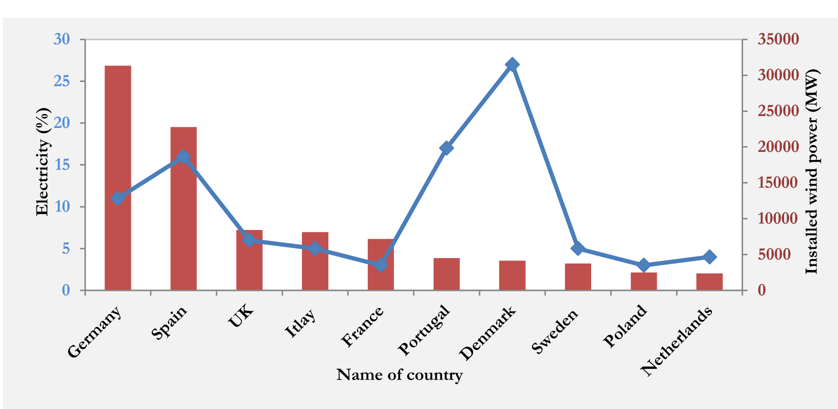

Fig. 1. Top 10 wind power installed capacity (MW) in the European Union 2012 [12].

[42], while others used more comprehensive criteria that covered technical, physical, anthropological, environmental as well as economic constraints [43]. However, renewable energy assessments rarely integrate biodiversity issues [44]. There is a need for a systemic approach that combine the main sustainability aspects of wind power development in order to quantify and visualize the wind energy potential in a comprehensive way, which would be necessary for use in well-informed policy discussions and to make sustainable and confident energy policy decisions.

1.4. Aims and objectives

This paper aimed to estimate and visualize the achievable technical onshore wind energy resource potential, in order to provide initial decision support for wind energy related policies and plans in Sweden. The technical wind energy potential represents the achievable wind energy generation after considering the wind turbine performance data, and topographic, environmental and other land use restrictions. Therefore, in order to estimate the technical onshore wind energy potential in Sweden, two restriction scenarios were developed and applied based on current national and municipal wind power plans as well as on the state of the art literature on wind farm localization. This study was intended to be useful for policy makers and municipalities for wind power development in Sweden. Focusing on specific wind power constraints, this study provides a initial step towards a systemic approach to estimate and visualize the preliminary technical wind energy potential available in each Swedish county and in the electricity bidding zones.

2. Materials and methods

2.1. Study area

The north European country Sweden has favorable wind conditions [45], especially in the mountains and along the coast, and was considered as a study area in this analysis. Forest covers two-thirds of the land surface and the lakes and wetlands are numerous [46]. In Sweden, there are 21 counties and 4 electricity bidding zones having 5,28,447 km^2 of total land area. The country is thinly populated especially in the northern region, its built-up areas and agricultural land represent a small proportion of the land surface but regional differences are significant, since urban areas and infrastructure are concentrated towards the southern part and to the coasts. However, single residential houses are scattered widely throughout large parts of the rural areas. Furthermore, large parts of the mountains and coastline have not only favorable wind conditions, but also contain large areas of high nature, culture and recreation values.

2.2. Methodology

The methodological steps used in this paper are shown in Fig. 2. The yearly average wind speed data at 90 m height was provided by the Swedish Energy Agency (SEA) [47]. In this paper, the total land area of 4,35,000 km^2 (equivalent to 435 thousands of 1 km $\times$ 1 km sized grid cells) was considered for the assessment of the wind energy potential in Sweden. The wind speed distribution curve was calculated for all 1 km $\times$ 1 km sized grid cells using Rayleigh distribution and modeled annual average wind speed. The Rayleigh distribution curve provides the frequency of occurrence of a particular wind speed reading at a given site. In order to determine the annual wind energy production and capacity factor of each grid cell, Rayleigh wind speed distribution curve was used along with the power curve of a Vestas-112 wind turbine (V-112) having 90 m hub height and 3 MW rated power. In this paper, grid cells with a capacity factor greater than 20% or with an average wind speed greater than 4.8 m/s at hub height were taken into account and exported to GIS for visualization of the wind energy potential [48]. Initially this study provided the theoretical wind energy potential of Sweden, which was then reduced to the technical potential. According to [49] and [50], the technical wind energy potential represents the achievable energy generation of a particular technology by considering the system performance, topographic limitations, as well as environmental and land use constraints. Therefore, the technical wind energy potential available in Sweden was calculated by considering a wind turbine spacing factor, array losses, exclusion of highly sloped and elevated areas, and also by considering Restriction Scenarios 1 and 2 related to Swedish wind power policy and planning. At the end GIS was used to calculate the technical wind energy potential available in each 1 km $\times$ 1 km sized grid cell throughout the land area of the 21 Swedish counties as well as of the four bidding zones. All spatial analyses were performed using ArcGIS 10.2 (ESRI 2011) [84].

2.3. Wind speed and spatial data layers

The spatial data layers used to create the Restriction Scenarios 1–2, and to estimate the wind energy potential in each Swedish county and bidding zone are mentioned in Tables 1 and 2. Initially, a spatial data set of annual average wind speed with 1 km $\times$ 1 km resolution throughout the land area of Sweden was obtained from SEA [47]. This annual average wind speed data set for Sweden was derived with the help of a three-dimensional meso-scale higher-order numerical model developed at the Meteorological Institute of Uppsala University (MIUU) in Sweden; aiming to investigate the wind climate in Sweden [51]. The meso-scale high order numerical models are used to predict the annual average wind speed and other weather phenomena having a horizontal grid reolution ranging between 1 km $\times$ 1 km–10 km $\times$ 10 km [52,53]. The MIUU-model is capable of mapping the annual average wind speed resources having resolutions between 0.5 and 10 km, using input data such as geostrophic wind (strength and direction), sea and land temperatures, topography, and roughness. In the MIUU-model, a technique of modeling a set of samples of the meteorological conditions leading to the wind climate at heights of interest for wind speed was used. In order to check the credibility of the modeled annual average wind speed data estimated by the MIUU-model, the correlation between the annual average wind speed data obtained from the model and 116 observation sites was calculated by the authors of Ref. [51]. The average difference between modeled and observed annual average wind speed was found to be less than -0.03 m/s at 105 observation sites. This demonstrates the accuracy of wind speed data derived from the MIUU model [51]. However, some marginal differences were found for 11 wind speed observation sites. Those 11 wind speed observation site were located in terrain with small-scale variability in topography, which could not be adequately represented by the MIUU-model with its 1 km $\times$ 1 km resolution. The detailed results of this correlation analysis performed by Ref. [51] are available in Appendix A (Fig. 12).

The distribution of the modeled annual average wind speed data (publically available at SEA) can be seen in Fig. 3, whereas different types of areas that could constitute restrictions to wind energy development in Sweden are illustrated by Fig. 4.

