Rammaáætlun
Vernd og orkunýting landsvæða

Application of Multi-Criteria Decision Analysis (MCDA) for assessing the location of energy options: A literature review on the use of GIS-MCDA to inform the Master Plan



David Cook andJón Geir Pétursson.

Environment and Natural Resources
University of Iceland

September 2025
© David Cook and Jón Geir Pétursson
Publisher: Environment and Natural Resources, University of Iceland
ISBN: 978-9935-9808-3-0

CONTENTS

1. Introduction 4
   - BACKGROUND 4
   - OBJECTIVES AND METHODS 4
   - STRUCTURE 5
2. MCDA and renewable energy siting choices 6
   - RENEWABLE ENERGY SITING VIEWED AS A MULTI-CRITERIA DECISION-MAKING PROBLEM 6
   - HOW MCDA OPERATES – THE FUNDAMENTALS 6
3. Iceland's energy system and the Master Plan 8
   - ICELAND'S ENERGY SYSTEM TODAY 8
   - ICELAND'S PRIOR HISTORY OF ENERGY CONTROVERSIES AND COMPETING INTERESTS 8
   - ICELAND'S MASTER PLAN – BACKGROUND 9
   - ICELAND'S MASTER PLAN – LEGAL STATUS 10
   - ORGANISATION OF THE MASTER PLAN 11
   - THE MASTER PLAN'S EXPERT WORKING GROUPS 12
   - WG1: NATURE, CULTURAL HERITAGE, LANDSCAPE AND WILDERNESS 12
   - WG2: IMPACTS ON OTHER LAND USES 14
   - WG3: SOCIETAL AND LOCAL DEVELOPMENT IMPACTS 15
   - WG4: ENERGY ALTERNATIVES, ECONOMIC PROFITABILITY AND COSTS 15
4. Literature review 17
   - METHOD. 17
5. Results 19
   - GEOTHERMAL POWER 19
   - HYDROPOWER 21
   - WIND POWER 22
6. Discussion 26
   - MASTER PLAN IMPLICATIONS 26
   - WEIGHTING AND AGGREGATION IN MCDA 26
   - PRACTICAL AND DECISION-MAKING IMPLICATIONS 27
   - STUDY LIMITATIONS 28
7. Conclusion 29

References 30

Appendix A – Geothermal Power, GIS and MCDA Studies 38

Appendix B – Hydropower, GIS and MCDA Studies 50

Appendix C – Wind Power, GIS and MCDA Studies 59

1. INTRODUCTION

BACKGROUND

Information gathering about likely environmental and social impacts can play a major role in assuaging public concerns about the location of energy infrastructure, particularly when such data is used to enlighten developers about the optimal location of onsite infrastructure (Kazak et al., 2017; Sliz-Szkliniarz et al., 2019). As such a determination depends on many factors, the use of Multi-Criteria Decision Analysis (MCDA) has become increasingly popular in energy planning (Kazak et al., 2017). MCDA constitutes a type of Multi-Criteria Decision-Making (MCDM) support system, which can model social, economic and environmental factors, helping to provide a broad perspective on the overall merits of energy projects and diminishing the risk that interests specific to one or two social groups could carry overwhelming weight in decision-making (Harper et al., 2019; McKenna et al., 2022). A broad variety of criteria can be incorporated into MCDA methods for comparing the characteristics of energy projects, including but not limited to land uses, distances to ports, urban areas and distribution and transmission systems, wind speed, slope, air density, and ecological impacts (Tahri, et al., 2015; Villacreses et al., 2017).

The quality of environmental information provided to inform MCDAs is a significant issue. In recent years, an increasing number of studies have utilised Geographic Information System (GIS) mapping in tandem with MCDA to enrich the data pool available to decision-makers. The aim of GIS mapping is to store, retrieve, manipulate, analyse and map geographical data (Church, 2002). The application range of GIS mapping is considerable, including but not limited to the mapping of landslide hazards (Carrara et al., 1995), health impacts (Brewer, 2006), ecosystem services (Troy and Wilson, 2006), place values (Brown et al., 2020), mineral prospectivity (Zuo et al., 2021), and solar radiation (Choi et al., 2019). MCDA operates via several approaches, which are commonly divided into two categories (i) multi-objective decision-making (MODM), and (ii) multi-attribute decision-making (MADM) (Ho, 2008; Pohekar and Ramachandran, 2004). MODM is a systematic process that aims to identify conflicts and trade-offs, reconciling these in a transparent manner through compromise and incorporating indicators of the strength of various preferences for specific objectives (Roijers, 2017). MADM involves the undertaking of preference decisions (including evaluation, prioritisation, and selection) concerning the available project alternatives that are typically characterized by multiple, conflicting attributes (Xu, 2015). The Analytic Hierarchy Process (AHP) has become one of the most applied approaches within MCDA. It compares multiple alternatives, each with several criteria to help identify the best option via pairwise comparisons (Vaidya and Kumar, 2006). This contrasts with approaches that utilise numerical values directly.

OBJECTIVES AND METHODS

Despite the increasing deployment of GIS approaches to inform MCDA in the context of various energy projects, the literature is scattered and, thus far, devoid of a review and synthesis of the main analytical approaches. Scrutinising the literature will help to identify the criteria in MCDA that are currently being informed by GIS mapping and the different types of MCDA platforms that are being used by decision-makers specific to energy projects. This information will be particularly useful for decision-makers who are considering the breadth of criteria that could make use of GIS-based information within MCDA, especially when such platforms are already applied and continuing to

evolve. This is the case with respect to Iceland's Master Plan for Nature Protection and Energy Utilisation (hereafter referred to simply as the 'Master Plan'), which is a complex decision-support tool with a national scope and based on MCDA principles. It endeavours to reconcile the frequently competing interests of nature conservation and energy utilisation during the earliest planning stages. First commenced in 1999, the Master Plan became enshrined in Icelandic law in 2013 and is shortly entering its fifth evaluative phase. The first two evaluative phases of the Master Plan only evaluated the merits of potential geothermal and hydropower projects in Iceland, however, the third phase also encompassed wind farms. All energy projects subject to the Master Plan's assessment are evaluated following consideration of multiple different interests, many of which are allocated weightings in the assessment process. This leads to an eventual ranking and the classification of all power plant options into one of three categories: utilisation, on hold, or protection.

This report conducts a Systematic Literature Review (SLR) to fulfil its objectives. A combination of the Search, Appraisal, Synthesis and Analysis (SALSA), together with the snowballing method, is used in this SLR. These methods have been widely adopted in SLRs in a broad variety of decision-making contexts, including in Arctic ecosystem services (Malinauskaite et al., 2019), MCDA studies on geothermal power projects (Cook et al., 2019), sustainable energy development (Gunnarsdóttir et al., 2020), and the systemic risk issues pertaining to the COVID-19 pandemic (Cook and Jóhannsdóttir, 2021).

STRUCTURE

This report commences in Section 2, where further background material is provided concerning how MCDA studies are typically structured and operate in a renewable energy project context. Section 3 articulates the history of the Master Plan in Iceland and its structure, including its overarching Steering Committee and four Working Groups, is set out. The remit of each Working Group is described, together with the main criteria under evaluation. Section 4 outlines the SALSA method used to conduct the systematic literature review and provides the main results specific to each of the energy generating technologies under study – geothermal power, hydropower, and onshore wind. Section 5 discusses the relevance of the outcomes for the Master Plan, and the main practical and decision-making implications of the GIS-MCDA studies reported in the examined literature. Section 6 provides a brief conclusion and outlines potential areas for future research.

2. MCDA AND RENEWABLE ENERGY SITING CHOICES

RENEWABLE ENERGY SITING VIEWED AS A MULTI-CRITERIA DECISION-MAKING PROBLEM

Decision-making concerning the optimal location of renewable energy projects and the scale of operations has frequently been viewed as a straight-forward identification of the sites that are most efficient, those possessing highest resource capacity and being least costly to develop (Shao et al., 2020). In recent years, though, there has been increasing recognition of the multifarious factors that can influence decision-making in this regard, including an array of technical, environmental, economic, and socio-cultural issues (Harper et al., 2019; McKenna et al., 2022). It is thus referred to as a Multi-Criteria Decision-Making (MCDM) problem, which has increasingly led to the deployment of structured methods which strive to resolve conflicts and trade-offs in a transparent manner. MCDA is one form of analysis, which employs multiple criteria or attributes to obtain an integrated decision-making result (Kumar et al., 2017; Shao et al., 2020).

HOW MCDA OPERATES – THE FUNDAMENTALS

Although there are many different approaches to MCDA, there are several commonalities to such studies in an energy project context. Six main stages have been identified by Shao et al. (2020): (1) the formulation of alternatives; (2) criteria selection; (3) data normalisation; (4) criteria weighting; (5) alternative evaluation; and (6) result validation.

In this first stage, researchers identify the problem and the spatial scale of the study area, which can vary from being a very local focus up to a national level evaluation in the case of Iceland's Master Plan for Nature Protection and Energy Utilization. MCDM/MCDA problems generally comprise of five components, which are goal, decision-makers preferences, alternatives, criteria, and outcomes (Kumar et al., 2017).

In stage two, criteria are determined. This is an important and often lengthy process whereby exclusion criteria are defined, whilst evaluative criteria are identified that are deemed to have a particular significance on the suitability of sites for renewable energy projects. The process of determining the criteria can involve use of many different research methods and forms of evidence gathering, including literature reviews, interviews and focus groups with experts and affected stakeholders, and surveys and questionnaires. Exclusion criteria can include sites located in protected areas, on roads or in urban settlements, mountainous areas, at airports and military locations, on highly vegetated landscapes, or areas with high cultural heritage value, etc. The evaluative criteria are mainly divided into five aspects: technical, economic, environmental, social, and institutional criteria (Kumar et al., 2017). Sometimes specific criteria are both used for the purposes of exclusions and evaluation – for example, in the case of onshore wind energy projects, wind speed and slope are important technical factors, yet poor performance can prevent sites from being considered as suitable, even if all other evaluative criteria are assessed as being very positive.

Data normalisation occurs in stage three. The initial quantitative data collected by experts and expert groups are normalised so that they can be utilised in quantitative calculations. Normalisation of quantitative and qualitative criteria leads to directionless and dimensionless operable values. Although less commonly used in MCDA studies on energy projects, qualitative data is initially incommensurate with quantitative. A

simple normalisation method for qualitative criteria is expert scoring. In this scoring method, experts give the evaluation value of criteria according to their own experience and/or objective data to transform the criteria into a quantitative score. This process can realise the quantification, directionlessness and dimensionlessness of the qualitative criteria in one step.

In the fourth stage, weightings are applied to the coefficients of the evaluative criteria. It is nearly always the case in an energy project context that MCDA studies will apply different weights since the criteria are unlikely to be deemed as having an equal degree of importance. Three factors are usually considered to obtain such weights: the variance degree of criteria, the independence of criteria, and the subjective preference of decision-makers. Various weighting methods can be used for projects involving rank-order rather than equal weighting, which include but are not limited to the Analytical Hierarchy Process (AHP), the Analytic Network Process (ANP), linguistic quantifiers, fuzzy measures, and rank correlation analysis (Shao et al., 2020). Of these, the AHP is by far the most widely applied, involving two main steps: pairwise comparison and weighted linear combination (WLC). Pairwise comparison is used to weight the different criteria, while WLC is the final stage in the AHP evaluation of the alternatives. An AHP-based determination of weights includes two steps. The first step establishes a judgment matrix based on people's judgment of the relative importance of each criterion at a given level, which is usually scored according to a scale from 1 to 9. The second step calculates the weights based on the judgment matrix and conducts a consistency test to indicate whether the comparison made is reasonable.

Stage five applies exclusion criteria to sift out unsuitable options. Following this, for the remaining potential energy projects, aggregations leading to rankings of the locations are conducted, and a variety of methods can be applied. According to Shao et al. (2020), the WLC, the second stage in the AHP, is currently by far the most used method in MCDA studies on renewable energy site selection. However, alternative approaches, such as Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Elimination and Choice Translating Reality (ELECTRE), Ordered Weighted Averaging (OWA), and ""VIekriterijumsko Kompromisno Rangiranje" (VIKOR), are increasingly commonly used, with each method often integrating varying degrees of fuzzy logic. TOPSIS chooses the alternative of shortest the Euclidean distance from the ideal solution and greatest distance from the negative ideal solution. ELECTRE involves partial aggregation based on the construction of relations of comparisons of the performances of each pair of solutions. OWA is an aggregation operator that provides a parameterised family of aggregation operators between the minimum and the maximum. VIKOR is often applied when compromises are sought, based on a determination by experts of the 'maximum group utility' and 'the minimum individual regret' (Kumar et al., 2017; Shao et al., 2020).

The sixth stage reviews and verifies the results and further analysis is conducted. Often a sensitivity analysis of the results is applied considering the implications of slightly different weighting or aggregation methods.

3. ICELAND'S ENERGY SYSTEM AND THE MASTER PLAN

ICELAND'S ENERGY SYSTEM TODAY

Iceland is one of the leading nations in the world when it comes to the use of renewable resources. In 2020, 90% of the 246.1 PJ of primary energy generation were sourced from renewables (NEA, 2021a). Of these, 70.4% were from geothermal energy sources, 19.3% from hydropower, 10.0% from oil, 0.4% from renewable fuels, and onshore wind energy (NEA, 2021a) made a negligible contribution. Regarding electricity production, in 2021, almost 100% of the 19,614 GWh was generated from renewable resources. This was sourced from hydropower (70.4%), geothermal energy (29.6%), onshore wind (0.03%), and fossil fuels (0.01%) (NEA, 2022). Since 1990, electricity generation in Iceland has more than quadrupled (NEA, 2022). This expansion has mostly occurred to satisfy the demands of heavy industry projects, which together were responsible for 77.8% of electricity consumption in 2021 (NEA, 2021b).

