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Spatial modelling of sustainable wind power development

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Referat

Spatiell modellering av hållbar vindkraftsutveckling
Martin Andersson

Åtgärder för att förhindra klimatförändring har aldrig varit en mer angelägen fråga än den är idag och den globala debatten om energisäkerhet, miljöförstöring och begränsade resurser har väckt intresset hos många världen runt att påverka beslutsfattare och ledare att titta på alternativa energikällor, förnybara källor. Svenska regeringen har som mål att göra hela sin inhemska elproduktion till 100 % återförnybar och fasa ut energiproduktion baserad på fossila bränslen helt till år 2040, där vindkraft till stor del kommer att bidra till det målet. Denna studie syftade till att översiktligt analysera var vindkraft är lämplig och inte lämplig att lokalisera med avseende på ekologiska, sociala och ekonomiska värden för hållbar utveckling.
För att göra detta genomfördes en multikriterieanalys baserad på metoden 'analytical hierarchy process' med förlängningen av att kombinera den med 'fuzzy triangular numbers'. Ekologiska värden sattes som skyddade områden ej lämpliga för etablering av vindkraft. Relevans av ekonomiska och sociala värden i förhållande till varandra differentierades genom att tillfråga fem sakkuniga yrkesutövare inom vindkraftsområdet att göra en parvis jämförelse mellan åtta olika faktorer. Denna jämförelse resulterade i relativa viktningar som illustrerar vikten av varje faktor. Dessa vikter fördes sedan in i en GIS-miljö där de modellerades för lämplighet tillsammans med områden som har formellt skydd och annan markanvändning vilket fungerade som begränsade områden i Ragunda kommun och Västernorrlands län. Olika scenarier modellerades som inkluderade eller inte inkluderade områden för renskötsel som ett begränsningsområde. De slutliga lämplighetskartorna jämfördes sedan med befintliga vindkraftverk samt områden av riksintresse för vindkraft i Sverige.

Resultaten visade att goda vindförhållanden var den mest framträdande faktorn att ta hänsyn till vid placering av vindkraftverk. Ingen större skillnad observerades när en 'fuzzy analytical hierarchy process' användes istället för den klassiska 'analytical hierarchy process' när lämplig lokalisering av vindkraftverk modellerades i en GIS-miljö. En analytisk metodik med hjälp av multikriterieanalys som applicerades i den här studien visar på potentiellt lämpliga områden som ännu inte har utnyttjats av vindkraft finns både i Ragunda och Västernorrland som tar hänsyn till ekologiska, sociala och ekonomiska kriterier för att stödja hållbar utveckling.

Keywords: vindkraft, vindkraftverk, vindkraftslokalisering, spatiell modellering, hållbar utveckling, GIS, multikriterieanalys, AHP, FAHP

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Abstract

Spatial modelling of sustainable wind power development
Martin Andersson

Measures to mitigate climate change has never been a more pressing matter than it is today and the global debate over energy security, environmental decline and limited resources is heated, which motivates decision makers and leaders to search for alternative energy sources, renewable sources. The Swedish government has set a goal to make its entire domestic electricity production 100 % renewable and phase out energy production based on fossil fuels entirely by year 2040, where wind power will contribute largely to that goal. This study aimed to generally analyse where it was suitable and not suitable to establish wind turbines with respect to ecological, social and economical values to achieve sustainable development.
To do this, a multi-criteria analysis was conducted based on the analytical hierarchy process method with the extension of combining it with fuzzy triangular numbers and then comparing the two methods. Ecological values were set as protected areas and not suitable for wind turbine placement. Relevance of social and economical values in relation to each other were differentiated by asking five experts in the field of wind power as renewable energy to perform a pairwise comparison between eight different factors. This resulted in relative weights illustrating the importance of each factor. These weights were then brought into a GIS environment where they were modelled for suitability along with areas subjected to formal protection and other land use acting as constraints in Ragunda municipality and Västernorrland county. Different scenarios were modelled that did or did not include areas for reindeer husbandry as a constraint. The final suitability maps were then compared to existing wind turbines as well as areas of national interest for wind power in Sweden.

Results showed that good wind conditions was the most prominent factor to consider when siting wind turbines. No significant difference was observed when fuzzy analytical hierarchy process was used instead of the classic analytical hierarchy process when modelling suitable wind turbine placement in a GIS environment. An analytical methodology combined with multi-criteria analysis applied in this study show that potential suitable areas that has not yet been exploited by wind power exists both in Ragunda and Västernorrland that takes into account ecological, social and economic criteria to support sustainable development.

Keywords: wind power, wind turbines, wind turbine siting, spatial modelling, sustainable development, GIS, multi-criteria analysis, AHP, FAHP

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Förord

Det här examensarbetet utgör det sista momentet av Civilingenjörsprogrammet i miljö- och vattenteknik (300 hp) som ges universitetsöverskridande mellan Uppsala universitet (UU) och Sveriges lantbruksuniversitet (SLU). Det här arbetet på 30 hp har utförts vid SLU och examinerats vid Uppsala Universitet.

Johan Svensson, forskare vid Institutionen för vilt, fisk och miljö (SLU) och Oskar Englund, docent vid Institutionen för ekoteknik och hållbart byggande (Mittuniversitetet) har varit handledare och Wiebke Neumann, Forskare vid Institutionen för vilt, fisk och miljö (SLU) har varit akademisk handledare och ämnesgranskare.
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Tack till Uppsala Universitet och Sveriges Lantbruksuniversitet för en god studiegång.
Slutligen vill jag tacka Räkneklubben som genom gemenskap har skapat många minnen och motivation under denna studietid.

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Populärvetenskaplig sammanfattning

Sverige har som mål att göra hela sin inhemska elproduktion till 100 % återförnybar och fasa ut energiproduktion baserad på fossila bränslen helt till år 2040. Där landbaserad vindkraft till stor del kommer att bidra till det målet. Vindkraft kan man däremot inte riktigt placera och bygga var som helst. Det är viktigt att det finns goda förhållanden för att producera vindenergi samtidigt som att man inte placerar det i områden med andra viktiga värden, i närheten av bebyggelse eller så att uppskattade landskapsbilder störs. Den här studien handlar om var det är lämpligt och inte lämpligt att placera vindkraftverk i Ragunda kommun och Västernorrland på ett så hållbart sätt som möjligt genom att ta hänsyn till ekologiska, sociala och ekonomiska värden. För att hitta lämpliga områden för vindkraft har en så kallad multikriterieanalys genomförts, där sakkunniga yrkesutövare fick göra en vikting av vilka förutsättningar som är viktigast för att etablera vindkraftverk. Dessa vikter kombinerades sedan med data om höga natur- och landskapsvärden, bebyggelse och annan viktig markanvändning i en programvara för att hantera geografiska data. Rennäring är ett exempel på markanvädning som är viktig för hållbarhet i ett helhetsperspektiv. Områden för rennäring tar upp stora arealer och kan hindra vindkraftsetablering om dessa ses som stoppområden. I den här studien hanteras detta genom att illustrera resultat där rennäringen utgör stoppområden och alternativt där de inte gör det och på så sätt se skillnader i potentiella platser för vindkraftsetablering. Slutprodukten blev alltså lämplighetskartor som visar var någonstans man kan placera vindkraftverk med så liten negativ hållbarhetspåverkan som möjligt.

Resultaten av den här studien visade att bra vindförhållanden är den absolut viktigaste förutsättningen för att etablera ny vindkraft samt att det finns många områden som är potentiellt lämpliga för vindkraft med avseende på hållbarhet som ännu inte är exploaterade av redan befintlig vindkraft i både Ragunda och Västernorrland.

Glossary

AHP - Analytical hierarchy process (a multi-criteria analysis method)

FAHP - Fuzzy analytical hierarchy process (a multi-criteria analysis method with fuzzy triangular numbers based on the AHP method)

MCA - Multi-criteria analysis, a decision making procedure

TWh - Terrawatt-hour, a unit of energy

GIS - Geographical Information System, software used to model data in a spatial environment

SWEREF 99 TM - A coordinate system commonly used in Sweden

Factor - A circumstance that can vary

Constraint - A limitation that needs to be met

Buffer - Increased distance around an object

Fuzzy triangular number - A number that takes into account vagueness and uncertainty

Matrix - Array or table of numbers used to represent a mathematical object

R.I. - Random Index, used in the AHP method to calculate consistency

C.I - Consistency Index, tells how well a comparison matrix is consistent or not

Contents

1 Introduction

Measures to mitigate climate change has never been a more pressing matter than it is today. The global debate over energy security, environmental decline and limited resources is heated, which motivates politicians and decision-makers to search for alternative energy sources, renewable sources. Wind power is such a resource and has been increasing in use and development over the past decade. It is a low carbon emitter, has the ability to decrease the dependency on fossil fuels and allows for nations to house the energy production domestically. At the same time, wind power causes conflicts with other land uses and landscape values (Kati et al. 2021), which calls for certain attention in planning of new wind power installations.

Background

The Swedish government has set a goal to make its entire domestic electricity production 100 % renewable and phase out energy production based on fossil fuels entirely by year 2040, where wind power will contribute largely to that goal (Energimyndigheten 2021a). Wind power alone stood for 12 % of the total energy production in Sweden year 2019 (19,8 TWh; SCB 2021a) and is expected to increase in share of total energy production according to the Swedish wind power strategy. In 2020, wind power produced 27,5 TWh electricity in Sweden. Since 2010, the production of electricity coming from wind power has increased by almost 650% and the number of wind turbines has more than doubled in that same time (Energimyndigheten 2021c). As the consumption of electricity increases and as we go towards a more electric dependent society with more electrical vehicles, devices, industrial processes and heating solutions, we also need to meet those demands by increasing the production of electricity and expanding its distribution capacity. Wind power is one of the most clean energy sources available today, with relatively low impacts on the environment. Wind power, in comparison with other energy producing technologies is, in principal, a source of free energy once the wind turbine has been built (Jacobson 2009; Kondili & Kaldellis 2012).

Wind power has many advantages apart from being a low carbon emitter, such as generating jobs, increasing land value and being a cost-effective energy source (U.S Department of Energy 2017). However, as the technological advance progresses, wind turbines increase in height and today it is not unusual for a turbine to reach heights over 250 meters. Higher and larger turbines claim more land and skyline coverage and consequently increase the impact on the environment and society (Kati et al. 2021). Wind power in contrast to many other energy sources, has a direct impact area that is mostly concentrated to its turbine location, if one does not include the production impact of the turbine (Kondili & Kaldellis 2012). Indirect impact, such as noise, vibration and light pollution may, however, extend across vast areas, as well as regional consequences and high local impact on sensitive populations of, for example, golden eagle (Sandgren et al. 2014). Large-scale wind parks can take up a significant area and has negative effects on biodiversity, loss and fragmentation of animal and bird habitats, ecosystem services, landscape aesthetics, recreation, noise and social acceptance. Many of the negative consequences from establishing new large-scale wind parks can be mitigated by clever siting (Sandgren et al. 2014; Peri & Tal 2020).

The Swedish Energy Agency have identified approximately 1,5% of the total coverage of land and water to be of national interest for wind power (Energimyndigheten 2017). These areas can overlap with other areas of national interest as well as formal protections, restricted areas and areas of other interest (Svensson et al. 2020). To be able to localize wind turbines in a sustainable way these overlapping areas need to be considered as well as factors regarding production efficiency such as wind conditions, land topography, accessibility to infrastructure etc. The energy demand increases and the expansion of wind power as a major renewable and environmental-friendly energy source calls for methods that allow decision makers to make rational choices in planning new large-scale wind parks in a sustainable way. Methods that promotes planning wind parks in a way that does not, or at least as little as possible, encroach on protected areas, natural- and social values and other land use for economical purposes are needed.

Study area

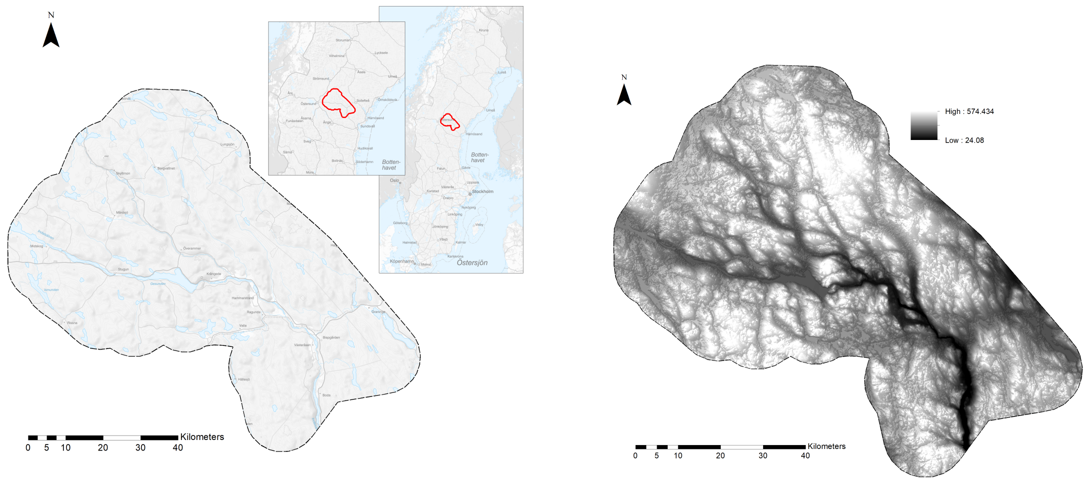
In this study, two zones were selected for analysis. The main study area was Ragunda municipality, which was the main target area for this study. The methodological approach was developed with Ragunda as a case, and the approach was then applied to the neighbouring Västernorrland county. Hence, Västernorrland county was used for reference and comparison and for testing the same methods used on Ragunda on a much larger area. Therefore, explained methods are based on Ragunda.

Since a lot of wind parks overlap with multiple counties and transcend the borders of many municipalities, a buffer of 10 kilometers was implemented on both Ragunda and Västernorrland to include wind turbines that are part of wind parks located on the borders of the study areas. All figures displaying Ragunda municipality and Västernorrland county will hence on include this buffer unless stated otherwise.

Ragunda municipality

Ragunda municipality is situated in the middle of Sweden at 63°05' N latitude and 16°20' E longitude and is part of Jämtland county (Figure 1). It has an total area of 2 527 km^2 and a population of 5 181 people making the population density roughly 2/km^2 (Ragunda Kommun 2021). The largest populated area is Hammarstrand with about 1000 residents. The river Indalsälven runs straight through the municipality, which is one of Swedens longest rivers and since long heavily exploited for hydropower production. Ragunda hosts a number of tributaries to Indalsälven along with many lakes. The topography within the municipality has an elevation ranging from 24 meters to 574 meters above sea level and is mostly covered by boreal forest.

There are currently (2021) wind turbines installed in Ragunda with a yearly production capacity of 0,715 TWh and there are also a few areas pointed out as areas of national interest for wind power as well.



(a) Extent and location of Ragunda municipality with buffer.

(b) Topography of Ragunda municipality with buffer.

Figure 1: Extent, location and topography of Ragunda municipality with buffer.

Ragunda share borders with five other municipalities; Östersund, Strömsund, Sollefteå, Sundsvall and Bräcke, as shown in Figure (2).