2.4. Restriction criteria

The total land area available for the installation of onshore wind energy potential in Sweden was estimated using two restriction scenarios which are described below. The buffer zone limits used

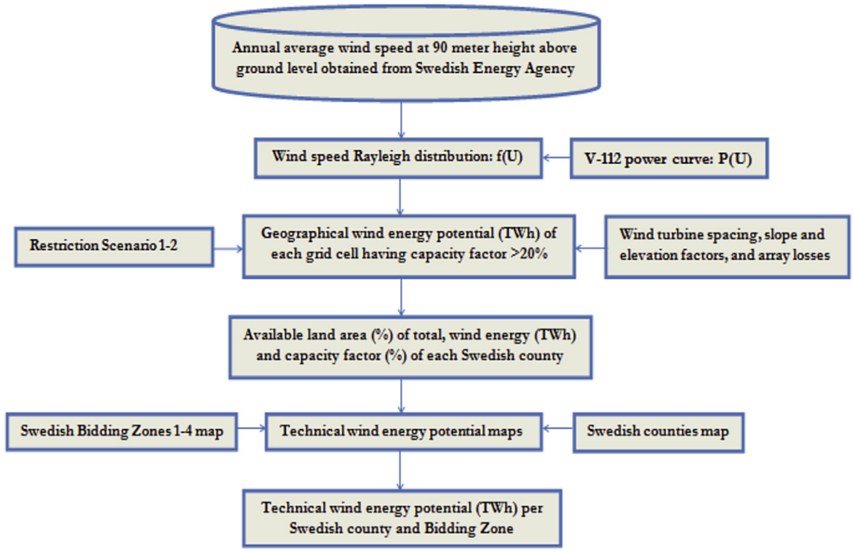

Fig. 2. Methodology flowchart.

Table 1
List of spatial data layers used in this study.

Geospatial data	Data source
Wind speed data	[47].
Elevation	[54].
Swedish counties	[55].
Swedish bidding zones	[56].

for Restriction Scenarios 1 and 2 are mentioned in Table 2. Finally, on the basis of the buffer zone limits, GIS was used to prepare the restriction maps for Restriction Scenarios 1 and 2 showing the percentage of land area available in each 1 km × 1 km grid cell throughout Sweden. The buffer zone limits mentioned in Table 2 were derived from a review of wind power plans evaluated by Ref. [37].

2.4.1. Restriction Scenario 1

In this restriction scenario, shoreline protection zones, urban areas with buffer zones, defense areas as well as safety zones to infrastructure were considered for exclusion. No consideration was given to the biodiversity and ecosystem services related to protected areas and areas of national interest for nature, culture or recreation values, nor related to single residential houses and churches. The distribution of Restriction Scenario 1 can be seen in Fig. 4a.

2.4.2. Restriction Scenario 2

In this restriction scenario, not only the restrictions mentioned in Restriction Scenario 1 were taken into account, but also protected areas, areas of national interest for nature, culture and recreation values, and buffer zone limits to single residential houses and

Table 2
Buffer zone limits used for restriction scenarios 1 and 2.

Restrictions	Buffer zone	Restriction scenario 1	Restriction scenario 2	Source
National roads	200 m	Yes	Yes	[57].
Railroads	200 m	Yes	Yes	[54].
Electricity grid (national and regional)	200 m	Yes	Yes	[54].
Airports (LFV)	2500 m[a]	Yes	Yes	[54,58].
Military zones	–	Yes	Yes	[55].
Lakes, watercourses and shorelines	100 m	Yes	Yes	[59].
Urban areas	1000 m	Yes	Yes	[54].
Single residential houses and churches	500 m	No	Yes	[54].
Protected areas	–	No	Yes	[60].
Areas of national interest for nature, culture and recreation values	–	No	Yes	[55].

[a] Within 55 km of range consultation is required.

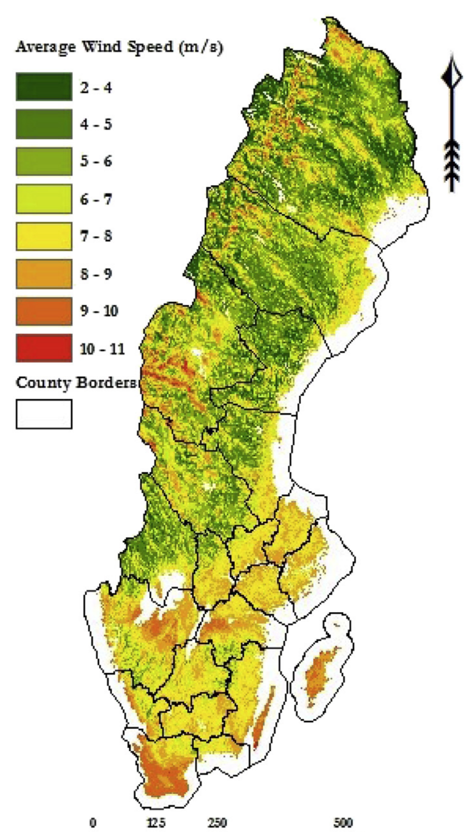

Fig. 3. Modeled annual average wind speed of the study area (i.e. the land area of Sweden) at 90 m height estimated by the MIUU-model (m/s), spatial data is publically available at the Swedish Energy Agency [47].