ICELAND'S PRIOR HISTORY OF ENERGY CONTROVERSIES AND COMPETING INTERESTS

Increased utilisation of Iceland's renewable energy resources through the 20th Century and early 21st Century did not occur without controversy, much of which has revolved about how to mitigate trade-offs between energy development and the conservation of nature. As far back as 1907, a developer expressed considerable interest in damming the internationally renowned Gullfoss falls in Hvíta (Karlsdóttir, 2010). The daughter of the local landowner was against the idea of destroying the waterfall and was reported to have famously hiked 100 km to Reykjavík to protest the hydropower project (Schwantes, 2017). These efforts were ultimately successful, since plans to harness the river for energy generation were abandoned in the 1920s (Environment Agency, n.d.).

A more challenging dispute occurred nearly 50 years later concerning plans to dam the Laxá river in North Iceland, with a view to increasing the generation of renewable electricity to satisfy burgeoning demand in Akureyri and reducing fossil fuel expenditure (Ólafsson, 1981). The controversies related to the impacts of a dam, which would threaten agriculture in the area and disturb the sensitive ecological balance in Lake Mývatn. Landowners from the Laxá-Mývatn region formed a coalition in opposition to the new dam and associated infrastructure. In August 1970, a select group of landowners who were vehemently opposed to the new hydropower plant, given its negative impacts, used dynamite to blow up a previously constructed dam at Miðkvisl on a branch of the Laxá river (Ólafsson, 1981). In the end, nationwide power grid development negated the need for increased electricity generation from the Laxá river.

Whilst the Laxá controversy was ongoing, another hydropower controversy emerged in the south of Iceland. Members of the Gnúpverjahreppur community in south-west Iceland protested a proposed reservoir development that would threaten parts of the Þjórsárver wetlands (Ögmundardóttir, 2011). The proposals by the developers included a 200 km^2 reservoir at the headwaters of the Þjórsá river to increase water availability for a hydroplant downstream. In contrast to the local scale dispute at Laxá-Mývatn, this one cultivated international attention, mostly due to the potentially significant environmental impacts, which included submergence of an entire wetland ecosystem, loss of habitat for up to three-quarters of the world's population of pink-

footed geese, loss of traditional sheep grazing lands, and diminished wilderness (Ögmundardóttir, 2011). Nowadays, the area is listed as a Ramsar site of international importance and protected as a nature reserve, although the development of smaller reservoirs is allowed provided the environmental impacts will not be considerable (Ögmundardóttir, 2011).

The arguably most heated case of opposition to hydropower development in Iceland concerns the Kárahnjúkar project in eastern Iceland. Planning for the 690 MW plant began in the 1980s, however, with construction beginning in 2003 and full production commencing in 2008 (Jóhannesson, 2010). The project was controversial due to its environmental impacts, as it required the damming of two large glacial rivers, and the creation of four reservoirs and six dams, which led to the submergence of 57 km^2 of land, geological features and sixty waterfalls (Newson, 2010).

The parties to these examples of protests against new energy projects in Iceland may vary, but there are several common themes which are at the heart of the economy-environment nexus. That is, due to the scale of energy infrastructure and impacts, there has been opposition in Iceland due to the potential of such projects to negatively affect the cultural, geological, economic and environmental attributes of regions where they are proposed. In the past few years, although not as heated as some of the aforementioned hydropower controversies, debates about energy projects in Iceland and their associated infrastructure have often focused on the visual impacts, such as aboveground pipelines, powerlines, dams, and wind turbines (Einarsdóttir et al., 2019; Guðmundsdóttir et al., 2018; Stefánsson et al., 2017; Tverijonaite et al., 2019; Tverijonaite et al., 2022).

ICELAND'S MASTER PLAN – BACKGROUND

The various controversies concerning Iceland's renewable energy projects exemplified the importance of decision-makers not only seeking to identify their economic advantages, but the consequences for other interests (Einarsdóttir et al., 2019). These include impacts to other uses of land, the environment, and cultural heritage (Cook et al., 2016). An early step towards a comprehensive evaluative framework of energy projects was undertaken by a committee of specialists from the Ministry of Industry, the National Power Company, the National Energy Authority, and the Nature Conservation Council (Steingrímsson et al., 2006). This group was active during the period from the passing of the first Nature Conservation Act (No. 47/1971) up until the 1990s, seeking to identify the nature conservation aspects of various potential power projects. Analysis of the environmental impacts of power projects above 10 MW in size became more formal in Iceland following the enactment of Iceland's first Act on Environmental Impact Assessment in 1994 (Cook et al., 2016). In 1997, the need for the development of a long-term strategic plan for the development of Iceland's energy projects was articulated in a white paper on sustainability by the Icelandic Government (Government of Iceland, 1997). In this white paper, it was emphasised that the experience of Norway in relation to their Samlet Plan for hydropower projects could be useful, particularly by separate analysis of the conservation and power plant aspects, which were then compared (ramma.is, n.d.).

Following the white paper, the Icelandic Government decided to develop a Master Plan for the utilisation of energy resources, which had the goal of pursuing sustainable development by evaluating energy projects and ranking them based on their energy and economic potential, and the likely impact they would have on the environment and

society (Steingrímsson et al., 2006). The ambitions of the Master Plan were manifold. The Master Plan shares some common traits with Strategic Environmental Assessment (SEA), with its policy and planning level approach, and intended goal of ensuring sustainable development of energy resources in Iceland (Thórhallsdóttir, 2007b). For the public and decision-makers, it helped to provide an objective and transparent process whereby the benefits and costs of energy projects could be identified at the pre-design stage (Cook et al., 2016). In addition, it enabled governance authorities in Iceland to protect project locations with the highest conservation value from energy developments by law. For energy companies, the information that would be gathered would help to identify and minimise opportunity costs and inform the future siting of proposed projects to avoid locations with the highest conservation value (Steingrímsson et al., 2006).

Work began on the Master Plan for Nature Protection and Energy Utilisation 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 2013-2017) and fourth phases (2017-2021) also evaluating wind power. A fifth phase began in 2021. In early 1999, the Icelandic government had introduced an action programme under the slogan of 'Man – utilisation – nature; a Master Plan concerning the utilisation of hydroelectric power and geothermal energy'. It stated that the Goal of the Master Plan was:

"*To assess and classify power plant options, both hydroelectric power and high temperature geothermal areas taking into consideration power generating capacity, feasibility and other macro-economic values, concurrently with the defining and classification of the impact of such options on natural conditions, natural and cultural historical relics as well as on the interests of those who utilise these same resources. In this way a foundation is built for the prioritising of power plant options taking into account the needs of society regarding economic activity, the preservation of natural resources, the strengthening of regional areas and the interests of all those who utilise these same resources having sustainable development as a guide."*

ICELAND'S MASTER PLAN – LEGAL STATUS

In 2011, the Icelandic parliament approved the law on the Master Plan. The law was approved during the ongoing work of the Steering Committee and was supposed to be enacted in two phases. The first, already in 2011, that provided the legal status of the Steering Committee, and then the rest of the Act was supposed to be enacted with the completion of the first decision of the Icelandic Parliament of the basis of the first suggestion brought to it via a parliamentary resolution. That took place in 2013 when the whole Act entered into force.

Article 1 of the Master Plan Act (No. 48/2011) reflected the overarching goal, stating that the objectives of this Act 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."*

The first phase of the Master Plan reviewed 43 potential power projects, which were comprised of 19 hydropower options and 24 geothermal projects in high-temperature fields. Phase 2 assessed 81 potential power projects, including 40 hydropower and 41 geothermal power ventures. Phase 3 of the Master Plan was the first to be carried out under the remit of the Master Plan Act, with 26 projects subjected to detailed evaluation (ramma.is, n.d.). The Master Plan is supposed to provide scientific analysis on the various trade-offs for all energy options on terrestrial Iceland - these are wind, geothermal and hydro power projects. Is it also subject to a size limit, hence all energy options of 10 MW or larger are mandated by the law to be assessed and agreed upon under the Master Plan.

ORGANISATION OF THE MASTER PLAN

The Master Plan is led by a Steering Committee which oversees the information-gathering activities of four expert Working Groups (WGs). The law identifies the National Energy Authority (Orkustofnun) as the competent authority to receive suggestions from developers on energy options and secure their proposal, which must fulfil minimum data criteria. The National Energy Authority then submits the energy options to the Steering Committee to assess and rank the energy options. Based on the outcomes from the four Working 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 utilisation, on-hold, or protection. Figure 1 provides a visualisation of the structure of the Master Plan and its regulatory and political oversight.

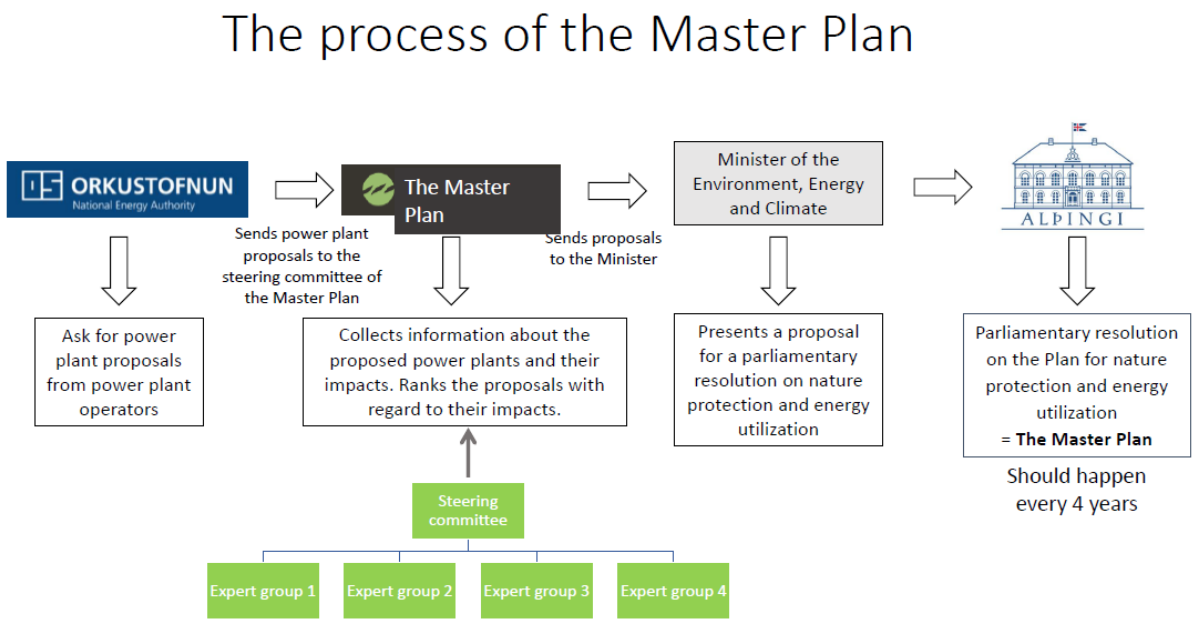


Figure 1. Master Plan structure and regulatory and political oversight. (Sourced from Sæþórsdóttir, 2022).

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 "utilisation" 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 "utilisation" 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.

THE MASTER PLAN'S EXPERT WORKING GROUPS

The law requires the Master Plan's Steering Committee to establish working groups. It does not specify their composition but outlines the issues that need to be examined. Since the law become enacted, there have been four expert working groups. The methods adopted by the respective WGs vary and the criteria under evaluation has evolved across the phases of the Master Plan. WGs 1 and 2 have applied an Analytic Hierarchy Process to rank projects according to value. The role of the Master Plan's Steering Committee is to utilise the information gathered by all the WGS as a basis for the ranking order of energy projects under evaluation, and the eventual categorisation. However, Phases 1 and 2 of the Master Plan were solely based on the outcomes from WGs 1 and 2, with the insights of WGs 3 and 4 providing additional information (ramma.is, n.d.).

The four WGs of the Master Plan gather information on the following issues:

- WG1: Nature, cultural heritage, landscape and wilderness
- WG2: Impacts on other land uses (tourism, outdoor activities, agriculture, fishing and hunting)
- WG3: Societal and local development impacts
- WG4: Energy alternatives, economic profitability and costs

The criteria under evaluation are summarised below, with emphasis on the current methodology to be deployed in Phases 4 and 5 of the Master Plan.

