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Site selection for onshore wind energy in Iceland using GIS-based mapping

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ABSTRACT

Iceland's significant onshore wind energy potential remains untapped, with no operational wind farms despite recognized opportunities for over a decade. Two wind energy projects, approved under Iceland's Master Plan for Nature Protection and Energy Utilization – a legally enshrined Multi-Criteria Decision Analysis (MCDA) tool – are poised to initiate this transition, supporting the nation's goal of achieving net-zero greenhouse gas emissions by 2040. Originally designed for geothermal and hydropower projects, the Master Plan's methodology is now adapting to evaluate onshore wind energy projects, amid growing global use of Geographic Information System (GIS) mapping to optimise site selection. This study's review examines the novel application of advanced GIS-based MCDA, including 3D visualisations and high-resolution data, to enhance Iceland's Master Plan for strategically identifying low-impact onshore wind energy sites while balancing environmental, social, and infrastructural factors. These include visual impacts, bird habitats, noise, shadow flicker, and proximity to protected areas and population centres. By integrating advanced GIS tools such as viewshed analysis and 3D visualizations, the study highlights how these methods can potentially mitigate adverse effects and improve social acceptance. The paper considers the potential for further integration of GIS-based analysis into Iceland's emerging wind energy regulatory framework, which could help to provide insights to national decision-makers who are seeking to balance appropriate renewable energy development with environmental and societal priorities.

1. Introduction

Onshore wind energy is a new technology in Iceland, currently comprising a few turbines and contributing a token 0.03 % of national electricity generation [1]. However, given the strong productive potential of onshore wind power [2–4] there are plans for its expansion [5], partly with the aim of helping to satisfy Iceland's commitments regarding reducing greenhouse gas emissions to net zero by 2040 [6]. All renewable energy projects of greater than 10 MW in scale must be assessed by Iceland's Master Plan for Nature Protection and Energy Utilization (Master Plan) and agreed by the nation's Parliament, a legal instrument which constitutes a comprehensive form of MCDA, a strategic evaluation incorporating environmental, socio-cultural, and economic impacts, the outcomes of which inform national decision-making [7–9]. A 120 MW wind farm at Búrfellslundur, where two 0.9 MW test wind turbines have operated for a decade, has been awarded a production license [10] and is likely to be the first major wind power project in Iceland, having been classed in the utilization category by the Icelandic Parliament once it agreed the Master Plan in 2022. Another project of 100 MW at Blöndulundur is also planned and classed in the utilization category by Iceland's Master Plan [11]. Recently, the fifth phase of the Master Plan's evaluation considered ten potential onshore wind energy projects in Iceland, placing these into the 'on hold' category, pending further information, and a further twenty-seven wind energy projects are set to be evaluated in future Master Plan phases.

Despite the various uses of wind power, its growing significance as a share of global electricity production [12–14], and environmental advantages in comparison to fossil fuel powered alternatives [15,16], the negative locational consequences of wind turbine installations and wind farms have often been to the fore in the public and planning discourse about the merits of the technology [17–20]. In the case of impacts located close to the site of onshore wind farms, the most often cited issues are negative effects on birds [21–23], altered landscape aesthetics (Vlami et al., 2016), shadow flickering and safety risks [24,25], and health impacts from noise [26]. The visual impacts of turbines and wind farm arrays are commonly cited concerns and can in some instances

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present a blight over long distances [27–29]. Offsite issues, such as the construction of access roads and power line infrastructure, often constitute additional concerns [30]. Connected to these various issues, several studies have also focused on the themes of social acceptance and how best to cultivate a social license to operate [28,31–34].

The various environmental, social, and economic implications of renewable energy projects and systems frequently demand advanced decision support platforms to determine the optimality of proposals [35–42]. This was the intention of Iceland's Master Plan, that has established analytical framework to evaluate the optimality of geothermal and hydropower projects and already done assessment of many such projects but is now advancing on assessing the upcoming wind energy projects. Each of these renewable energy options has its own attributes and characteristics that are important to understand. Important for Iceland is that elsewhere, an increasing number of studies have utilised Geographic Information System (GIS) mapping in tandem with Multi-Criteria Decision Analysis (MCDA) to enrich the data pool available to decision-makers for determining optimal scale and location, as well as suitable distance thresholds away from various features, including birds, antennae, and protected areas, among many others [41,43,44]. The aim of GIS mapping is to store, retrieve, manipulate, analyse, and map geographical data [24,37,45], approaches that are frequently conducted globally in MCDA to evaluate the optimality and sustainability of onshore wind energy projects [41,43,44]. The recent study by Cook and Pétursson [46] appraised the increasingly significant role of GIS-based analysis, finding that the criteria most commonly evaluated in the GIS-MCDA literature on onshore wind energy projects include the following.

- Environmental impacts (e.g., visual, noise, birds, bats, shadow flicker, soil texture, presence of geological formations, etc.).
- Location specifics (e.g., predicted productive capacity; relief and topography; other land uses; and distance to electricity sub-stations, powerlines, telecommunications, roads, tourist sights, cities, towns, railways, etc.).
- Land use and legal restrictions (e.g., protected areas, airports, military zones, forests, sand dunes, farms, vegetated areas, wetlands and rivers, urban locations, etc.).
- Socio-demographics (e.g., population density and social acceptability of proposals).

However, it evident from the literature that a comprehensive assessment of the potential of GIS-mapping to inform specific decision-making contexts related to onshore wind energy constitutes a research gap. Given the task of Iceland's Master Plan to robustly evaluate the strategic suitability of onshore wind energy projects and the rapid advancement in the use of GIS-mapping to inform such MCDA-based platforms [46], this study is based on a narrative literature review which has the following aims.

1) To consider how the various GIS-MCDA criteria for onshore wind energy projects could apply to the Icelandic context.
2) To evaluate the extent to which GIS-based analysis is already utilised in Iceland and which additional aspects could be considered to aid in determining strategically optimal locations, providing potentially useful information to aid Iceland's Master Plan for Nature Protection and Energy Utilization and the development of the nation's future regulatory framework for onshore wind energy.

Section 2 of this study provides background details on Iceland's Master Plan instrument, including the reasons for its formation, its goals, and how it operates. Section 3 describes the method applied in this inquiry's narrative literature review. Section 4 identifies the current GIS-based work on onshore wind energy projects that is ongoing in Iceland and the extent to which it has and could be utilised to inform Iceland's Master Plan. Section 5 discusses the implications of using GIS mapping in the context of Iceland's emerging regulatory apparatus for onshore wind energy, before reflecting on the capacity to use such information to potentially identify locations of optimal suitability, and considering the broader, international implications of the outcomes. Section 6 concludes with recommendations on how best to apply GIS-based analysis in the context of onshore wind energy projects evaluated by Iceland's Master Plan.

This paper makes several academic and policy-related contributions. The primary academic contribution of the study is its analysis of the feasibility of incorporating the GIS-MCDA methodology, commonly utilised globally for the selection of wind energy project sites, into Iceland's established Master Plan for Nature Protection and Energy Utilization. Considering the nation's pursuit of net-zero greenhouse gas emissions by 2040, this issue holds significant relevance for both domestic energy policy and international climate objectives. The 'state of the art' in this paper lies in its pioneering consideration of how use of advanced GIS-based MCDA, particularly through 3D visualisations and high-resolution data, is and could enhance Iceland's Master Plan for onshore wind energy site selection. This approach not only addresses Iceland's unique environmental and social challenges but also sets a precedent for integrating cutting-edge spatial analysis into national energy planning, offering a model for other regions aiming to balance renewable energy development with sustainability goals.

2. Background

2.1. Overview of energy conflicts in Iceland and need for the Master Plan

Iceland is endowed with multiple renewable energy resources that provide almost all of its electricity [47]. Only a limited proportion of it is, however, needed for the local power market given its relatively small population of around 400,000 people. The build-up of its renewable energy resources has therefore been characterised with a strategy of concurrently building energy intensive industries for its utilization, with approximately 82 % of total electricity generation consumed by industry [48]. In addition, due to the geographical isolation of the island in the North Atlantic, with no interconnectors to other nations, its power potential is therefore somehow "stranded" [49].

Iceland's pursuit of renewable energy, particularly through hydropower and geothermal projects, and subsequent development of energy intensive industries, has sparked significant controversies over the past century, reflecting tensions between economic development and environmental preservation [50]. These disputes highlight the complex interplay of cultural, ecological, and economic interests in the nation, factors which led to the development of a structured national Master Plan to balance these competing priorities [7].

One of the earliest recorded energy disputes in Iceland occurred in 1907, when a developer proposed damming the Hvítá river, threatening the iconic Gullfoss waterfall. Local opposition, led by a local woman, successfully halted the project by the 1920s, preserving the waterfall's natural beauty [51–53]. During the 1970s, the Laxá river controversy in North Iceland further exemplified local resistance to hydropower development. Plans to build a dam to meet growing electricity demands in Akureyri town threatened agriculture and the ecological balance of Lake Mývatn. Over 200 landowners formed a coalition, and in 1970, some resorted to dynamiting a dam in a branch of the Laxá river. Ultimately, the expansion of Iceland's national power grid reduced the need for this project, averting further conflict [54]. Simultaneously, a proposed reservoir at the þjórsá river's headwaters in south-west Iceland raised concerns about flooding the þjórsárver wetlands, a critical, biodiversity rich highland ecosystem. This project drew international attention due to its potential to destroy a wetland ecosystem and diminish wilderness areas. Local and global advocacy led to the area's designation as a Ramsar site, with protections limiting reservoir development to minimise environmental harm [55].

The Kárahnjúkar hydropower project in eastern Iceland, planned in the 1980s and constructed between 2003 and 2008, remains the most contentious case. This 690 MW project, designed to power an aluminium smelter, involved damming two glacial rivers, creating four reservoirs and six dams, and flooding 57 km^2 of land, including sixty waterfalls and the Dimmugljúfur canyon. The project caused major environmental damage, however, despite the National Planning Agency's recommendation to reject the project due to its severe impacts, the Minister of the Environment approved it for its economic benefits, highlighting the economy-environment tension [7,56–58].