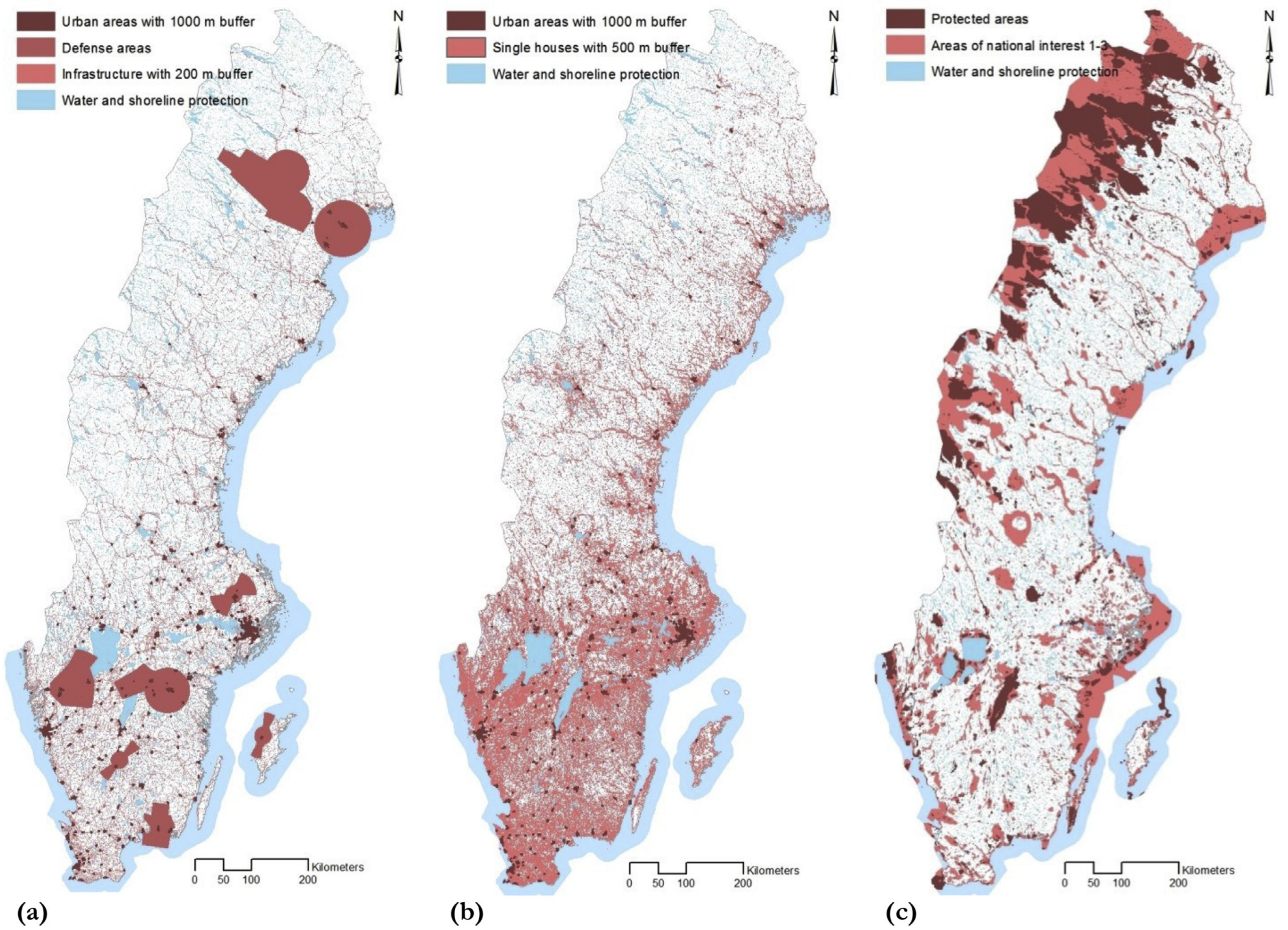

Fig. 4. (4a) Urban areas with buffer zones, defense areas and safety zones to infrastructure, (4b) urban areas and single residential houses and churches with buffer zones, and (4c) protected areas and areas of national interest for 1) nature, 2) culture and 3) recreation values, spatial data (c) Lantmäteriet [i2012/920] [54] and [55].

churches. The distribution of Restriction Scenario 2 can be seen in Fig. 4b and c. According to a more recent national plan for wind power [13], the minimum permissible area for onshore wind power in Sweden is set to 5 km^2 for Bidding Zones 1, 2 and 3. For Bidding Zone 4, which is the most densely developed part of the country; this value is set to 3 km^2. Therefore, keeping in view these regulations, the available land area obtained by Restriction Scenario 2 was further refined by considering the grid cells having clusters of at least 3 km^2 out of the grid cells having 60% and 80% land availability and lying within 10 km range of national and regional electric grid lines, for each county. In the next step, in order to get the most refined available land area, the grid cells making at least 5 km^2 clusters of grid cells having 80% land availability and lying within 10 km of national and regional electric grid lines were quantified for each bidding zone.

2.4.3. Additional exclusions

Apart from Restriction Scenario 1 and 2, some additional exclusion related to wind energy installation were also taken into account in order to get more realistic wind energy potential of Sweden:

- *High elevation areas*: Areas with elevations higher than 2000 m were excluded from this analysis, because of their higher transportation and transmission costs and their lower air density [48,61,62].
- *Steep slope areas*: Further, areas having ground slopes greater than 15° were excluded. The reason is that steeper slopes give rise to stronger wind flow, but on the lee side of ridges steeper slopes also give rise to high turbulence [48,61,62].

2.5. The wind energy assessment process

In this section, it is explained how average wind speed available at each grid cell was processed in order to get the yield of yearly wind energy potential in a single grid cell with the size of 1 km × 1 km.

2.5.1. Wind speed distribution

The wind speed distribution provides the frequency of occurrence of a particular wind speed at a location. Most of the time, for wind energy assessment at a location, Weibull distribution is used with hourly wind speed data obtained from specific wind speed observation sites located there. However, the wind speed observation sites are located many kilometers away from each other throughout the land area of the country [52,63]. Therefore, hourly wind speed data obtained from those scattered wind speed observation sites cannot be used directly to estimate the Weibull parameters and the wind energy potential available in each 1 km × 1 km sized grid cell throughout the land area of a country, for GIS-based studies. Consequently, in order to assess the preliminary wind energy potential at this resolution, the modeled annual average wind speed of each grid cell plays a key role. But still there is no straightforward method available to estimate the Weibull parameters using annual average wind speed for wind energy assessment [64]. In such circumstances, according to [38,64–67], in the presence of the modeled annual average wind speed of each grid cell, a modified form of the Weibull distribution, i.e. the Rayleigh distribution with the shape factor k = 2, can be used to estimate the preliminary wind energy potential on county or country level in GIS-based studies. The variability of the wind speed at any location is shown by the dimensionless shape factor (k-value) ranging from 1.5 to 3, where lower k-value shows more variation in wind speed at given site. In this paper, we also used the Rayleigh distribution over the modeled annual average wind speed data of each 1 km × 1 km sized grid cell throughout the land area of Sweden produced by the MIUU-model. The standard formula of the Rayleigh distribution is [68]:

$$f(U) = \frac{\pi}{2}\cdot\frac{U}{U_{mean}^2}\cdot\exp\left\{-\frac{\pi}{4}\left(\frac{U}{U_{mean}}\right)^k\right\}$$

where f(U) is the probability of occurrence of a specific wind speed reading, U is wind speed reading 1–25 m/s with an interval of 1 m/s and U_{mean} is the average wind speed of a single grid cell, and k is the dimensionless shape factor equal to 2.

2.5.2. Wind energy calculation

In this paper, we used the Vestas-112 wind turbine (V-112) for the wind energy assessment. The detailed characteristics of V-112 wind turbines are mentioned in Table 3. The power output of the wind turbine changes with variations in the wind speed, therefore manufacturers provide a power curve of each wind turbine as a function of wind speed. The power curve helps in predicting the wind energy production of a wind turbine. The power curve of the V-112 wind turbine and the wind speed Rayleigh distribution of a sample grid cell are shown in Fig. 5. The power curve was multiplied with the wind speed Rayleigh distribution of a single grid cell to estimate the expected wind power production of a single grid cell, and finally this process was repeated for each grid cell in the study area. The expected power production by a single V-112 wind turbine in a single grid cell was calculated by using the equation [39]:

$$P_{expected} = \int_{U=0}^{U=cut_{out}} P(U)\cdot f(U)dU \approx \sum_{\text{wind class}} P(U)\cdot f(U)$$

where $P_{expected}$ is the wind power output of a single Vestas-112 wind turbine in MW, U is the wind speed from 1 to 25 m/s with an interval of 1 m/s, P(U) is the power curve of the V-112 wind turbine as a function of wind speed at a given hub height, and f(U) is the probability of occurrence of a specific wind speed U.

The expected yearly wind energy production of a single grid cell was calculated by introducing the wind turbine availability factor and the total number of hours of a year into the wind power equation. The wind turbine availability factor is the percentage of time that a wind turbine is available or capable to produce electricity from the wind. The availability factor of modern wind turbines now ranges from 96% to 99%, in our study we used 96% availability, as it was used by Ref. [69] and [70]. Theoretically a wind turbine could be available for 100% of the operation time. However, some time of the year could be used for scheduled maintenance and inspections which could take up 1–4% of the available operating time [71]. The final formula used for the calculation of yearly wind energy production of a single grid cell is written as [39]:

$$E_{expected} = \mu\cdot T \int_{U=0}^{U=cut_{out}} P(U)\cdot f(U)dU \approx \mu\cdot T \sum_{\text{wind class}} P(U)\cdot f(U)$$

where $E_{expected}$ is the wind energy production of a single Vestas-112 wind turbine in MWh, U is the wind speed from 1 to 25 m/s with an interval of 1 m/s, μ is the availability factor of the wind turbine in %, which is assumed to be 96% in this study, and T is the total time in hours available in a year.

Table 3
Specifications of the Vestas-112 wind turbine.