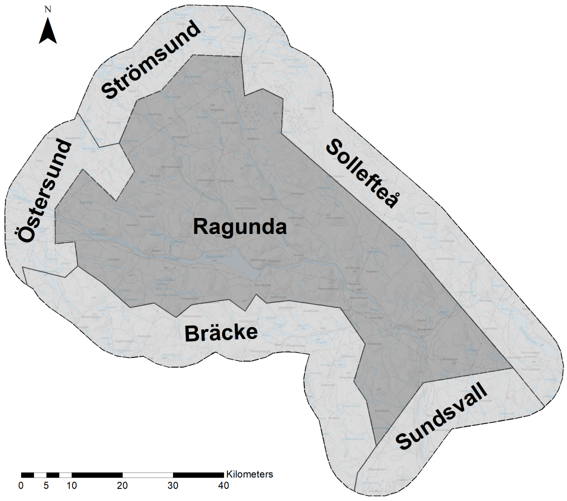


Figure 2: Borders of Ragunda municipality along with its neighbouring municipalities.

Västernorrland county

Västernorrland county is a large area comprised of seven municipalities and is located in the middle part of northern Sweden at 62°44' N latitude and 16°56' E longitude. It is connected to the Baltic Sea in the east and has an total area of 21 500 km^2 and a population of 244 824 people (Region Västernorrland 2021; SCB 2021b), making the population density roughly 11,3 residents/km^2. The largest city is Sundsvall with a population of 58 477 and most of the more population-dense areas are located along the coast.

Västernorrland is the county that produces the most electricity from wind power in all of Sweden with 3,8 TWh produced in year 2020 alone which was 14% of the total production from wind power in the country (Energimyndigheten 2021c).

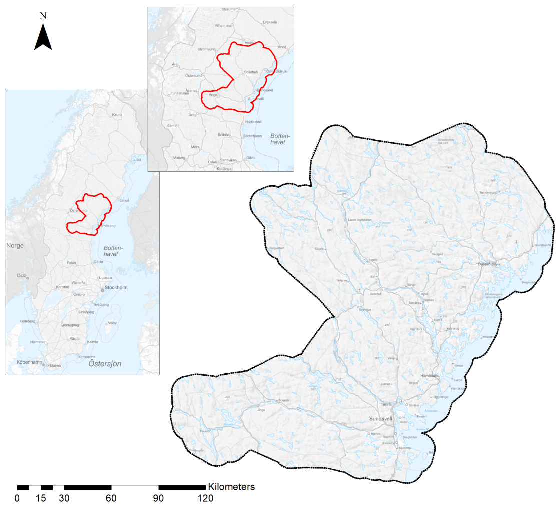


Figure 3: Extent and location of Västernorrland county with buffer.

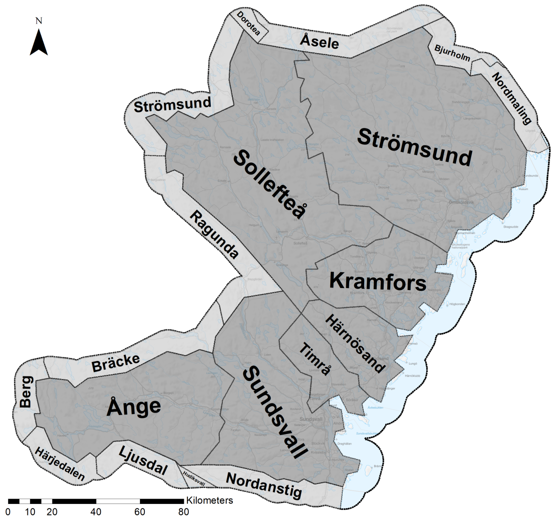


Figure 4: Borders of Västernorrland county along with neighbouring municipalities.

Problem description

Planning and establishing new wind turbines can be a rather complex matter since there are many stakeholders that have an interest in where these are placed as well as legal restrictions and policies that need to be adhered to. This also means that the process of building a wind turbine can take time. To make fact-based location decision, the planning of wind turbine placement need careful consideration based on relevant data, priority processing and compromises based on multiple interests and opinions. Historically, studies has not evaluated the full extent of the effects of wind turbine placement (Waldo et al. 2013). Currently, there appears to be no consensual method about how to identify the most suitable location alternatives with respect to suitability across all aspects. Multiple research projects in Sweden, both on a national and regional level, has been carried out that explores the impact wind turbines has on e.g. birds and bats, marine biology, mammals and human interaction (Taubmann et al. 2021; Rydell et al. 2017; Wikström & Granmo 2008; Alemu et al. 2021; Bolin et al. 2021). However no extensive research exists in Sweden that investigates methods that yield the most suitable and sustainable placement of wind turbines. As more wind turbines are being built than ever before, consideration needs to be taken to the factors that are important to deciding the placement of wind turbines. Consideration also needs to be taken to the consequences the location will have on other values and interests that renewable wind energy production can bring (Ek et al. 2017).

Purpose and issues to be resolved

The purpose of this study was to develop, analyse and apply a model for suitable localization of wind turbines in northern Sweden with respect to aspects reflecting ecological, economical and socio-cultural sustainability dimensions.

The research questions to be resolved were:

– Where, with respect to ongoing other land use and also ecological and social values, was it not suitable or less suitable to establish new wind turbines?

– Where, with respect to ongoing energy production (wind power), energy distribution and other infrastructure, was it suitable and effective to establish new wind turbines?

These research questions were explored in the following context: Where can new wind turbines be established to achieve best possible sustainability and societal benefit, with respect to impact on other economical, ecological and social prerequisites and also with respect to existing energy infrastructure and other infrastructure? With societal benefits being referred to as localization of new wind turbines to such sites where it was more suitable, with respect to both negative impact on other land usage and values and with respect to localization to such sites that was suitable and effective with close energy- and other infrastructure.

Delimitations

This study was delimited to;

– Only analyse areas for onshore wind power production.

– Not include specific ecological values but instead formal protection areas (7§ Miljöbalken, SFS 2021:1018, Miljödepartementet 2021), areas of national interests (3-4§§ Miljöbalken, SFS 2021:1018, Miljödepartementet 2021) and ecological core areas (Miljödataportalen, Naturvårdsverket 2021).

– Not include military areas, points of interest for military use and other military-related protected areas since these are classified.

– Not include municipal comprehensive plans and layouts regarding wind turbine placement.

This study was intended to be synoptic and create an overview of suitable areas for wind turbine placement and therefore certain factors acted as proxies for a more generalized attribute. In depth consideration for local variations and niche occurrences were beyond the scope of this study.

Existing research

There are some studies internationally that has carried out similar research into suitable siting of wind turbines combined with multi-criteria analyses and GIS modelling. There are, however, almost no such studies that has been performed in Sweden. Kandy (2018) carried out a master thesis of suitable wind turbine locations in Västernorrland county using the multi-criteria analysis method AHP and 29 different criteria affecting placement, with a by-hand pairwise comparison based on discussions and workshops with professionals with extensive knowledge. The results yielded three different scenarios based on a 'green', an economic and a tourism oriented alternative.

Bertsiou et al. (2020) modelled eligible sites for wind turbine installation in the North Aegean island, Greece, using GIS and AHP resulting in a technical-, cultural- and financial scenario and found wind potential to have the highest priority in all scenarios.

Ali et al. (2017) have had success identifying suitable locations for on-shore wind farms using a GIS-MCDM methodology in South Korea. The study used the AHP method combined with fuzzy triangular numbers to select sites based on a scale from 1 to 8. They used seven different criteria in their AHP and pairwise comparisons was carried out by experts in renewable energy resulting in suitable locations for wind farms based on each experts weights along with a baseline scenario where all criteria received equal weights.

In Ecuador, Villacreses et al. (2017) modelled feasible locations for wind power using GIS software and compared a range of multi-criteria decision-making methods, all producing similar results.

Van Haaren & Fthenakis (2011) presented a method of site selection for wind turbines in New York state based on three stages. The first stage that excluded sites that were infeasible based on land and geological constraints, the second stage identified the best sites based on expected net value from four major cost and revenue categories that were spatially dependent and the third stage that assessed the ecological impacts on birds and their habitats.

Siyal et al. (2015) carried out a study that assessed the wind energy potential in Sweden using a GIS-based approach and by considering system performance, topographic limitations, environmental and land use constraints, yielding two restriction scenarios based on different criteria. They concluded that sufficient wind energy potential and land area was available to secure future renewable energy targets.

2 Theory

Sustainability

Sustainability means in its basic form the capacity to maintain an entity, outcome or process over a period of time, to sustain something (Basiago 1998). However, in a more modern perspective, sustainability has become a slogan and chant for many agencies, activists, companies, authorities, practitioners, academics and the public whom have become more aware of climate change and natural conservation or other issues with multiple and potentially conflicting interests and thus integrative planning is needed (Carlsson et al. 2017). Sustainability can be associated with sustainable development, which can be defined as; an evolutionary process in which the human capacity increases in terms of initiating new structures, coping with problems, adating to continious change and striving purposefully and creatively to attain new goals (Peet 1999). Sustainable development is a theory that has been embraced across many fields and professional structures. There are many different definitions regarding this term and perhaps different definitions can be used depending on the context in which context it appears. The most cited context may perhaps be; a development that meets the needs of the current generation without compromising the ability of future generations to meet their own needs (Brundtland 1987; Schaefer & Crane 2005). Sustainable development can be divided into three aspects; environmental (ecological), socio-cultural, and economical and can be illustrated with a well known Venn diagram as shown in Figure (5). The diagram illustrates a concept where all the three aspects are given equal weight and value and must be in harmony to achieve full sustainability. It is a simplification in order to give a general understanding of what sustainable development is. It does not convey the contents of the different aspects, since they can vary depending on situation, nor does it say anything about the relationships between overlapping interests.

To achieve sustainable development, decisions should seek to satisfy the needs of these three aspects.

The UN have set 17 goals for sustainable development covering a sustainable future for humanity and the environment (UN 2021). Sweden has the environmental objectives system that consists of sixteen environmental objectives that serves as guidelines for companies, authorities and agencies in their work to achieve a sustainable society and these give an insight into what sustainability in regard to environment means in a Swedish context.

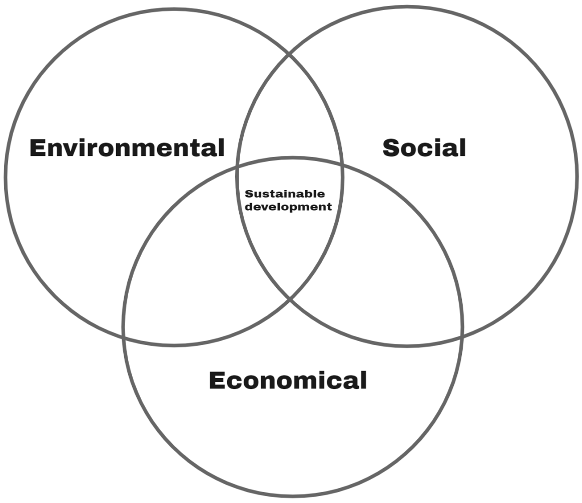


Figure 5: Venn diagram of sustainable development.

Environmental (ecological)

Environmental sustainability refers to aspects related to the environment and ecosystems. This is a broad complex but can involve ecosystem services, biodiversity, land use, water resources, quality of water, quality of air and climate processes. Humanity needs resources for growth and survival. Aarts & Nienhuis (2009) argued that a step in achieving a sustainable environment is 'determining the maximum allowable expansion of human use within the limits set by the resilience of ecosystems' (Aarts & Nienhuis 2009:90). Dhunny et al. (2019) stressed the importance of inclusion of biodiversity components in selection of wind farm sites. The rate at which biodiversity is being loss exceeds the natural rate of extinction (Díaz et al. 2019). It has been found that wind turbines can affect 3-14% of suitable airspace for flying for birds and this can be limited by planning low-impact placement of wind turbines (Marques et al. 2020). Capercaillie living in boreal areas has been observed to be affected by wind turbines when it comes to habitat selection and available resources (Taubmann et al. 2021). Another study has shown bats feeding at wind turbines sites thanks to insect swarming at the top of the wind turbines (Jansson et al. 2020). There is difficulty in speculating how a loss of biodiversity could affect the future but some bats for example are known to be of importance in consuming insects that are crop pests (Ledec et al. 2011). Negative impact on biodiversity and other ecological premises can be mitigated by adaptive planning in many cases (Kati et al. 2021), but in other cases it is not possible to avoid and a question of not building wind power or building and accepting the impact arises.

Apart from impacts concerning animals and biodiversity, wind power can have an impact on the environment by in what manners the components and materials are produced. A typical wind turbine blade of 45,2 meters has a lifetime impact of 795 GJ (CO_2 footprint 42,1 tonnes) dominated by manufacturing and raw materials (Liu et al. 2017).

The impact from production processes and transportation of parts can however vary and were beyond the scope of this study.

Socio-cultural

Social sustainability is a difficult aspect to define and usually needs to be put into context. In general, social sustainability refers to the well being of humans, justice, rights and power and meeting the needs of the individual at a global level is what social sustainability deals with (KTH 2021b). At a social level sustainability means fostering the development of people, communities and cultures to help achieve meaningful life (Saith 2006). It is more difficult to model social sustainability since, unlike environmental and economical, social systems do not have as easily observable flows and cycles and the dynamics are more intangible (Saner et al. 2020).

Social impact from wind power can come in form of visual landscape and aesthetics, noise levels, encroachment on recreational areas and ice throw safety concerns, for example. For a long time visual impacts has been the leading socio-environmental constraint when installing new wind turbines and the associated transmission lines (Anshelm & Simon 2016) but careful site selection can reduce the visual impact (Ledec et al. 2011). Average annoyance of residents near wind farms in Europe and the U.S. are low and fewer than 5% of residents were strongly annoyed by the noise coming from the wind turbines, but as the wind turbines grow in size, decline in public acceptance of them might occur and it is still of high social relevance to secure valid information about consequences on residents (Hübner et al. 2019). Lack of visual appeal has shown to be a great motivator for opposition against wind turbines and wind turbines can cause impact on heritage landscape, buildings and areas of cultural significance and developers should assess alternative locations to avoid placing wind turbines in such areas (Fast et al. 2016). Sound and visual impacts of wind turbines are strongly tied to annoyance and opposition and if these factors are not addressed it can cause conflict especially if participatory processes are overlooked (Rand & Hoen 2017).

Economical

The concept of economical sustainability is one that differs depending on which angle you choose to look at it. It has several definitions and one could be understood as economic development that does not jeopardize the stability of ecological or social sustainability and an increase in economic capital must therefore not be at the expense of a negative decrease of natural- or social capital (KTH 2021a). Another way to look at it is that economical sustainability equals economic growth which is, as per the definition of sustainable, sustainable as long as the capital increases and thus it does not take ecological and social decline into consideration (ibid.).

Wind turbine prerequisites

Wind turbines inherently cannot operate in every condition and under every circumstance which makes it possible to identify the minimum requirements for wind turbine installment. Modern wind turbines can produce wind energy at wind speeds between 4-25 m/s and the potential effect of the wind increases in a cubic relationship to the wind speed, which means double wind speed generates eight times more effect (Boverket 2009). Wind turbines do not have optimal performance for every wind speed and higher wind speeds limit their effect and the amount they can produce and the yearly production does not increase in a cubic manner all the way through the operating range (ibid.). Swedish wind turbines in good wind conditions can produce energy during 6000-7000 of the hours of a year (ibid.). Wind turbines can have heights that vary greatly from 50-300 meters and construction height increases. In the low zone under 100-200 meters the wind speed is affected by the topography and the friction that is caused by vegetation, buildings and other obstacles (ibid.). Wind turbines need to be placed with noise disturbance on local residents in mind. There are also constraints on how close wind turbines can be placed to certain objects. There is no official distance from buildings that has to be met and every case is assessed individually but a benchmark value of 40 dB(A) is used by Swedish authorities when assessing noise disturbance from wind turbines and minimum distance is usually set accordingly (Boverket 2009).