The recurring conflicts underscored the need for a balanced approach to energy development. Early efforts to address this began with a committee formed under Iceland's first Nature Conservation Act (1971), involving experts from the Ministry of Industry, National Power Company, National Energy Authority, and Nature Conservation Council. This group evaluated the environmental impacts of power projects [59]. The 1994 Act on Environmental Impact Assessment formalised assessments for projects exceeding 10 MW, marking a step toward systematic evaluation [7]. In 1997, a government white paper on sustainability proposed a long-term strategic plan for energy development, drawing inspiration from Norway's Samlet Plan for hydropower. The paper emphasised evaluating conservation and energy potential separately to ensure sustainable development [60]. This led to the creation of Iceland's Master Plan, which ranks energy projects based on their economic and energy benefits against their environmental and societal impacts, aiming to harmonise development with preservation [59]. The Master Plan represents a structured response to these challenges, aiming to guide sustainable energy development while addressing the concerns of diverse stakeholders. Nevertheless, Icelandic renewable energy projects and impact assessment remains a hotly debated topic, and recent debates in Iceland have shifted toward the visual and environmental impacts of energy infrastructure, such as pipelines, powerlines, dams, and wind turbines, though these are less intense than the earlier hydropower disputes [61,62].

2.2. Formation of Master Plan and overarching goal

Work began on the Master Plan for Nature Protection and Energy Utilization in 1999, with the first two phases of the project, completed between 1999-2003 and 2004–2011, respectively, focused on geothermal and hydropower projects, with the third (completed from 2013 to 2017) and fourth phases (2017–2021) also beginning to evaluate onshore wind energy projects. A fifth phase began in 2021 and ended in 2025. The sixth phase started in May 2025 (ramma.is, n.d.).

In 2011, the Icelandic parliament approved the law on the Master Plan. The Master Plan is intended to provide scientific analysis on the various trade-offs of all terrestrial energy options in Iceland – these are currently geothermal, hydro power and wind energy projects. Article 1 of the Master Plan Act (No. 48/2011) reflected its overarching goal, stating that the objectives were:

> "*To ensure that the utilisation of geographical areas where there are power plant options, is based on long-term views and a comprehensive assessment of the interests taking into account the conservation value of the nature and the cultural historical relics, the cost effectiveness and profitability of various different utilisation options and other values that affect the national interests, as well as the interests of those who use these same resources having sustainable development as a guide."*

2.3. Organisation and operations of the Master Plan

The Master Plan is led by a ministerially nominated Steering Committee which oversees the information-gathering activities of Expert Groups (EG) it appoints. The four EGs of the Master Plan currently focus on gathering information related to the following issues: EG1 (Nature, environment, and cultural heritage); EG2 (Impacts on other land uses); EG3 (Societal, human well-being and regional development impacts); and EG4 (economic profitability and costs). Although each of the EGs is theoretically given equal weight in the overall Master Plan evaluation of a renewable energy project, the specific weighting applied to criteria within the respective EGs varies. For example, EG1 gives a 20 % weighting to impacts to species, but only applies a 10 % weight to cultural heritage; equally, EG2 is currently weighted 88.57 % for impacts to tourism and outdoor activities, 5.25 % to freshwater fishing and hunting, and 6.17 % to agricultural impacts [63].

The Master Plan Act identifies the Icelandic Environment and Energy Agency as the competent authority to receive suggestions from developers on energy options and secure their proposal, which must fulfil minimum data criteria. The Icelandic Environment and Energy Agency then submits the energy options to the Steering Committee to assess and rank the energy options. Based on the outcomes from the four Expert Groups, and in accordance with the legal requirements of the Master Plan Act, the Steering Committee has an advisory role and is asked by law to place the proposed energy projects into one of three categories: energy utilization, on hold, or protection.

This determination is submitted to the Minister of the Environment, Energy and Climate. The Minister can the make changes on the proposal from the Steering Committee or they can present it as a proposal for a parliamentary resolution in the Icelandic Parliament. It is then the Icelandic parliament that takes the decision on categorisation of the energy options based on the parliamentary resolution, which only becomes legally binding after the Icelandic Parliament has passed the proposal. Once passed, the implications for energy options in the "protect" category are that they are subject to be conserved according to the Nature Conservation Act. Energy options in the "utilization" category can be considered for energy development and those "on-hold" are subject to further studies (ramma.is, n.d.). Importantly, no energy options can be considered for development until the Icelandic Parliament has approved its status in the "utilization" category. To date, the Icelandic Parliament has agreed three parliamentary resolutions involving the ranking of energy options: firstly, in 2013, then an intermediate phase in 2015, and a third phase in 2022 (Hjaltadóttir and Magnússon, 2022). These decisions thus constitute the Icelandic Government's key legislative instrument in providing overviews of the status of its energy options and quantifies the potential energy development options in the country.

3. Methods

This study's findings derived from a narrative literature review [64, 65], which was deemed by the authors to be the most suitable approach given the need to consider the nature and extent of GIS-based MCDA research conducted to date and to place this into the very specific context of Iceland's Master Plan. As noted by Ahmad [66], narrative literature reviews avail a more flexible and qualitative approach than systematic reviews, allowing researchers to synthesise and interpret the findings of many different studies, which are often from diverse disciplines. This was the case in this study, which needed to evaluate the potential of GIS-based data to inform both practice and policy-making, including different dimensions of Iceland's Master Plan relating to the environmental, economic, and socio-cultural impacts of onshore wind energy projects.

This review accorded with the approach to narrative literature reviews advocated by Gregory and Denniss [67], which involves the sequential stages of sourcing, searching, evaluating, synthesising, and inferring. Conducted over the period of January to October 2025 and prioritising academic and grey literature published since 2010, various academic databases (ScienceDirect, Google Scholar, Web of Science, and Scopus) and the grey literature (via Google) were scrutinised to provide useful information related to research question (1) on how the various GIS-MCDA criteria for onshore wind energy projects could apply to the Icelandic context. Specific search terms used in this search accorded with the approach of Cook and Pétursson [46] and included "wind power" in conjunction with "GIS", "MCDA" and "multi-criteria decision and analysis", alongside usage of standard BOOLEAN search strings (i.e., AND/OR). In the evaluating, synthesising and inferring stages, and in order to answer research question (2) relating to the applicability of the GIS-based information to Iceland's Master Plan, the authors used expert judgment and chose to focus on reviewing evaluative materials published at ramma.is, the official website for this national MCDA platform.

4. GIS mapping in Iceland related to onshore wind energy projects

4.1. Recent and ongoing research

GIS mapping has been undertaken by the Global Wind Atlas,[1] which broadly highlights the areas in Iceland with the greatest mean wind speed and mean power density. This provides a crude informative showing some of the locations that are likely unsuitable. Iceland-specific analysis was carried out by Nawri et al. [3], using downscaling simulations with the Weather Research and Forecasting model ad local wind speed distributions derived from Weibull statistics. A further 14 test sites were selected for more detailed analyses using the Wind Atlas Analysis and Application Program (WAsP). Nawri et al. [3] concluded that Iceland's potential wind energy sites were comparable to those in the highest wind energy class elsewhere in Europe, and that wind conditions were not a constraining factor on onshore wind energy production.

Much of the ongoing work in Iceland involving GIS analysis and onshore wind energy projects has investigated the extent of the visual impacts on surroundings. The recent work of Ostman and Árnason [68] evaluated the visual impacts of eight proposed onshore wind farms that were potentially going to be assessed in the fourth phase of Iceland's Master Plan for Nature Protection and Energy Utilization. The data collection for each wind energy project was guided by the Icelandic Landscape Project (ILP) methodology, employing a 5 × 5 km point-based grid system that has been applied in previous data collection phases for Iceland's Master Plan.

Ostman and Árnarson [68] utilised for further analysis Viewshed Explorer to create a Zone of Theoretical Visibility (ZTV), applying a maximum visibility radius of 40 km as recommended by Scottish National Heritage guidelines. This approach was considered suitable due to the diverse, exposed, and variably sloping nature of Iceland's landscape types. Priority was given to points within a 10 km radius of proposed onshore wind energy projects, which were defined as the outer limits of the intermediate zone, unless settlements or other sensitive areas were located between 10 and 40 km from the site. Ostman and Árnarson [68] not only utilised basic GIS-based analysis to determine zones of theoretical visibility (ZTV) and assess potential impacts on specific landscape types. They also incorporated photomontage (2D) and 3D panoramic visualisations to more accurately simulate the visual impact of wind turbines. While their report does not specify the use of weather and daylight analyses, such factors, along with line-of-sight analysis, are commonly incorporated in broader environmental impact studies to enhance the understanding of visual impacts under varying conditions. Line of sight analysis investigates whether an object, in this case a wind turbine, is visible in a straight line from specific viewpoints. In GIS mapping, data points are typically classified as green if the wind turbine is visible from a specific location and red if not.

The study by Hrabalíková et al. [69] expanded upon the foundational GIS methods previously described, introducing potential of a 3D web map[2] for the assessment of wind power projects in Iceland. This map integrates detailed GIS data on visual impacts, including the effects of weather, daylight, and line-of-sight analysis, thereby offering a more dynamic and comprehensive assessment of how wind turbines arrays might visually integrate into landscape. Such an approach extends the degree of objectivity of GIS-based analysis in informing Iceland's Master Plan beyond the level often found in academic GIS-MCDA studies, which generally rely only on zone of theoretical visibility assessments [70]. Typically, these studies have been limited to static assessments based on proximity to sensitive locations, such as settlements, protected areas, important bird species, and critical infrastructure, that are deemed most likely to be affected by an onshore wind power project [71,72].

The use of advanced 3D visualisation techniques enables more effective simulation of potential impacts, facilitating the design of wind farms that minimise adverse effects like shadow flicker and noise. Given the local incidence of such effects, restriction zones can be applied via straight-forward 'distance to' analysis, as is commonly applied in academic GIS-MCDA studies on onshore wind energy projects [71]. For instance, Doheny [73] suggests no less than a 1400-m setback from residential or commercial buildings to mitigate shadow flicker based on the altitude and azimuth of the sun in Iceland. The same 1400-m threshold could also be applied to roads to prevent any potential disorientation of drivers via shadow flicker effects. Besides the case of Scotland, this distance exceeds the threshold applied in the twenty-four nations and states assessed by Haugen [74], also being close to the 1500-m margin currently applied by Norway [75].