Specification type (unit)	Quantity
Rated power output (kW)	3000
Hub height (m)	90
Rotor diameter (m)	112
Swept area (m^2)	9852
Cut in speed (m/s)	3
Rated wind speed (m/s)	12
Cut out speed (m/s)	25
Operating temperature range (°C)	−20–40

2.5.3. Capacity factor calculation

The capacity factor of a wind turbine is defined as the ratio of the expected wind energy production to the wind energy production by the wind turbine at its rated power during a given time period [70]. The expected wind energy production and the rated power of a single Vestas-112 wind turbine were used to calculate the expected capacity factor of a single grid cell. It is used as a performance indicator of a wind farm and it can be used for comparing different sites before installation of wind farms. The expected capacity factor was calculated by the formula [39,70]:

$$CF_{expected} = \frac{E_{expected}}{P_{rated} * T} * 100$$

where $CF_{expected}$ is the expected capacity factor, $E_{expected}$ is the expected wind energy production in (MWh) after considering the total losses in electricity production and availabilty factor, P_{rated} is the rated power of a V-112 wind turbine equal to 3 MW and T represents the total number of hours in a year, which is equal to 8760 h.

2.5.4. Wind turbine spacing

The wind turbine spacing is also an important parameter to keep in mind while deciding the number of wind turbines to be installed in a grid cell having the dimensions 1 km × 1 km. In the large scale, wind power plants wake effect reduces the wind speed, which consequently causes reduction of power output of down-wind turbines which are installed at some distance behind the initial wind turbine [72]. Therefore a proper distance between wind turbines should be decided to get a decent compromise between grid connection costs and wake effects. Recent studies have shown that if wind turbines are spaced at the distance of 4D to 8D (D = Rotor Diameter) from each other, then the power losses taking place due to wake effects can be in the range of 5%–15% of the total power produced by the wind farm [73]. In this study, spacing criteria used for the Vestas-112 wind turbines was 10D in the prevailing wind direction and 5D in the crosswind direction [39].

2.5.5. Slope factor

According to [74], the number of installed wind turbines depends on the terrain slope. In this study terrain slope up to 15° were considered suitable for wind turbine installation. The influence of the slope was kept in mind during the wind energy calculations; in this study we used the capacity of 5 MW per km^2 for slopes between 0° to 3°, 3 MW per km^2 for slopes between 3° to 5° and 2.5 MW per km^2 for slopes between 5° to 15°.

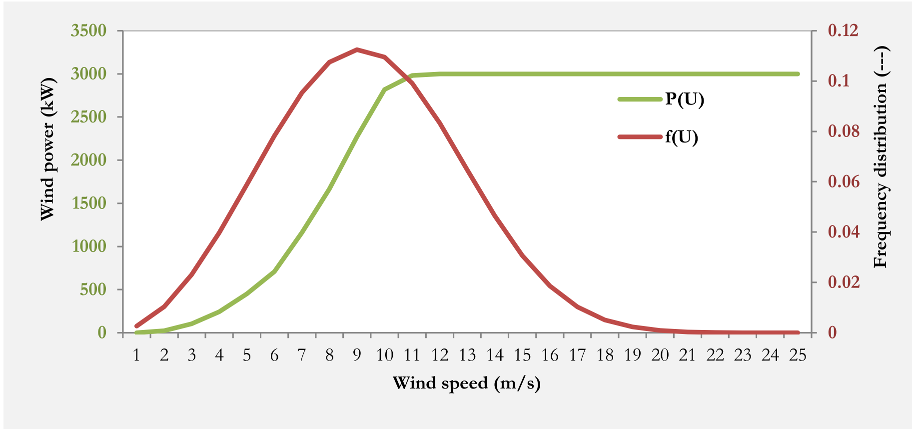

Fig. 5. Power curve of a V-112 wind turbine and the wind speed Rayleigh distribution of a sample grid cell.

2.5.6. Array losses

The array losses were also taken into account since they play a significant role in the annual energy yield of a wind farm. Array losses depend on the space between wind turbines and the nature of the wind regime as well as on the number of turbines, the size of the wind farm and the frequency distribution of the wind direction [70,75]. In this paper we considered 10% array losses [71].

3. Results and discussion

In this section, results concerning the land area available for wind energy, as well as the wind energy potential of each county and bidding zone considering Restriction Scenario 1 and 2 are presented and discussed.

3.1. Land area available for wind energy

The distribution of land area availability in Sweden for wind energy installations on the basis of Restriction Scenario 1 and 2 is shown in Fig. 6. The details of the land area availability in each county on the basis of Restriction Scenario 1 and 2 is tabulated in Appendix B (Tables 4 and 5). For each county, results showing the available land area provided by grid cells clusters of at least 3 km^2 out of grid cells having 60% and 80% land availability on the basis of Restriction Scenario 2, and lying within 10 km range of national and regional electric grid lines, are tabulated in Appendix B (Table 6). Furthermore, for Bidding Zones 1–4, results showing the percentage of available land area, given by grid cells making at least 5 km^2 clusters out of grid cells having 80% availability within 10 km of the grid lines, are tabulated in Appendix B (Table 7). In Table 7, it can be observed that overall Bidding Zones 1 and 2 have higher availability of land area as compared to Bidding Zones 3 and 4.

On a national level, Restriction Scenario 1 and 2 excluded approximately 35% and 69% of the Swedish land area respectively as shown in Fig. 7. In this figure, the percentage share of exclusion by the buffer zone limits for single houses, protected areas, and areas of national interest for nature, culture and recreation values are also illustrated separately for each bidding zone. According to Fig. 7, Bidding Zone 4, which is the smallest bidding zone in the most southern part of Sweden, has the highest amount of excluded areas, up to 80% according to Restriction Scenario 2. The major part of the excluded areas in Bidding Zone 4 on the basis of Restriction Scenario 2 was due single residential houses, which excluded up to 70% of the zone, followed by 22% excluded areas, partly overlapping, due to protected areas and areas of national interest for nature, culture and recreation. In Bidding Zone 4, a low amount of excluded areas was due to protected areas (4.8% of the zone). This zone contains the city of Malmö and other urban areas, but even with the 1000 m buffer zone to urban areas, those excluded only 4.5% of this zone.

Bidding Zone 3 is likewise quite developed as it contains some major urban centers, such as the Stockholm region, Gothenburg and Uppsala. Also here, relatively large part of the excluded areas on the basis of Restriction Scenario 2 was due to single residential houses with 500 m buffer, which excluded up to 54% of the zone area as shown in Fig. 7. In Bidding Zone 3, the protected areas, areas of national interest for nature, culture and recreation together excluded around 24% of the zone area, where as protected areas individually excluded up to 7% of this zone.

Bidding Zones 1 and 2 in the north had excluded areas of 11% and 20% respectively due to single houses with 500 m buffer, while urban areas with 1000 m buffer zones covered as low as 0.4 and 0.5% of the zone area, respectively. Even though there are cities and towns also present within these zones, they have much lower population than Bidding Zones 3 and 4 in the south. Bidding Zones 1 and 2 also have much higher shares of protected areas as well as of areas of national interest for nature, culture and recreation values as shown in Fig. 7.