Multi-Criteria Analysis (MCA)

Making proper and qualified decisions has been present throughout history for individuals and organisations equally. A multi-criteria analysis can be applied in every decision making case, even though it is not likely to be used in small everyday decisions with a short time frame. Some decisions are more complex and significant and require a more thorough deliberation, that is where MCA comes in handy. MCA has been used in many different fields and professions by decision makers and there are a number of different methods and models to be used depending on what outcome the decision maker wants to achieve. These methods has, since their birth, continuously been growing and evolving (Wallenius et al. 2008) and the number of publications involving some kind of MCA has been increasing (Ishizaka & Nemery 2013).
MCA is used when there are decision problems involving multiple criteria that conflicts with one another and the goal is to find the most suitable option. Typically there does not exist an optimal option and the MCA incorporates the decision makers subjective preferences to differentiate between solutions. The outcome of an

MCA can be of different characteristics, choosing one most suitable option, sorting alternatives into defined categories, ranking a set of options by a predefined score system or describing the options by their consequences (Roy 1981).

Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process is a MCA method originally developed by Saaty (1980) and is typically best to use when there is no possibility to formulate an utility function (Ishizaka & Nemery 2013). The AHP breaks down a complex multi-criteria problem into a set of more easy to handle pairwise comparison problems. The problem is arranged into a hierarchy of goals, options and criteria. When the goal of the outcome is known e.g. choosing the best alternative, options are formulated to choose from. These options will be accompanied by a set of criteria to help decide which alternative is better in a pairwise comparison. The expert's pairwise comparison is synthesised into a matrix which shows the ratio of each criterion against each other according to the expert. These ratios are converted to a score system, usually 1 to 9, that corresponds to weights set by the expert, the higher score the greater the relative preference with respect to the considered criterion. Finally the AHP combines the weights of the criteria and the options score along the hierarchy of the model and produces an overall ranking through linear algebraic procedures according to most to least suitable option. The overall ranking is an aggregated normalized sum of the pairwise comparison matrix.

The AHP is a powerful tool when important decisions needs to be made as it is able to convert the qualitative and quantitative evaluations of the experts into a ranking system. The effort to execute the AHP is, at least for problems with a low number of criteria, fairly low and it does not require a specialized software nor rely on large sets of data to make a decision since the experience and knowledge of the expert is embedded (Ishizaka & Nemery 2013). In addition, optional consistency and accuracy computations of the evaluations can be made in order to tackle biases and human error. However, a simple AHP has some weaknesses and drawbacks such as it does not take into account the possibility for mutual dependency between criteria, more experts, decision makers and a higher number of criteria makes it more complex (Ali et al. 2017). One significant drawback is that it operates under the assumption that the experts can make entirely accurate ratios of the criteria but in reality the human nature is less than perfectly accurate. There will always be a level of uncertainty, vagueness and bias from the experts doing the pairwise comparisons even with the aid of consistency and accuracy tests.

Fuzzy triangular numbers

The theory of fuzzy sets deals with the problem of vagueness and imprecision in decision environments and was introduced by Zadeh (1965). The problem originates to when there are no distinct boundaries between one option and the other when making a decision. Statements are not always crisp and precise like yes and no but can be more vague of a more-or-less kind of type and precision assumes that the parameters of a model represents reality exactly, which is seldom the case (Zimmermann 2010). The fuzziness in the data can be describes by a membership function which basically is a graphical way of visualising the degree of membership of any value in a given fuzzy set. In this study a triangular membership function was used, which is the most widely used function. Such a membership function can be describes as:

$$f_{triangle}(w) = \begin{cases} 0, & w \leq l \\ \frac{w-l}{m-l}, & l \leq w \leq m \\ \frac{u-w}{u-m}, & m \leq w \leq u \\ 0, & u \leq w \end{cases} \tag{1}$$

The value input can be fuzzified by a triangle of three parameters where lower and upper boundaries defines the base and the middle defines the height as shown in Figure (6).

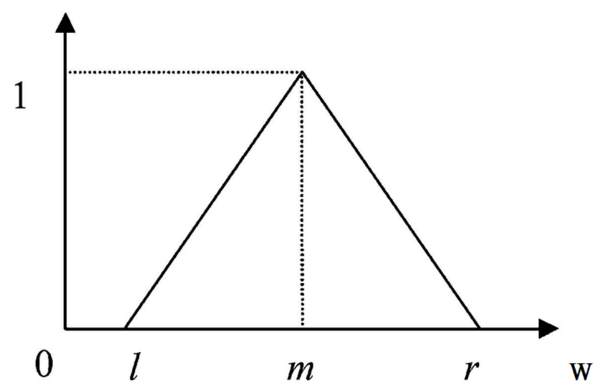


Figure 6: Fuzzy triangular membership function.

The very in depth details of fuzzy sets has been described very well by Klir & Yuan (1995) and will not be explained here.

Fuzzy triangular numbers can be incorporated into the AHP method to form the fuzzy trangular hierarchy process first introduced by (Laarhoven & Pedrycz 1983) and later evolved by Buckley (1985). This is an extension of the classic AHP using fuzzy numbers instead of real crisp numbers. The idea is that it will make it more accurate. Since then, the FAHP method has been adapted rapidly (Chan et al.

2019). Saaty has commented that there is no real need to include fuzzy logic into the AHP since by making decisions via AHP is already fuzzy enough (ibid.).

It has been found that there are differences in results between AHP and FAHP even at small scales but increases with the level of fuzziness and the matrix size (Chan et al. 2019).

3 Method

The method used was; a multi-criteria analysis where pairwise comparisons were carried out by five experts in the field of wind power. The MCA was conducted based on eight different factors regarding economical and socio-cultural aspects. The MCA method AHP was used in combination with fuzzy triangular numbers to deal with vagueness of the weighting of factors. Fuzzy theory in spatial modelling has seen an increase in development in recent years. The AHP and FAHP methods were therefore compared to explore differences between these two when modeled within a GIS environment. The results of the MCA that yielded weights of all the factors in relation to each other was then brought into a GIS environment for modelling suitability maps covering the study areas. The suitability maps were then subjected to the ecological and social constraints where areas that constituted a constraint were removed from the suitability maps. Finally the top 20% most suitable sites were selected yielding maps containing the most suitable sites for two scenarios where areas for reindeer husbandry was included and not included respectively. Reindeer husbandry, recognized as a national interest in the national Environmental Code (Svensson et al. 2020), was selected to represent a default land use system with extensive land cover and also simultaneously representing an economic use and a high profile socio-cultural expression in northern Sweden (Skarin et al. 2018). The results were compared with existing wind turbines and areas of national interest for wind power.

Coordinate system

The x-y coordinate system used in this study was SWEREF99 with the national map projection SWEREF99 TM. The study area was fairly large and many data sets were generally delivered with a nation wide coverage which makes it feasible to use a joint coordinate system. Data based on different coordinate systems were projected to SWEREF99 before being utilized.

Data

In this study, data was divided into two groups, factors and constraints. Factors were part of a multi-criteria analysis since they were non-binary, on a scale from low to high suitability according to results from a multi-criteria analysis. These factors were mean wind speed, ground slope, distance to roads, distance to power stations, distance to power lines (main grid), distance to buildings, distance to railroads and visibility from residential areas. The constraints on the other hand were considered binary as optional or prohibited for wind power establishment and generally covered ecological an socio-cultural aspects. The prohibited areas were predefined and protected by Swedish regulations and policies (Table 1). In theory, wind turbines could potentially be placed in a prohibited area provided that municipal, county and national regulations allows and put priority to changed ongoing land-use, but for the sake of this study, these areas were set as stop zones. Both factors and constraints were used in a GIS environment to model wind turbine placement suitability.

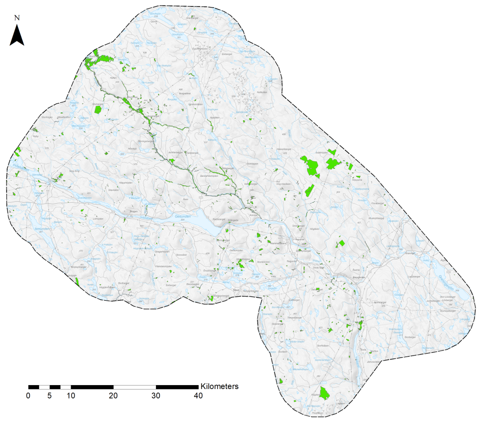
Ecological

Ecological data was related to environmental sustainability and only consisted of constraints and was used to exclude areas that are protected, such as natural reserves, or areas where it is impossible to place wind turbines, such as rivers and lakes. The idea was that by excluding these areas entirely from wind turbines siting, ecological sustainability can be ensured.

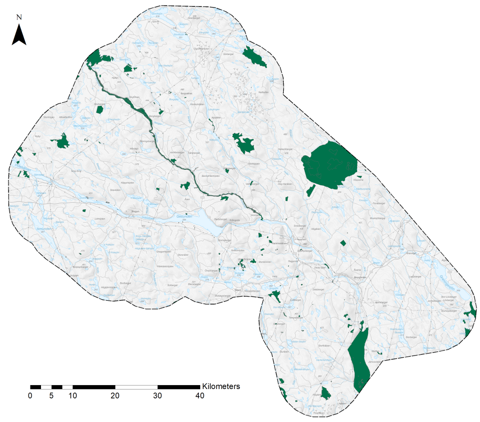
Table 1: Data related to ecological sustainability and their source.

Data type	Source	Revision year	URL
Key biotopes	Swedish Environmental Protection Agency	2018	Link
Animal and plant protected areas	Swedish Environmental Protection Agency	2020	Link
The Birds Directive	Swedish Environmental Protection Agency	2018	Link
The Habitats Directive	Swedish Environmental Protection Agency	2018	Link
State forests worthy of protection	Swedish Environmental Protection Agency	2020	Link
Protected meadows and pastures	Swedish Environmental Protection Agency	2015	Link
Protected streams and wetlands	Swedish Environmental Protection Agency	2021	Link
Lakes and rivers	Swedish Mapping, Cadastral and Land Registration Authority	2020	Link
Natural reserves	Swedish Environmental Protection Agency	2020	Link
Areas of natural conservation	Swedish Environmental Protection Agency	2020	Link
Areas of natural conservation agreements	Swedish Environmental Protection Agency	2020	Link
Areas of national interest for reindeer	Swedish Environmental Protection Agency	2015	Link
Protected mountains and mountain ranges	Swedish Environmental Protection Agency	2020	Link
National parks	Swedish Environmental Protection Agency	2020	Link
Topographies	Swedish Mapping, Cadastral and Land Registration Authority	2021	Link

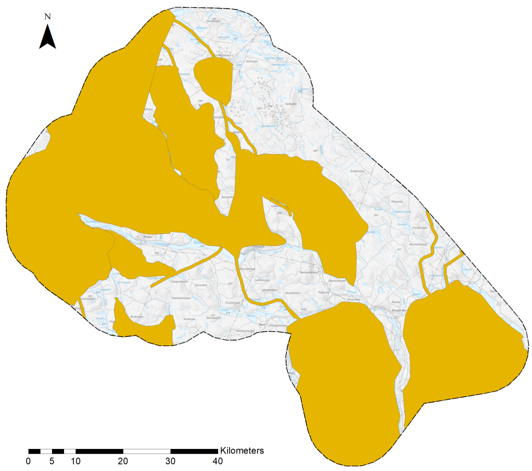
Data related to ecological sustainability were grouped together into four different maps (Figure 7) showing their spatial coverage in Ragunda municipality.



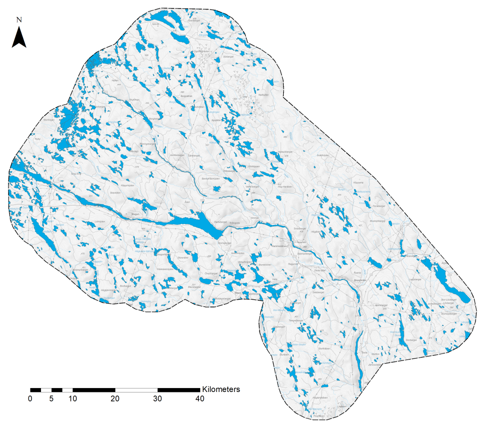
(a) Areas of protected habitats and biotopes. Including; areas of key biotopes, areas of protected biotopes, the Swedish bird habitat directive, the Swedish species and habitat directive and animal and vegetation protected areas.



(b) Areas of environmental protection. Including; national parks, nature reserves, state owned forests worthy of protection, meadows and pastures, nature conservation areas, areas of national interest for nature conservation and protected mountain ranges.



(c) Areas of national interest for reindeer husbandry.



(d) Wetlands and streams.

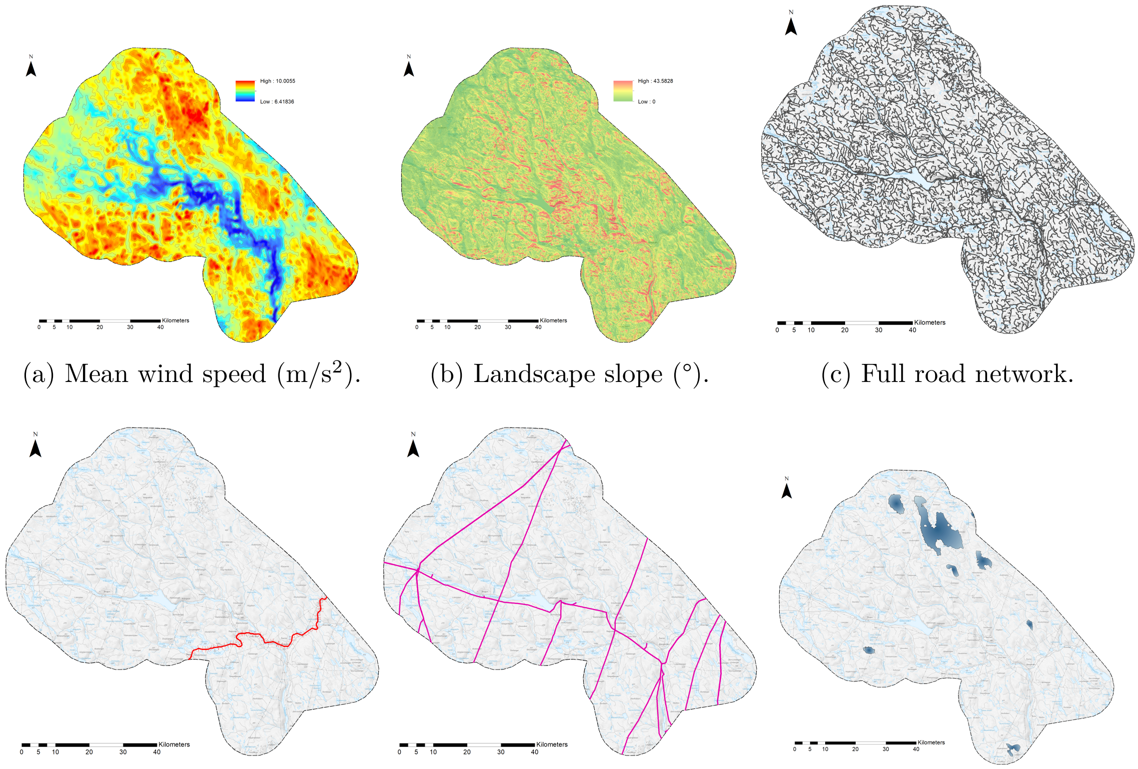
Figure 7: Factors and criteria related to ecological sustainability for Ragunda municipality.