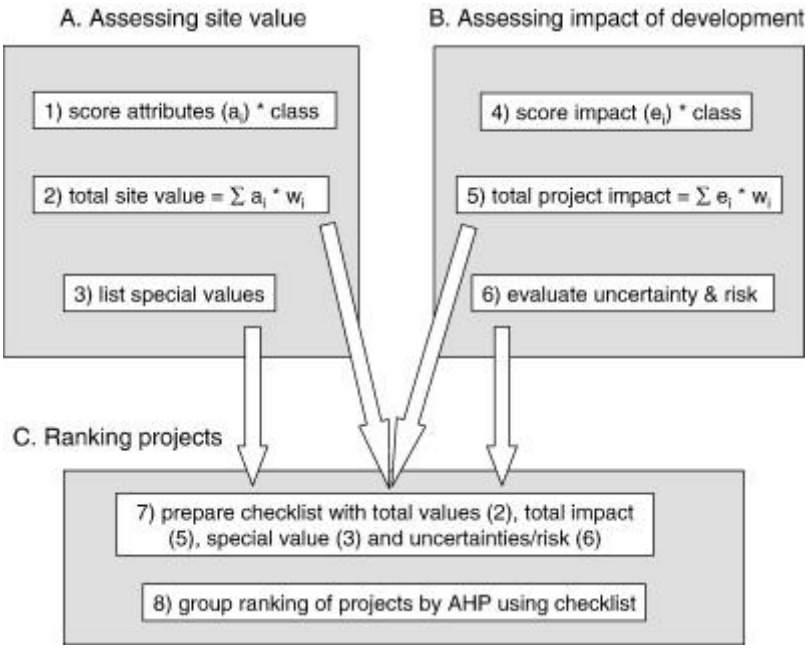
WG1: NATURE, CULTURAL HERITAGE, LANDSCAPE AND WILDERNESS

WG1 considers the impacts of energy production on five classes, which constitute the group of phenomena that may be valuable and impacted. These are as follows, with the respective weightings for each class determined by a Delphi process involving expert-based determination:

- Geological heritage and hydrology (including bedrock, sediments, hydrology, and rivers and lakes); weighted 25%
- Species (birds, aquatic life, plants, and bacteria in geothermal ecosystems); weighted 20%
- Ecosystems and soils; weighted 20%
- Landscape and wilderness; weighted 25%
- Cultural heritage; weighted 10%

Three of the classes above are further divided into sub-classes: geological heritage and hydrology, species, and landscape and wilderness.

The process of evaluation in WG1 is based on the analytic hierarchy process of MCDA and includes three stages, as visualised in Figure 2. Stage (A) entails an expert-led assessment of site values. Stage (B) is a consideration of the impacts of the proposed energy project, with Stage (C) ranking the projects from worst to best choice using the Analytic Hierarchy Process, based on the site values and impacts. Evaluation of each class and sub-class involves identifying valuable properties based on up to six distinct attributes: (1) richness-diversity; (2) rarity; (3) size-pristineness; (4) international responsibility; (5) information value; and (6) aesthetic value. However, the number of attributes considered varies by category, for example, four attributes are assessed for geological heritage and hydrology, birds, ecosystems, landscapes and cultural heritage while only two are used for wilderness areas. Notably, aesthetic value (attribute 6) is evaluated only for landscapes. The value of each attribute pertaining to each potential power plant is evaluated on a non-linear five-point scale, whereby 1 = inconsiderable, 4 = modest, 8 = considerable,13 = high and 20 = very high. The same scale applies for impacts, with the addition of a sixth point of 0 = no impact. The value score for the attributes of each class is weighted, with the classes assigned weight factors to arrive at a unique numeric score and ranking for each potential energy project. An assessment of risk and uncertainty is also incorporated into the final ranking, based on a determination of either A (small), B (significant) and C (high) (Thórhallsdóttir, 2007a; 2007b; Ægisdóttir et al, 2024).



Where a = attribute, w = weight and i = class

Figure 2. Schematic representation of the three-stage assessment procedure of WG1. (Sourced from Thórhallsdóttir, 2007a).

When the final checklist in Stage (C) is prepared, the most notable values of the sites are identified in two columns. The first highlights acknowledged qualities, with the second pinpointing very high (class multiplied by attributes) scores for individual

attributes that a site has received. Using the checklists and applying the Analytical Hierarchy Process, two energy projects are compared at a time. In Phases 1 and 2 of the Master Plan's evaluation, it was found that there was a close correlation between the rank position determined by the Analytical Hierarchy Process and the ranking order of the impact score, and that removing the unequal class weightings had little impact on the impact rank order. (Thórhallsdóttir, 2007a; 2007b; Ægisdóttir et al., 2024.

WG2: IMPACTS ON OTHER LAND USES

WG2 used the so-called Delphi method. The idea behind the method is to use the knowledge of experts to objectively evaluate issues that require judgment on very complex issues that are not easily dealt with using conventional questionnaires or interview-based research methods (Garrod and Fyall, 2005; Linstone and Murray, 2002). This method has been utilized in various fields, including tourism (Choi and Sirakaya, 2006; Garrod and Fyall, 2000; Green et al., 1990; Lee et al., 2008; Liggett et al., 2011; Spenceley, 2008) and as a tool for applying multi-stakeholder approaches in policy-making (Gordon, 1994).

The tasks of WG2 are to evaluate the impacts of proposed power plants on other land uses, such as tourism, outdoor recreation, agriculture, fishing, and hunting. The weight of each of these sectors in the analysis is based on their respective contributions to Iceland's Gross Domestic Product, as follows: tourism and outdoor activities (88.57%), freshwater fishing and hunting (reindeer and birds) (5.25%) and agriculture (6.17%). Thus, its overwhelming focus on tourism and recreation is due to its enormous contribution to the Icelandic economy (Sæþórsdóttir, 2024).

When evaluating the impacts of proposed power plants on tourism and outdoor recreation, WG2 furthermore applied a systemic approach, with each step of the work described in the papers by Sæþórsdóttir and Ólafsson (2010a, 2010b). A six-stage process is carried out: (1) define spatial boundaries of tourism regions; (2) evaluate the value of attributes; (3) determine the effect of proposed power plants on attributes; (4) re-evaluate the attributes of affected tourist regions; (5) calculate the impact coefficient; and (6) rank proposed power plant projects according to their impacts (Sæþórsdóttir and Ólafsson, 2010a; 2010b). In the 5th phase of the Master Plan, the country was divided into 191 tourism regions. Out of these, 109 regions were affected by the proposed energy projects in the 5th phase. These projects include four hydropower projects, one geothermal, and ten wind energy projects (Sæþórsdóttir, 2024).

An attribute-based methodology was created to evaluate the value of three main categories of attributes for tourism and recreation in Iceland: experience (33%), recreational opportunities (34%) and use (33%) (Sæþórsdóttir, 2023). These categories were further divided into 23 specific attributes. For example, protected areas constitute 3% of the 33% experience weighting, or 1% of the overall attributes. For each of the attributes, a five-point scale was used for the evaluation, similar to the one applied in WG1. For example, 0 = no value, 1 = insignificant value, 3 = some value, 6 = high value, and 10 = very high value. Power project impacts are split into those affecting the construction and impacts to regions (Sæþórsdóttir and Ólafsson, 2010a; 2010b), with the former relating predominantly to effects in the direct vicinity of the proposed infrastructure and the latter relating to broader impacts to the surrounds, and potentially involving several tourism regions (Tverijonaite et al., 2022). By comparing the likely value of impacted tourism areas pre and post development, the total impact

of the proposed energy project is calculated via an impact coefficient, which is quantified by multiplying the pre-development value of the tourism regions with the expected change. The impact coefficient specific to each energy project is determined by aggregating all the impact coefficients in the tourism regions affected by the proposed project. Using the aggregated impact coefficients, these are then ranked from the highest impact down to lowest (Sæþórsdóttir and Ólafsson, 2010a; 2010b).

A similar before and after evaluative process is applied for freshwater fishing and hunting and agriculture. In the case of the former, the entire watershed in which the power project is constructed is considered as the impact area, regardless of whether it is a hydropower or geothermal project (Sæþórsdóttir, 2024).

WG3: Societal and local development impacts

Until now, the efforts of WG3 have been focused on providing qualitative information on the impacts of potential energy projects upon society, endeavouring to inform the debate as to the respective degree of social consensus. WG3 has now outlined the key classes and their sub-classes for its analysis, deriving from the International Association of Impact Assessment on the social impacts of projects that has been developed by the International Association for Impact Assessment (IAIA), (Esteves et al., 2012). This has been long in development but are not used widely as a form of guidance (Vanclay, 2023; Arce-Gomez et al., 2015).

WG3 applies seven classes that are grouped into two categories. In the first category are the following 3 classes of 1) local economy impact; 2) energy security and access; and 3) community cohesion, which the group considers most important classes and give 20% weight to each, equivalent to around 60% overall weight. The other four are 4) infrastructure development; 5) conservation potential; 6) visual impact; and 7) economic benefits outside the local region, which are all allocated weights of around 10, or 40% when combined (Kalmansson et al., 2023).

WG3 employs mixed methods in their analysis of the energy options, both quantitative survey methods and qualitative research methods. This has included opinion polls in specific municipalities and at the national level, resident meetings, focus groups with local residents, attitudinal surveys of local and national residents concerning existing and under construction power plants (including attitudes to wind power), and interviews with local government officials and stakeholders. The findings from the analysis of the different classes enables the group to do a categorical ranking of the impacts of the individual energy options, where they employ a 7-grade scale ranging from projects having a very positive impact to those having very negative impact. Regarding the influence from the visibility of power plants and related infrastructure in the locality, WG3 uses GIS data from the National Land Survey of Iceland to evaluate proximity and impacts to the views from the homes of local residents, recreational areas, and main roads (Kalmansson et al., 2023).

WG4: Energy alternatives, economic profitability and costs

The focus of WG4 is on the technical and economic potential of future energy projects. Issues examined by WG4 include expected energy capacity in GWh/annum, estimates of the Levelized Cost of Electricity (LCOE) in kr/kWh/annum, Net Present Value over the anticipated lifetime of the project, predicted cash flow analysis, and estimates of the rate of return on investment. Different profitability models are used depending on the type of energy project, with variable components including the expected lifetime of

the project (25 years for wind, 40 years for geothermal, and 50 years for hydropower) and assumed operational costs (0.8%, 2% and 3.5% of CAPEX costs for hydropower, geothermal and wind power, respectively). WG4 also seeks to assess the other economic effects of power plant options due to connection costs and effects on the structure of the main electricity transmission system, including the factoring in of sources of income other than energy sales, for example, the expected multi-use of resource flows from geothermal power plants or sales of balancing power from hydropower plants against the variable power of wind power. In addition, the increased costs of needing to purchase balancing power from hydropower facilities are accounted for when evaluating the economic feasibility of wind power projects (Steingrímsson et al., 2006; Jensson, 2023).

Once the results from the respective WGs have been completed, the Master Plan's Steering Committee has the role of integrating the data and combining the rank orders into one final rank order for the energy options.

4. LITERATURE REVIEW

METHOD

The systematic literature review in this study was carried out in accordance with the Search Appraisal, Synthesis and Analysis (SALSA) framework (see Figure 3). Originating in the health sciences, the method has recently been utilised in a broad variety of contexts, including literature reviews on Arctic ecosystem services (Malinauskaite et al. (2019), indicators of sustainable energy development (Gunnarsdóttir et al., 2020), the ecosystem services of volcanoes (Cook et al., 2022), and the ecosystem services and disservices of agroecosystems (Merida et al., 2022).

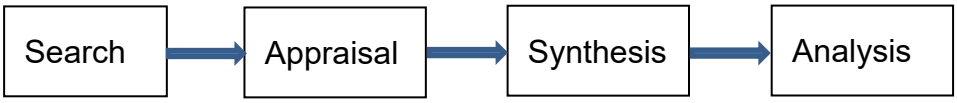


Figure 3. SALSA Method. (Adapted from Malinauskaite et al. (2019)).

The main stages in the method were carried out in the chronological order described below:

1) Search
    - An initial search using the terms “geothermal power”, “hydropower” and “wind power” in conjunction with “MCDA” and “multi-criteria decision and analysis”. These terms and standard BOOLEAN search strings (i.e., AND/OR) were used to scrutinise four academic databases (Web of Science, Google Scholar, Scopus and ScienceDirect). The search was restricted to publications in the period January 2017 to May 2023, thus focusing it on recent GIS and MCDA studies.
    - Initially, this resulted in a considerable volume of publications, totalling X for the three energy generating technologies and split as follows: n = 37 for geothermal power, n = 131 for hydropower, and n = 286 for wind power. Subsequently, after removing duplicate studies across the four databases, inaccessible articles due to paywalls, and those of peripheral relevance to this study, the number of studies under evaluation was reduced to n = 22 for geothermal power, n = 109 for hydropower, and n = 184 for wind power. Regarding the determination of peripherality, studies were excluded at this stage if: (a) it became apparent that they were of limited relevance to a specific energy project context, or (b) GIS/MCDA were merely considered as incidental topics in the discussion sections of articles. Studies that were found to relate to offshore wind energy projects were also excluded at this stage.
2) Appraisal
    - All abstracts, discussions and conclusions were read in full to determine their relevance to this study. Studies were considered to be relevant for inclusion on the basis that they addressed a) GIS-modelled criteria for inclusion in MCDA for one of the three types of energy project, b) weighting determinations for criteria that could, in theory, be modelled by GIS in energy projects, or c) deliberations on the potential future scope

of GIS modelling and its utility to MCDA in the context of geothermal power, hydropower or wind energy projects.

- A total of 41 articles were selected to be read in full. These were split as follows: n = 13 for geothermal power, n = 9 for hydropower, and n = 19 for wind power. Many hydropower studies were rejected from the initial pool of publications at the Search stage because they focused on GIS-based methods, whilst not endeavouring to integrate this information in MCDA platforms.

3) Synthesis
    - Each of the selected publications were reviewed in their entirety with respect to objectives and location, methods, scope of criteria modelled by GIS mapping, and the main discussion topics.
    - For all these studies, specific details were extracted and summarised in the detailed Appendices A-C of this report on geothermal power, hydropower, and wind power, respectively. In addition, where a study's GIS modelling of criteria demonstrated potential usefulness for Iceland's Master Plan, this was denoted using a simple tick-based system for each of the four WGs.
4) Analysis
    - The analysis of the detailed findings in Appendices A-C was carried out via a process of thematising the most common MCDA criteria evaluated using GIS methods, and considering how this information was used in MCDA with respect to the three energy-generating technologies under evaluation by the Master Plan (Section 4).
    - Where criteria overlap with the focuses of the WGs of the Master Plan was identified, this was deemed to be a discussion topic, together with potential future uses of GIS mapping to inform decision-making in relation to energy projects and other interesting discussion topics (Section 5).