Restriction principles which have significant implications on the availability of land area for wind energy development were related to biodiversity and ecosystem services. From a national perspective, these issues could be represented by protected areas as well as by areas of national interest for nature, culture and recreation values. The latter cover large areas and they were sometimes excluded from wind energy development in the municipal wind power plans [76], which could be seen as an adaption to local conditions. Yet, their lower protection status means that their land use should be weighed against other interests in the planning process, which in other parts of the country may open some of these areas for wind energy development. By contrast, according to [76], it was not uncommon among Swedish municipalities to consider also protected areas for wind power development, under certain circumstances, depending e.g. on what the purpose of the protection status was. However, according to the final version of the areas of national interest for wind power [11], protected areas were not considered for wind power development. Also from an international perspective, protected areas are most often avoided, and even a buffer zone approach is commonly applied to these, such as the 300 m distance mentioned in Ref. [17,43].

Outside of protected areas, the areas of national interest for nature conservation should represent biodiversity values but have as mentioned a weaker protection status. In addition, there are areas with high biodiversity values that do not necessarily have any protection at all, but would at best be recognized by national, regional or local inventories and/or plans on a national level [77]. In

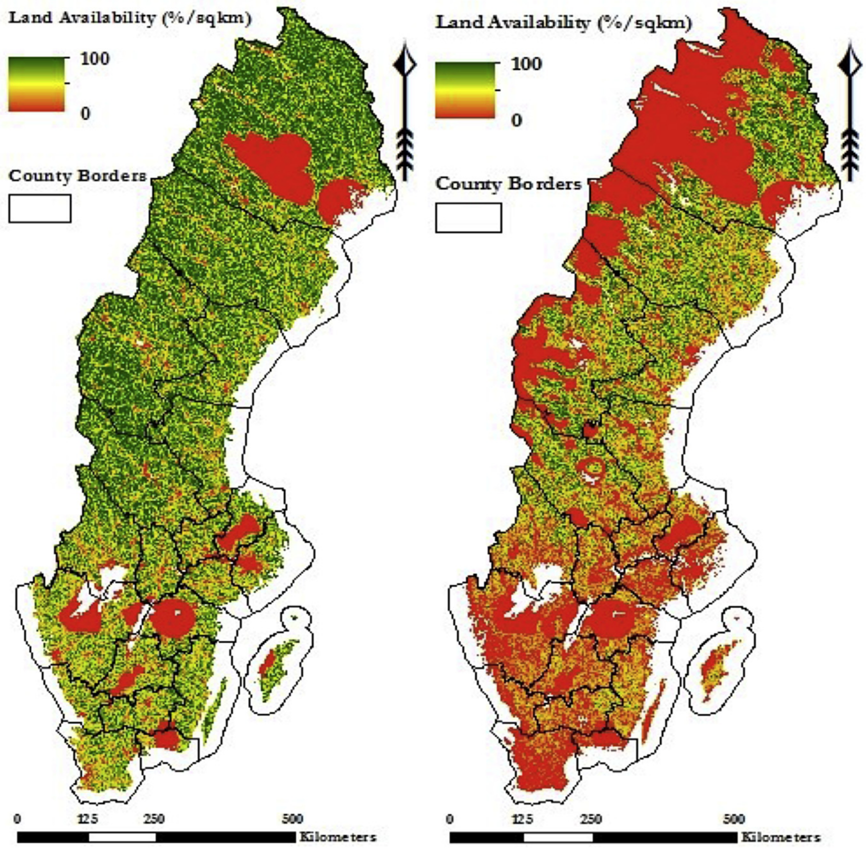

Fig. 6. Availability of land area in each grid cell on the basis of Restriction Scenario 1 (left) and Restriction Scenario 2 (right).

the Swedish municipal wind energy plans, those were considered to some extent, based on their compatibility with wind power development [76]. Moreover, areas of national interest for culture and recreation values and also the buffer zones to single houses can be considered to represent cultural ecosystem services, including scenic values, tourism, cultural and historical landscapes. In the current study, it was observed that at the same time these areas often cover large territories which coincide with areas of high wind speed to a significant extent, see the red regions in Figs. 4 and 7.

3.2. Wind energy potential

The average wind energy capacity factor of each Swedish county is presented in Fig. 8. It was found that counties like Gotland, Kalmar and Blekinge located in the southern part of Sweden were leading in average capacity factor with 37%, 31% and 29% respectively. Counties like Norrbotten, Västerbotten and Jämtland län, located in the northern part of Sweden, possessed the average capacity factor of 19%, 20% and 25%, respectively. According to the results, the overall estimated average wind energy capacity factor in Sweden was 28%, which is in line with the overall average capacity factor in Sweden as reported by the International Energy Agency (IEA), which was 26% [78]. High capacity factors in the range of 37% and 35% were achieved for Gotland and Skåne Counties, respectively. Being an island in the Baltic Sea, Gotland County is characterized by a an annual average wind speed of 7–9 m/s at 90 m height. Skåne County, which is located in the southern far end of Sweden is characterized by an annual average wind speed of 6–8 m/s at the same height. These high capacity factor calculations of Gotland and Skåne counties are in line with previous studies, in which the authors estimated capacity factors up to 35% at

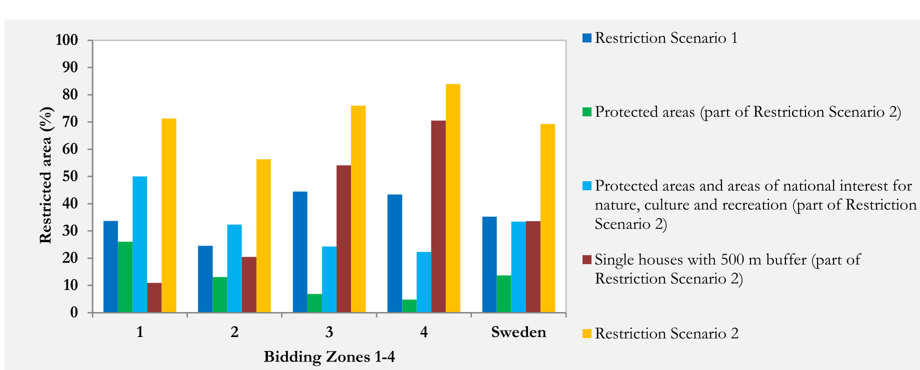

Fig. 7. Area covered by restricted areas per bidding zones and for the entire country, according to Restriction Scenarios 1 and 2. The restricted areas of different kinds were in many places overlapping.

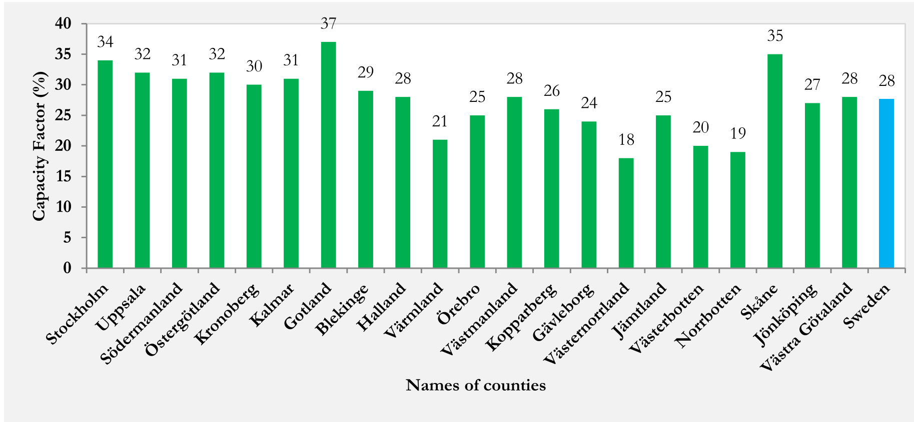

Fig. 8. Average capacity factor for wind power for each Swedish county (%).

locations having average yearly wind speeds of 7 m/s, in other parts of the world [67,79–80].