Regarding any potential negative impacts from the noise of rotating turbines, GIS analysis has been undertaken in Iceland to assess dB at various distances. An investigation by Landsvirkjun, Iceland's national power company, into the loudness of two test turbines in the Hafið area, near the soon-to-be constructed 120 MW wind power project at Búrfellslundur, found noise levels adjacent to the turbines of 103 dB, which reduced to 45 dB at a distance of 340 m. However, the loudness diminished to 36–40 dB at 500 m from the turbines, which aligns with the World Health Organization's safe level of 40 dB [76]. Concerning electromagnetic noise from rotating wind turbines, as far as the authors are aware, no studies have been undertaken yet into its potential incidence in Iceland. However, given the potential for significant disturbances to weather radar, as evidenced in other nations, a precautionary approach should be considered. Thus GIS-mapping could identify all the locations within Iceland that lie within a 5 km distance of a weather radar station, which aligns with the strict exclusion zone recommended by the World Meteorological Organization [77].

In recent years, GIS-based research on breeding birds has focused on gaining greater understanding in Iceland of the areas where the most common birds are likely to be present. A study by Mendéz and Gunnarsson [78] estimated the likely presence of the 12 most common land birds in Iceland. This included the development of a species diversity map, which displayed the locations in Iceland where species diversity exceeds a threshold of 0.5, i.e., there is a greater than 50 % likelihood that a particular species will be found in a plot. Although there are areas of considerable species diversity around Iceland, Mendéz and Gunnarsson [78] found that these are most often observed in the southern areas of the nation, especially the flat lowlands which tend to be warmer and wetter. The southern region is also the area most associated with the migratory pathways of many bird species in the spring and autumn periods.

Regarding the earliest onshore wind energy project proposals in Iceland, much of the research into the likely environmental impact concerned threats to birds. Preliminary assessments by Landsvirkjun [76] into the potential impacts to birds at Bjarnalón and Hafið identified impacts to five bird species via density measurements, three of which were nesting locally. Flight monitoring detected 17 species, including the pink-footed goose, European golden plover, whimbrel, common ringed plover, less black-backed gull, and raven. Although the likelihood of collision was considered low when calculated for the pink-footed goose and European golden plover, the disturbance to the habitat of birds by Bjarnalón in the Hafið area was more substantial during the construction period [76].

More recently, a study on birdlife in three parts of the nation where

[1] See: https://globalwindatlas.info/en/area/Iceland and https://vindatlas.vedur.is/.

[2] See: https://ramma-vindorka.gis.is/.

wind energy projects are proposed focused on the effects on nesting birds and pathways of migratory species. The research on migratory species has included the gathering of information about the specific species flying to Iceland, the routes, number of birds and altitude [79]. In addition, based on criteria for defining Important Bird Areas (IBAs) by BirdLife International, the Icelandic Institute of Natural History has defined 121 areas of international importance for the 81 species of birds that are breeding or regular visitors to Iceland, which fall into three categories: (a) seabird colonies, (b), rocky coast and shallow marine waters, and (c) wetlands and other inland areas. It is recommended by the Institute that onshore wind energy projects are planned in areas outside of their classification of important bird areas [80].

Most of the IBAs in Iceland are important breeding sites, with a few having importance as staging, moulting, or wintering sites. Lake Mývatn and Breiðafjörður serve all four functions [81]. In relation to the specific vulnerabilities of bird species in Iceland, research in Germany has found that white-tailed sea eagles are one of the bird species that are most often killed by wind turbines. These are a vulnerable keystone species that is slowly recovering in Iceland, with approximately 250 located in the area between the southern Westfjords and Snæfellsnes [82,83], and potential wind turbine collisions are likely a more serious concern in Iceland than habitat impacts [83].

Given the cold climate of Iceland, the potential for wind turbine blade icing is pronounced [84]. A study by IEA (2016) found that 30 % of the total installed wind power capacity in the world was situated in cold climate locations that are vulnerable to icing. Gao et al. [85] found that ice accretion on blade topics could extent to a thickness of up to 30 cm at blade tips, leading to slower turbine rotation and ice-induced power losses of up to 80 %. In some cases, turbines shut down completely. In addition, safety issues can arise due to the potential for ice-throw, whereby shards of ice are cast from the turbine [86]. The icing potential of Icelandic wind energy projects has been modelled by the Icewind project, which has used GIS-mapping to develop an icing atlas for the Nordic nations. A map showing the maximum simulated ice load at the surface has been developed, which demonstrated the locations in Iceland where ice load is particularly likely to negatively impact the power generation of onshore wind energy projects, which include mountainous areas in the Westfjords, northern parts of Iceland, the south-east, and East Fjords. The areas of least vulnerability included the Reykjanes peninsula, southern lowlands, Borgarfjörður, and Melrakkaslétta [87].

In addressing exclusion zones related to different land uses, Iceland could adopt a precautionary approach similar to the UK, which sets a 10 km distance threshold around airport. Furthermore, energy projects are prohibited within the nation's national parks in þingvellir, Snæfellsjökull and Vatnajökull, and most of Iceland's other protected areas, covering currently around 25 % of its terrestrial area. Concerning impacts to residents, a 10 km distance constitutes the upper end of the general intermediate zone of visual impact reported by Hrabalíková et al. [69], however, there is the potential for visual impacts to extend far beyond this in the case of Iceland, as evidenced in Section 3.3 of this study.

Concerning the social acceptability of onshore wind energy projects in Iceland, the spatial mapping study by Tverijonaite et al. [62] has demonstrated how GIS mapping can identify potential zones of negative impact from the perspective of specific stakeholders, such as Icelandic tourist operators. It is important for the success of future onshore wind energy projects to secure the endorsement of affected stakeholders, in particular, local people. Utilising the Public Acceptance Rating in conjunction with GIS mapping could significantly aid this process. Hrabalíková et al. [69], in their comprehensive review, highlighted the utility of photomontage data in evaluating public acceptance, where positive mean values indicate acceptable proposals, and negative values denote unacceptable visual impacts. In theory, a survey-based approach could determine the perspectives of various stakeholders to further inform project design. Such an approach is exemplified by The Ministry of Forests, Lands and Natural Resource operations in British Columbia (2016), which wind energy proposals into four categories: Class A (preservation), Class B (retention), Class C (partial retention), and Class D (modification). Of these, only Class D's proposals were found to have a negative Public Acceptance Rating, with the wind turbines appearing as large and distinctive features of the landscape. In the best case, Class A, they were barely visible. Gathering and analysing data from diverse distances and viewpoints can create a comprehensive GIS map of public acceptability, akin to the recent work of Tverijonaite et al. [62] on the visual and tourism mobility impacts of the proposed wind farm at Búrfellslundur.

4.2. Current GIS-based evaluation of onshore wind energy projects by Iceland's Master Plan

The use of GIS-based analysis in the Master Plan's most recent summary report, which pertained to the ten wind energy projects (see locations in Fig. 1) evaluated within the Icelandic Master Plan's fifth phase (2021–2025). The fifth phase report highlighted various environmental concerns and trade-offs, with four proposed projects being located in close promixity to Breiðafjörður, a protected bay between the southern Westfjords and Snæfellsnes that is highly significant for bird life [70]. The presence of sea eagles and their potential overflight in these areas raises concerns about collisions with wind turbines or habitat disruption. These issues indicate that wind farm placement must carefully consider the ecological sensitivity of bird habitats, migration patterns, and protected areas to minimise environmental impacts. Sites near important bird areas or migration routes in Iceland, such as Breiðafjörður or areas with sea eagle activity, face greater scrutiny due to potential adverse effects on bird populations.

The visuals impact of the ten proposed projects evaluated within the Master Plan's fifth phase are shown in Figs. 2–11. Four of these were considered as possessing potentially significantly negative visual close proximity to the capital area and busy highway between Mosfellsheiði and þingvellir National Park, a UNESCO World Heritage Site (see, for example, Figs. 7 and 8) [70].

The most recent fifth evaluative phase of Iceland's Master Plan also found that several social issues were influencing public attitudes to proposed onshore wind energy projects. This was perhaps demonstrated most clearly in relation to one project, which was considered by EG3 as likely having significant negative perceptions regarding its visibility from immediate surroundings, with residents viewing it as highly disruptive and contributing to strong opposition. Some of the projects had conducted very limited public engagement, however, there were also two examples where community engagement was deemed to have been extensive, and in these cases, there was generally a higher degree of social acceptance and limited disputes with neighbours. This could, perhaps, have also been by virtue of the more limited visual impacts of the proposals [70].

4.3. Potential contributions of GIS mapping to Iceland's Master Plan evaluation

Table 1 provides a summary of the main GIS mapping approaches that are currently being utilised and could be applied, the EGs of the Master Plan that could be informed, and whether this work is currently informing the Master Plan's EGs.

In addition to the issues outlined in Table 1, several other factors may make land unsuitable for wind energy use in Iceland. Sloping terrain of at least 20° is poorly suited, whilst land use types such as water bodies, snow- and ice-covered terrain, and wetlands are also generally unsuitable due to the installation and anchorage challenges. Another critical environmental factor specific to Iceland is the occurrence of dust plumes or dust storms [88], which can significantly impact the suitability of certain areas for wind energy projects. Moreover, poorly located wind energy projects can degrade high carbon soils and habitats [89].