5. RESULTS

The results of this study are reported in turn for each energy generating technology. These have also been reported in a recent publication in the Journal of Energy Strategy Reviews (Cook and Pétursson, 2025).

GEOTHERMAL POWER

The predominant focus of the geothermal GIS-MCDA literature has, thus far, been on resource prospectivity and addressing the issue of risk. In the case of the former, the studies have addressed various geological, geophysical and geochemical characteristics of the potential sites, with a view to informing about the potential of various geothermal areas. Social criteria, such as acceptance or proximity of centres of population, were rarely considered in the literature under examination, which equally applied to conflicts with other land uses.

The study by Yalcin and Gul (2017) exemplified the type of resource prospectivity studies in which GID-MCDA is currently deployed. The purpose of this analysis was to carry out a first stage feasibility analysis in the process of geothermal exploration, which has the capacity to aid in the implementation of geophysical and geochemical methods, leading to informed reconnaissance drilling. In this study, focused on the case study of the Akarcay Basin in Turkey, where the AHP and GIS mapping was utilised to grade the potential of various geothermal areas. Criteria included land surface temperature anomalies, distance to hot springs, distance to fault lines, topography, and wetlands and settlement boundaries. The results of their study were compared with the existing hot spring locations in the Gazligol, Omer, Gecek, Kizik, Uyuz, and Heybeli geothermal fields. They found that all the existing hot springs are in the extremely high classes of the geothermal favourability map, implying the usefulness of retrospective GIS-MCDA analysis. Brahim et al. (2020) also focused on geothermal productivity in Turkey and applied a hydrogeochemical approach to map geothermal potential using two approaches – the weighted overlay and Boolean model. Geothermal areas were then bracketed according to whether they had low, moderate, or high priority.

Other studies had similar aims, with Anwarzai and Nagasaka (2018) using GIS-MCDA to carry out inferred temperature mapping at various depths in Afghanistan. In this case, the study was based on a combination of geological and geophysical characteristics, including crust thickness, surface heat flow, mantle heat flow, surface temperature, and sediment thickness. Cambazoğlu, et al., (2019) used similar criteria but a more elaborate method to determine geothermal favourability in the Geediz Graben region of Turkey. Their study involved GIS mapping of criteria, some of which were distance based, with each layer weighted using AHP. However, as an extension at the mapping of favourability stage, the Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) was used to order the geothermal favourability from most to least favourable. The study by Yal et al. (2020) also used TOPSIS to rank the geothermal prospectivity of areas in the Büyük Menderes Graben in Turkey. GIS-mapped criteria in this study included distance to faults; fault density; distance to graben centre; distance to cap rock; distance to hot springs; b-value; night-time surface temperature; and slope angle. Regardless of whether TOPSIS was applied, other studies utilised similar criteria and the AHP to determine the potential of geothermal

sites in China (Meng et al. 2021; Xu et al., 2023), Africa (Elbarbary et al., 2022), and Kenya (Ng'ethe, and Jalilinasrabady, 2023).

The Kenyan study by Ng'ethe and Jalilinasrabady (2023) used GIS-MCDA to generate a Silica Saturation Index (SSI) for selecting the best direct use scenarios for geothermal resources in the Central and Southern Rift Valley. This was an integrated application of GIS-MCDA, since it not only focused on utilisation potential, but also the optimal scenario for how energy is to be used in the future. In this study, it was determined that the accurate matching of geothermal resource characteristics to economic activities and its proximity to thermal needs and existing infrastructure, such as roads, water, and topography, is the most influential stage of analysing and precisely predicting the best direct use scenarios. Each geothermal resource has different direct use scenarios that match its resource traits, such as fluid volume, temperature, pH, and silica content.

Some studies went further than others in terms of criteria, basing their prospectivity determinations on an extensive array of parameters. The assessment by Tinti et al. (2018) on the suitability of shallow geothermal technologies, such as Ground Source Heat Pumps, investigated many parameters to arrive at a Geolocalised Suitability Index and map. These included shallow geology; hydrogeology; thickness of sediments and bedrock; bedrock compressive strength; sediment compressive strength; bedrock thermal conductivity; ambient yearly average temperature; ambient yearly temperature amplitude; land cover; population; and geothermal heat flow.

The role of machine learning and algorithmic analysis featured in a couple of the more recent studies in the literature. Xu et al. (2023) conducted an evaluation of the potential of geothermal areas on the Hangjiah Plain of Zhejiang Province in China. The AHP was used in tandem with Back Propagation (BP) neural network for establishing geothermal potential target evaluation models. The authors contended that determination of the five potential geothermal areas by the BP neural network reduces reliance on experts' judgment and prior knowledge, as is commonly applied in the AHP. Thus, the designation of prospectivity is potentially more scientific and data driven. Nascimento's (2022) PhD dissertation on the potential of geothermal zones in Portugal used machine learning, applying the Random Forests and Extreme Gradient Boosting algorithms to assess the thermal properties of geothermal regions. This study was focused on just two parameters – geothermal gradient and surface heat flow density – but it was felt that the use of machine learning and Artificial Intelligence (AI) could have a considerable role in the future in reducing the costs of exploring geothermal areas, which require expensive field surveys, together with geological, geophysical, and geochemical analyses, in addition to exploratory drilling.

Only two studies in the examined literature conducted any form of sensitivity analysis. The study by Mostafaeipour et al. (2020) evaluated the geothermal potential of projects in Afghanistan. The Stepwise Weight Assessment Ratio Analysis (SWARA) method was used to weigh each criterion while the Additive Ratio Assessment (ARAS) method was used to rank potential geothermal sites. TOPSIS, VIKOR (from the Serbian 'VIekriterijumsko Kompromisno Rangiranje') and the Weighted Aggregated Sum Product Assessment (WASPAS) methods were also used in this study as part of a sensitivity assessment on the rankings. Another study by Kiavarz and Jelokhani-Niaraki, (2017) considered prospectivity in tandem with project riskiness when evaluating the potential of geothermal areas in Japan. An Ordered Weighted Averaging

approach was applied to a model that generates geothermal prospectivity maps with different pessimistic or optimistic strategies. The geothermal prospectivity maps were constructed under the assumption that the weights of the criteria remain fixed through the scenarios, and 'ORness', the measure of risk, was the only value that changed, from 0 to 1.

HYDROPOWER

The focus of GIS-MCDA studies in the context of hydropower was broader than that evidenced in the geothermal energy literature. Although several addressed the subject of resource potential in a narrow sense, and several studies also integrated data on conflicts with society and other land uses. ArcGIS was widely used, with the AHP and TOPSIS approaches again prominent.

The study by Lu and Wang (2017) exemplified the relief and hydrological parameters considered in determining the productive capacity and optimality of various hydropower project options. Addressing potential project sites in Tibet, Lu and Wang (2017) applied ArcGIS to extract the elevation of all water bodies and to calculate the surface slope within the study area. A "zonal statistics as table" tool was used to obtain the elevation of each lake, which was calculated as the average elevation of each pixel. The potential productive capacity of hydropower projects was assessed with respect to the parameters of elevation and slope, as well as distance to lakes and reservoirs, minimum head threshold, minimum lake size, maximum difference in elevation, and minimum flow accumulation.

Lu and Wang's (2017) was demonstrative of a rather narrow GIS-MCDA study that focused on theoretical productive capacity, which approach was equally apparent in the Egyptian feasibility study by Eshra et al. (2021), the Malaysian by John and Naharudin (2022), the Ethiopian by Moshe and Tegegne (2022), the Pakistani by Munir (2022), and the Indian by Prakasam and Saravanan (2023). Badang et al. (2018) produced a wider assessment that focused predominantly on theoretical energy generation at six possible hydropower project locations in Rogongon, Iligan City, and considered project cost; difficulty in transporting materials; accessibility to project site; obstructions to the site; and social conflicts. In terms of methodology, Badang et al. (2018) applied the AHP for the weighting of criteria, with the combination of TOPSIS for the determination of scores and ranking for alternative sites. Thematic maps were created in ArcGIS showing hydropower potential at sites, with their corresponding ranking added in an attribute table. The study by Hagos et al. (2022) on suitable dam site identification using GIS-based MCDA, focused on the Chemoga watershed, Ethiopia, also used ArcGIS and considered some of the trade-offs pertaining to hydropower projects, specifically impacts to soils, agronomy, and socio-economic performance.

Arguably the broadest study in the hydropower GIS-MCDA literature, in terms of the breadth of information offered to decision-makers, concerns the work by Laks et al. (2023), which provides an optimal evaluation of increasing the damming level at Rosko SHP in Poland. This study applies fuzzy AHP, outlining a methodology for assessing the operation of SHPs and supporting decision-making processes when it is necessary to change the operating regime of a small hydropower plant due to, for instance, changes in its hydrological conditions. An array of economic, legal, technical, and socio-environmental criteria is evaluated using GIS. Economic included the consequences for revenue generation, maintenance costs, permit costs, and

document preparation costs. Legal included environmental agreements, and the costs of compensation to farm owners and entrepreneurs. Technical included the required development of technical infrastructure, impacts on damming structure, and risk of dam failure. Socio-environmental included the extent of potential social opposition and protests, environmental impacts, impacts to tourism and water transportation, and predicted reductions in carbon dioxide emissions.

WIND POWER

In comparison to most of the GIS-MCDA studies on potential geothermal and hydropower projects, those focused on onshore wind power embraced a much wider remit and can generally be considered as sustainability analyses rather than predictions regarding resource potential. Based on the literature examined in this review, the GIS-MCDA studies on onshore wind power most commonly focus on determining the optimal location for such projects. This includes mapping and suitability index studies that only consider environmental impacts, such as bird habitats, noise, visual blight and aesthetics, safety, and shadow flicker. Equally, there are several studies that go further, considering multiple economic, technological, social, and environmental criteria. Some focus on the impacts of spatial and environmental criteria on the likely economic returns of wind energy projects. A variety of methodological approaches are adopted, including AHP, fuzzy AHP, hybrid forms of AHP, PROMETHEE, and the fuzzy Analytical Network Process.

The GIS-MCDA study by Ali et al. (2017), determining the optimal location of onshore wind energy projects in South Korea, exemplifies the use of fuzzy AHP and a variety of production-related, land-use restriction, and locational attributes that can be considered. Productive capacity in such studies is a function of average wind speed, which is easily estimated. The various land-use restrictions considered by Ali et al. (2017) were the presence of airports; military zones; wetlands, rivers, lakes, and streams; protected areas; tourism, historical, cultural, and religious places; natural and federal areas; railways and subways; and public and community interest sites. Certain restricted areas were immediately removed as potential sites of wind farms, including military zones, federally protected areas, and wetland areas. In the study by Ali et al. (2017), locational attributes were distance-related to electricity sub-stations, powerlines, roads, cities and towns, and railways. Distance to cities and towns was used as a proxy for visual impact. After the exclusion of certain restricted areas, all remaining areas were evaluated by Ali et al. (2017) according to seven criteria, which were allocated relative weights using fuzzy AHP. Six scenarios were considered in this study and wind farm suitability maps (scaled from 1 to 8: with 1 being the least suitable site and vice versa for 8) were constructed for all scenarios.

The approach of Ali et al. (2017) chimes with several other studies in the examined literature. Anwarzai and Nagasaka (2017) conducted a similar evaluation focused on Afghanistan. In their work, ArcGIS was used to apply the MCDA system according to the following process: (1) selection of data layers and union of polygons; (2) selection by attributes and location; (3) aggregate polygons; and (4) intersection. The National Renewable Energy Laboratory developed Geospatial Toolkit for Afghanistan, which was relied upon for the GIS-based wind related information. Land-use restrictions were also applied to immediately strike off certain locations, including those pertaining to protected areas and lakes, land beyond 10 km road access, sand dunes and permanent snow areas, marshland, irrigated land, natural forest, and urban settlements. Pamučar et al. (2017) followed a similar approach, estimating the optimal

location for wind farms using a GIS multi-criteria hybrid model, based on fuzzy logic and rough numbers. The authors' model is based on combined use of GIS with multi-criteria techniques of Best-Worst method (BWM) and Multi Attributive Ideal-Real Comparative Analysis (MAIRCA). After applying land-use restrictions relating to plant cover, agricultural land, protected areas, aquatic zones, forests, and urban areas, the MAIRCA method ranked alternatives based on the total value of the gap, whereby the best alternative is selected as the one that has the lowest value of the gap, or the one that is closest to the ideal alternative. The worst alternative is the one that has the highest value of the gap, or the one that is farthest from the ideal alternative. Other studies following a similar approach to these included the works of Sheng et al. (2018) on potential wind power sites in Mongolia, Harper et al. (2019) on the United Kingdom, Barzehkar et al. (2021) on Iran, Nasery et al. (2021) on Afghanistan, Ajanaku et al., (2022) on West Virginia, the United States, and Raza et al. (2023) on Pakistan.

Harper et al.'s (2019) study was noteworthy in two regards: firstly, as a nationwide study, and secondly, for its attention to the likely social implications of wind energy projects, as well as economic and land-use restriction issues. The topic of social acceptability and the social license to operate was determined via the perceived likelihood of winning planning permission, based on locational factors and the political affiliation of the affected municipality. The absence of local studies on attitudes concerning proposed onshore wind farms perhaps diminishes the usefulness of the insights that can be drawn in a national study. However, the authors acknowledged the need for more fine-grained analysis at the local level.