The spatial distribution of wind energy potential in each 1 km × 1 km grid cell throughout Sweden is shown in Fig. 9. The total wind energy potential in each county is tabulated in Appendix C (Table 8). It was estimated that without any restrictions, the total wind energy potential in Sweden is up to 7440 TWh, while after considering the Restriction Scenarios 1 and 2, it was reduced to 2976 TWh and 1275 TWh respectively. In Table 8, it can be seen that despite lower capacity factors (see Fig. 8) the counties in the northern part of Sweden (i.e. Norrbotten, Västerbotten, Jämtland, Västernorrland and Kopparberg) had the highest wind energy potential. This is mainly due to the availability of larger land areas, with less excluded areas compared to the southern part of Sweden, see Appendix B (Tables 4 and 5) and Fig. 6. Correspondingly, the northern Bidding Zones 1 and 2, which cover these northern counties, were leading in wind energy potential. The total wind energy potential of Sweden was further reduced to 487 TWh and 205 TWh respectively, when the grid cells showing 60% and 80% land availability, making clusters of at least 3 km^2, within 10 km distance of regional and national electricity grids, were taken into account using Restriction Scenario 2, see Figs. 10 and 11. The total wind energy potential of Sweden was further reduced to 190 TWh, when the grid cells making clusters of at least 5 km^2 and lying within 10 km of the national and regional electricity grids were taken into account; Appendix C (Table 9).

The wind energy potential of each bidding zone is plotted in Fig. 11. Bidding Zone 2 was leading in wind energy potential followed by Bidding Zones 1 and 3. Bidding Zone 4 seemed to have very limited wind energy potential due to a high amount of

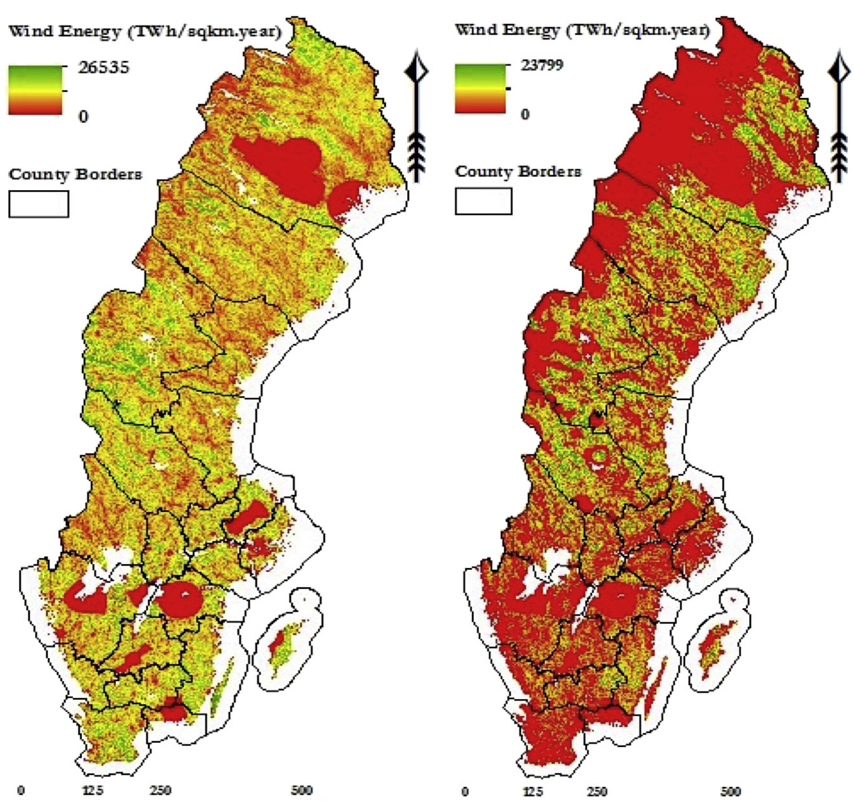

Fig. 9. Wind energy distribution in Sweden (TWh/sqkm.year) on the basis of Restriction Scenario 1 (left) and by Restriction Scenario 2 (right).

restricted land area. Bidding Zones 3 and 4 have much higher population as these zones contain the largest cities of the country, as compared to Bidding Zones 1 and 2. In Bidding Zone 4, the energy demand would be much higher due to high population and more urbanization. By contrast, in Bidding Zones 1 and 2 less energy demand can be expected due to the low population and less urbanization. The high wind energy potential of Bidding Zone 2, having higher proximity to the grid system and lower amount of restricted areas compared to Bidding Zone 1, can imply a promising situation for wind energy development in the future.

4. Discussion

The total unrestricted wind energy potential of 7440 TWh achieved is this study is comparable with previous estimations of the total unrestricted wind energy potential in Sweden, which was calculated to be around 5000 TWh by Ref. [65]. On the basis of Restriction Scenario 1, a total wind energy potential of 2976 TWh was achieved. Restriction Scenario 1 considered a minimum of general restrictions without considering biodiversity and ecosystem services, and it excluded approximately 35% of the total land area in Sweden. By contrast, on the basis of Restriction Scenario 2, a total wind energy potential of 1275 TWh was achieved. Restriction Scenario 2 excluded almost 69% of the total land area of Sweden by taking into account protected areas as well as areas of national interest for nature, culture and recreation values. The total restricted wind energy potential of 487 TWh achieved in this paper is very near to the previous assessment by Ref. [81], in which they estimated a total of 510 TWh of technical onshore wind energy potential available in Sweden. In their study, areas either unavailable for development or prone to different conflicts in development orientations where excluded.

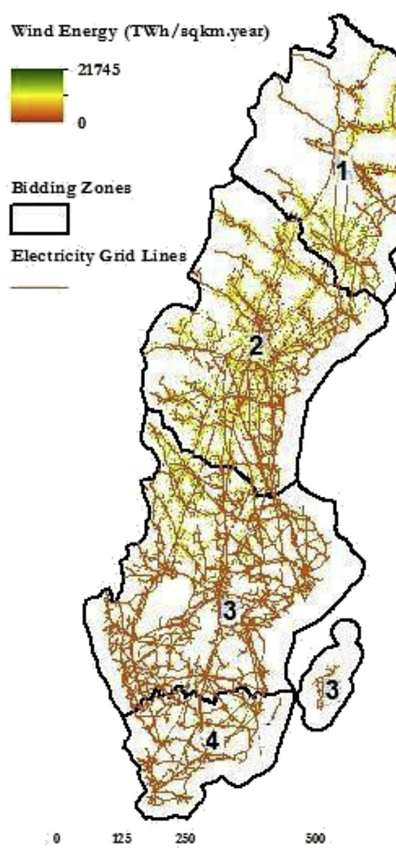

Fig. 10. Wind energy distribution in Sweden (TWh/sqkm.year) in grid cells with 80% land availability, in clusters of at least 3 km^2 and lying within 10 km of national and regional electric grids.

Sweden's total wind energy potential seems to be much greater than the national goal of 30 TWh by 2020, of which 20 TWh are from onshore and 10 TWh from offshore wind energy. Now keeping in view the available wind energy potential in Sweden, the capacity of the national and regional grid system to integrate the variable wind energy source on large scale may be of great importance in future studies. According to a study by Ref. [82], up to 45 TWh of wind energy would be possible to integrate into the Swedish grid system, using hydropower for storage and regulation. Thus, the power output of wind power plants is always stochastic [2,3] and this must be kept in mind while considering its large-scale integration. Furthermore, in order to get a more large-scale penetration of the variable wind energy resource in the Swedish energy system, other energy storage technologies such as compressed air, hydrogen production and pumped hydro could be considered as possible options.