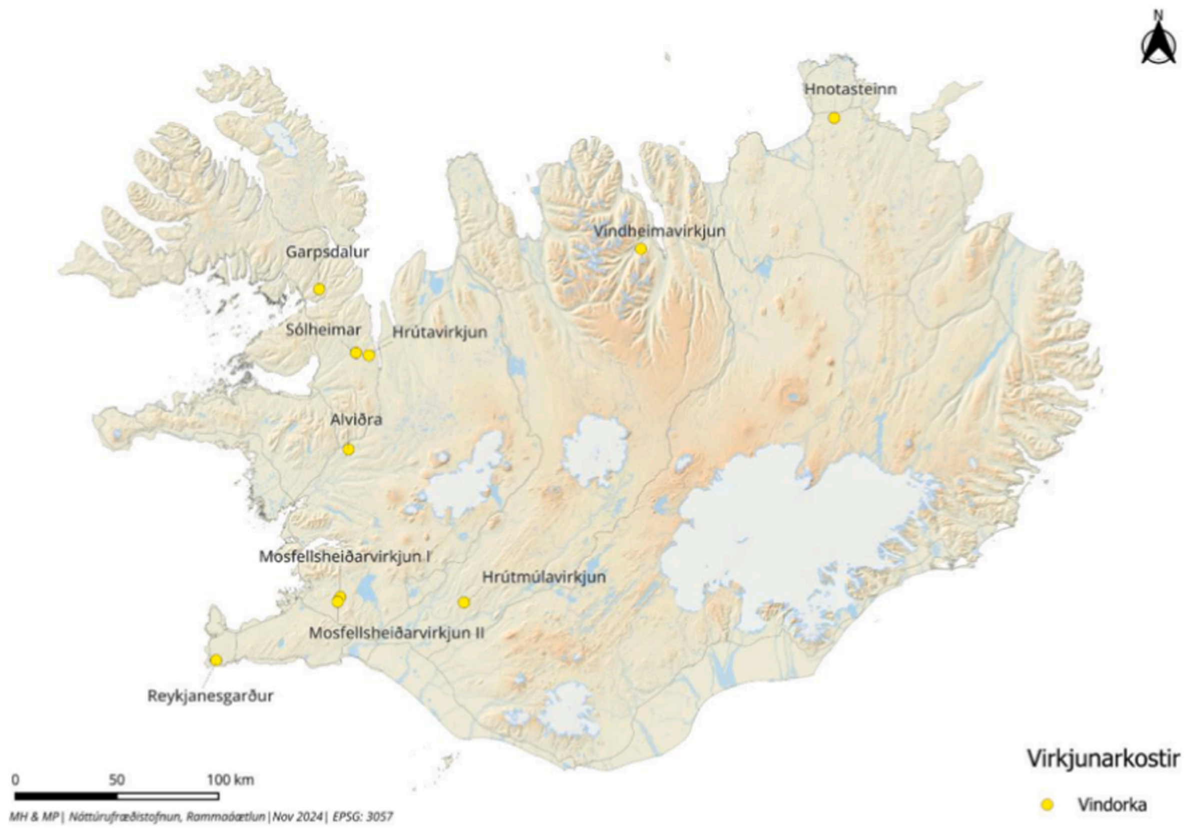

Fig. 1. Location of ten wind farms evaluated in the fifth phase of Iceland's Master Plan. (sourced from [70]).

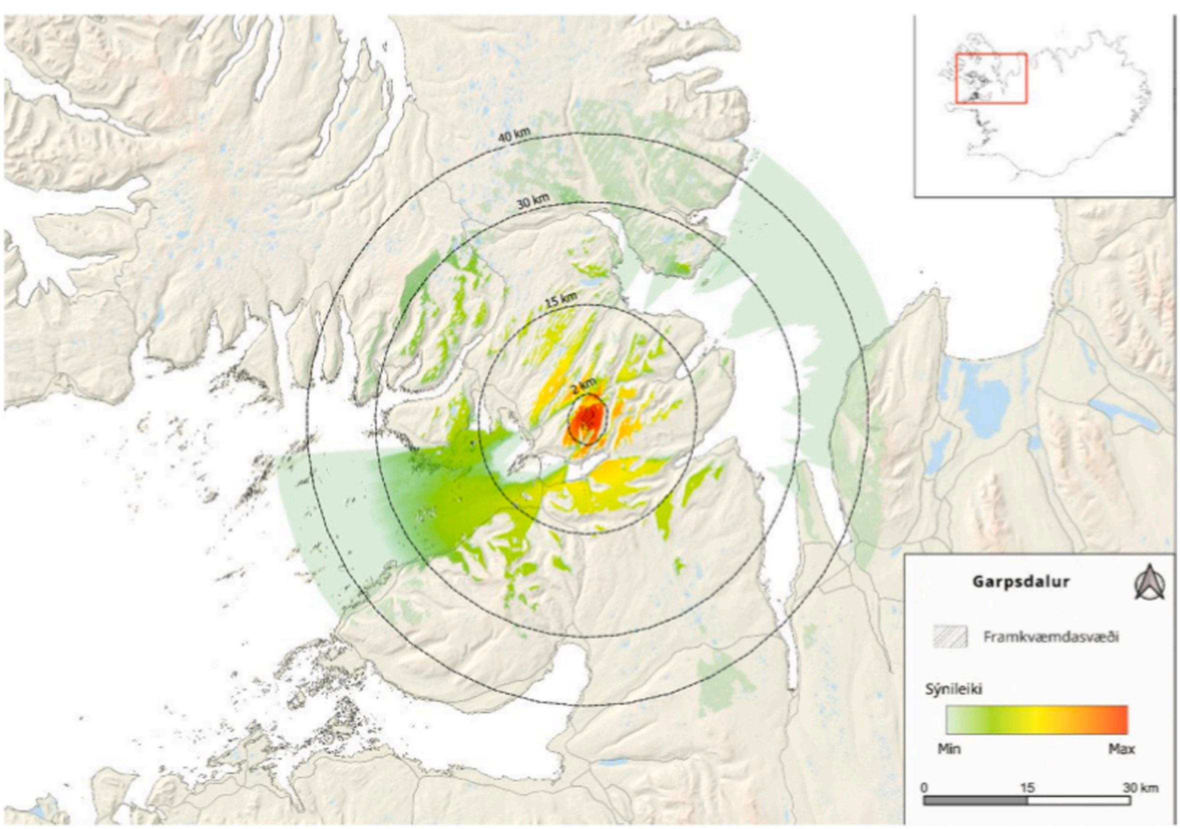

Fig. 2. Location and visibility impact analysis of the proposed wind energy project at Garpsdalur. (sourced from [70]).

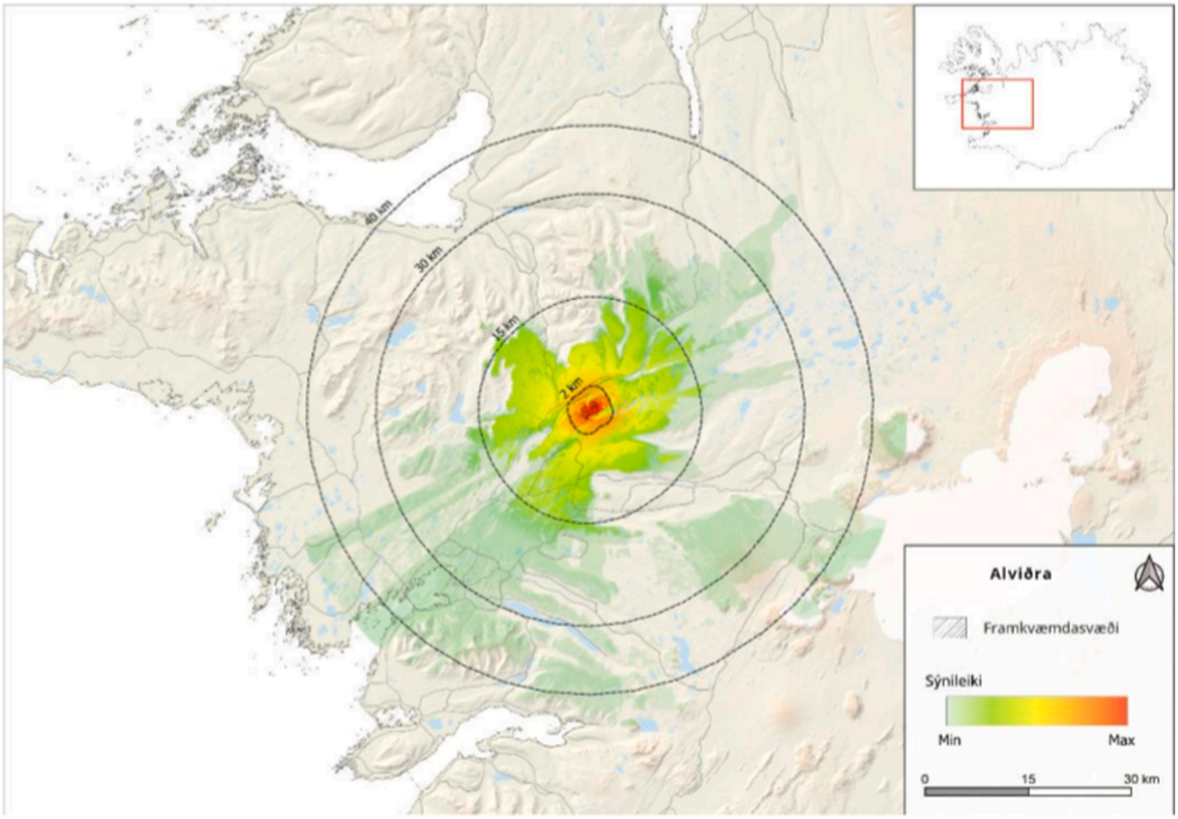

Fig. 3. Location and visibility impact analysis of the proposed wind energy project at Alviðra.
(sourced from [70]).

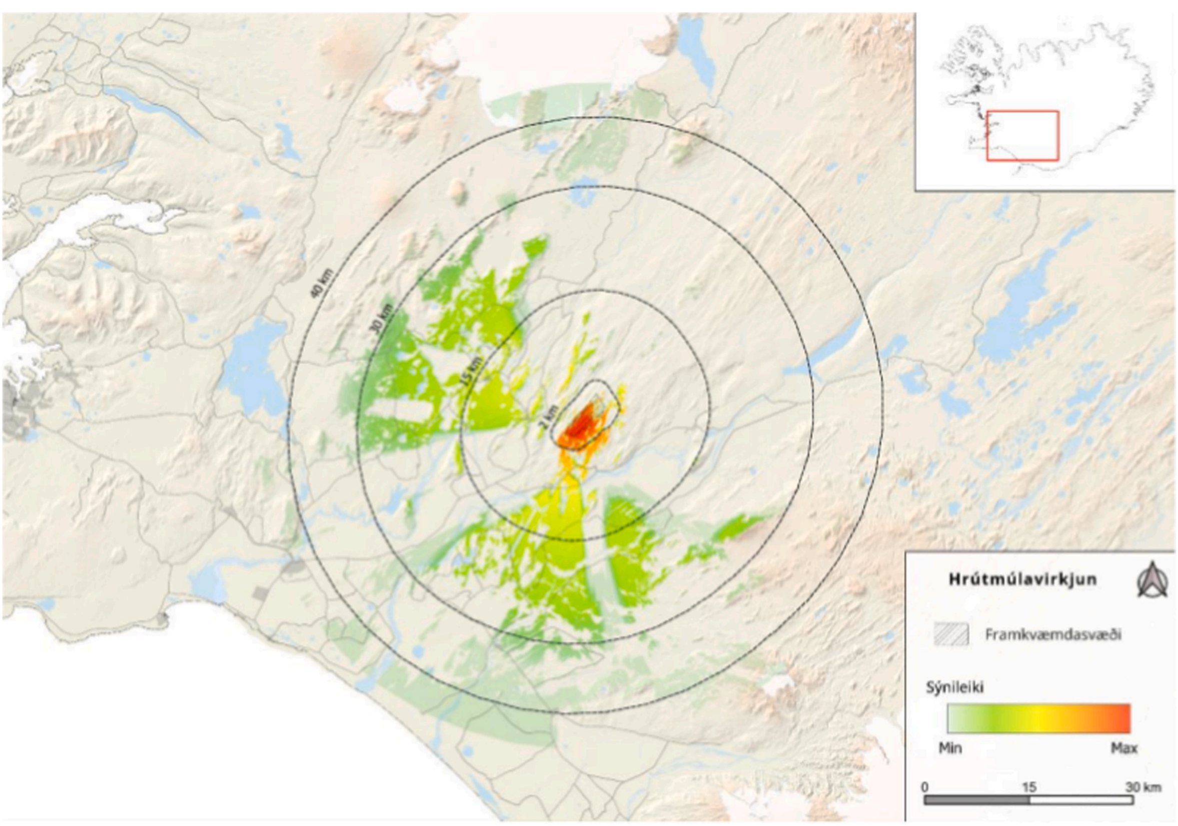

Fig. 4. Location and visibility impact analysis of the proposed wind energy project at Hrútmúlavirkjun.
(sourced from [70]).