Economical

Data related to economical suitability was used to model suitable economical conditions in a generalized state. Higher wind speeds were preferable in the way that they generate more effect thus increasing the amount of electricity produced and generating more revenue (Figure 8a). Ground slope was used to model ease of installment where steeper ground slope meant increasing work and build costs, especially above 40°angles (Figure 8b). Roads, power stations, power lines and railroads was modelled as distance-cost factors where a higher distance meant increasing costs (Figure 8c-8d). Placing a wind turbine far away from a road or a power line would mean new roads would have to be built and new power lines to be put up. This was of course a simplification of real situations but to lower the complexity in this study, these factors was used as a proxy for infrastructure and economical suitability (Table 2).

Table 2: Data related to economical sustainability and their source.

Data type	Source	Revision year	URL
Mean wind speed	New European Wind Atlas (NEWA)	2021	Link
Roads	Swedish Transport Administration	2021	Link
Power stations	Swedish electrical power transmission authority	2021	Link
Power lines (main grid)	Swedish electrical power transmission authority	2021	Link
Railroads	Swedish Transport Administration	2021	Link
Areas of national interest for wind power - (Only used for comparison and not in the GIS model)	Swedish Energy Agency	2015	Link
Already existing and granted wind turbines - (Only used for comparison and not in the GIS model)	Swedish Energy Agency	2021	Link



(a) Mean wind speed (m/s^2). (b) Landscape slope (°). (c) Full road network.

(d) Railways network. (e) Electrical power lines and power stations. (f) Area of national interest for wind power.

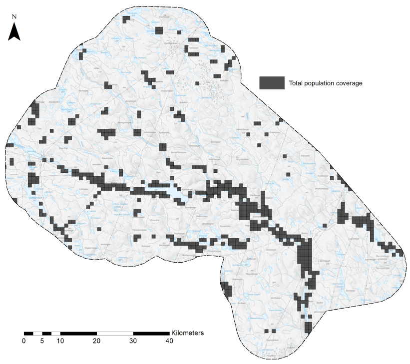
Figure 8: Factors and criteria related to economical sustainability for Ragunda municipality.

Socio-cultural

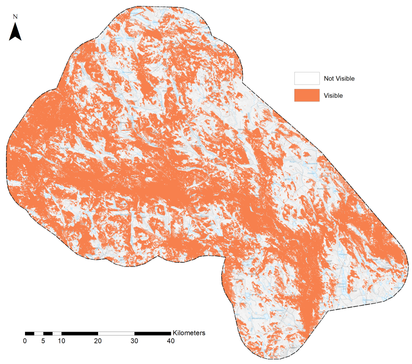
Data related to social sustainability (Table 3) consisted of both a factor and constraints. The constraints regarded mainly cultural and recreational protected areas and heritage sites (Figure 9d) whereas the factor dealt with visibility from residential areas (Figure 9b). Populated areas such as towns and villages (Figure 9c) was used as a binary area and excluded entirely from potential suitable wind turbine locations.

Table 3: Data related to socio-cultural sustainability and their source.

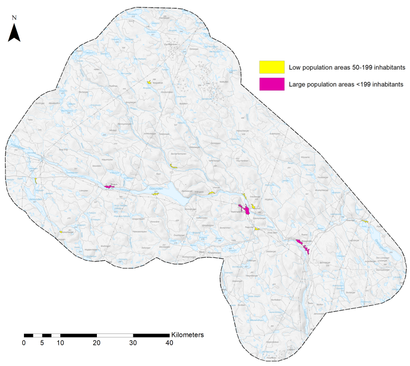
Data type	Source	Revision year	URL
Large population areas (>199 inhabitants)	Statistics Sweden, Central Bureau of Statistics	2020	Link
Low population areas (50-199 inhabitants)	Statistics Sweden, Central Bureau of Statistics	2015	Link
Natural heritage sites	Swedish Environmental Protection Agency	2020	Link
Areas of national interest for recreation	Swedish Environmental Protection Agency	2017	Link
Areas of national interest as cultural environment	Swedish Environmental Protection Agency	2017	Link
Cultural reserves	Swedish Environmental Protection Agency	2020	Link
Population density coverage	Statistics Sweden, Central Bureau of Statistics	2021	Link



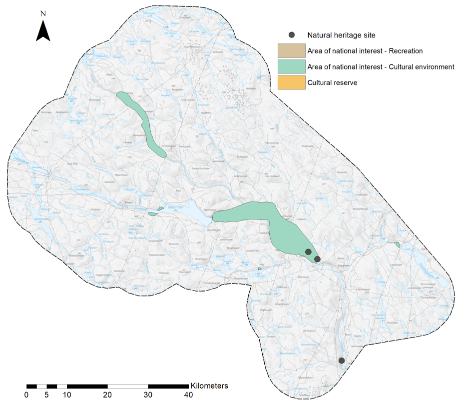
(a) Total population coverage divided into squares the size of one square kilometer.



(b) Combined visibility from any of the population squares.



(c) Large and small residential areas.



(d) Areas of cultural importance. Including; cultural reserves, areas of national interest for recreation, areas of national interest for cultural protection and natural heritage sites.

Figure 9: Factors and criteria related to societal sustainability for Ragunda municipality.

Areas of national interest

Swedish authorities have pointed out areas that are of national interest for varying purposes and that are worthy of significant protection (Svensson et al. 2020). Boundaries for areas of national interest are not completely defined but they represent areas with high core value or are of high interest for the society. Areas of national interest for recreation, cultural environments, natural conservation, natural conservation agreements and reindeer husbandry was all used as a binary no-go-zone in this study. These are included in Tables 1, 2, 3.

Areas of national interest for wind power was used as a comparison to the final results of this study. These areas has been selected by the Swedish Energy Agency and are selected on predefined criteria (Energimyndigheten 2013). There should be a yearly mean wind speed higher than 7,2 m/s 100 meters above ground, areas should not be smaller than 5 km^2 and a minimum distance to buildings should not be lower than 800 meters. Areas of national interest for wind power has also considered the certain areas to be no-go-zones (ibid.). These include areas of national interest for coastal regions, areas of national interest for mountains and mountain ranges, birds and habitats directives, national parks as well as natural and cultural reserves.

Areas for reindeer husbandry

Wind power and reindeer husbandry has long been a highly debated matter but recently court decisions[1][2] and wind power assessments has taken a stronger view towards reindeer husbandry and the people that practice it[3] (Darpö & Sandström 2021). Reindeer herding has been around for a long time in Nordic history and there are many people that still count reindeer herding as their main profession and depend on reindeer for food and income (Sametinget 2021). This is why authorities have pointed out many areas of national interest concerning reindeer husbandry.

In this study, areas of national interest for reindeer husbandry were given binary properties as a no-go-zone but since these areas take up such an incredibly large space of the study areas they were also excluded entirely in order to show two scenarios, one where areas for reindeer husbandry was considered and one where they were not.

[1] Umeå tingsrätts, mark- och miljödomstolen, dom 2016-11-23 i mål nr M 1425-15.
[2] Umeå tingsrätts, mark- och miljödomstolen, dom 2017-07-03 i mål nr M 3051-15.
[3] Miljöbalken 3:5.

Buffers

In order to ensure that a minimum distance was kept from various objects, buffers was created.

Minimum distance from buildings was set to 800 meter according to Energimyndigheten (2013) to avoid noise disturbances. The minimum distance to roads and railroads is currently the same as the height of the wind turbine in question but since this was a generalized study, the minimum distance was set to 50 meters. When it comes to power lines, no information of a minimum distance was found and instead a hypothetical minimum distance of 55 meters was set.

A buffer was also created for the study areas of 10 kilometers in order to model wind turbines that are close to the borders of Ragunda municipality and Västernorrland county or are part of cross-border wind parks.

Weighting of factors

Any sort of MCA, or any sort of weighting for that matter, should typically be performed by experts in the field in question, or by people with extensive knowledge and experience enough to perform a reasonable accurate weighting. In this study a total of 5 experts were asked to do a pairwise comparison of 8 factors according to the classical AHP Saaty scale of integers 1 to 9, corresponding to verbal terms. These people were selected from diverse backgrounds and experiences ranging from energy authorities, major wind power contractors, county administrative boards and renewable energy associations. When a comparison matrix had been formed, the inputs were converted into fuzzy triangular numbers according to the FAHP scale. The AHP scale and the corresponding verbal terms and FAHP scale is illustrated in Table (4).

Table 4: AHP scale and corresponding verbal terms and FAHP scale.

AHP scale	**Verbal term**	**FAHP scale**
1	Equally important	(1, 1, 1)
3	Weakly important	(2, 3, 4)
5	Fairly important	(4, 5, 6)
7	Strongly important	(6, 7, 8)
9	Absolutely important	(9, 9, 9)
2	Interpolation scale	(1, 2, 3)
4	Interpolation scale	(3, 4, 5)
6	Interpolation scale	(5, 6, 7)
8	Interpolation scale	(7, 8, 9)

Multi-criteria analysis

In this study, both a traditional AHP, developed by Saaty (Saaty 1980) and a fuzzy AHP was conducted. The outcome of these two methods was then taken into a GIS software and compared against each other to see if there was significantly different results when producing weighted overlay maps.

There are many different types of ways fuzzy numbers can be incorporated into AHP but perhaps the most common method is one developed by Buckley (1985) and was used in this study.

Firstly, experts wind power and renewable energy performed a pairwise comparison of each of the factors according to Saatys scale (1 to 9) with associated verbal terms. These numbers were then converted to a set of corresponding fuzzy triangular numbers with upper and lower bounds. If e.g. factor F1 was deemed to be strongly more important than another factor F2 it then received a 7 on the Saaty scale and thus in a converted fuzzy triangular number scale it received the triangular scale of (6, 7, 8). Similarly in reverse the factor F2 would receive a 1/7 on the Saaty scale and the triangular scale of (1/8, 1/7, 1/6) illustrating its less importance compared to the factor F1, it has in other words reciprocal properties. By comparing all of the factors against each other two square matrixes was formed, one matrix containing numbers according the Saaty scale and one matrix containing correspondent fuzzy triangular numbers.

A simple AHP has in its basic form, if global goal and factors has already been defined, three steps; generating a pairwise comparison matrix, computing each of the factors weights and finally checking the consistency of the calculated weights.

A pairwise comparison matrix can be formed by comparing each of the factors against each other according to eq.(2). This is ideally done by individuals with vast knowledge and experience in the field in which the MCA is conducted. Since a pairwise comparison in an AHP is done according to a 1 to 9 scale, it only has positive integers and satisfies the reciprocal property of eq.(3), as stated by Saaty (1980).

$$A = \begin{bmatrix} A_{11} & A_{12} & \dots & A_{1n} \\ . & . & \dots & . \\ . & . & \dots & . \\ . & . & \dots & . \\ A_{n1} & A_{n2} & \dots & A_{nn} \end{bmatrix} \tag{2}$$

$$A_{ji} = \frac{1}{A_{ij}} \tag{3}$$

To calculate the weight of each factor, first, each of the columns in the pairwise comparison matrix is summed according to eq.(4). Then the pairwise comparison matrix must be normalized using eq.(5). Then the priority vector, which is the normalized principal eigen vector, $W = [w_1, w_2, w_3 ... w_n]$, is computed from the matrix by the principal eigenvector procedure according to eq.(6). Thus the final relative weights of each factor has been obtained. The priority vector shows the relative weights among the compared factors and the sum of these weights are 1.

$$A_{ij} = \sum_{i=1}^{n} A_{ij} \quad j = 1, 2, 3...n \tag{4}$$

$$X_{ij} = \frac{A_{ij}}{\sum_{i=1}^{n} A_{ij}} \quad j = 1, 2, 3...n \tag{5}$$

$$W_{ij} = \frac{\sum_{j=1}^{n} X_{ij}}{n} \quad i = 1, 2, 3...n \tag{6}$$

The resulting vector W will contain the weights of each factor from the pairwise comparison in relation to each other as percentage ratios.

The fuzzy triangular number matrix is formed based on the simple AHP matrix and adding upper and lower boundaries to each weight in the matrix illustrated by eq.(7). The tilde sign (~) is used to denominate fuzzy triangular numbers.

$$\tilde{A} = \begin{bmatrix} \tilde{A}_{11} & \tilde{A}_{12} & ... & \tilde{A}_{1n} \\ . & . & ... & . \\ . & . & ... & . \\ . & . & ... & . \\ \tilde{A}_{n1} & \tilde{A}_{n2} & ... & \tilde{A}_{nn} \end{bmatrix} \tag{7}$$

When working with fuzzy numbers, one first have to calculate the geometric mean for every factor using eq.(8). The fuzzy weights are obtained by using eq.(9).

$$\tilde{g}_i = (\prod_{j=1}^{n} \tilde{A}_{ij})^{\frac{1}{n}}, \quad i = 1, 2, ...n \tag{8}$$

$$\tilde{w}_i = r_i \cdot (r_1 + r_2 + ... + r_n)^{-1} = (l_{w_i}, m_{w_i}, u_{w_i}) \tag{9}$$

Where r_i is the geometric mean, l is the lower limit, m is the moderate probable value and u is the upper limit. These weights need to be defuzzificated in order to obtain factor weights with crisp numbers. This is done by averaging the fuzzy weights of each factor using eq.(10).

$$M_i = \frac{(l_{wi} + m_{wi} + u_{wi})}{3} \tag{10}$$

The final weights from the fuzzy comparison matrix is then obtained by normalizing the non-fuzzy weights according to eq.(11).

$$N_i = \frac{M_i}{\sum_{i=1}^{n} \cdot M_i} \tag{11}$$

AHP consistency

It is usually recommended to perform a consistency analysis when doing an AHP. When experts compare each element in a comparison matrix there is bound to be some inconsistency in the matrix. Perfect consistency is when the expert does not contradict themselves. This however, can be troublesome to achieve, especially as the number of factors to consider increases. Say factor F1 is preferred over factor F2 (F1>F2) and factor F2 is preferred over factor F3 (F2>F3). The logical thing to expect is that factor F1 is also preferred over F3. If however it is the other way around (F3>F1), there exists inconsistency. There are different methods in which one could check the consistency in an AHP but in this study the method developed by Saaty (1980) was used since it is the most commonly accepted method.

According to Saaty (1980), for a consistent reciprocal matrix, the largest eigenvalue of the comparison matrix is equal to the order of the same matrix. The consistency, C.I., can therefore be calculated using eq.(12).

$$C.I. = \frac{\lambda_{max} - n}{n - 1} \tag{12}$$

Where λ_{max} is the largest eigenvalue and n is the order of the pairwise comparison matrix.

Saaty (1980) also developed a random index, R.I., dependent on the size of the matrix that is derived from the average C.I. of a large number of randomly generated multiplicative preference relations (Liu et al. 2017). According to Saaty, some level of departure from consistency can be accepted in varying practical situations.

The final consistency ratio (C.R.) can be calculated using eq.(13), where a consistency, C.R.>0,10, is generally considered acceptable.

$$C.R. = \frac{C.I.}{R.I.} \tag{13}$$

One cannot assume that the expert is fully rational when weighing the factors against each other. It can in reality be quite difficult for a human being to provide an exact numeric quantification on factors when making a complex and practical decision (Liu et al. 2017).