The GIS-based approach used in this paper outlined potential and favorable areas where it could be technically and environmentally feasible to launch wind power projects. The results of the study would obviously differ with different wind energy policy and planning practice, due to e.g. variation of buffer zone limits for urban areas, single houses and infrastructure, as well as treatment of areas of importance for biodiversity and ecosystem services with and without protection status, etc., and these can cause substantial variations in the final results [17,43]. However, while planning for wind power installations, the results can guide in the localisation of new areas where investment in wind energy can give good profit and progress. As wind energy site selection is time consuming and also a costly step, the results presented in this study can provide information essential for site selection keeping in view some environmental constraints related to biodiversity and ecosystem services in Sweden. The county based wind energy potential estimated in this paper with the help of the modeled annual average wind speed and Rayleigh distribution is a preliminary step, which can be used to locate potential places for wind energy installation in Sweden. However, before launching any wind power plant at any area of interest, it is necessary to thoroughly assess the environmental impacts as well as to install wind speed observation instruments to record the long term hourly wind speed data, which can be used for more precise estimation of Weibull parameters and wind energy at those sites.

The results obtained in this paper are preliminary, which can change in the future on the basis of variations in the restrictions to wind energy installations. In the future, in order to achieve more precise estimations of the wind energy potential in Sweden, the use of high resolution modeled average wind speed data alongwith high resolution modeled k-values of each grid cell would be of great importance, which was also pointed out by the authors of the MIUU-model [51]. Moreover, more detailed spatial assessments of biodiversity and ecosystem services concerns can be obtained, for instance for areas with weak or no protection, using GIS-based ecological models [83].

To promote a sustainable wind energy development in Sweden, the policy instruments should contain objectives which can ensure a certain amount of success in target achievement related to wind energy projects. The development pace of the available wind energy potential on community level would depend on the willingness of local people to harness the wind energy at local scale. In this regard, development of proper policy incentives can play a main role; otherwise strong opposition of local communities can delay the launch of new wind energy projects in Sweden. Another main issue is the capacity of local grids to absorb the variable wind energy on a large scale, therefore in the future studies presenting different forecast scenarios related to large scale integration of wind energy would be of great importance.

In future studies, this wind energy resource mapping could further be connected with the economic analysis of wind generated electricity

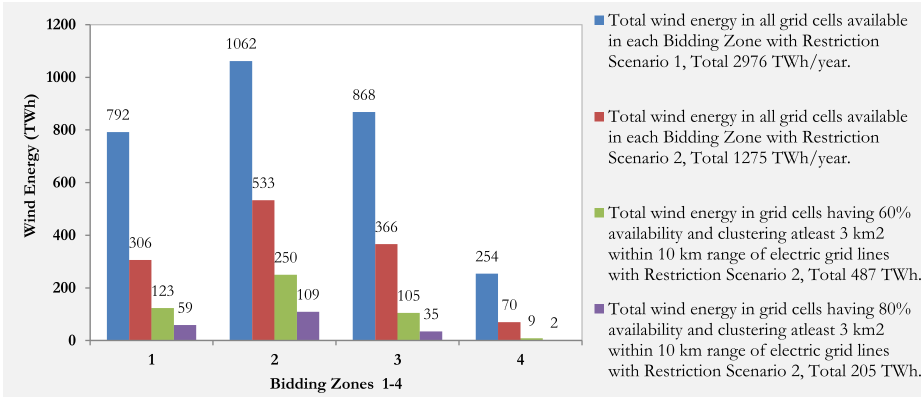

Fig. 11. Total wind energy (TWh) potential available in each bidding zone on the basis of Restriction Scenario 1–2 and by considering the grid cells making at least 3 sqkm clusters with at least 60% and 80% land availability.

in each county and bidding zone, which would allow exploration of the expected economic feasibility of wind energy. In this paper, we used only the V-112 wind turbine for wind energy assessment, however in future studies for economic analyses, different types of wind turbines can be used and detailed results can be compared.

The present wind energy capacity in Sweden is 10 TWh, which is far behind the available wind energy potential achieved by this study. The wind energy growth in Sweden is slow as compared to other countries in the European Union, and possible reasons behind this could be conflicting sustainability goals and lack of public acceptance of wind energy, which issues can be addressed through development and implementation of appropriate policy and planning support. Therefore, results obtained in this study as well as the methodology, that can be applied to emerging scenario discussions, could help guide authorities with the sustainable integration of wind energy into the Swedish energy system. The GIS-based scenario approach opens up for analysis of wind energy options in policy and planning, which can integrate technical, environmental and economic analyses for sustainable wind energy development.

5. Conclusions

In this paper, the onshore wind energy potential available in Sweden was estimated, by applying two restriction scenarios related to environmental and land use constraints, and technical criteria related to wind energy installations. Additionally, in this paper by using a GIS-based approach we presented a straightforward way to find potential sites for wind energy installations throughout the land area of Sweden. The results could be a guide for large scale wind energy installations even in those geographical places where physical meteorological stations do not exist. It was estimated that up to 69% of the total land area was excluded due to the constraints given by biodiversity and ecosystem services, in the form of areas of national interest for nature, culture and recreation values, as well as single houses with buffer zones. At the end, the most refined wind energy potential of 190 TWh was obtained.

The results of this paper would differ with wind energy planning practice due to variation of buffer zone limits for urban areas, single houses and infrastructure, as well as treatment of nature areas, etc., and these can cause substantial variations in the final results. Furthermore, site-specific environmental impacts have to be carefully considered. Still, the results as well as the methods presented in this study can be very useful for decision makers and intended investors of wind energy projects. Using these results, decision makers can set different parameters related to exclusion zones, in order to analyze their impact on the environment and the wind energy yield in specific regions and in the country. In short, the GIS-based scenario approach opens up for analysis of wind energy options in policy and planning, which can integrate technical, environmental and economic analyses for sustainable wind energy development.

Acknowledgments

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Appendix A. Results of correlation between annual average wind speed measured by the MIUU-model and observation sites, according to [51].

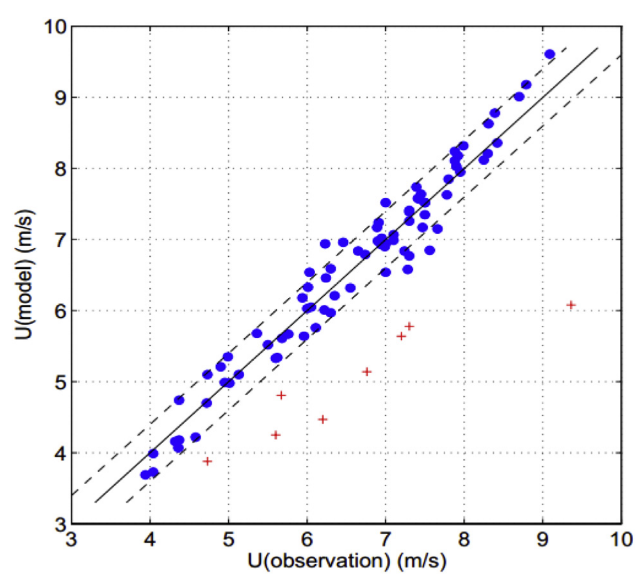

Fig. 12. Results of correlation between modeled and observed annual average wind speed at the selected observation sites. Sites marked with blue color bullets have shown the difference of −0.03 m/s, whereas sites marked with red color '+' have shown the marginal difference and are located in terrain having a topographical variability on smaller scale (Taken from Ref. [51]).