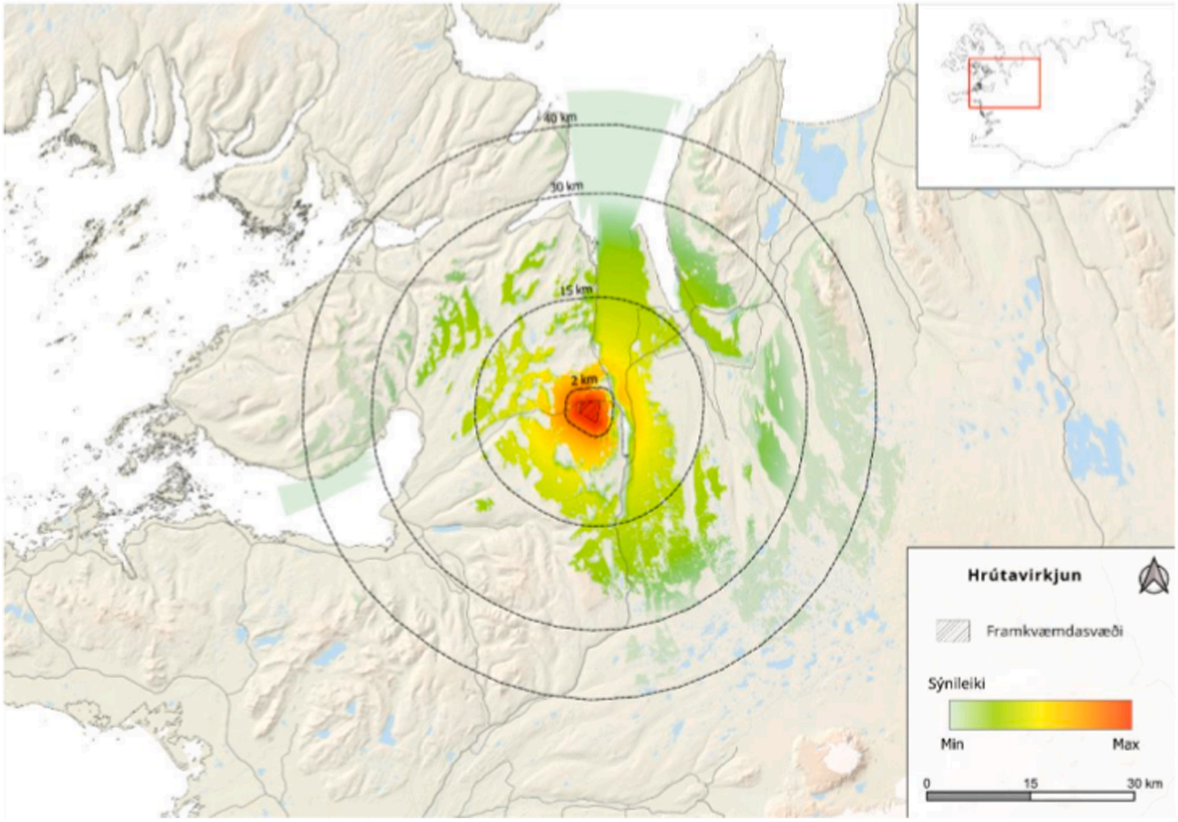

Fig. 5. Location and visibility impact analysis of the proposed wind energy project at Hrútavirkjun. (sourced from [70]).

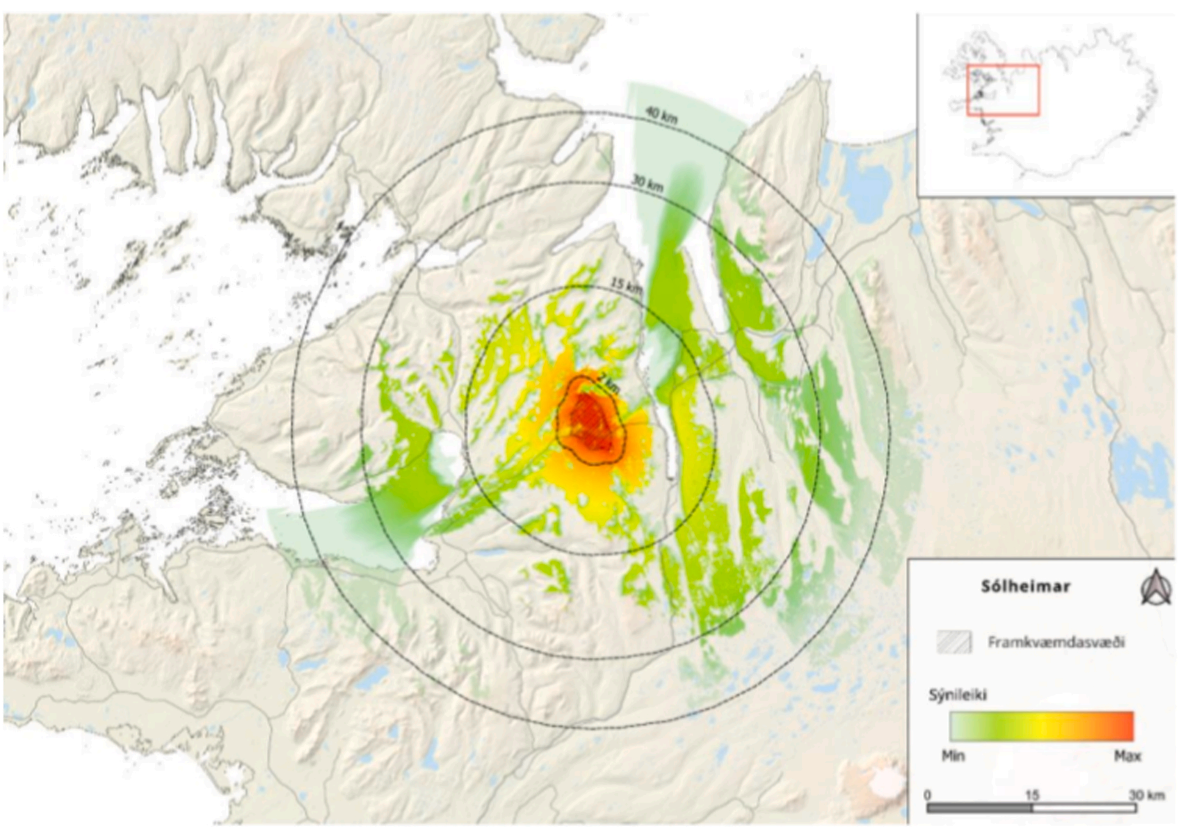

Fig. 6. Location and visibility impact analysis of the proposed wind energy project at Sólheimar. (sourced from [70]).

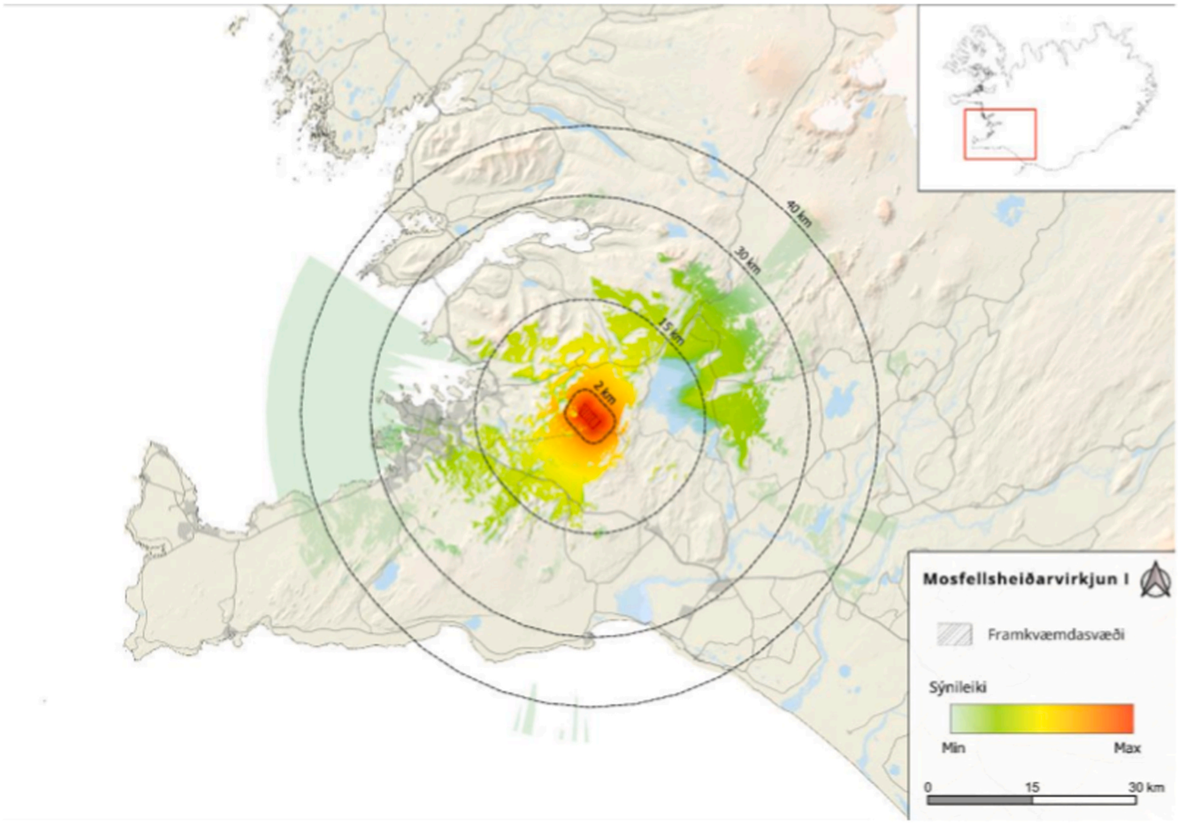

Fig. 7. Location and visibility impact analysis of the proposed wind energy project at Mosfellsheiðarvirkun I. (sourced from [70]).