Fuzzy AHP consistency

When it comes to fuzzy environments it is difficult to estimate consistency. Several methods to estimate the consistency when incorporating fuzzy numbers into AHP has been published. Gogus & Boucher (1998) have suggested one method which is based on Saaty's method but uses the upper and lower boundaries of the fuzzy triangular numbers to find the geometric mean, the maximum eigenvalue and using this new eigenvalue to calculate the consistency in a similar fashion like in a simple AHP. They even devised their own R.I. index arguing that when using fuzzy triangular numbers, one have to deal with non-integer numbers. However as argued by **Liu2017:16**, that the restrict argument of consistency is incompatible when bringing fuzzy numbers into a pairwise comparison, 'Since the judgements of the decision maker are vague, it seems unreasoning and meaningless to require the strict equality of two fuzzifying judgements obtained by using direct and indirect comparisons respectively'. Therefore, no consistency calculations regarding the FAHP method was carried out.

GIS model

The final relative weights from the MCA were brought into a GIS environment using ArcGIS where a weighted overlay was performed from the spatial analyst toolbox. The weighted overlay thus provides a given value of suitability for a given place within the environment. Several different suitability maps were created, one for the individual weights of each expert and two maps were the mean weights across all experts based on both the classical AHP method and the FAHP method showing a gradient from low to high suitability. In order to execute the weighted overlay, a visibility simulation had to be run since one of the factors of the MCA was 'Visibility from buildings'. This was done by calculating the frequency of each visible pixel of the topographic raster dataset (Figure 1b) from each point in the population density data coverage (Figure 9a). The population data coverage was set as points representing a square kilometer of populated area. This means that from every point in the population data coverage, what in the landscape, based on the topography, could be seen. The sum of every visible pixel resulted in the total visibility from every population point. Ground slope had also to be calculated. This was done with the Slope tool in ArcGIS, using the topography as input data.

The suitability map based on the mean non-fuzzy relative weights was then subjected to the constraints since only factors had been used this far. The data for the constraints were loaded into the GIS environment where their areas were subtracted from the suitability map. Buffers were created around factors regarding infrastructure such as roads and power lines and converted into polygons that were also subtracted from the suitability map.

What areas remained were those that did not overlap with any areas subjected to formal protections or legislation. From this, the top 20% most suitable areas were selected resulting in the final most suitable areas for wind turbine placement based on the parameters of this study.

4 Results

There were some significant differences between the experts weighing of the factors F1-F8 (Table 5). Factor F1 (mean wind speed) received absolutely more importance over every other factor by Expert 5. Contrary, for Expert 1, where factor F1 (mean wind speed) was deemed to not be the most important factor and several other factors (F2, F6, F8) were actually more important. Since both a classical AHP and a fuzzy AHP were conducted for comparison, the pairwise comparison matrices of the classic AHP and the FAHP are shown in Appendice (A.1-A.5, B.1-B.5).

The most important factor was F1 (mean wind speed) for Expert 2-5 (Table 5). This priority would favor economical sustainability in terms of production efficiency. Expert 1 however considered factor F6 (distance to buildings) to be the most important, which favors social sustainability instead. The importance of the rest of the factors varied among all experts. Factor F6 was of second most importance to Expert 2 and 4 while factor F8 (visibility from buildings) was second most important to Expert 1. All experts except for Expert 4 deemed factor F7 to be of little importance.

Averaging across all experts, the mean relative weights show that the most important factors when considering wind turbine placement were good wind conditions followed by distance to buildings (Table 5).

The C.R. varied quite a lot between the experts and for two of them the C.R. was above the desired maximum of 0.10, while for the other experts they were satisfyingly at around 0.10 (Table 5). The mean C.R. (0.18) is close to the 0.10 threshold and can be considered acceptable.

Just as for the classic AHP method, the non-fuzzy weights from the FAHP show that the most important factor when considering suitable wind turbine placement was good wind conditions (F1, Table 5b) for all but one of the experts (Expert 1). The second most important factor was proximity to buildings (F6) for Expert 2, 4 and 5, but ground slope (F2) for Expert 3. The visibility of the wind turbines from populated areas was of more importance for some but not for all. The least important factor was proximity to railways (2.77 %), and thus was not considered to play a role when planning wind power placement. Good wind conditions (31.60 %), proximity to buildings (21.15 %) and visibility from populated areas (13.95 %) were the most important factors to consider when suitably placing wind turbines if averaging across all experts.

Results from the classical AHP and the FAHP method did not differ very much. There was only a 1 percent difference at most (Table 5a, 5b), which suggests the FAHP method is not superior over the classical AHP method if the FAHP is conducted in the same way and with the same matrix size as in this study.

Table 5: Final relative non-fuzzy weights according to each expert and combined mean weights using the AHP and the FAHP method. Factor F1-F8; mean wind speed, ground slope, distance to roads, distance to power stations, distance to power lines (main grid), distance to buildings, distance to railroads and visibility from residential areas.

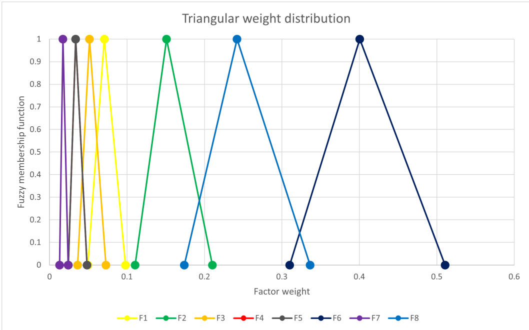
(a) Final relative non-fuzzy weights according to each expert and combined mean weights using the AHP method.

Factor	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Mean weights
F1	8.14	32.10	37.26	28.79	47.44	30.75
F2	15.55	2.48	17.16	1.94	9.30	9.29
F3	6.22	4.56	12.27	4.16	10.69	7.58
F4	3.69	6.73	16.99	6.59	5.47	7.89
F5	3.69	7.38	1.58	8.14	10.69	6.30
F6	38.13	24.55	7.59	22.75	11.57	20.92
F7	1.95	4.06	1.58	7.33	1.45	3.27
F8	22.63	18.13	5.57	20.30	3.39	14.01
C.R.	0.12	0.07	0.41	0.06	0.24	0.18

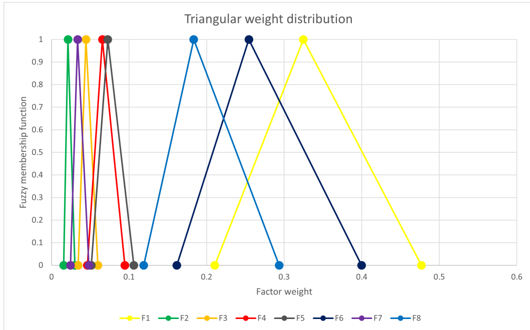
(b) Final relative non-fuzzy weights according to each expert and combined mean weights using the FAHP method.

Factor	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Mean weights
F1	7.05	31.91	42.23	28.70	48.10	31.60
F2	15.27	2.11	16.73	1.73	9.63	9.09
F3	5.19	4.36	11.39	3.86	11.43	7.25
F4	3.44	6.51	18.95	6.65	3.73	7.85
F5	3.44	7.24	1.28	8.31	11.43	6.34
F6	39.52	25.72	4.91	23.05	12.55	21.15
F7	1.75	3.36	1.28	6.43	1.03	2.77
F8	24.34	18.79	3.23	21.27	2.10	13.95

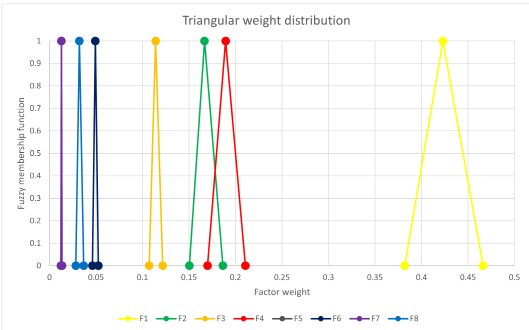
Each of the experts individual weights (Table 5) can be graphically visualized (Figure 10) and clearly shows good wind conditions as a prominent factor for wind turbine placement. Expert 3 and 5 have distinctly weighted factor F1 as more important than the other factors (Figure 10c, 10e) and Expert 2 and 4 (Figure 10b, 10d) have similar weights on all of the factors.



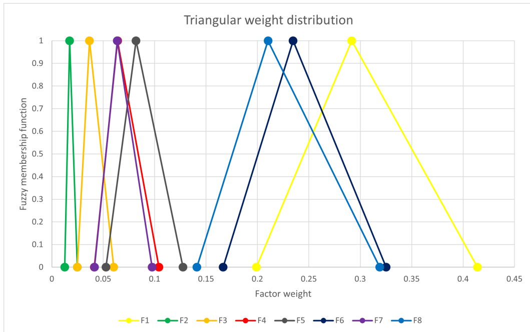
(a) Expert 1.



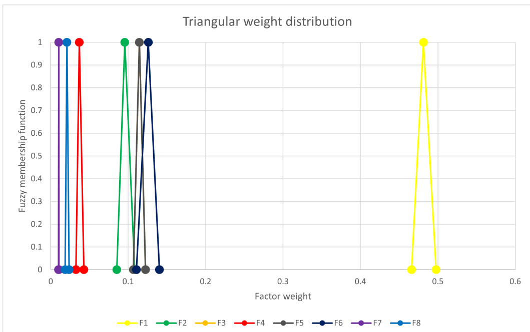
(b) Expert 2.



(c) Expert 3.



(d) Expert 4.

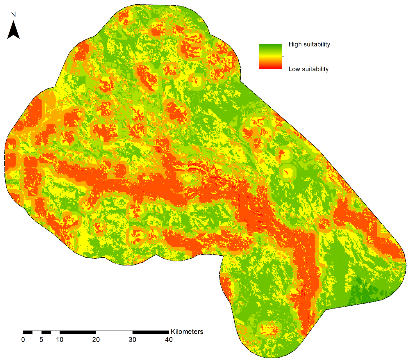


(e) Expert 5.

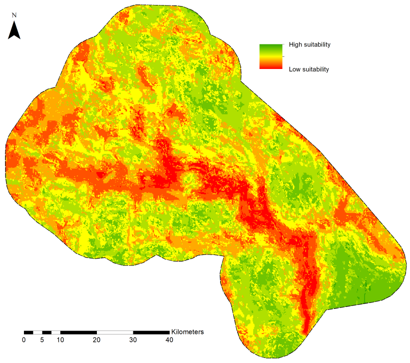
Figure 10: Distribution of non-fuzzy triangular weights of each factor according to each of the five experts where higher numbers equals more weight.

Weighted suitability in Ragunda municipality according to each expert

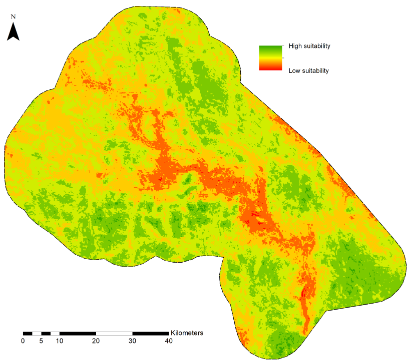
Several different suitability maps were created in a GIS environment based on the weights of each factor according to each expert (Table 5b, 11).



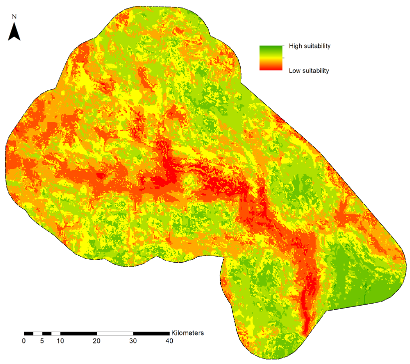
(a) Expert 1.



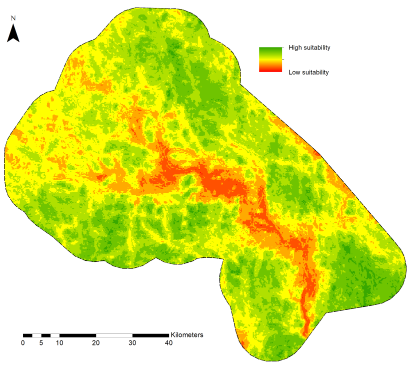
(b) Expert 2.



(c) Expert 3.



(d) Expert 4.



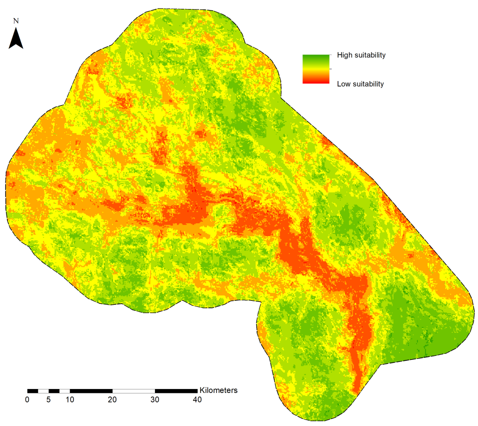
(e) Expert 5.

Figure 11: Wind turbine suitability maps of Ragunda municipality according to non-fuzzy relative weights set by each of the five experts using the FAHP method. Darker green areas represents the highest suitability and darker red areas represent very low suitability.

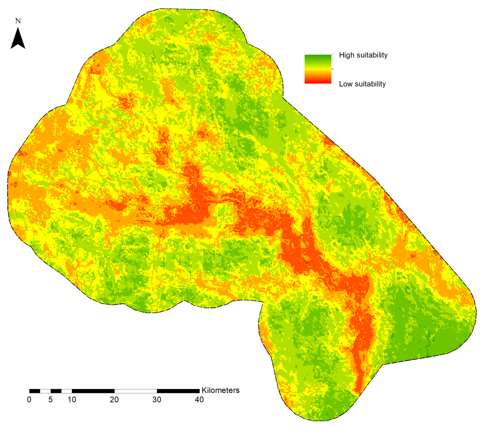
The best areas suitable for placing wind turbines generally were away from the middle and out closer towards the buffer edge, mostly to the north-east and south-east but also some suitability was present in the south-western area (Figure 11). The most import factors when choosing locations for wind turbines were good wind conditions, proximity to buildings and visibility from residential buildings (Table 5b). Corresponding to Expert 2-5, who deemed factor F1 to be of most importance, we can see similar areas being more suitable since good wind conditions was the most prominent factor (Figure 11b-11e). One overall finding among all of the suitability maps (Figure 11a-11e) was the low suitability through the middle of Ragunda municipality, which is associated with the stretch of the river Indalsälven. The river is a low-laying segment in the landscape where there are poor wind conditions. Also, the high population areas are located close to the river. For example, the most non-suitable areas highlighted in red due to Expert 1 ranking distance to buildings as the most important factor (Figure 11a).

Mean weighted suitability in Ragunda municipality

As suggested by the small difference among the weights generated by the two methods (Table 5), the output of spatial modelling of the two methods did not differ when taking the weights from both methods into a GIS environment. These maps however (Figure 12), that were based on the mean weights, show some difference from Figure (11), created with the experts individual weighing, altough they also share some similarities. The most suitable areas were mostly areas where there are high mean wind speeds and where there are no buildings close by and also where there are low chances for visibility from residential areas.



(a) Fuzzy analytical hierarchy process (FAHP).



(b) Analytical hierarchy process (AHP).

Figure 12: Wind turbine suitability maps of Ragunda municipality based on mean weights across all the experts using the AHP (b) and the FAHP (a) method.

Mean weighted suitability in Västernorrland county

For Västernorrland county, the most suitable areas for wind turbine placement were generally located away from the coast and towards the inland (Figure 13). There are good wind conditions along the coast thanks to its flat terrain and strong headwinds from the sea.