In terms of the comprehensiveness of evaluating environmental and social impacts and the strictness of criteria applied, the study by Peri and Tal (2020) stood out. Using the case study of northern Israel, the authors applied a GIS-MCDA approach to evaluate optimal turbine design, with focus on minimising environmental impact. The environmental and social criteria considered by the authors were as follows: noise; shadow flicker; birds; bats; land cover; open lands; topography; and settlement populations. Intriguingly, the authors determined that only 0.5% of the possible sites in the study area were suitable for wind energy projects according to the strictest environmental constraints. Anthropocentric environmental impacts from turbines were found to be significant whenever sites were located less than 750 metres from settlements. Ecological impacts, however, were not found to correlate with the distance of a possible wind power project from protected areas.

Another insightful GIS-MCDA study was conducted by Vavatsikos et al. (2019), concentrating on the economic implications of GIS-based suitability analysis for wind power projects. Drawing on the case study of Thrace in north-eastern Green, Vavatsikos et al. (2019) applied the AHP in tandem with a MCDM-based portfolio formation, which sought to select a subtotal of alternative investments that produce the highest sum of gained suitability under the standard constraints that underlie capital rationing methods. The outputs of the model were a Portfolio Selection Index and Portfolio Alternative Selection Index. A set of production, design, social and land use criteria were applied. The social aspects focused on landscape and aesthetics' perceptions in the presence of wind turbines. Due to the spatial nature of renewable energy sector-related decisions, the synergy of GIS and MCDA models in studies, such as Vavatsikos et al.'s (2019), can potentially enrich the quality of the related decisions given their ability to effectively support land management considerations. Traditional Net Present Value-based analysis aims to maximise investors' opportunities in

monetary terms. Alternately, MCDA-based portfolio formation takes into consideration a variety of decision-making dimensions and thus reduces possible risks that are usually spatially related. Moreover, their implementation significantly enriches the performance of the traditional capital projects evaluation methods (CPEM) by providing physical data to the sizing process in a quick and accurate manner. Thus, decision-making frameworks that combine GIS-based suitability analysis with traditional financial evaluation techniques can significantly enrich the planning phase to achieve efficient installations in terms of required area, power generation maximisation, and any restrictions relating to local characteristics.

Since the GIS-MCDA literature in the context of wind energy is more advanced than the other energy generating technologies explored in this review, there is greater evidence of innovation and novelty in methodological matters. A few selected studies from our review exemplify this point. Gigović et al. (2017) developed a hybrid MCDA-GIS-MABAC spatial model for the selection of locations of wind farms, tested on the case study of Vojvodina, Serbia. The proposed model was based on the combined application of Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA), using the multi-criteria technique of Decision-Making Trial and Evaluation Laboratory (DEMATEL), the Analytic Network Process (ANP) and Multi-Attributive Border Approximation Area Comparison (MABAC). ANP is a generalisation of the AHP method, in that it replaces the hierarchy with a network by means of feedback. ANP, unlike hierarchically-structured problems considers different forms of dependence and feedback. The DEMATEL-ANP (DANP) method is used to determine the weight coefficients of the evaluation criteria, and the MABAC method is used to rank the selected viable locations. The final map of benefits is presented using raster cells (alternatives), which are evaluated in the range of 1 (least suitable) to 7 (most suitable).

Villacreses et al. (2017) conducted a nationwide assessment of the most suitable locations in Ecuador for onshore wind energy projects. The authors adopted the AHP method that was implemented for calculating the weights, as well as the (OWA) Occupational Repetitive Actions (OCRA), VIKOR and TOPSIS. An Overall Performance Index (OPI) was applied to evaluate the results. Finally, the mutual correspondence between MCDM methods was evaluated by Pearson correlation coefficient.

Sotiropoulou and Vavatsikos (2021) specified a new decision-making framework that combines GIS and PROMETHEE II, a multi-attribute decision-making (MADM) method, to enable the GIS-assisted wind farm suitability analysis of the Thrace region in north-eastern Greece.

Finally, Shafiee (2022) assessed optimal locations for onshore wind energy projects, seeking to address the subject of uncertainty. The case study was a hypothetical 25 MW onshore wind energy project in Iran, and the authors integrated the fuzzy Analytic Network Process (FANP) and the fuzzy technique for order performance by similarity to the ideal solution (TOPSIS) to evaluate and prioritise the potential sites for wind power development. The results are discussed and compared with those obtained using the traditional AHP, ANP and ANP-TOPSIS decision-making approaches. The required information was collected from a literature review, Delphi and on-site interviews with key stakeholders involved in the renewable energy sector of the

country, GIS platforms, and Iran’s wind energy resource atlas. Social criteria related to the degree of social acceptance.

6. DISCUSSION

MASTER PLAN IMPLICATIONS

The literature review demonstrates that GIS-MCDA studies in the context of geothermal energy, hydropower and wind energy projects currently embrace topics of relevance to all four WGs in Iceland's Master Plan. The breadth is greatest in the case of onshore wind energy projects, with GIS-MCDA projects on geothermal energy mostly focusing on issues relating to technical feasibility, likely to be only relevant to the activities of WG4. Few issues of relevance to WGs 1, 2 and 3 were observed in the geothermal energy studies. GIS-MCDA studies on hydropower projects also focused overwhelmingly on issues of energy generation of relevance to WG4, however, slightly greater attention was paid to the topics of social conflicts and trade-offs, and environmental implications than was the case for geothermal power. In contrast to the geothermal and hydropower GIS-MCDA studies, those on onshore wind energy often pinpointed land-use restrictions as an initial constraint on a possible project location, before also considering technical feasibility issues and potentials. Environmental impacts of relevance to WG1 and social aspects of interest to WG3, including issues of acceptance and proximity to population centres, were to the fore in the GIS-MCDA studies on onshore wind energy. The issue of trade-offs with other land-uses was very lightly covered across all three energy generating technologies, although there was limited consideration in the case of the onshore wind energy studies.

WEIGHTING AND AGGREGATION IN MCDA

This study revealed that a variety of approaches are undertaken with respect to the aggregation and weightings of criteria in recent MCDA studies on renewable energy projects. Most studies used either the AHP or TOPSIS approaches. The weightings afforded to MCDA criteria and the selected criteria themselves are liable to being accused of arbitrariness (Steele et al., 2009). The Master Plan is equally vulnerable to this accusation, especially concerning the weightings applied to environmental and land-use components in the work of WGs 1 and 2. Given the spatial scope of the Master Plan and its strategic remit, local specificities may be under or overrepresented in terms of their importance. For example, some remote sites may be of very low importance for tourism, yet critical for grazing, and therefore the fixed weightings that have been applied in the Master Plan's WG2 would not necessarily capture this.

The Master Plan should not seek to resolve these local versus national dilemmas in its assessment processes. Rather, on the contrary, it should seek to emphasise the robustness of its approach in terms of considering complexity, multiple criteria, experts, and actors, reflective of multiple stakeholder interests. It is important to recognise that a unique, 'optimal' solution in MCDA does not exist, however it is calculated, but rather the aim of a tool such as the Master Plan is to identify the most likely suitable locations, based on stakeholder inputs, ones that maximise consensus and minimise the potential for conflicts. The type of pairwise comparison used in the AHP process, as applied in WG1 of the Master Plan, facilitates an organised structure for group discussions and encourages experts to discuss areas of agreement and disagreement. Due to its transparency and capacity for re-examination, this is why the AHP has been favoured as a decision-making method and been widely used in various renewable energy projects (Hanssen et al., 2018). The role of GIS in this process can be to render decision-making an even more spatially explicit process.

A further issue that should be reiterated when considering the robustness of the Master Plan concerns its uniqueness as a tool for evaluating a whole nation's proposed energy projects. Although its methodology was partly derived from the Norwegian Master Plan Plan for Water Resources (Sæþórsdóttir and Ólafsson, 2010), the Icelandic Master Plan is required to be far broader in its scope, given that it must not only evaluate potential hydropower projects but also geothermal and onshore wind energy, concluding about the relative merits of these very different proposals simultaneously in accordance with its phases. Additionally, the Master Plan Act facilitates the capacity to re-evaluate projects from earlier phases based on new information, so long as it is not now in a protected area. Therefore, the Master Plan constitutes a uniquely complex strategic appraisal on a national scale that also constitutes a pioneering form of iterative MCDA. As such, although its methods have similarities with other MCDA studies, it cannot be directly compared to any other decision-support platform.

PRACTICAL AND DECISION-MAKING IMPLICATIONS

This review has reinforced the importance of developing resilient, cost-effective, environmentally sustainable, and socially acceptable renewable energy infrastructure, which can help to ensure broad access to affordable, reliable, and modern energy services. The selection and siting of renewable energy technology is driven by natural resource availability, and various physical and regulatory constraints. These factors inform early-stage feasibility of renewables, helping to focus the investment of time and money, and this emphasis was prominent in the case of the geothermal and hydropower MCDA studies. However, understanding the relative importance of different criteria influencing the sustainability of energy projects and identifying the most suitable technologies remains a highly complex task due to the disparate and often unconnected sources of data and information needed, and the volume of different methodological approaches applied in GIS-MCDA analysis. Although certain GIS-MCDA studies, such as those on geothermal power, did not cover aspects addressed in studies on the other generating technologies, there is no reason why they could not be incorporated in future works.

Many of the GIS-MCDA studies reported methodological challenges regarding GIS-MCDA studies. Often the cloudiness of the weightings determined by the AHP was recounted in the discussion sections of the papers under study. For example, Brahim et al. (2020) reported on how the criteria used in the GIS analysis could be improved by expert deliberation and it should not just be based on a literature review and data availability. Other studies, such as Lu and Wang (2017), discussed how the narrow focus of their GIS-MCDA work inevitably meant that several important criteria were omitted, requiring consideration in an expanded analysis. The authors comment that their study only selected the theoretical potential sites and analysed the distances from potential sites to grid connections. If a series of social, infrastructure, environmental, and economic constraints are also considered, better understanding of the potential of hydropower sites would be cultivated for decision-makers. Where environmental and social issues were considered, the authors of papers were generally of the view that GIS-MCDA analysis provided information of considerable value to decision-makers. Prakasam and Saravanan (2022) affirmed that the outcomes of their study provided recommendations for better planning and management of the environment and ecosystem of the Beas River basin. Such analysis and planning strategies can be applied to other river systems where similar types of terrain are present. Equally, Elmahmoudi et al. (2020) contended that their onshore wind energy GIS-MCDA study, regardless of its lack of environmental or social focus, was very useful to identify the

areas having very high wind potentiality, with a best wind farm location map prepared. The map, using the overlay function in GIS, exhibited the most and least suitable areas for the location of wind farms in Morocco. In the opinion of the authors, the approach could help identify suitable wind farm locations in other areas using their geographic information.

STUDY LIMITATIONS

As it the case with every systematic literature review, this study's methodology is subject to some limitations. The decision to only scrutinise academic databases and include peer reviewed work may have led to the omission of important grey literature that would have otherwise met the inclusion criteria. Furthermore, the search terms that were used may have led to the omission of some relevant articles, especially those in non-English languages. Restricting the research to the period from January 2017 to May 2023 may have led to the omission of some relevant GIS-MCDA articles, particularly in the case of onshore wind energy, given that such work commenced around a decade ago. However, the aim of this study was to focus on the most relevant and recent works, and it is the opinion of the authors that saturation was reached through analysis of the 41 articles under study in this review. Despite this, the qualitative nature of the methodology and extraction of the most applicable aspects remains prone to a degree of selective subjectiveness of the part of the authors.

7. CONCLUSION

This study has related the outcomes of a literature review into the focal points of GIS-MCDA studies in the academic literature, addressing the technologies of geothermal power, hydropower, and onshore wind power. The widely adopted SALSA method was applied to conduct the interrogation of academic databases and analyse the appraised studies. A total of 41 articles were selected to be read in full, based on the most relevant publications in the period January 2017 to May 2023. These were split as follows: n = 13 for geothermal power, n = 9 for hydropower, and n = 19 for wind power.

Geothermal studies focused on resource prospectivity and minimisation of risk. There was emphasis in the studies on the usefulness of GIS-MCDA for reducing the costs of planning activities, including through machine learning and AI. Some analysis focused on how best to use the geothermal energy to potentially maximise economic returns. Hydropower projects mostly address productive capacity issues, similarly to the geothermal GIS-MCDA studies, however, in comparison to the geothermal GIS-MCDA literature, there was greater focus on providing a broader set of information for decision-makers about the legal, technical, environmental, and social consequences of projects. The use of fuzzy AHP logic was applied to deal with uncertainty in such studies. GIS-MCDA is already used extensively to inform decision-makers concerning the suitability of locations for onshore wind power projects, and there is evidence of methodological innovation and novelty, with analytical methods becoming increasingly advanced. The remit of such studies is frequently broad, considering not only the issues of productive capacity, but also environmental impacts, land use designations (e.g., the constraints of protected areas and other uses), and the topic of social acceptance.

Although most studies addressed issues of relevance to WG4 of Iceland's Master Plan, criteria of relevance to all WGs were covered in the literature. The scope of issues covered by the onshore wind energy GIS-MCDA studies was more extensive than for hydropower or geothermal, with issues concerning population density, social acceptance, and social license to operate likely to be of keen interest with WG3. Land use restrictions were prominent but lesser attention was paid to the type of land-use trade-offs that might be of interest to WG2 of Iceland's Master Plan when evaluating proposals for onshore wind energy projects. A wide spectrum of environmental impacts, of direct relevance to the activities of WG1, were considered in several GIS-MCDA studies on onshore wind energy.

Future analysis in Iceland needs to consider how the criteria currently applied in the GIS-MCDA literature can be applied to the energy project decision-making context, informing the Master Plan. This is the case for hydropower and geothermal power, but perhaps especially for wind power projects, given the ongoing debate in Iceland about the best way of evaluating the merits of proposals. Additionally, further consideration needs to be given as to how specific criteria apply to GIS-MCDA studies on energy projects in Iceland, including various issues such as bird migratory pathways, land-use restrictions, trade-offs with other land uses, and the social acceptability of proposals.