Evaluating the suitability of the soil depth and type for the construction of roads to the project site and for the turbine foundations, with the latter necessitating soil extraction [70]. Proper soil condition classification and monitoring is essential for turbine foundation selection [73].

National decision makers in Iceland will need to consider the breadth of environmental and locational issues that are modelled using GIS mapping to inform the Master Plan's outcomes. The adoption of too many criteria and application of the strictest possible regulatory restrictions could lead to a situation whereby very little terrestrial land is deemed strategically suitable as a site for onshore wind energy projects. This was the case in a recent Multi-Criteria Decision Analysis exercise on potential sites in Israel, which led to only 0.5 % of all land being deemed as potentially suitable [71].

5. Discussion

5.1. Key factors influencing strategically suitable sites for onshore wind energy projects in Iceland

As well as guiding national decision making in Iceland regarding the optimal location of onshore wind energy projects, GIS-based tools can play an important role in the design of proposals, helping to identify the best fitting locations and avoid locations with undesirable characteristics from the outset. This is a key issue for Iceland as there is not yet any operational wind farm in the country and it is important that unsuitable locations are clearly identified. The most recent fifth phase evaluation in the Icelandic Master Plan of ten proposed wind energy projects highlighted several key environmental, social, economic, and technical issues of importance when determining strategically optimal locations. It was evident that locating wind farms in Iceland requires balancing environmental preservation, particularly for birdlife and protected areas, with strong community engagement to mitigate potential social opposition and careful consideration of tourism impacts. Some projects located near high-traffic or protected areas could risk significant tourism impacts, while others have been deemed as having minimal effects. Effective community engagement is critical for minimising potential public opposition, with visibility and sensory impacts being major concerns. Proposed sites located near protected areas or others with a high birdlife value face significant environmental constraint. Low grid connection costs enhanced the potential economic viability for most of the proposed sites, but high costs for two of the projects might be restrictive on suitability [70].

Given these important issues, GIS mapping can be very useful in helping to determine the most suitable locations for wind energy projects in Iceland, informing the evidence based underpinning the phased evaluations undertaken by Iceland's Master Plan. The mapping of various exclusion zones, such as residential or commercial buildings within 500 m of wind turbines, 15 km of airports, in protected areas, or in bird breeding or flightpath zones, can support energy project developers in avoiding locations of obvious unsuitability in Iceland. Visual impact analysis such as viewshed models, visibility indices, and line of sight tools can be used to consider turbine arrangement and height to minimise visibility from sensitive locations. The capacity to access 3D visual analysis further extends the potential of GIS mapping in aiding pre-proposal design and public consultation, potentially boosting the social acceptance of projects prior to formal assessment by the Master Plan's EGs. Cranmer et al. [90] found that more immersive forms of media tended to lead to more positive impressions about wind energy projects in the US than 2D maps. Furthermore, both 2D and 3D mapping approaches can enable some of the worst effects relating to the scale, size and configuration of a turbine array, or contrast effects, to be entirely prevented.

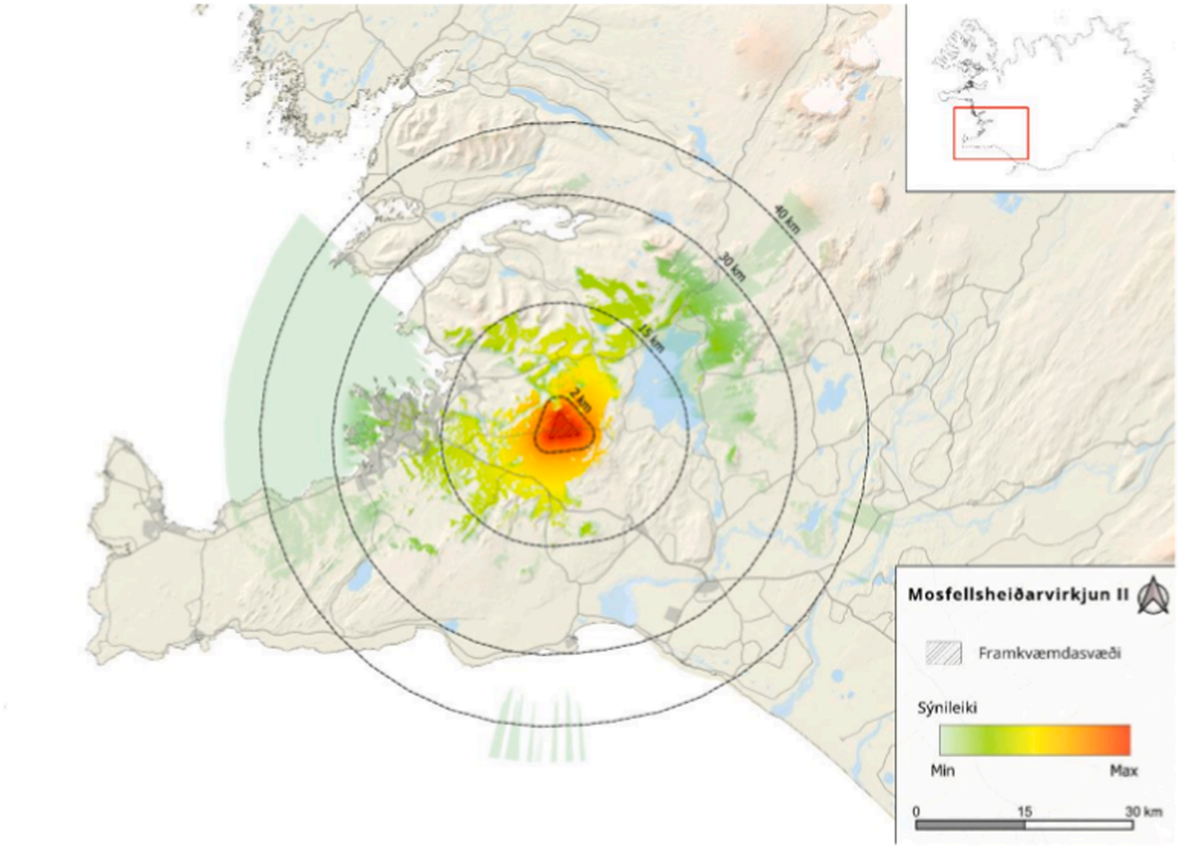

Fig. 8. Location and visibility impact analysis of the proposed wind energy project at Mosfellsheiðarvirkun II (sourced from [70]).

5.2. Icelandic regulatory framework for onshore wind energy in development

In Iceland, the regulatory framework for onshore wind energy is currently under development, yet, given the considerable interest in having projects assessed by the Master Plan, it is likely that wind energy will play a role in providing renewable electricity to support Iceland's transition to becoming a net zero carbon society by 2040. Moreover, in the charter of the current government, it states that a special law will be enacted on the use of wind energy with the aim of simplifying the development of wind power plants. For that purpose, the Minister of Environment, Energy and Climate initiated a working group that published an overview of policy options in April 2023 and then developed a draft legislative amendment to streamline wind energy analysis in the Master Plan and a draft wind energy policy for Iceland with guidance on priority locations. However, this has not yet been approved by the Icelandic parliament.

It is evident that GIS mapping can play a major role in helping to resolve some of the complex issues that still need to be resolved within Iceland's decision-making apparatus for onshore wind energy projects. This is especially the case concerning the location and sizing of wind energy projects. As the report by Government of Iceland [91] called for, areas should be determined where the installation of wind energy will be prohibited and where they are most suitable. It is common in other nations for wind farms to be built in areas close to transmission lines and substations. Equally, wind farms are not typically built in areas close to settlements for reasons of visual impacts, and nor are they constructed excessively far from human habitation. Additionally, GIS mapping can play a major role in not only determining but helping to mitigate at the earliest design stage the potential environmental impacts of onshore wind energy proposals. This will aid the Icelandic government in setting rules regarding the location of wind energy projects and avoidance of important bird areas and bird migration routes, visual and acoustic impacts. In addition, there should be a requirement for the best available technologies to mitigate impacts and deliver decommissioning and recycling at the end of operation. It is necessary to examine whether energy acquisition needs to be prioritized in the interest of climate goals and obligations. In that context, various topics need to be evaluated, e. g., a) whether licensing for energy exchange should be organized within the administration; b) the percentage of permits for energy exchange that should be conditioned; c) how production capacity should be tendered in the interests of the climate; d) the grants, incentives, concessions, and fees and taxes that should be implemented, if any; e) the compensation (if any) that should be provided to neighbours, land-owners and others who might be negatively affected by wind farms; and e) how to ensure conformity with European competition laws and the internal market in accordance with Iceland's participation in the European Economic Area Agreement as a member of the European Free Trade Association.