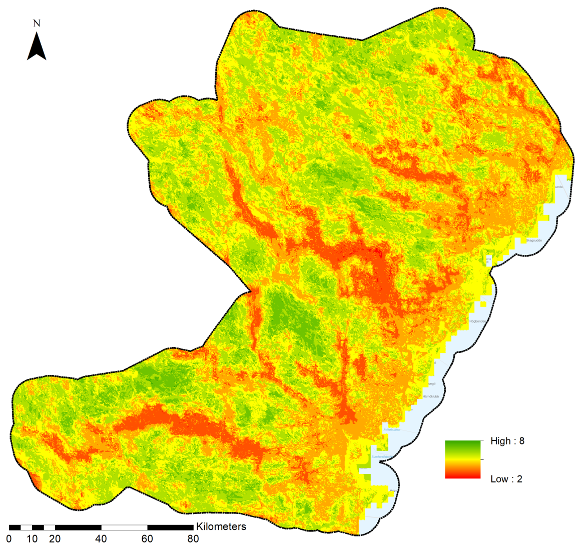


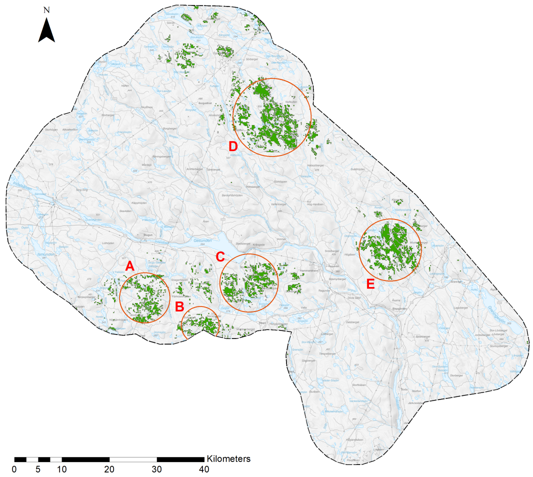
Figure 13: Wind turbine suitability map of Västernorrland county based on mean weights across all the experts using the FAHP method.

Just like for Ragunda, the lowlands and valleys of Västernorrland county's inland offers poor wind conditions and denser population which makes these places least suitable for wind turbines and show up as dark red. The best areas were mostly located inland between major rivers and populated areas and where there are good wind conditions in combination where there is not any visibility from residential areas.

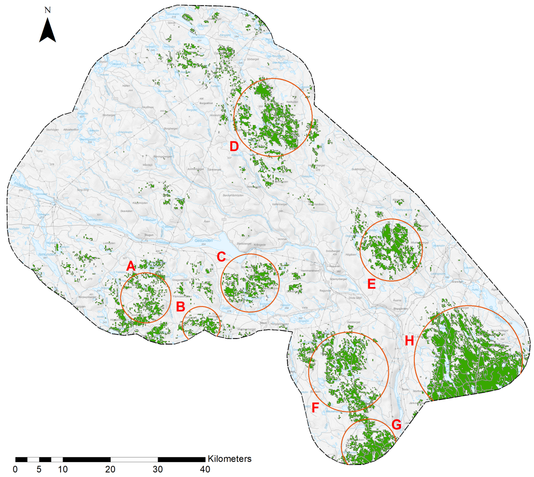
Selection of most suitable areas

From the suitability heat maps for Ragunda municipality (Figure 12) the top 20 % most suitable sites for wind turbines were selected (Figure 14).

The most suitable areas for establishing new wind turbines in Ragunda were clustered into three major areas in the northern, south-west and somewhat east parts (Figure 14a). This map was generated with areas of national interest for reindeer husbandry in mind as a stop zone. However, we can see that large areas become available if wind turbines were allowed to be placed within areas of national interest for reindeer husbandry, mainly in the south-eastern region (Figure 14b).



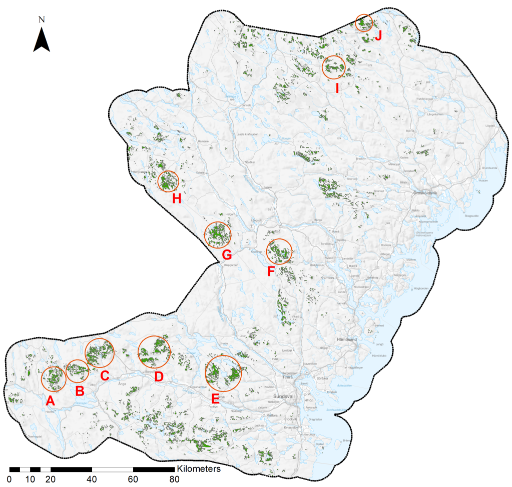
(a) Reindeer husbandry included.



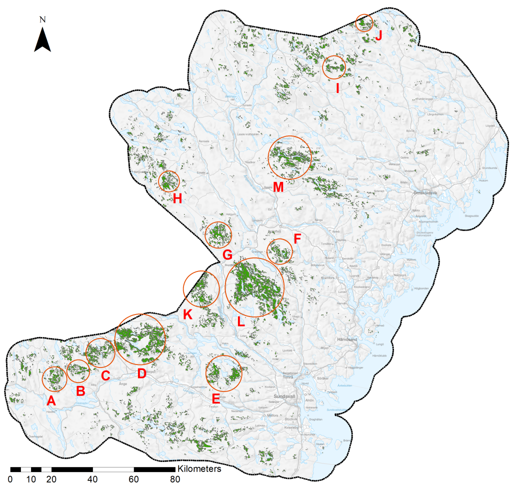
(b) Reindeer husbandry not included.

Figure 14: Most suitable (20 %) larger homogeneous areas to establish wind power turbines in Ragunda municipality, with respect to sustainability. Both with and without areas of national interest for reindeer husbandry included.

The most suitable sites in Västernorrland county were quite scattered and again these sites tend to be located towards the inland and no larger areas were located at the coast (Figure 15a). Reindeer husbandry has a large impact on available areas to choose from, illustrated by larger homogeneous areas opening up when areas of national interest for reindeer husbandry were excluded as a stop zone (Figure 15b).



(a) Reindeer husbandry included.



(b) Reindeer husbandry not included.

Figure 15: Most suitable (20 %) larger homogeneous areas to establish wind power turbines in Västernorrland county, with respect to sustainability. Both with and without areas of national interest for reindeer husbandry included.

Since large-scale wind turbine parks require a large area that can accommodate the numerous wind turbines, emphasizing the need for larger homogeneous areas that can be of interest for large-scale wind turbine planning, larger areas was highlighted with circles by visual inspection (Figure 14, 15).

If including areas for reindeer husbandry, large homogeneous areas such as area F, G and H (Figure 14) and areas L, K and M (Figure 15) disappear as potential locations for wind turbines. Excluding areas for reindeer husbandry would in other words promote economical sustainability but on the other hand, including these areas would promote social and ecological sustainability. There would be fewer disturbances from wind turbines close to residential areas and also more space for active reindeer herding.

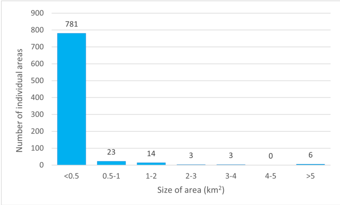
Statistical distribution of suitable areas

One important selection parameter when planning large-scale wind turbine parks is having a large enough area to accommodate a large number of wind turbines. Since Figure (14) and Figure (15) show the full extent of suitable areas, they also contain a large number of small polygons where there is not room for more than a few wind turbines or even more than one. For this purpose, Figure (16) was prepared to highlight the statistical distribution of polygons based on size from these suitability maps.

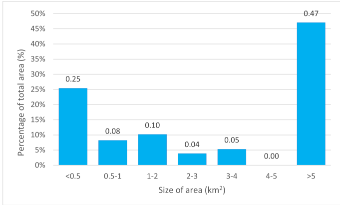
This selection highlights that there were a lot of polygons that had a size less than 0.5 km^2 and quite few that had a size that was larger than 0.5 km^2, at least when areas for reindeer husbandry was included as shown in Figure (16a). When areas for reindeer husbandry was excluded on the other hand we can see an increase across the whole of the size range, especially for areas with a size of 0.5-1 km^2 (Figure (16c).

Although there were more polygons in the lower size range, they only made up 20-25 % of the total area of the polygons and the few but very large homogeneous areas in the upper size range made up 47-60 % of the total area depending on if areas for reindeer husbandry was included or not, as shown by Figure (16b, 16d).

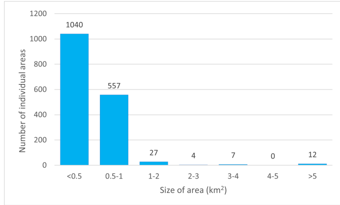
Same distribution of Figure (16a-16d) can be seen in Västernorrland as in Ragunda (Figure (16e-16h), where smaller polygons had higher frequency. Yet, when excluding areas for reindeer husbandry, the few larger areas above 5 km^2 made up the largest share of the total area, just like in Ragunda, but when areas for reindeer husbandry was included, the smaller areas below 0.5 km^2 made up the largest share of the total area instead (Figure 16f, 16h).



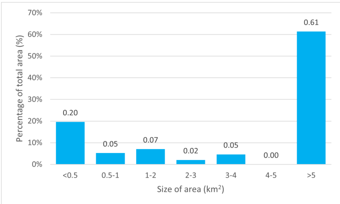
(a) Number of individual suitable areas for Ragunda municipality with areas for reindeer husbandry included.



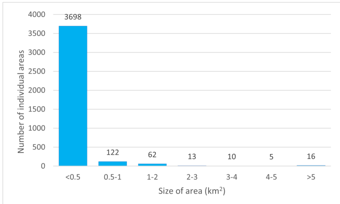
(b) Percentages of total suitable areas for Ragunda municipality with areas for reindeer husbandry included.



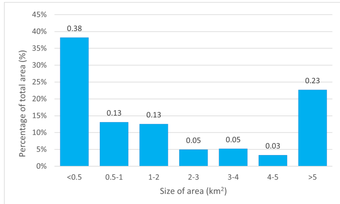
(c) Number of individual suitable areas for Ragunda municipality with areas for reindeer husbandry not included.



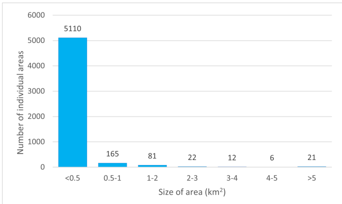
(d) Percentages of total suitable areas for Ragunda municipality with areas for reindeer husbandry not included.



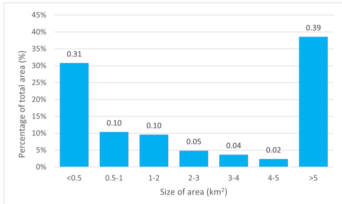
(e) Number of individual suitable areas for Västernorrland county with areas for reindeer husbandry included.



(f) Percentages of total suitable areas for Västernorrland county with areas for reindeer husbandry included.



(g) Number of individual suitable areas for Västernorrland county with areas for reindeer husbandry not included.

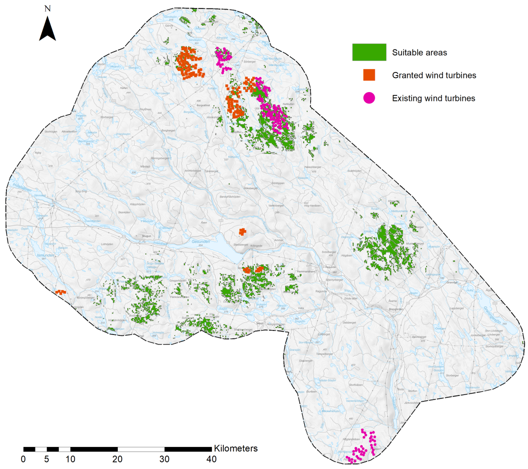


(h) Percentages of total suitable areas for Västernorrland county with areas for reindeer husbandry not included.

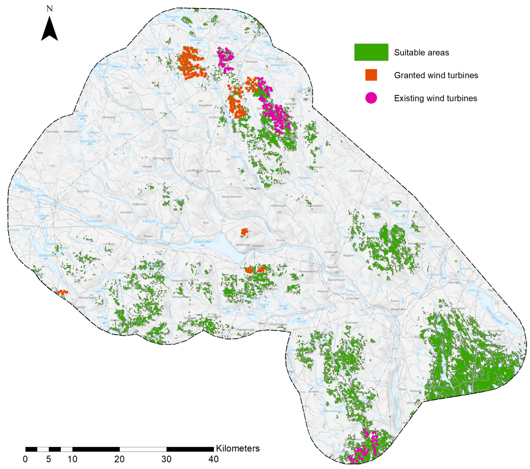
Figure 16: Total amount of individual suitable areas not connected with each other and percentages of total suitable areas, along a scale of different sizes of area in km^2, for Ragunda municipality and Västernorrland county. Both with and without areas for reindeer husbandry included.

Comparison between suitable areas and existing features

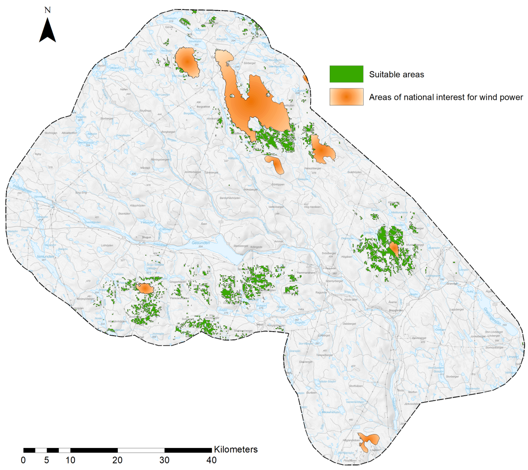
Comparison between sites deemed suitable by the parameters of this study and already exploited land by both existing wind turbines and turbines that has been granted but not yet been built was carried out (Figure 17).



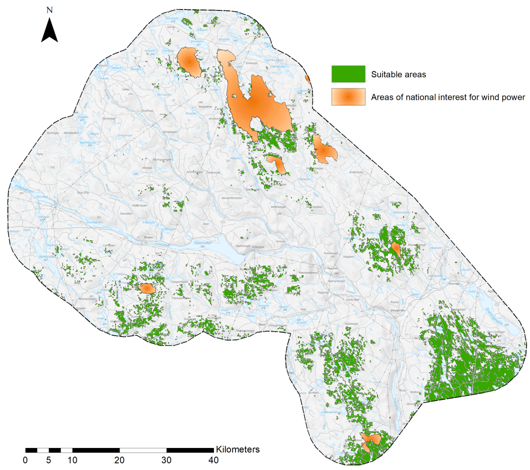
(a) Reindeer husbandry included.



(b) Reindeer husbandry not included.



(c) Reindeer husbandry included.

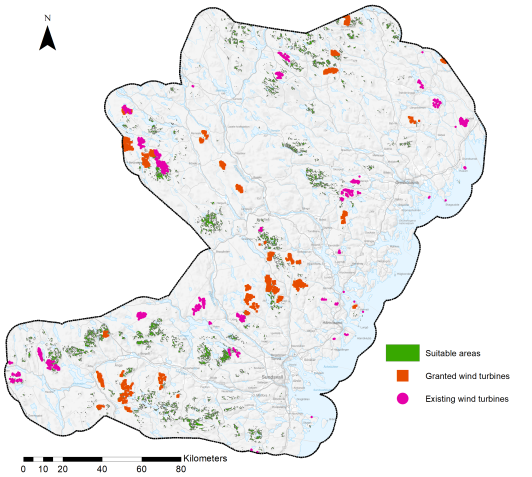


(d) Reindeer husbandry not included.