REFERENCES

Ajanaku, B. A., Strager, M. P., & Collins, A. R. (2022). GIS-based multi-criteria decision analysis of utility-scale wind farm site suitability in West Virginia. *GeoJournal*, *87*(5), 3735-3757.

Ali, S., Lee, S. M., & Jang, C. M. (2017). Determination of the most optimal on-shore wind farm site location using a GIS-MCDM methodology: Evaluating the case of South Korea. *Energies*, *10*(12), 2072.

Anwarzai, M. A., & Nagasaka, K. (2017). Utility-scale implementable potential of wind and solar energies for Afghanistan using GIS multi-criteria decision analysis. *Renewable and Sustainable Energy Reviews*, *71*, 150-160.

Anwarzai, M. A., & Nagasaka, K. (2018). A GIS-based analysis of earth's crust temperature at depth for geothermal energy exploration in Afghanistan. *International Journal of Environmental Science and Development*, *9*(1), 0-137.

Arca, D., & Keskin Citiroglu, H. (2022). Geographical information systems-based analysis of site selection for wind power plants in Kozlu District (Zonguldak-NW Turkey) by multi-criteria decision analysis method. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *44*(4), 10720-10732.

Badang, D. A. Q., Sarip, C. F., & Tahud, A. P. (2018, November). Geographic information system (GIS) and multicriteria decision making (MCDM) for optimal selection of hydropower location in Rogongon, Iligan City. In *2018 IEEE 10th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management (HNICEM)* (pp. 1-5).

Barzehkar, M., Parnell, K. E., Mobarghaee Dinan, N., & Brodie, G. (2021). Decision support tools for wind and solar farm site selection in Isfahan Province, Iran. *Clean Technologies and Environmental Policy*, *23*, 1179-1195.

Brahim, F. B., Boughariou, E., Makni, J., & Bouri, S. (2020). Evaluation of groundwater hydrogeochemical characteristics and delineation of geothermal potentialities using multi criteria decision analysis: Case of Tozeur region, Tunisia. *Applied Geochemistry*, *113*, 104504.

Brewer, C. A. (2006). Basic mapping principles for visualizing cancer data using geographic information systems (GIS). *American journal of preventive medicine*, *30*(2), S25-S36.

Brown, G., Reed, P., & Raymond, C. M. (2020). Mapping place values: 10 lessons from two decades of public participation GIS empirical research. *Applied Geography*, *116*, 102156.

Cambazoğlu, S., Yal, G. P., Eker, A. M., Şen, O., & Akgün, H. (2019). Geothermal resource assessment of the Gediz Graben utilizing TOPSIS methodology. *Geothermics*, *80*, 92-102.

Carrara, A., Cardinali, M., Guzzetti, F., & Reichenbach, P. (1995). GIS technology in mapping landslide hazard. *Geographical information systems in assessing natural hazards*, 135-175.

Choi, Y., Suh, J., & Kim, S. M. (2019). GIS-based solar radiation mapping, site evaluation, and potential assessment: A review. *Applied Sciences*, *9*(9), 1960.

Church, R. L. (2002). Geographical information systems and location science. *Computers & Operations Research*, *29*(6), 541-562.

Cook, D., & Jóhannsdóttir, L. (2021). Impacts, systemic risk and national response measures concerning COVID-19—The island case studies of Iceland and Greenland. *Sustainability*, *13*(15), 8470.

Cook, D., & Pétursson, J. G. (2025). The role of GIS mapping in multi-criteria decision analysis in informing the location and design of renewable energy projects-A systematic review. *Energy Strategy Reviews*, *59*, 101765.

Cook, D., Davíðsdóttir, B., & Kristófersson, D. M. (2016). Energy projects in Iceland–Advancing the case for the use of economic valuation techniques to evaluate environmental impacts. *Energy Policy*, *94*, 104-113.

Cook, D., Fazeli, R., & Davíðsdóttir, B. (2019). The need for integrated valuation tools to support decision-making–The case of cultural ecosystem services sourced from geothermal areas. *Ecosystem Services*, *37*, 100923.

Cook, D., Malinauskaite, L., & Davíðsdóttir, B. (2022). Peering into the fire–An exploration of volcanic ecosystem services. *Ecosystem Services*, *55*, 101435.

Einarsdóttir, S. R., Cook, D., & Davíðsdóttir, B. (2019). The contingent valuation study of the wind farm Búrfellslundur-Willingness to pay for preservation. *Journal of cleaner production*, *209*, 795-802.

Elbarbary, S., Abdel Zaher, M., Saibi, H., Fowler, A. R., & Saibi, K. (2022). Geothermal renewable energy prospects of the African continent using GIS. *Geothermal Energy*, *10*(1), 1-19.

Elmahmoudi, F., Abra, O. E. K., Raihani, A., Serrar, O., & Bahatti, L. (2020). Elaboration of a wind energy potential map in Morocco using GIS and Analytic Hierarchy process. *Engineering, Technology & Applied Science Research*, *10*(4), 6068-6075.

Environmental Agency. (n.d.). *Gullfoss: Culture and History*. Retrieved online from: https://ust.is/nattura/natturuverndarsvaedi/fridlyst-svaedi/sudurland/gullfoss/menning-og-saga/ (accessed 13th March 2023).

Eshra, N. M., Zobaa, A. F., & Aleem, S. H. A. (2021). Assessment of mini and micro hydropower potential in Egypt: Multi-criteria analysis. *Energy Reports*, *7*, 81-94.

Gigović, L., Pamučar, D., Božanić, D., & Ljubojević, S. (2017). Application of the GIS-DANP-MABAC multi-criteria model for selecting the location of wind farms: A case study of Vojvodina, Serbia. *Renewable energy*, *103*, 501-521.

Government of Iceland. (1997). Sustainable Development in Iceland Society. An Action Plan until the next millennium.

Greiner, C., Klagge, B., & Owino, E. A. (2023). The political ecology of geothermal development: Green sacrifice zones or energy landscapes of value?. *Energy Research & Social Science*, *99*, 103063.

Guðmundsdóttir, H., Carton, W., Busch, H., & Ramasar, V. (2018). Modernist dreams and green sagas: The neoliberal politics of Iceland's renewable energy economy. *Environment and Planning E Nature and Space*, *1*, 579-601.

Gunnarsdóttir, I., Davidsdottir, B., Worrell, E., & Sigurgeirsdóttir, S. (2020). Review of indicators for sustainable energy development. *Renewable and Sustainable Energy Reviews*, *133*, 110294.

Hagos, Y. G., Andualem, T. G., Mengie, M. A., Ayele, W. T., & Malede, D. A. (2022). Suitable dam site identification using GIS-based MCDA: a case study of Chemoga watershed, Ethiopia. *Applied Water Science*, *12*(4), 69.

Hanssen, F., May, R., van Dijk, J., & Rød, J. K. (2018). Spatial multi-criteria decision analysis tool suite for consensus-based siting of renewable energy structures. *Journal of Environmental Assessment Policy and Management*, *20*(03), 1840003.

Harper, M., Anderson, B., James, P., & Bahaj, A. (2019). Assessing socially acceptable locations for onshore wind energy using a GIS-MCDA approach. *International Journal of Low-Carbon Technologies*, *14*(2), 160-169.

Hjaltadottir, J. V., & Magnússon, P. (2022). *Framework plan approved by Althingi*. Retrieved online from: https://www.ruv.is/frett/2022/06/15/rammaaaetlun-samthykkt-a-althingi (accessed 14th March 2023).

Ho, W. (2008). Integrated analytic hierarchy process and its applications–A literature review. *European Journal of operational research*, *186*(1), 211-228.

Ifkirne, M., El Bouhi, H., Acharki, S., Pham, Q. B., Farah, A., & Linh, N. T. T. (2022). Multi-Criteria GIS-Based Analysis for Mapping Suitable Sites for Onshore Wind Farms in Southeast France. *Land*, *11*(10), 1839.

Jensson, P. (2023). Faghópur 4 – kynning. Powerpoint presentation at the National Museum of Iceland on 15th February 2023.

John, B., & Naharudin, N. (2022, October). Potential Sites for Micro-Hydropower Station by using Spatial-MCDA. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1067, No. 1, p. 012038). IOP Publishing.

Kalmansson, J. Á., Einarsson, H, B., Jóhannesson, H., & Vilhemsdóttir, S. (2023). Virkjanir í neðri hluta þjórsár. Álit faghóps 3 vegna nokkurra álitamála um áhrif á samfélag.

Karlsdóttir, U. B. (2010). Þar sem fossarnir falla: Náttúrusýn og nýting fallvatna á Íslandi 1900− 2008. *Reykjavík: Hið íslenska bókmenntafélag*.

Kazak, J., Van Hoof, J., & Szewranski, S. (2017). Challenges in the wind turbines location process in Central Europe–The use of spatial decision support systems. *Renewable and Sustainable Energy Reviews*, *76*, 425-433.

Kiavarz, M., & Jelokhani-Niaraki, M. (2017). Geothermal prospectivity mapping using GIS-based Ordered Weighted Averaging approach: A case study in Japan's Akita and Iwate provinces. *Geothermics*, *70*, 295-304.

Kumar, A., Sah, B., Singh, A. R., Deng, Y., He, X., Kumar, P., & Bansal, R. C. (2017). A review of multi criteria decision making (MCDM) towards sustainable renewable energy development. *Renewable and Sustainable Energy Reviews*, *69*, 596-609.

Laks, I., Walczak, Z., & Walczak, N. (2023). Fuzzy analytical hierarchy process methods in changing the damming level of a small hydropower plant: Case study of Rosko SHP in Poland. *Water Resources and Industry*, *29*, 100204.

Landsvirkjun. (2003). *Kárahnjúkar hydropower project - Summary of EIA, environmental assessment report, EIA final conclusion*. Landsvirkjun: Reykjavik.

Lu, X., & Wang, S. (2017). A GIS-based assessment of Tibet's potential for pumped hydropower energy storage. *Renewable and Sustainable Energy Reviews*, *69*, 1045-1054.

Malinauskaite, L., Cook, D., Davíðsdóttir, B., Ögmundardóttir, H., & Roman, J. (2019). Ecosystem services in the Arctic: a thematic review. *Ecosystem Services*, *36*, 100898.

McKenna, R., Pfenninger, S., Heinrichs, H., Schmidt, J., Staffell, I., Bauer, C., ... & Wohland, J. (2022). High-resolution large-scale onshore wind energy assessments: A review of potential definitions, methodologies and future research needs. *Renewable Energy*, *182*, 659-684.

Meng, F., Liang, X., Xiao, C., & Wang, G. (2021). Geothermal resource potential assessment utilizing GIS-based multi criteria decision analysis method. *Geothermics*, *89,* 101969.

Merida, V. E., Cook, D., Ögmundarson, Ó., & Davíðsdóttir, B. (2022). Ecosystem services and disservices of meat and dairy production: A systematic literature review. *Ecosystem Services*, *58*, 101494.

Mokarram, M., Pourghasemi, H. R., & Mokarram, M. J. (2022). A multi-criteria GIS-based model for wind farm site selection with the least impact on environmental pollution using the OWA-ANP method. *Environmental Science and Pollution Research*, *29*(29), 43891-43912.

Moshe, A., & Tegegne, G. (2022). Assessment of run-of-river hydropower potential in the data-scarce region, Omo-Gibe Basin, Ethiopia. *International Journal of Energy and Water Resources*, 1-12.

Mostafaeipour, A., Hosseini Dehshiri, S. J., Hosseini Dehshiri, S. S., Jahangiri, M., & Techato, K. (2020). A thorough analysis of potential geothermal project locations in Afghanistan, *Sustainability*, *12*(20), 8397.

Munir, B. (2022). Assessment of hydropower potential of Neelum River using remote sensing and GIS techniques, *Pakistan Journal of Science*, *74*(1).

Nascimento, M. L. D. (2022). *Investigation of Geothermal Potential Zones with Machine Learning in Mainland Portugal*. Doctoral dissertation, University of Lisbon, Portugal.

Nasery, S., Matci, D. K., & Avdan, U. (2021). GIS-based wind farm suitability assessment using fuzzy AHP multi-criteria approach: the case of Herat, Afghanistan. *Arabian Journal of Geosciences*, *14*(12), 1091.

NEA. (2021a). Primary energy use in Iceland 1940-2020. Retrieved online from: https://orkustofnun.is/gogn/Talnaefni/OS-2021-T008-01.pdf (accessed 22nd February 2023).

NEA. (2021b). Energy statistics in Iceland 2021. Retrieved online from: https://orkustofnun.is/gogn/os-onnur-rit/Orkutolur-2021-enska-A-4.pdf (accessed 22nd February 2022).

NEA. (2022). Development of electricity production in Iceland (2021). Retrieved online from: https://orkustofnun.is/gogn/Talnaefni/OS-2022-T003-01.pdf (accessed 22nd February 2023).

NEA. (n.d.). Map collection. Retrieved online from: https://nea.is/the-national-energy-authority/energy-data/map-collection/ (accessed 16th May 2023).

Newson, S. (2010). Preserving wilderness versus enabling economic change: Iceland and the Kárahnjúkar Hydropower Project. *Geography*, *95*(3), 161-164.

Ng'ethe, J., & Jalilinasrabady, S. (2023). GIS-based multi-criteria decision making under Silica Saturation Index (SSI) for selecting the best direct use scenarios for geothermal resources in Central and Southern Rift Valley, Kenya. *Geothermics*, *109*, 102656.