Appendix B. Results of land area available for wind energy.

Table 4
Land area distribution of each county in terms of (%) of the total area on the basis of land availability (0–100%), using Restriction Scenario 1. The total area of all counties is 435000 km^2.

	Availability	(0–20%)	(20–40%)	(40–60%)	(60–80%)	(80–100%)
County/län	Total area (km^2)	Area (%)	Area (%)	Area (%)	Area (%)	Area (%)
Stockholm	6428	19	9	15	22	35
Uppsala	7125	36	5	9	16	34
Södermanland	6516	8	10	19	25	38
Östergötland	11,434	44	5	9	15	27
Kronoberg	9140	9	8	16	26	41
Kalmar	11,465	3	6	15	26	50
Gotland	3098	20	4	10	21	45
Blekinge	2937	50	7	13	14	16
Halland	5641	4	8	18	28	42
Värmland	19,325	4	8	13	22	53
Örebro	9229	6	8	16	25	45
Västmanland	6589	6	8	14	25	47
Kopparberg	30,104	2	4	10	18	66
Gävleborgs	19,519	3	6	11	20	60
Västernorrland	22,964	2	5	11	21	61
Jämtland	53,237	2	4	8	17	69
Västerbotten	58,832	1	4	9	20	66
Norrbotten	104,028	18	2	6	12	62
Skåne	11,155	8	11	20	26	35
Jönköping	11,223	17	9	16	24	34
Västra Götaland	25,001	23	8	15	22	32

Table 5
Land area distribution of each county in terms of (%) of total area on the basis of land availability (0–100%), using Restriction Scenario 2. The total area of all counties is 435000 km^2.

	Availability	(0–20%)	(20–40%)	(40–60%)	(60–80%)	(80–100%)
County/län	Total area (km^2)	Area (%)	Area (%)	Area (%)	Area (%)	Area (%)
Stockholm	6428	63	19	10	5	3
Uppsala	7125	59	15	11	8	7
Södermanland	6516	59	25	10	4	2
Östergötland	11,434	65	17	10	5	3
Kronoberg	9140	38	29	18	10	5
Kalmar	11,465	35	27	20	12	6
Gotland	3098	49	22	15	8	6
Blekinge	2937	85	12	3	0	0
Halland	5641	53	25	14	6	2
Värmland	19,325	25	20	18	16	21
Örebro	9229	36	23	17	14	10
Västmanland	6589	33	24	18	13	12
Kopparberg	30,104	26	12	15	18	29
Gävleborgs	19,519	22	15	17	20	26
Västernorrland	22,964	17	13	15	20	35
Jämtland	53,237	37	9	11	15	28
Västerbotten	58,832	26	10	14	18	32
Norrbotten	104,028	60	5	6	8	21
Skåne	11,155	77	16	5	1	1
Jönköping	11,223	46	28	16	6	4
Västra Götaland	25,001	68	18	8	4	2

Table 6
Percentage of land area available in each county, for grid cells with a land availability up to 60% and 80%, and making 3 km^2 clusters within 10 km of national and regional electric grids, using Restriction Scenario 2. The total area of all counties is 435000 km^2.

County	Total area (km^2)	Percentage of land area given by grid cells with 60% land availability in clusters of 3 km^2	Percentage of land area given by grid cells with 80% land availability in clusters of 3 km^2
Stockholm	6428	0	1
Uppsala	7125	14	3
Södermanland	6516	2	0
Östergötland	11,434	4	1
Kronoberg	9140	8	2
Kalmar	11,465	9	2
Gotland	3098	11	2
Blekinge	2937	0	0

Table 6 (*continued*)

County	Total area (km^2)	Percentage of land area given by grid cells with 60% land availability in clusters of 3 km^2	Percentage of land area given by grid cells with 80% land availability in clusters of 3 km^2
Halland	5641	3	0
Värmland	19,325	36	13
Örebro	9229	19	4
Västmanland	6589	24	6
Kopparberg	30,104	53	22
Gävleborg	19,519	54	17
Västernorrland	22,964	80	33
Jämtland	53,237	55	27
Västerbotten	58,832	57	33
Norrbotten	104,028	32	27
Skåne	11,155	1	0
Jönköping	11,223	3	0
Västra Götaland	25,001	2	0

Table 7
Percentage of land area available in each bidding zone, considering grid cells having 60% and 80% land availability and clustering up to 3 km^2 and 5 km^2, lying within 10 km of national and regional grid lines, using Restriction Scenario 2.

Bidding zone	Percentage of total land area with 60% land availability in clusters of 3 km^2	Percentage of total land area with 80% land availability in clusters of 3 km^2	Percentage of total land area with 80% land availability in clusters of 5 km^2
1	33	25	13
2	53	26	18
3	17	6	4
4	3	1	0

Appendix C. Results of wind energy potential.

Table 8
Wind energy potential in each county using Restriction Scenarios 1 and 2, without considering distance to electric grid lines.

County/län	Total WE (TWh) without any restriction	Total WE (TWh) with Restriction Scenario 1	Total WE (TWh) with Restriction Scenario 2
Stockholm	145	34	9
Uppsala	158	37	16
Södermanland	140	45	10
Östergötland	238	46	17
Kronoberg	178	62	24
Kalmar	235	85	33
Gotland	77	22	8
Blekinge	57	10	1
Halland	109	37	9
Värmland	253	115	59
Örebro	175	65	29
Västmanland	136	50	25
Kopparberg	506	230	130
Gävleborg	326	140	83
Västernorrland	276	145	88
Jämtland	940	438	197
Västerbotten	936	450	246
Norrbotten	1600	690	231
Skåne	247	78	8
Jönköping	209	65	22
Västra Götaland	499	132	30
Sweden	7440	2976	1275

Table 9
Wind energy potential in each county, considering grid cells having 60% and 80% land availability, making clusters of at least 3 km^2 and 5 km^2 within 10 km range of national or regional electricity grids.

County/län	Total wind energy (TWh) in grid cells with 60% land availability in clusters of 3 km^2	Total wind energy (TWh) in grid cells with 80% land availability in clusters of 3 km^2	Total wind energy (TWh) in grid cells with 80% land availability in clusters of 5 km^2
Stockholm	1	0	0
Uppsala	4	1	1
Södermanland	1	0	0
Östergötland	2	0	0
Kronoberg	3	1	1

(*continued on next page*)

Table 9 (*continued*)

County/län	Total wind energy (TWh) in grid cells with 60% land availability in clusters of 3 km^2	Total wind energy (TWh) in grid cells with 80% land availability in clusters of 3 km^2	Total wind energy (TWh) in grid cells with 80% land availability in clusters of 5 km^2
Kalmar	4	1	1
Gotland	2	0	0
Blekinge	0	0	0
Halland	1	0	0
Värmland	22	8	8
Örebro	7	2	1
Västmanland	7	2	1
Kopparberg	57	22	20
Gävleborg	36	12	11
Västernorrland	50	23	21
Jämtland	96	42	39
Västerbotten	101	45	42
Norrbotten	90	46	44
Skåne	0	0	0
Jönköping	1	0	0
Västra Götaland	2	0	0
Sweden	487	205	190

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