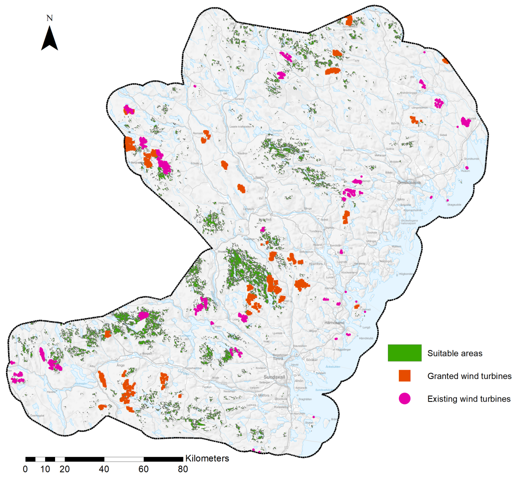
Figure 17: Comparison between existing and granted wind turbines, areas of national interest for wind power and suitable areas, where these overlap in Ragunda municipality. Both with and without areas for reindeer husbandry included.

Many of the existing and granted wind turbines are located in the northern region of the study area and especially the already existing ones are placed in fairly suitable locations in both the north and the south (Figure 17a, 17b). Some of the granted wind turbines are however located in some less suitable areas specifically a large cluster in the north-west. If areas for reindeer husbandry is included (Figure (17a), the existing wind turbines in the southern region are located poorly with respect to suitability. There are also some significant areas that could be exploited in the south and south-eastern parts if areas for reindeer husbandry is excluded as a stop zone (Figure (17b).

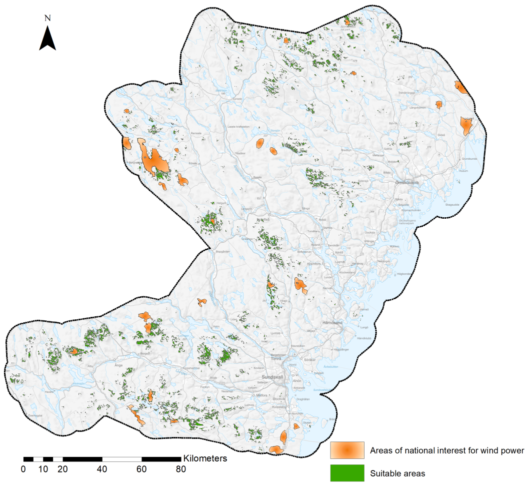
Concerning areas of national interest, these overlap fairly well with the suitable areas (Figure 17c, 17d). The largest area being in the northern part where there were suitable areas for wind turbines. However, the orange areas of national interest for wind power are all homogeneous whereas the areas deemed suitable in this study were more of a cluster of smaller areas. Again, if areas for reindeer husbandry are excluded, large areas in the south-eastern region are being overlooked as potential sites for wind turbine placement.



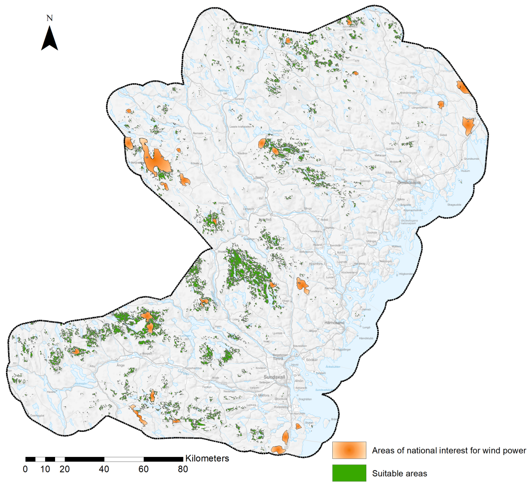
(a) Reindeer husbandry included.



(b) Reindeer husbandry included.



(c) Reindeer husbandry not included.



(d) Reindeer husbandry not included.

Figure 18: Comparison between existing and granted wind turbines (a, b), areas of national interest for wind power and suitable areas (c, d), where these overlap in Västernorrland county. Both with (a, c) and without (b, d) areas for reindeer husbandry included.

A lot of wind turbines are located at less suitable places (Figure (18a, 18b). A large number of wind turbines are located close to the coast where there were very low suitability. If areas for reindeer husbandry are excluded as a stop zone a smaller number of wind turbines are placed less suitable, especially in the central region of the county. The wind turbines are more scattered in Västernorrland county and there are also a number of groups that contain few individual wind turbines which require a smaller homogeneous suitable area.

There are also areas of national interest for wind power in Västernorrland that are located close to the coast but do not overlap with any suitable areas (Figure 18c, 18d). The largest area of national interest is located in the north-western part, being the same area that is in Ragunda thanks to the buffer.

Just as in Ragunda, Västernorrland also has large areas that go overlooked as potential sites for wind turbines if areas for reindeer husbandry is excluded.

5 Discussion

This study takes into account the aspects of sustainable development when siting wind turbines to find the most suitable locations for wind turbines and provide an overview of potential suitable sites that potentially can be implemented in municipal and county territorial planning.

It was not surprising that that good wind conditions was the dominating factor for wind power placement. It was however interesting that it was not the most important factor for all of the experts. One expert thought good wind conditions was the fourth most important factor when choosing wind turbine placement from their perspective. Good wind conditions was indeed the most important factor but it shows that experts have different opinions on what constitute suitable locations. Consequently, as a starting point for evaluation there is a need to compile and analyse a wide set of data that reflects wide perspectives and opinions.

Based on the factor for mean wind speed alone, locating on-shore wind turbines along the coast would be a good idea. However, most people live by the coast and since proximity to buildings and visibility from residential areas were the second and third most important factors, it makes the coast a less suitable area for establishing wind turbines if considering sustainability as a whole.

Multi-criteria analysis is a powerful tool to combine with GIS and different weights affect the outcome of suitable areas. There were low and high values of suitability present in almost the same locations in every one of the individual suitability maps of each expert but it is the values in between, where compromises on suitability could be made, that were changing across all experts and choice of weights.

In this study, 8 factors and 23 constraints were used to model wind turbine suitability but more data could be used and could yield different results. Military areas and objects were not included in this model but could be used as constraints just as Ali et al. (2017), Van Haaren & Fthenakis (2011) and Siyal et al. (2015) did in their research. There is not really any limit on how many constraints to use in the model and by excluding more protected areas and attributes, the sustainability generally increases. However, constraints might in some cases be in conflict. For example, a constraint inherent to the environmental aspect can conflict a constraint inherent to the social aspect. Affordable and clean energy (UN Agenda 2030 goal 7, UN 2021) in the form of more wind turbines is conflicting sustainable cities and communities (UN Agenda 2030 goal 11, UN 2021) because local residents are opposed to wind turbines being built in proximity to their homes. Which should be prioritised? Probably none of them if total sustainability is the goal (Nilsson et al. 2016). An analysis on a local level based on the parameters of the specific situation is always preferable and should be performed in order to further distinguish between options on a macro and micro scale an thus making it easier to make a decision.

Uncertainties and errors

The main uncertainty of the final results as seen in Figure (14, 15) was due to the visibility analysis made for residential areas as seen in Figure (9b). Figure (9b) was created based on topographical data and the population density coverage. The idea was originally to use topographical data combined with data on height and coverage of vegetation and buildings, and assumptions on the height of wind power plants. It was however difficult to procure and shortcuts had to be made and no vegetation or buildings are present in the visibility analysis, only the ground elevation. The other problem with the visibility analysis was that buildings were not really represented as viewpoints. The only data available at the time of this study was population in form of a grid of squares of one square kilometer and no data on individual buildings as points were available, which would have been preferable. Since a visibility analysis in a GIS environments deal with observer points, the only option was to create points at the center of the population squares, making it even less accurate. There is also the problem with varying height of wind turbines. Since construction height can vary a lot and future wind turbines becoming increasingly higher (Energimyndigheten 2021b), it is difficult to model visibility across a large amount of observer points with varying heights of target objects over a landscape with varying vegetation and building heights. Manchado et al. (2013) proposed an alternative visibility modelling procedure which can be implemented during the design process to evaluate different locations, focusing only on visibility of wind turbines. They stated that it could be combined with MCA but further improvements was needed to incorporate this method with other criteria. One could set an offset mean height across all of the landscape, same goes for trees and other vegetation but that would assume that wind turbines could be placed anywhere and the height of trees are the same across the whole landscape which is not feasible. So instead the vegetation and buildings as obstacles were not included in the model which opts for more visibility due to lack of hindering objects but wind turbines had been set to height zero. The two errors works against each other since one overestimates the visibility and the other underestimates it but it is still a poor representation of real conditions. One other option would be to let the wind turbines be set as observer points and simulate visibility across the landscape with different heights of the wind turbines. In this way, several maps could be produced, highlighting the visibility across the landscape based on varying turbine height. The visibility data was part of the weighted overlay with weights from the MCA. Visibility from buildings did not receive a very high weight of importance in the MCA, coming in at around 14 % which does not make it contribute a significant deal but nonetheless noticeable.

The inconsistency for some of the experts in the pairwise comparisons of the multi-criteria analysis could be, to some degree, explained by some experts had limited knowledge of some of the factors and could not to a full extent weigh all factors against each other desirably and had to set an arbitrary weight. This shows that MCA needs to be made with the recipients in mind so that they can perform rational pairwise comparisons that does not contradict each other and are feasible in regard to actual conditions.

Reindeer husbandry

The subject of reindeer husbandry along with wind power has been a highly debated topic in Sweden (Helldin et al. 2012). Wind turbines has been sited inside areas for reindeer husbandry historically and can potentially be today as well but since many of these areas became of national interest to preserve reindeer herding, it has become more difficult to justify siting in such areas since wind turbine construction affect reindeer habitat selection and calving sites (Skarin et al. 2018; Skarin et al. 2021). For the sake of this study, since these areas take up a substantial amount of land coverage, it seemed reasonable to model two different scenarios where areas for reindeer husbandry were incredibly important and set as no-go-zones and where they were completely overlooked, showing both sides as it were and with the argument that a situational assessment of individual cases should always be carried out any way. The results show that large areas for potential wind turbine placement opens up if areas for reindeer husbandry are removed as a constraint and since wind power is especially important and of national interest to achieve both the renewable energy goal by 2040 and to do it in a sustainable manner, the potential suitable areas for wind power inside areas for reindeer husbandry are conflicting and is still highly debatable. Reindeer husbandry is found only in the most northern parts of the world, and this makes it a regional phenomenon to include in this sort of GIS study. This constraint was not found in any other GIS MCA study in Sweden except for Kandy (2018) who modelled reindeer husbandry as a stop zone. Here, wind turbine placement was prohibited but they did not analyse alternatives where it would be allowed to place wind turbines inside areas for reindeer husbandry as was conducted in this study.

Multi-criteria analysis

The multi-criteria analysis performed in this study was in itself not an issue and worked very well regarding the operability of creating pairwise comparison matrices and calculating the weights. The issue lied with how the pairwise comparisons were gathered from experts, their perception of what the factors actually means could differ. Many of the experts expressed concerns about how difficult it was to decide if a factor was more or less important than a factor that they do not work with in a professional capacity, which Esmail & Geneletti (2018) also states as a common pitfall in MCA. Take ground slope as an example. One expert had no problem comparing it to mean wind speed while another thought ground slope was unimportant and had difficulties comparing its importance to mean wind speed because the expert had no inherent knowledge about to which degree slope mattered in a more detailed context. Esmail & Geneletti (2018) states that objectives and criteria must be chosen to fit the problem according to the stakeholders concerns rather than to conform to any expert-based hierarchy or criteria. Esmail & Geneletti (2018) also suggests that the problem definition should be carried out before choosing the criteria along with decision-makers, stakeholders and topic-experts. These results emphasize the relevance of experts background and previous knowledge when weighting different factors against each other. Which also suggests that involving individuals from the public when using technical factors can be difficult but can be highly relevant when considering social factors. Moreover, it highlights the importance of clarifying the meaning of each factor previous the survey to each participant. Higher inconsistency in their pairwise comparison may suggest different perception of the meaning of the factors by the experts as seen for Expert 3 and 5 in this study. Perhaps it could be advantageous to perform workshops where experts can discuss pairwise comparisons and exchange experience and knowledge to get a better and more consistent weighing just like Kandy (2018) performed. Also more experts participating would lower the overall inconsistency. One would first have to decide what sort of MCA to conduct since when using fuzzy triangular numbers in combination with MCA methodology, increases the difficulty of calculating consistency and Ali et al. (2017) did likewise as in this study, choose to exclude calculating consistency when using FAHP methodology.

AHP vs FAHP

As shown in this study, there was no large difference between the two MCA methods when modelling in a GIS environment. This is supported by Chan et al. (2019) findings that there is a difference between AHP and FAHP even for small matrix sizes but a significant difference cannot usually be observed unless the level of fuzziness is high. The FAHP method that involves fuzzy triangular numbers was more time consuming to use and only yielded a difference of a mere 1 percent between the same factors when comparing with the AHP method. There is nothing really arguing for involving fuzzy theory and methodology when doing a MCA in order to find most suitable locations for wind turbine placement with a small matrix size. The AHP method would suffice in this instance as it is a method that is easier to use and less time consuming. Fuzzy triangular numbers in MCA procedures could have its place if more factors would be used and larger comparison matrices needed to be used and as well as a more fuzzy terminology in the verbal terms, as suggested by Chan et al. (2019). The main advantage of the AHP method is that consistency calculations can be performed to evaluate the MCA framework and improve it.

Further studies and improvements

Further studies should focus on acquiring better underlying data such as lidar data that includes vegetation, especially trees and buildings to be able to model visibility more accurately. There is room to explore different kinds of data to build constraints and factors connected to ecological, socio-cultural and economical sustainability that further captures the wide spectrum of sustainability. Relatively large areas was modelled in this study but there is no reason even larger areas could be subjected to this kind of methodology. The challenge when working with large spatial areas is handling the very huge datasets that comes with it, depending on what level of accuracy and precision is sought after. A very large study area might be susceptible to lesser precision than a smaller local area because high precision might be less vital over a large area. It varies from case to case and what is being modelled. There is however a limit on how small areas that can be modelled since formal protections and land use usually cover a significant area, modelling smaller areas that does not contain multiple factors and constraints seems futile and pointless.

One useful improvement would be to explore ways a multi-criteria analysis could be conducted since there were some issues regarding the setup of the multi-criteria analysis in this study. The main issue being the MCA was not adapted fully to the experts backgrounds which led to inconsistency in the pairwise comparison matrices since lack of knowledge about one factor was difficult for the experts to weigh against the other factors. Improving the relevance of the factors for the individuals doing the weighing could improve consistency as well. Of course to obtain weights that are well represented could mean more people that are involved in weighing the factors and perhaps including the public opinion would be a way to further stabilize the social sustainability aspect.

6 Conclusion

Sustainable wind turbine placement was modelled in a GIS environment based on constraints and factors weighted by experts in a fuzzy analytical hierarchy process in Ragunda municipality and Västernorrland county. The most suitable wind turbine locations were selected and compared to existing wind turbines and areas pointed out as national interest for wind power. Results showed that good wind conditions was the most prominent factor to consider when siting wind turbines. No significant difference was observed when fuzzy analytical hierarchy process was used instead of classic analytical hierarchy process when modelling suitable wind turbine placement in a GIS environment. Potential suitable areas that has not yet been exploited by wind power exists both in Ragunda and Västernorrland that takes into account ecological, social and economic criteria to maximize sustainable development. Care however should be taken when forming the framework for the multi-criteria analysis and when choosing factors to weigh and varying cases can need different frameworks. Not every individual might have the experience or knowledge necessary to be able to weigh a certain factor. Also, choosing relevant factors for the situation is important.