Ögmundardóttir, H. (2011). *The Shepherds of Þjórsárver.: Traditional Use and Hydropower Development in the Commons of the Icelandic Highland*.

Olafsson, H. (1981). A True Environmental Parable: The Laxá-Mývatn Conflict in Iceland, 1965–1973 An Ecological and Anthropological Approach. *Environmental Review*, *5*(2), 2-38.

Pamučar, D., Gigović, L., Bajić, Z., & Janošević, M. (2017). Location selection for wind farms using GIS multi-criteria hybrid model: An approach based on fuzzy and rough numbers. *Sustainability*, *9*(8), 1315.

Peri, E., & Tal, A. (2020). A sustainable way forward for wind power: Assessing turbines' environmental impacts using a holistic GIS analysis. *Applied Energy*, *279*, 115829.

Pohekar, S. D., & Ramachandran, M. (2004). Application of multi-criteria decision making to sustainable energy planning—A review. *Renewable and sustainable energy reviews*, *8*(4), 365-381.

Prakasam, C., & Saravanan, R. (2022). Application of GIS Techniques and Environmental Flow Norms to Assess Hydropower Impact on the Environment: A Case Study of Binwa and Larji Hydropower Projects in Himachal Pradesh, India. In *Environmental Change in South Asia: Essays in Honor of Mohammed Taher* (pp. 121-137). Cham: Springer International Publishing.

Ramma.is. (n.d.). The Master Plan for Nature Protection and Energy Utilization. Retrieved online from: https://www.ramma.is/english (accessed 14th March 2023).

Raza, M. A., Yousif, M., Hassan, M., Numan, M., & Kazmi, S. A. A. (2023). Site suitability for solar and wind energy in developing countries using combination of GIS-AHP; a case study of Pakistan. *Renewable Energy*, *206*, 180-191.

Roijers, D. M., Whiteson, S., Brachman, R., & Stone, P. (2017). *Multi-objective decision making*. Morgan & Claypool.

Sæþórsdóttir, A. D. (2023). Áherslur í vinnu faghóps 2 í 5 áfanga Rammaáætlunar. Powerpoint presentation at the National Museum of Iceland on 15th February 2023.

Sæþórsdóttir, A. D. (2024). Áhrif virkjana á ferðamennsku, útivist og landbúnað. Mat faghóps 2 í 5. áfanga rammaáætlunar Vatnsafl og jarðvarmi.

Sæþórsdóttir, A. D., & Ólafsson, R. (2010). Nature tourism assessment in the Icelandic Master Plan for geothermal and hydropower development. Part I: rapid evaluation of nature tourism resources. *Journal of Heritage Tourism*, *5*(4), 311-331.

Sæþórsdóttir, A. D., & Ólafsson, R. (2010). Nature tourism assessment in the Icelandic Master Plan for geothermal and hydropower development. Part II: assessing the impact of proposed power plants on tourism and recreation. *Journal of Heritage Tourism*, *5*(4), 333-349.

Schwantes, S. (2017). The Role of Young Environmental Activists in Iceland and Furthering Youth Engagement with Environmental Issues.

Shafiee, M. (2022). Wind Energy Development Site Selection Using an Integrated Fuzzy ANP-TOPSIS Decision Model. *Energies*, *15*(12), 4289.

Shao, M., Han, Z., Sun, J., Xiao, C., Zhang, S., & Zhao, Y. (2020). A review of multi-criteria decision making applications for renewable energy site selection. *Renewable Energy*, *157*, 377-403.

Sheng, X., Zeng, P. P., Xing, H., Lienhart, P., & Dai, Q. (2018, November). A GIS+ MCDA based assessment method of potential onshore wind power development sites in Mongolia. In *2018 International Conference on Power System Technology (POWERCON)* (pp. 1465-1471). IEEE.

Sliz-Szkliniarz, B., Eberbach, J., Hoffmann, B., & Fortin, M. (2019). Assessing the cost of onshore wind development scenarios: Modelling of spatial and temporal distribution of wind power for the case of Poland. *Renewable and Sustainable Energy Reviews*, *109*, 514-531.

Sotiropoulou, K. F., & Vavatsikos, A. P. (2021). Onshore wind farms GIS-Assisted suitability analysis using PROMETHEE II. *Energy Policy*, *158*, 112531.

Steele, K., Carmel, Y., Cross, J., & Wilcox, C. (2009). Uses and misuses of multicriteria decision analysis (MCDA) in environmental decision making. *Risk Analysis: An International Journal*, *29*(1), 26-33.

Stefánsson, Þ., Sæþórsdóttir, A., & Hall, C. (2017). When tourists meet transmission lines: The effects of electric transmission lines on tourism in Iceland. *Energy Research & Social Science*, *34*, 82-92.

Steingrímsson, B., Björnsson, S. & Aðalsteinsson, H. (2006). Master Plan for Geothermal and Hydropower Development in Iceland. Presented at Workshop for Decision Makers on Geothermal Projects in Central America, organized by UNU-GTP and LaGeo, El Salvador. Retreived online from: https://orkustofnun.is/gogn/flytja/JHS-Skjol/El%20Salvador%202006/15_SteingrimssonMasterPlan.pdf (accessed 14th March 2023).

Tahri, M., Hakdaoui, M., & Maanan, M. (2015). The evaluation of solar farm locations applying Geographic Information System and Multi-Criteria Decision-Making methods: Case study in southern Morocco. *Renewable and sustainable energy reviews*, *51*, 1354-1362.

Thórhallsdóttir, T. E. (2007a). Strategic planning at the national level: Evaluating and ranking energy projects by environmental impact. *Environmental Impact Assessment Review*, *27*(6), 545-568.

Thórhallsdóttir, T. E. (2007b). Environment and energy in Iceland: A comparative analysis of values and impacts. *Environmental Impact Assessment Review*, *27*(6), 522-544.

Tinti, F., Kasmaee, S., Elkarmoty, M., Bonduà, S., & Bortolotti, V. (2018). Suitability evaluation of specific shallow geothermal technologies using a GIS-based multi criteria decision analysis implementing the analytic hierarchic process. *Energies*, *11*(2), 457.

Troy, A., & Wilson, M. A. (2006). Mapping ecosystem services: practical challenges and opportunities in linking GIS and value transfer. *Ecological economics*, *60*(2), 435-449.

Tverijonaite, E., Sæþórsdóttir, A. D., Olafsdottir, R., & Hall, C. M. (2022). How close is too close? Mapping the impact area of renewable energy infrastructure on tourism. *Energy Research & Social Science*, *90*, 102574.

Tverijonaite, E., Sæþórsdóttir, A. D., Ólafsdóttir, R., & Hall, C. M. (2019). Renewable Energy in Wilderness Landscapes: Visitors' Perspectives. *Sustainability*, *11*(20), 5812.
Vaidya, O. S., & Kumar, S. (2006). Analytic hierarchy process: An overview of applications. *European Journal of operational research*, *169*(1), 1-29.

Vavatsikos, A. P., Arvanitidou, A., & Petsas, D. (2019). Wind farm investments portfolio formation using GIS-based suitability analysis and simulation procedures. *Journal of environmental management*, *252*, 109670.

Villacreses, G., Gaona, G., Martínez-Gómez, J., & Jijón, D. J. (2017). Wind farms suitability location using geographical information system (GIS), based on multi-criteria decision making (MCDM) methods: The case of continental Ecuador. *Renewable energy*, *109*, 275-286.

Xu, L., Wu, W., Qian, J., Huang, S., Xie, B., Hu, T., ... & Hu, C. (2023). Analysis of geothermal potential in Hangjiahu area based on remote sensing and geographic information system. *Frontiers in Earth Science*, *10*, 1031665.

Xu, Z. (2015). *Uncertain multi-attribute decision making: Methods and applications*. Springer.

Yal, G. P., Cambazoglu, S., Eker, A. M., Sen, O., & Akgun, H. (2020). Assessment of the Ability of GIS Based MCDA Methods to Reveal the Geothermal Potential of the Büyük Menderes Graben. In *Proceedings World Geothermal Congress* (p. 1).

Yalcin, M., & Gul, F. K. (2017). A GIS-based multi criteria decision analysis approach for exploring geothermal resources: Akarcay basin (Avyonkarahisar). *Geothermics, 67*, 18-28.

Zuo, R., Kreuzer, O. P., Wang, J., Xiong, Y., Zhang, Z., & Wang, Z. (2021). Uncertainties in GIS-based mineral prospectivity mapping: Key types, potential impacts and possible solutions. *Natural Resources Research*, *30*, 3059-3079.

Ægisdóttir, H. H., Lárusdóttir, B., Waage, E. R. H., Jóhannesdóttir, G. R., Zoega, G., Benediktsson, Í, Ö, Jónsson, J. E., Ólafsson, J. S., Svavarsdóttir, K. & Jónasson, K. (2024). Aðferðafræði og niðurstöður faghóps 1 í 5. áfanga rammaáætlunar.

APPENDIX A – GEOTHERMAL POWER, GIS AND MCDA STUDIES

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
Kiavarz, M., & Jelokhani-Niaraki, M. (2017). Geothermal prospectivity mapping using GIS-based Ordered Weighted Averaging approach: A case study in Japan's Akita and Iwate provinces. *Geothermics*, *70*, 295-304.	Geothermal prospectivity analysis in the Akita and Iwate provinces of Japan	Distance method via GIS mapping Ordered Weighting Averaging Grading of geothermal areas Geothermal prospectivity mapping Grid maps divided into five grades of favourability.	Heat degree Distance based: Fumarole Alternation zone Hot spring locations Fault lines Volcanic rock Volcanic crater	Addresses issue of risk. The use of OWA-based approach provides a model that generates geothermal prospectivity maps with different pessimistic or optimistic strategies (risk). The geothermal prospectivity maps have been constructed under the assumption that the weights of the criteria remain fixed through the scenarios, and only the value of 'ORness' changes. The grid maps represent the occurrence of geothermal resources along the continuum from pessimistic (or risk-averse) to optimistic (or risk-taking) strategies based on the number between 0 (no probability of geothermal resources) and 1 (the highest probability of geothermal resource). Therefore, the capabilities of risk modelling and uncertainties in OWA-based approach and fuzzy logic, respectively, could be combined to generate more				✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
				accurate geothermal prospectivity maps.				
Yalcin, M., & Gul, F. K. (2017). A GIS-based multi criteria decision analysis approach for exploring geothermal resources: Akarcay basin (Avyonkarahisar). *Geothermics, 67*, 18-28.	Geothermal potential analysis on sites in the Akarcay Basin, Turkey	Distance method via GIS mapping Grading of geothermal areas AHP	Geological map Land surface temperature anomalies Distance based: Hot spring locations Fault lines Topographic map Wetlands and settlement boundaries	GIS based MCDM is used as a feasibility study in the first phase of geothermal exploration. It could help in the implementation of geophysical and geochemical methods and lead to reconnaissance drilling, narrowing the research area limits. Paper says that future research could also factor in mineral alteration zones, given that the use of remote sensing techniques continues to increase.				✓
Anwarzai, M. A., & Nagasaka, K. (2018). A GIS-based analysis of earth's crust temperature at depth for geothermal energy exploration in Afghanistan [J]. *International Journal of Environmental Science and Development*, *9*(1), 0-137.	Geothermal potential in Afghanistan at drilled depths of 3.5-10.5 km.	Inferred temperature mapping at various depths	Earth's crust thickness Surface heat flow Mantle heat flow Surface temperature Sediment thickness	All maps are estimated based on either measurement (airborne, gravity, and field) or evidence (geological, geophysical, and geochemical). Some of the input layers or a part of the maps in the analysis are derived from either estimation or geological evidence. It has been suggested that the field measurement should be				✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
				carried out in the most feasible geothermal fields to define the accuracy of the maps. The authors suggest that field measurement of earth surface (groundwater) temperature, surface heat flow, thermal conductivity, would be more helpful for further improvement. Moreover, for the future research, the radioactive heat generation in the crust should be studied to determine the potassium, uranium, and thorium heat generation in relation to different lithology of the crust.				
Tinti, F., Kasmaee, S., Elkarmoty, M., Bonduà, S., & Bortolotti, V. (2018). Suitability evaluation of specific shallow geothermal technologies using a GIS-based multi criteria decision analysis implementing the analytic hierarchic process. *Energies*, *11*(2), 457.	Suitability analysis of shallow geothermal fields (GSHPs) in Europe of maximum 50 metres depth	AHP Geolocalised Suitability Index, with suitability map – maps of 'drillability' and ground temperature at depth of neutral zone, which were compared to heating and cooling needs to determine final maps of suitability.	14 parameters: Shallow geology Hydrogeology Thickness of sediments and bedrock Bedrock compressive strength Sediment compressive strength	The method presented in this paper has the potential to be extended to various GSHP technologies provided appropriate hierarchy level modifications are made to the criteria in the light of design differences of the plant in question. The method could help future customers, energy planners, and stakeholders to identify the best combination of drilling machine, borehole heat exchanger, and heat pump technology for the different locations, climate, site conditions, and energy data				