Some additional factors will likely influence and possibly constrain wind energy development in Iceland in the near future. The need for nearby balancing power when the wind does not blow sufficiently, the current limited strength of the Icelandic electricity grid, and proximity to transmission lines and sub-stations are likely to be a major constraining factor on the harnessing of onshore wind energy in Iceland in the period up to at least the year 2030. For many years in Iceland, grid instability and transmission restrictions have led to problems in the operation of the Icelandic electricity network, with transmission bottlenecks undermining the potential to fully utilise the installed capacity of power plants by transferring electricity from one region to another [92]. It is likely that these pitfalls will continue to increase at least in the period up to the year 2026 and then be resolved only gradually thereafter [93]. The Icelandic Government is placing emphasis on the importance of improving the connectivity of the transmission system

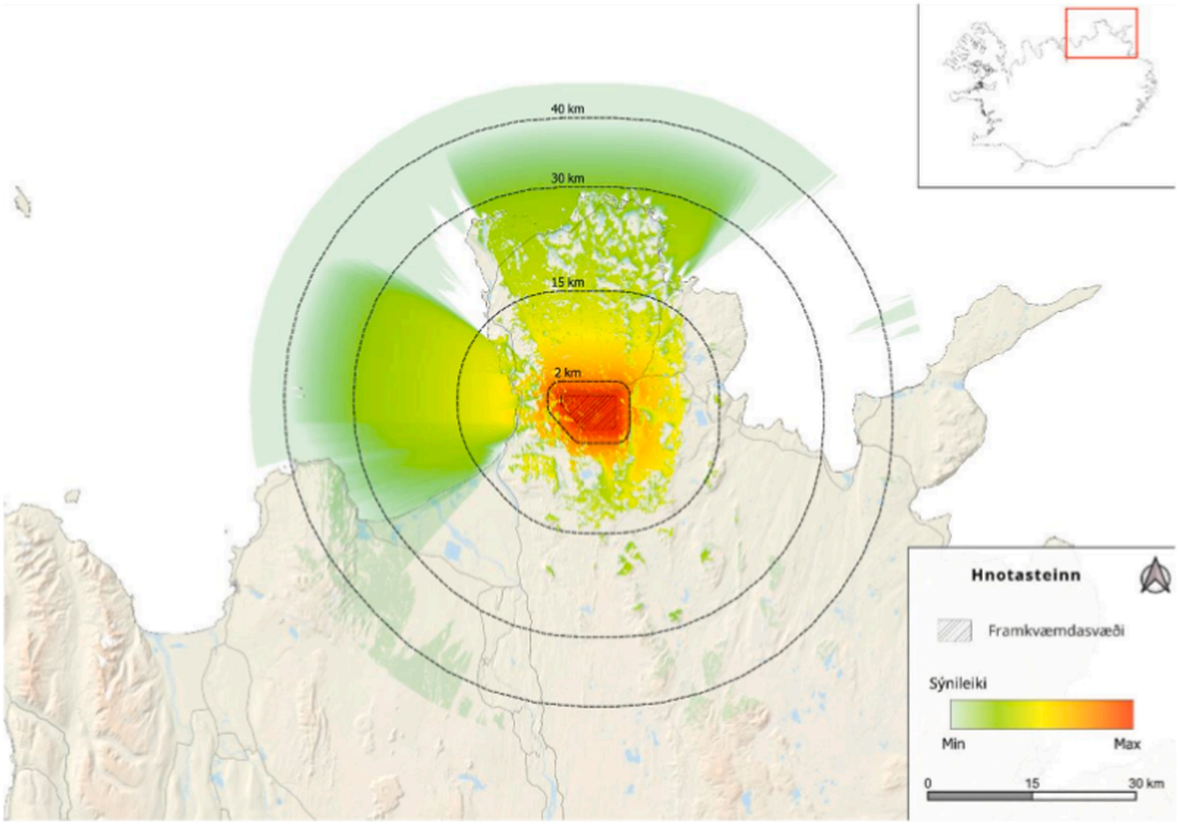

Fig. 9. Location and visibility impact analysis of the proposed wind energy project at Hnotasteinn. (sourced from [70]).

between regions, for example, from Northeast Iceland to Blanda Power Station, and between the Hengill area and Southern Peninsula, although these initiatives are expected to take several years before they are actualised [92].

In the closed/stranded energy system of the island state, sourcing balancing power for Icelandic wind energy projects will need to be from hydropower, as is commonly the case in other Nordic nations. Electricity generation from a hydropower plant can in some cases be adapted to meet market needs, unlike geothermal power in Iceland, which is inflexible in the short-term and largely used as baseload capacity for heavy industry purposes, and therefore, is not currently suitable for providing balancing power. Approximately 75 % of Icelandic electricity production is from hydropower and this is set to increase in recent years with the expansion of existing plants and new planned plants, making balancing power more available, however, its availability remains a seminal, even defining factor for how large a share onshore wind energy can become in the Icelandic renewable energy mix. Other, currently unresolved issues related to Iceland's future regulatory framework for onshore wind energy relate to potential revenue sharing with local municipalities and compensation to locals affected negatively by such developments [94].

5.3. GIS data needs for the Master Plan

In addition to the general application of GIS mapping to inform Iceland's Master Plan, another critical factor that significantly influences the efficacy of GIS mapping in wind energy site selection is the quality and resolution of the input data [95]. High-resolution data are indispensable for accurately mapping and analysing the geographic and environmental characteristics essential for locating onshore wind projects [96]. For example, data with a 10-m resolution provides nine times more data points than a 30-m resolution over the same geographic area, allowing for a much finer and detailed representation of the terrain [95]. This high granularity enables more precise modelling of subtle geographic features, such as geological formations and stratigraphic layers, thereby reducing the margin of error in interpreting maps and making strategic decisions [97]. However, while higher resolution data enhances detail and accuracy, it also introduces specific challenges. The integration of high-resolution data with lower resolution datasets can lead to inconsistencies, particularly in areas where high-resolution data is not uniformly available [98]. This mismatch can skew results and potentially lead to inaccurate assessments of visual impacts, biodiversity risks, and other critical factors. Additionally, higher resolution data demands more substantial processing power and more complex data management strategies, which can increase the operational costs and time required for analysis [99].

Furthermore, the scale at which the data is used can affect the applicability of the results. Data that is highly detailed may not be necessary for broad-scale strategic assessments and can complicate the analysis without providing additional useful insight. Conversely, for fine-scale site-specific assessments, high-resolution data is indispensable for accurately identifying and mitigating potential impacts [95]. Therefore, it is imperative for planners and decision-makers to carefully select the appropriate resolution and scale of GIS data based on the specific requirements of each project [100]. They must also be vigilant about the integration of multi-resolution datasets to ensure consistency and reliability across GIS analyses [101]. Understanding these nuances and preparing for the associated challenges is essential for maximising the effectiveness of GIS tools in the planning and development of onshore wind energy projects in Iceland.

5.4. International implications

The international implications of this study extend beyond Iceland,

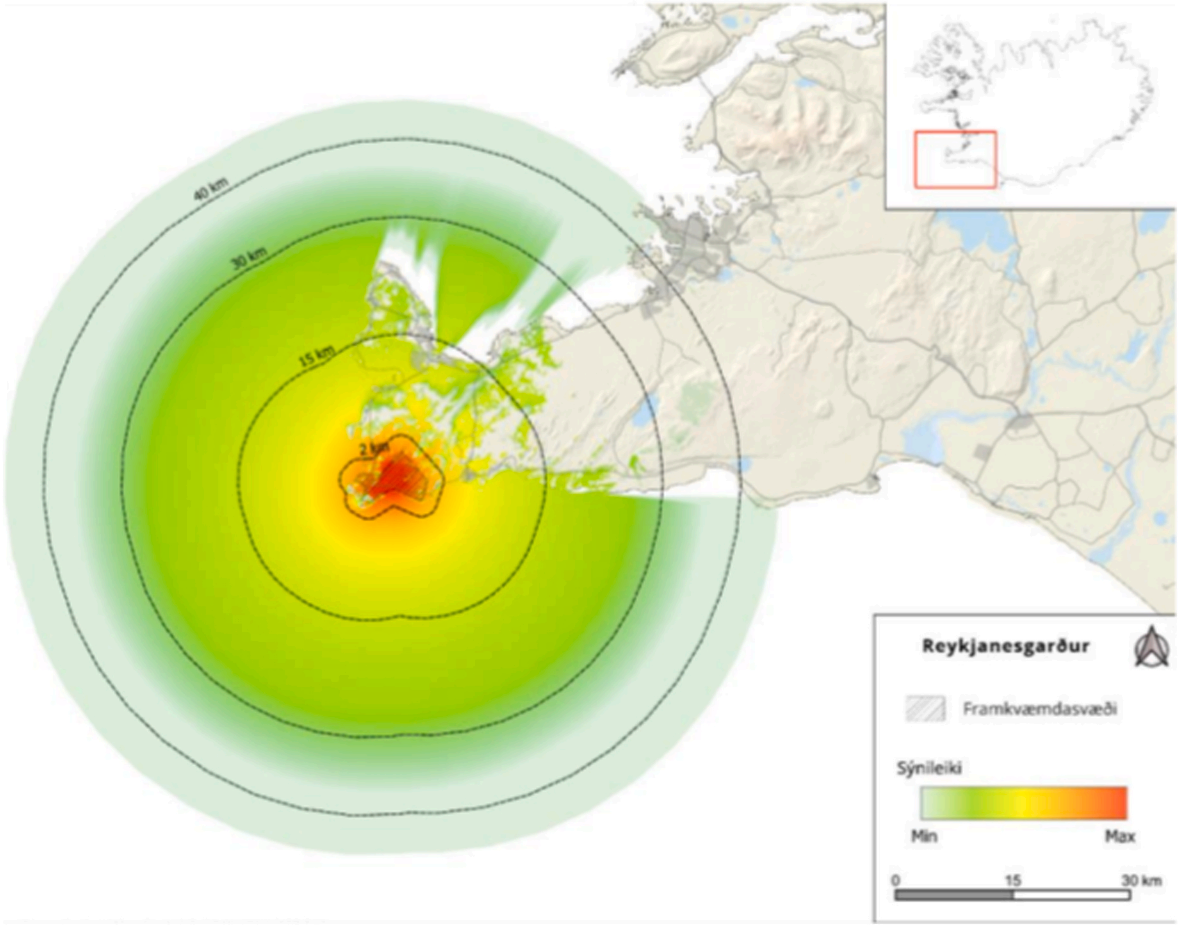

Fig. 10. Location and visibility impact analysis of the proposed wind energy project at Reykjanesgarður. (sourced from [70]).

offering a replicable and systematic approach for integrating advanced GIS-based MCDA into national energy planning, particularly in regions pursuing ambitious renewable energy transitions while safeguarding environmental and social values. Iceland's Master Plan, as a legally enshrined MCDA tool, demonstrates how GIS mapping, when enhanced with 3D visualisations, viewshed analysis, and high-resolution data, can optimise onshore wind site selection to minimise negative impacts on biodiversity, landscapes, and communities. This approach addresses global challenges in renewable energy deployment, where conflicts between development and conservation are prevalent, as evident in studies such as those by Hastik et al. [30] and Ramalho et al. [20].