The methodology used in this study in order to select suitable places for wind turbines offers a way to relatively easily promote sustainable development and satisfactory account for ecological, socio-cultural and economical sustainability. It yields results that are easy to comprehend and the insight can help decision makers find the best locations to establish new wind turbines and take into account different viewpoints and aspects of sustainability, meeting the demands of modern debate.

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Appendices

A Analytical Hierarchy Process pairwise comparison matrices

Table A.1: AHP pairwise comparison matrix containing weights set by Expert 1. Factor F1-F8; mean wind speed, ground slope, distance to roads, distance to power stations, distance to power lines (main grid), distance to buildings, distance to railroads and visibility from residential areas.

Factor	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**
F1	1	1/5	3	3	3	1/9	7	1/7
F2	5	1	5	6	6	1/6	7	1/4
F3	1/3	1/5	1	3	3	1/9	5	1/7
F4	1/3	1/6	1/3	1	1	1/7	3	1/5
F5	1/3	1/6	1/3	1	1	1/7	3	1/5
F6	9	6	9	7	7	1	9	3
F7	1/7	1/7	1/5	1/3	1/3	1/9	1	1/7
F8	7	4	7	5	5	1/3	7	1

Table A.2: AHP pairwise comparison matrix containing weights set by Expert 2. Factor F1-F8; mean wind speed, ground slope, distance to roads, distance to power stations, distance to power lines (main grid), distance to buildings, distance to railroads and visibility from residential areas.

Factor	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**
F1	1	8	5	5	5	2	9	3
F2	1/8	1	1	1/5	1/5	1/8	1/5	1/7
F3	1/5	1	1	1	1	1/6	1	1/5
F4	1/5	5	1	1	1	1/5	3	1/4
F5	1/5	5	1	1	1	1/4	4	1/3
F6	1/2	8	6	5	4	1	8	2
F7	1/9	5	1	1/3	1/4	1/8	1	1/8
F8	1/3	7	5	4	3	1/2	8	1

Table A.3: AHP pairwise comparison matrix containing weights set by Expert 3. Factor F1-F8; mean wind speed, ground slope, distance to roads, distance to power stations, distance to power lines (main grid), distance to buildings, distance to railroads and visibility from residential areas.

Factor	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**
F1	1	7	9	7	9	9	9	8
F2	1/7	1	9	1/5	9	9	9	8
F3	1/9	1/9	1	1	9	9	9	8
F4	1/7	5	1	1	9	9	9	8
F5	1/9	1/9	1/9	1/9	1	1/9	1	1/9
F6	1/9	1/9	1/9	1/9	9	1	9	7
F7	1/9	1/9	1/9	1/9	1	1/9	1	1/9
F8	1/8	1/8	1/8	1/8	9	1/7	9	1

Table A.4: AHP pairwise comparison matrix containing weights set by Expert 4. Factor F1-F8; mean wind speed, ground slope, distance to roads, distance to power stations, distance to power lines (main grid), distance to buildings, distance to railroads and visibility from residential areas.

Factor	F1	F2	F3	F4	F5	F6	F7	F8
F1	1	8	6	6	5	1	6	2
F2	1/8	1	1/5	1/5	1/5	1/8	1/6	1/8
F3	1/6	5	1	1/2	1/2	1/7	1/4	1/7
F4	1/6	5	2	1	1	1/3	1/2	1/3
F5	1/5	5	2	1	1	1/3	3	1/3
F6	1	8	7	3	3	1	6	1
F7	1/6	6	4	2	1/3	1/6	1	1/5
F8	1/2	8	7	3	3	1	5	1

Table A.5: AHP pairwise comparison matrix containing weights set by Expert 5. Factor F1-F8; mean wind speed, ground slope, distance to roads, distance to power stations, distance to power lines (main grid), distance to buildings, distance to railroads and visibility from residential areas.

Factor	F1	F2	F3	F4	F5	F6	F7	F8
F1	1	9	9	9	9	9	9	9
F2	1/9	1	1	5	1	1/3	9	7
F3	1/9	1	1	7	1	1	9	7
F4	1/9	1/5	1/7	1	1/7	1/5	9	7
F5	1/9	1	1	7	1	1	9	7
F6	1/9	3	1	5	1	1	9	7
F7	1/9	1/9	1/9	1/9	1/9	1/9	1	1/9
F8	1/9	1/7	1/7	1/7	1/7	1/7	9	1

B Fuzzy Analytical Hierarchy Process pair-wise comparison matrices

Table B.1: Comparison matrix containing fuzzy triangular weights according to Expert 1.Factor F1-F8; mean wind speed, ground slope, distance to roads, distance to power stations, distance to power lines (main grid), distance to buildings, distance to railroads and visibility from residential areas.

Factor	F1	F2	F3	F4	F5	F6	F7	F8
F1	(1, 1, 1)	(1/6, 1/5, 1/4)	(2, 3, 4)	(2, 3, 4)	(2, 3, 4)	(1/9, 1/9, 1/9)	(6, 7, 8)	(1/8, 1/7, 1/6)
F2	(4 ,5 ,6)	(1, 1, 1)	(4, 5, 6)	(5, 6, 7)	(5, 6, 7)	(1/7, 1/6, 1/5)	(6, 7, 8)	(1/5, 1/4, 1/3)
F3	(1/4, 1/3, 1/2)	(1/6, 1/5, 1/4)	(1, 1, 1)	(2, 3, 4)	(2, 3, 4)	(1/9, 1/9, 1/9)	(4, 5, 6)	(1/8, 1/7, 1/6)
F4	(1/4, 1/3, 1/2)	(1/7, 1/6, 1/5)	(1/4, 1/3, 1/2)	(1, 1, 1)	(1, 1, 1)	(1/8, 1/7, 1/6)	(2, 3, 4)	(1/6, 1/5, 1/4)
F5	(1/4, 1/3, 1/2)	(1/7, 1/6, 1/5)	(1/4, 1/3, 1/2)	(1, 1, 1)	(1, 1, 1)	(1/8, 1/7, 1/6)	(2, 3, 4)	(1/6, 1/5, 1/4)
F6	(9, 9, 9)	(5, 6, 7)	(9, 9, 9)	(6, 7, 8)	(6, 7, 8)	(1, 1, 1)	(9, 9, 9)	(2, 3, 4)
F7	(1/8, 1/7, 1/6)	(1/8, 1/7, 1/6)	(1/6, 1/5, 1/4)	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)	(1/9, 1/9, 1/9)	(1, 1, 1)	(1/8, 1/7, 1/6)
F8	(6, 7, 8)	(3, 4, 5)	(6, 7, 8)	(4, 5, 6)	(4, 5, 6)	(1/4, 1/3, 1/2)	(6, 7, 8)	(1, 1, 1)

Table B.2: Comparison matrix containing fuzzy triangular weights according to Expert 2. Factor F1-F8; mean wind speed, ground slope, distance to roads, distance to power stations, distance to power lines (main grid), distance to buildings, distance to railroads and visibility from residential areas.

Factor	F1	F2	F3	F4	F5	F6	F7	F8
F1	(1, 1, 1)	(7, 8, 9)	(4 ,5 ,6)	(4 ,5 ,6)	(4 ,5 ,6)	(1, 2, 3)	(9, 9, 9)	(2, 3, 4)
F2	(1/9, 1/8, 1/7)	(1, 1, 1)	(1, 1, 1)	(1/6, 1/5, 1/4)	(1/6, 1/5, 1/4)	(1/9, 1/8, 1/7)	(1/6, 1/5, 1/4)	(1/8, 1/7, 1/6)
F3	(1/6, 1/5, 1/4)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1/7 ,1/6, 1/5)	(1, 1, 1)	(1/6, 1/5, 1/4)
F4	(1/6, 1/5, 1/4)	(4 ,5 ,6)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1/6, 1/5, 1/4)	(2, 3, 4)	(1/5, 1/4, 1/3)
F5	(1/6, 1/5, 1/4)	(4 ,5 ,6)	(5, 6, 7)	(4 ,5 ,6)	(3, 4, 5)	(1, 1, 1)	(7, 8, 9)	(1, 2, 3)
F7	(1/9, 1/9, 1/9)	(4, 5, 6)	(1, 1, 1)	(1/4, 1/3, 1/2)	(1/5, 1/4, 1/3)	(1/9, 1/8, 1/7)	(1, 1, 1)	(1/9, 1/8, 1/7)
F8	(1/4, 1/3, 1/2)	(6, 7, 8)	(4 ,5 ,6)	(3, 4, 5)	(2, 3, 4)	(1/3, 1/2, 1)	(7, 8, 9)	(1, 1, 1)

Table B.3: Comparison matrix containing fuzzy triangular weights according to Expert 3. Factor F1-F8; mean wind speed, ground slope, distance to roads, distance to power stations, distance to power lines (main grid), distance to buildings, distance to railroads and visibility from residential areas.

Factor	F1	F2	F3	F4	F5	F6	F7	F8
F1	(1, 1, 1)	(6, 7, 8)	(9, 9, 9)	(6, 7, 8)	(9, 9, 9)	(9, 9, 9)	(9, 9, 9)	(7, 8, 9)
F2	(1/8, 1/7, 1/6)	(1, 1, 1)	(9, 9, 9)	(1/6, 1/5, 1/4)	(9, 9, 9)	(9, 9, 9)	(9, 9, 9)	(7, 8, 9)
F3	(1/9, 1/9, 1/9)	(1/9, 1/9, 1/9)	(1, 1, 1)	(1, 1, 1)	(9, 9, 9)	(9, 9, 9)	(9, 9, 9)	(7, 8, 9)
F4	(1/8, 1/7, 1/6)	(4 ,5 ,6)	(1, 1, 1)	(1, 1, 1)	(9, 9, 9)	(9, 9, 9)	(9, 9, 9)	(7, 8, 9)
F5	(1/9, 1/9, 1/9)	(1/9, 1/9, 1/9)	(1/9, 1/9, 1/9)	(1/9, 1/9, 1/9)	(1, 1, 1)	(1/9, 1/9, 1/9)	(1, 1, 1)	(1/9, 1/9, 1/9)
F6	(1/9, 1/9, 1/9)	(1/9, 1/9, 1/9)	(1/9, 1/9, 1/9)	(1/9, 1/9, 1/9)	(9, 9, 9)	(1, 1, 1)	(9, 9, 9)	(6, 7, 8)
F7	(1/9, 1/9, 1/9)	(1/9, 1/9, 1/9)	(1/9, 1/9, 1/9)	(1/9, 1/9, 1/9)	(1, 1, 1)	(1/9, 1/9, 1/9)	(1, 1, 1)	(1/9, 1/9, 1/9)
F8	(1/9, 1/8, 1/7)	(1/9, 1/8, 1/7)	(1/9, 1/8, 1/7)	(1/9, 1/8, 1/7)	(9, 9, 9)	(1/8, 1/7, 1/6)	(9, 9, 9)	(1, 1, 1)

Table B.4: Comparison matrix containing fuzzy triangular weights according to Expert 4. Factor F1-F8; mean wind speed, ground slope, distance to roads, distance to power stations, distance to power lines (main grid), distance to buildings, distance to railroads and visibility from residential areas.

Factor	F1	F2	F3	F4	F5	F6	F7	F8
F1	(1, 1, 1)	(7, 8, 9)	(5, 6, 7)	(5, 6, 7)	(4 ,5 ,6)	(1, 1, 1)	(5, 6, 7)	(1, 2, 3)
F2	(1/9, 1/8, 1/7)	(1, 1, 1)	(1/6, 1/5, 1/4)	(1/6, 1/5, 1/4)	(1/6, 1/5, 1/4)	(1/9, 1/8, 1/7)	(1/7, 1/6, 1/5)	(1/9, 1/8, 1/7)
F3	(1/7, 1/6, 1/5)	(4 ,5 ,6)	(1, 1, 1)	(1/3, 1/2, 1)	(1/3, 1/2, 1)	(1/8, 1/7, 1/6)	(1/5, 1/4, 1/3)	(1/8, 1/7, 1/6)
F4	(1/7, 1/6, 1/5)	(4 ,5 ,6)	(1, 2, 3)	(1, 1, 1)	(1, 1, 1)	(1/4, 1/3, 1/2)	(1/3, 1/2, 1)	(1/4, 1/3, 1/2)
F5	(1/6, 1/5, 1/4)	(4 ,5 ,6)	(1, 2, 3)	(1, 1, 1)	(1, 1, 1)	(1/4, 1/3, 1/2)	(2, 3, 4)	(1/4, 1/3, 1/2)
F6	(1, 1, 1)	(7, 8, 9)	(6, 7, 8)	(2, 3, 4)	(2, 3, 4)	(1, 1, 1)	(5, 6, 7)	(1, 1, 1)
F7	(1/7, 1/6, 1/5)	(5, 6, 7)	(3, 4, 5)	(1, 2, 3)	(1/4, 1/3, 1/2)	(1/7 ,1/6, 1/5)	(1, 1, 1)	(1/6, 1/5, 1/4)
F8	(1/3, 1/2, 1)	(7, 8, 9)	(6, 7, 8)	(2, 3, 4)	(2, 3, 4)	(1, 1, 1)	(4, 5, 6)	(1, 1, 1)

Table B.5: Comparison matrix containing fuzzy triangular weights according to Expert 5. Factor F1-F8; mean wind speed, ground slope, distance to roads, distance to power stations, distance to power lines (main grid), distance to buildings, distance to railroads and visibility from residential areas.

Factor	F1	F2	F3	F4	F5	F6	F7	F8
F1	(1, 1, 1)	(9, 9, 9)	(9, 9, 9)	(9, 9, 9)	(9, 9, 9)	(9, 9, 9)	(9, 9, 9)	(9, 9, 9)
F2	(1/9, 1/9, 1/9)	(1, 1, 1)	(1, 1, 1)	(4 ,5 ,6)	(1, 1, 1)	(1/4, 1/3, 1/2)	(9, 9, 9)	(6, 7, 8)
F3	(1/9, 1/9, 1/9)	(1, 1, 1)	(1, 1, 1)	(6, 7, 8)	(1, 1, 1)	(1, 1, 1)	(9, 9, 9)	(6, 7, 8)
F4	(1/9, 1/9, 1/9)	(1/6, 1/5, 1/4)	(1/8, 1/7, 1/6)	(1, 1, 1)	(1/8, 1/7, 1/6)	(1/6, 1/5, 1/4)	(9, 9, 9)	(6, 7, 8)
F5	(1/9, 1/9, 1/9)	(1, 1, 1)	(1, 1, 1)	(6, 7, 8)	(1, 1, 1)	(1, 1, 1)	(9, 9, 9)	(6, 7, 8)
F6	(1/9, 1/9, 1/9)	(2, 3, 4)	(1, 1, 1)	(4 ,5 ,6)	(1, 1, 1)	(1, 1, 1)	(9, 9, 9)	(6, 7, 8)
F7	(1/9, 1/9, 1/9)	(1/9, 1/9, 1/9)	(1/9, 1/9, 1/9)	(1/9, 1/9, 1/9)	(1/9, 1/9, 1/9)	(1/9, 1/9, 1/9)	(1, 1, 1)	(1/9, 1/9, 1/9)
F8	(1/9, 1/9, 1/9)	(1/8, 1/7, 1/6)	(1/8, 1/7, 1/6)	(1/8, 1/7, 1/6)	(1/8, 1/7, 1/6)	(1/8, 1/7, 1/6)	(9, 9, 9)	(1, 1, 1)