For similar island nations and remote regions with "stranded" energy resources, such as New Zealand or the Faroe Islands, Iceland's methodology provides insights into balancing isolation-induced grid constraints with wind potential. By mapping exclusion zones for protected areas, bird migration routes, and visual impacts, the framework mitigates risks such as avian collisions and social opposition, which are universal concerns [21,23]. The emphasis on precautionary setbacks aligns this study's recommendations with international standards and could inform policies in countries such as Scotland or Norway, where similar cold-climate issues, including turbine icing, prevail [84,87].

Globally, the study's integration of GIS into MCDA supports the United Nations' Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 15 (Life on Land), by promoting evidence-based planning that enhances social acceptance [31,32]. In densely populated or tourism-dependent areas, such as parts of Europe or the United States, the use of immersive 3D tools for public consultation could help to reduce NIMBY (‘Not In My Backyard’) resistance, as evidenced by Cranmer et al. [90]. Moreover, the paper's caution against overly restrictive criteria, potentially limiting suitable land to minimal percentages [71], warns against policy overreach, a relevant issue for nations such as Germany or Brazil which are facing several land-use trade-offs [17,19].

6. Conclusion

Iceland stands at a pivotal juncture in its pursuit of a net-zero carbon future by 2040, with onshore wind energy emerging as a complement to its established hydropower and geothermal resources. The strategic deployment of onshore wind energy projects, however, demands a delicate balance between harnessing renewable energy potential and safeguarding Iceland's unique environmental, cultural, and social landscapes. This study's theoretical and operational insights potentially position GIS-based MCDA as a transformative tool for Iceland's onshore wind energy development, offering a model for other regions seeking to align renewable energy expansion with sustainability goals. The paper's actionable recommendations for standardising GIS protocols and addressing Iceland-specific challenges in the context of onshore wind energy projects provides a basis for operationalising these theoretical advancements within Iceland's Master Plan.

GIS-based tools offer a robust framework for identifying optimal locations for onshore wind projects by systematically evaluating environmental, social, economic, and technical criteria. Through advanced techniques such as viewshed analysis, 3D visualisations, and exclusion zone mapping, GIS enables decision-makers to assess visual impacts, protect critical bird habitats, mitigate noise and shadow flicker, and

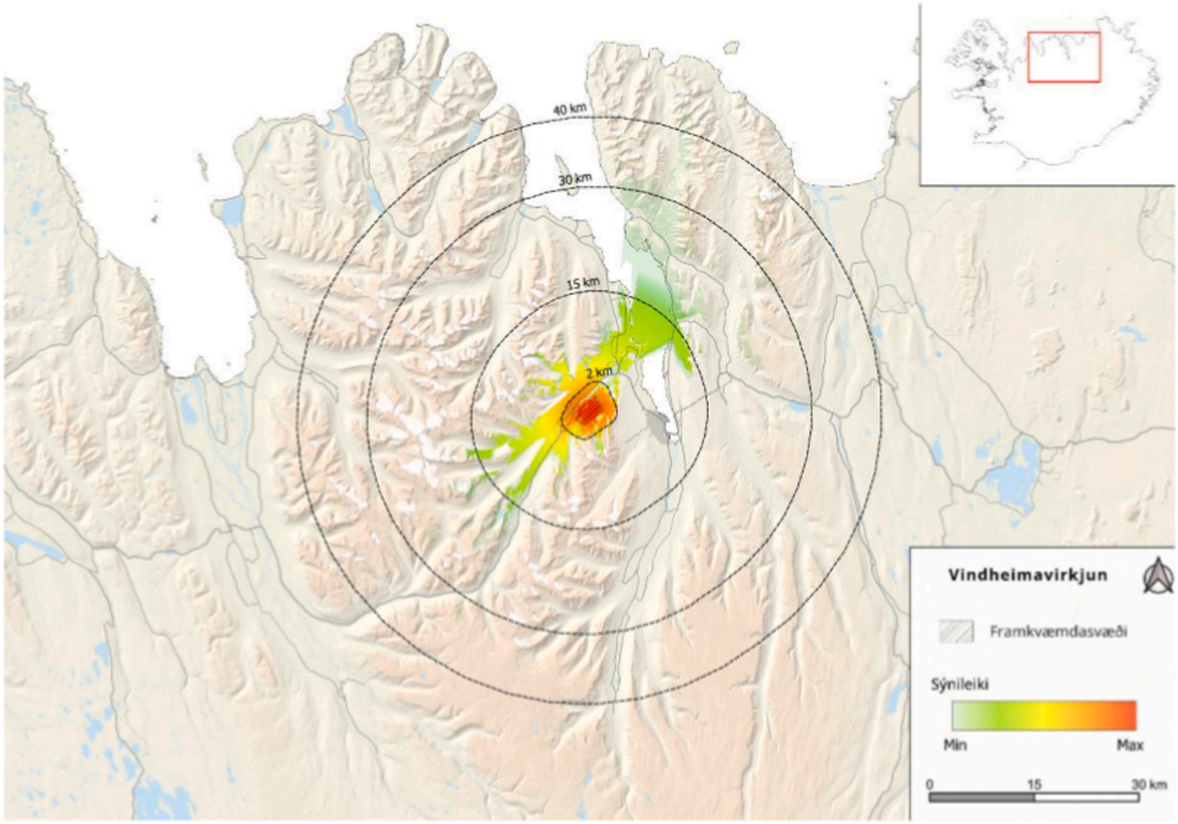

Fig. 11. Location and visibility impact analysis of the proposed wind energy project at Vindheimavirkjun. (sourced from [70]).

ensure compatibility with infrastructure and population centres. The integration of high-resolution data, as highlighted, enhances the precision of these assessments, allowing for nuanced evaluations of terrain, biodiversity, and social acceptability. The findings from the Master Plan's fifth phase evaluation of ten wind energy projects reveal the complexity of site selection, with significant environmental constraints near protected areas and social concerns in visually sensitive regions. GIS mapping can help to address these challenges in Iceland and further afield by informing pre-proposal designs, optimising turbine placement to reduce visibility, and fostering public engagement through immersive visualisations that enhance social acceptance. Furthermore, GIS supports the development of Iceland's emerging regulatory framework for wind energy by identifying priority and prohibited zones, aligning with the government's commitment to streamlined yet sustainable development.

To maximise the efficacy of GIS-based analysis within the Master Plan, we recommend: (1) standardising 2D and 3D visualisation protocols to assess visual and ecological impacts consistently; (2) establishing clear exclusion zones for sensitive areas; (3) integrating species diversity and migratory pathway data to protect birdlife; and (4) enhancing public consultation through GIS-driven tools such as Public Acceptance Ratings to build stakeholder trust and gain locally a social licence to operate. These measures can guide project developers and policymakers in avoiding unsuitable locations and prioritising sites with minimal environmental and social impacts.

Regarding this study's limitations, it must be remembered that Iceland's regulatory framework for onshore wind energy is still under development, which constrain to some extent the immediate practical applicability of its GIS-based recommendations for national decision-making. Technical challenges may also present methodological challenges, not least the integration of subjective elements such as perceived visual impact with conventional objective GIS data. Furthermore, data availability challenges may hinder the practical application of some of the recommendations. For example, there is variability in community engagement across proposed projects, with some lacking sufficient public consultation, which could hinder the social acceptance data needed for robust GIS-based Public Acceptance Ratings. Additionally, relating to environmental criteria, Iceland-specific issues such as the presence of rare birds of prey may pose challenges that require further GIS modelling, but current data may not fully address these localised factors. Finally, Iceland's Master Plan seeks to balance nature protection with energy utilization, and thus decision-makers must take care not to adopt too many GIS-MCDA criteria or overly strict regulatory restrictions, as these could severely limit the suitable land for onshore wind energy projects.

Several areas of future research can derive from this initial review study. In particular, involving practical applications of its GIS-based recommendations. These could include conducting a prototype national suitability analysis for onshore wind energy in Iceland under multiple scenarios, integrating various constraints, opportunities, and social criteria. The included scenarios, as a minimum, could include a comparison between strict conservation and balanced development, which would facilitate useful indications of national capacity potential for decision-makers. In order to facilitate these endeavours and inform Iceland's Master Plan, the creation of a ‘standardisation box’ would be beneficial, incorporating criteria such as viewshed parameters, 2D/3D visualisation settings, noise and shadow protocols, bird buffers, icing assessments, and proximity to the electricity grid.

Credit author statement

David Cook: Conceptualisation; data curation; formal analysis; investigation; methodology; validation; visualisation; writing – original draft; writing – review and editing. Jón Geir Pétursson:

Table 1
Potential scope of GIS-based analysis in informing the Icelandic Master Plan.

Criteria	Suitable GIS-based tools of analysis	Master Plan Focal Areas
Visual impact	Zone of theoretical visibility – viewshed and visual impact models Visibility indices 2D photomontage 3D panoramic visualisation, incorporating line of sight analysis and animations	Nature, environment, and cultural heritage; impacts on other land uses; societal, human well-being and regional development impacts
Shadow flicker	Zone of theoretical impact (proximity analysis – roads, commercial buildings, and residential dwellings) 2D photomontage 3D panoramic visualisation	Nature, environment, and cultural heritage
Low frequency noise	Exclusion zones	Nature, environment, and cultural heritage
Electromagnetic noise	Exclusion zones	Nature, environment, and cultural heritage
Birds	Exclusion zones – breeding sites of international importance Exclusion zones – major migratory routes Exclusion zones – 3 km avoidance areas for vulnerable nesting birds	Nature, environment, and cultural heritage
Icing	Exclusion zones	Nature, environment, and cultural heritage
Social acceptability	Photomontage linked to Public Acceptance Ratings	Impacts on other land uses; societal, human well-being and regional development impacts
Proximity to airports and military radar	Exclusion zones	Societal, human well-being and regional development impacts
Proximity to protected areas	Exclusion zones	Nature, environment, and cultural heritage; societal, human well-being and regional development impacts
Proximity to population centres	Exclusion zones, with varying distance depending on population size	Societal, human well-being and regional development impacts
Power generation and economic prospectivity	Mapping of mean wind energy speeds and mean power density, providing inputs into LCOE analysis	Energy alternatives, economic profitability, and costs

Conceptualisation; funding acquisition; investigation; metohodlogy; project administration; supervision; validation; writing – review and editing. Michaela Hrabalíková: Methodology; validation; visualisation; writing – original draft; writing – review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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