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
			Bedrock thermal conductivity Ambient yearly average temperature Ambient yearly temperature amplitude Land cover Population Geothermal heat flow	(building needs and fuel alternatives). Given that this technology relates to GSHPs, which are not a type of geothermal technology evaluated in Iceland's MP, its approach is not deemed relevant to any of the Master Plan's WGs.				
Cambazoğlu, S., Yal, G. P., Eker, A. M., Şen, O., & Akgün, H. (2019). Geothermal resource assessment of the Gediz Graben utilizing TOPSIS methodology. *Geothermics*, *80*, 92-102.	Geothermal prospectivity analysis of the Geediz Graben region in Turkey	GIS mapping of criteria, some distance-based. Each layer was weighted by using the pairwise comparison method (AHP). Then, an ideal point methodology, Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS), was used to rank the geothermal favourability from most to least favourable, in the geothermal favourability mapping stage.	Distance to faults and fault density Distance to cap rock units Hot springs and graben centre Gutenberg-Richter b-value map Night-time surface temperature NDVI and slope.	In this study a knowledge-based methodology was followed, where the judgment of the expert is involved in the decision-making process through a weighting process. However, since these methods involve a certain amount of bias as imposed by the judgment of the expert, it would be highly desirable to perform a data-driven approach, where a sufficient amount of training data is available. It should also be noted that the discovery process of geothermal resources is biased by the accessibility factors. If the				✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
		Note: At the time of writing, this was the first application of TOPSIS in the literature.		criteria layers are correlated with the factors that drive exploration activities, the final predictive map may be biased.				
Brahim, F. B., Boughariou, E., Makni, J., & Bouri, S. (2020). Evaluation of groundwater hydrogeochemical characteristics and delineation of geothermal potentialities using multi criteria decision analysis: Case of Tozeur region, Tunisia. *Applied Geochemistry*, *113*, 104504.	Geothermal prospectivity analysis in the low-moderate temperature fields of the Djerid Basin, Turkey	Hydrogeochemical approach to map geothermal potential using two approaches – the weighted overlay model and Boolean model. Areas determined as being of low, moderate, or high priority. Literature review and data availability assessment by others to determine criteria used in the GIS mapping.	Four key aspects were evaluated: (1) the evolution of the water chemistry, (2) the origin of thermal waters and their reservoir temperature, (3) the mixing mechanism of geothermal fluid and (4) the mapping of geothermal potentialities with (MCDA) using GIS platform. Regarding (4), the specific criteria were spatial distribution of emergence temperature, productivity of the aquifer (flow rate), proximity to faults and lineaments, and water salinity.	Potential for the criteria used in the GIS analysis to be improved by expert deliberation rather than just being based on a literature review and data availability. However, overall, a useful assessment for identifying the potential of thermal tourism, housing heating, greenhouse and balneotherapeutic applications, which already contribute to renewable energy production in Tunisia. The approach could reduce potential conflicts with other land uses, given that the area has a long history of using shallow groundwater for oases irrigation.			✓	✓
Mostafaeipour, A., Hosseini Dehshiri, S. J., Hosseini Dehshiri,	Geothermal prospectivity	The Stepwise Weight Assessment Ratio	Fault density	The only study in this literature which set out to consider the			✓	✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
S. S., Jahangiri, M., & Techato, K. (2020). A thorough analysis of potential geothermal project locations in Afghanistan, *Sustainability*, *12*(20), 8397.	Analyses for 21 provinces in Afghanistan.	Analysis (SWARA) method was used to weigh each criterion while the Additive Ratio Assessment (ARAS) method was used to rank potential geothermal sites. The technique for order of preference by similarity to ideal solution (TOPSIS), VIKOR and the Weighted Aggregated Sum Product Assessment (WASPAS) methods were also used in this study as part of a sensitivity assessment on the rankings.	Volcanic dome density Hot spring density Hot mineral spring density Drainage density Intrusive rock density Population density University density Area of the province	impacts of a sensitivity analysis. The results changed significantly according to the method and criteria used. Sensitivity analysis indicated that a 5% change in criteria weight affected the rankings of all four methods, except VIKOR.				
Yal, G. P., Cambazoglu, S., Eker, A. M., Sen, O., & Akgun, H. (2020). Assessment of the Ability of GIS Based MCDA Methods to Reveal the Geothermal Potential of the Büyük Menderes Graben. In *Proceedings World Geothermal Congress* (p. 1).	Geothermal prospectivity analysis of the Büyük Menderes Graben in Turkey.	Expert-based weighting of criteria. TOPSIS method, leading to production of a geothermal favourability map. Six classes of favourability determined from most to least.	Criteria including: Distance to faults Fault density Distance to graben centre Distance to cap rock	The datasets used in this study were only intended for extensional or amagmatic systems. Thus, they may fail to successfully identify favourable areas in a magmatic geothermal system, which are common in Iceland.				✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
			Distance to hot springs b-value Night-time surface temperature Slope angle Vegetation					
Meng, F., Liang, X., Xiao, C., & Wang, G. (2021). Geothermal resource potential assessment utilizing GIS-based multi criteria decision analysis method. *Geothermics*, *89,* 101969.	Geothermal potential analysis on sites in the Changbai Mountain region of north-eastern China	Geothermal forecast mapping using GIS, including grading of geothermal areas. Use of AHP and entropy weighting. Grid maps divided into six grades of favourability from most to least. The criteria were used to generate five grid maps based on temperature distribution, distance to fault lines, distance to hot springs, distance to	Shallow ground temperature Distance based: Fault lines Hot spring locations Basalt distribution Isogravity lines	A combination of the AHP and EWM was used to determine the weight of each criterion, making it more objective and reasonable. The correctness of the favourability map was analysed by comparing the results map with the location of existing geothermal wells. This type of study can provide an important basis for the early exploration of geothermal resources. The authors call for future studies to strengthen the fcriteria analysis of the geothermal potential in the study area and more decision-making criteria should gradually be added to improve the accuracy of the forecast results.				✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
		basalts, and distance to grabens.						
Elbarbary, S., Abdel Zaher, M., Saibi, H., Fowler, A. R., & Saibi, K. (2022). Geothermal renewable energy prospects of the African continent using GIS. *Geothermal Energy*, *10*(1), 1-19.	Geothermal prospectivity analysis for regions within Africa	Geothermal potential / favourability mapping using GIS. AHP adopted for criteria weighting coefficients. Weighted overlay method to integrate various geo-datasets and create grids of favourability based on a suitability scale from 0-9.	Geological thematic layers (rock units and faults) Geophysical layers (heat flow derived from aeromagnetic data and seismicity) Geothermal layers (hot springs and volcanoes)	14 high potential zones identified. Determining the weight value and criteria for each thematic layer forms a crucial step in this approach and exerts a major influence on the resulting map. This was performed by considering the opinions of geothermal experts, existing literature, and the characteristics of the study area. Potential for future geospatial data to add to the analysis and enhance it.				✓
Nascimento, M. L. D. (2022). *Investigation of Geothermal Potential Zones with Machine Learning in Mainland Portugal*. Doctoral dissertation, University of Lisbon, Portugal.	Geothermal potential analysis involving two machine learning algorithms, focused on the case study of Mainland Portugal	Application of the Random Forests and Extreme Gradient Boosting algorithms to assess the thermal properties of geothermal regions. Grid mapping	Geothermal gradient Surface heat flow density	Approach can potentially reduce the costs of exploration by highlighting some of the most important criteria central to geothermal feasibility. Exploration of geothermal regions requires field surveys, geological, geophysical, and geochemical analyses, as well as drilling campaigns. However, some data limitations were noted. Improving the accuracy of the models could be achieved with more and better spatially distributed training data, as				✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
				well as by fitting other important features related to geothermal parameters into the model. Adding more data regarding the physical and chemical parameters of the ground will probably improve the model prediction capacity. Remote sensing images such as thermal infra-red, radar and multispectral images should also be explored, since they have many applications in the geothermal field. Evaluating other types of algorithms, such as deep learning, could also be very informative.				
Ng'ethe, J., & Jalilinasrabady, S. (2023). GIS-based multi-criteria decision making under Silica Saturation Index (SSI) for selecting the best direct use scenarios for geothermal resources in Central and Southern Rift Valley, Kenya. *Geothermics*, *109*, 102656.	Scenario-based analysis to determine the optimal direct use applications of the geothermal resource in six high-enthalpy fields in Kenya.	AHP-WASPAS method in QGIS to create a visual framework for conducting feasibility studies for direct use in regions with geothermal resources. This is a hybrid of the AHP and Weighted Aggregate Sum Product Assessment method. Incorporates Analysis of the Silica Saturation Index (SSI) and pH effects on the SSI. **Note**: Silica saturation leads to scaling of	Distance to greenhouses Distance to surface freshwater Distance to grain farms Population distribution Distance to tourist resorts Distance to industrial zones Slope	From this research, the accurate matching of geothermal resource characteristics to economic activities and its proximity to thermal needs and existing infrastructure such as roads, water, and topography is the most influential stage of analysing and precisely predicting the best DU scenarios. Each geothermal resource has different DU scenarios that match its resource traits, such as fluid volume, temperature, pH, and silica content. The two main			✓	

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
		direct use facilities and reinjection well. Nine utilisation scenarios considered for the six high-enthalpy fields. The nine potential direct uses were: greenhouse warming; crop drying; chicken hatchery; milk pasteurisation; industrial heating; water desalinisation; spa and bathing; and mineral extraction. Methods led to the formation of best direct use maps.	Brine flow Brine temperature Brine silica content	limitations of the model were identified as 1) its inability to consider surface manifestations that lack hot brine, such as fumaroles, and 2) its inability to work with scattered criteria such as grain farms, horticultural greenhouses, and sparse population density. This led to under-developed geothermal prospects, such as Elementaita, Suswa and Longonot, being rated poorly despite their high number of tourists annually and numerous small-scale direct uses from fumaroles. **Note**: no real relevance to WG4 of the Master Plan since study focuses on best end-use rather than informing decision-making. However, some limited relevance potentially to WG3 given focus on population density and social benefits.				
Xu, L., Wu, W., Qian, J., Huang, S., Xie, B., Hu, T., ... & Hu, C. (2023). Analysis of geothermal potential in Hangjiahu area based on remote sensing and geographic	An evaluation of the potential of geothermal areas on the Hangjiah	AHP and Back Propagation (BP) neural network used for establishing geothermal	Formation lithology Distance to fault zones	Determination of the five potential areas by the BP neural network reduces reliance on experts' judgment and prior knowledge. Thus, the				✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
information system. *Frontiers in Earth Science*, *10*, 1031665.	Plain of Zhejiang Province.	potential target evaluation models. **Note**: BP is a neural network and type of multilayer feedforward neural network which is trained according to the error back propagation. Geothermal potential map divided into five grades, ranging from extremely high to very low potential. This is determined by the BP neural network.	Distance to surface water system Distance of seismic point Magmatic and volcanic rock distances Surface water temperature of farmland and forest land	designation is potentially more scientific and data driven. The results demonstrated that it is feasible to analyse geothermal potential targets based on the AHP and BP neural network, and the distribution characteristics of surface thermal environment, fault activity, surface water system and other related factors are also related to geothermal distribution. The prediction results of the model coincided with the existing geothermal drilling sites in 92% of cases, with 123 of the 134 existing wells in the extremely high potential zone.				

APPENDIX B – HYDROPOWER, GIS AND MCDA STUDIES

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
Lu, X., & Wang, S. (2017). A GIS-based assessment of Tibet's potential for pumped hydropower energy storage. *Renewable and Sustainable Energy Reviews*, *69*, 1045-1054.	Evaluate the pumped hydropower storage (PHS) potential in Tibet using GIS-based analyses.	Utilising ArcGIS, the main objectives of the data pre-processing stage were to extract the elevation of all water bodies and to calculate the surface slope within the study area. A "zonal statistics as table" tool was used to obtain the elevation of each lake, which was calculated as the average elevation of each pixel. The elevation of each lake was regarded as the average elevation within each lake's extent. The slope of Tibet was calculated using the "slope" tool.	Elevation Slope Distance to lakes and reservoirs Minimum head threshold Minimum lake size Maximum difference in elevation Minimum flow accumulation	Other criteria should be considered in further work. This study only selects the theoretical potential sites and analyses the distances from potential sites to grid connections. If a series of social, infrastructure, environmental, and economic constraints are also considered, a better understanding of the potential of PHS would be cultivated for decision-makers.				✓
Badang, D. A. Q., Sarip, C. F., & Tahud, A. P. (2018, November). Geographic information system (GIS) and multicriteria decision making (MCDM) for optimal selection of hydropower location in Rogongon, Iligan City. In *2018 IEEE 10th International*	Use of GIS technology to support the selection of six potential hydropower sites	AHP was chosen as the suitable approach for the weighing of criteria, with the combination of TOPSIS for the determination of scores and ranking for alternative sites.	Site capacity Load demand Length of transmission lines Project cost	The potential sites were ranked according to their capacity, and the Malagsum River was found to have the greatest potential. The project cost is directly related to the capacity of the site (i.e., the greater the potential, the		✓	✓	✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management (HNICEM) (pp. 1-5). IEEE.		Thematic maps were created in ArcGIS showing hydropower potential at sites, with their corresponding ranking added in an attribute table. The ranking values were based on the results obtained from the ranking carried out by TOPSIS.	Difficulty in transporting materials Accessibility to project site Obstructions to the site Social conflicts Water resource problems	higher the cost). The obstruction to site was evaluated by the researchers who visited the site, and the results demonstrated an obstruction index ranging between 2 to 3 for six potential sites. The social conflict for all alternatives was scored 1 for all locations since the residents in the community approved any projects in the said area. Both the social conflict and water resource problems were rated by the Indigenous People (IP) leaders of the community.				
Eshra, N. M., Zobaa, A. F., & Aleem, S. H. A. (2021). Assessment of mini and micro hydropower potential in Egypt: Multi-criteria analysis. *Energy Reports*, *7*, 81-94.	Assess mini and micro hydropower's potential in Egypt for main grid areas.	Eight sites were selected and ranked as based on available hydraulic data. The rank of the most suitable energy generation sites was determined with the aid of spatial maps based on the flow duration curves, capacity factor, and MCDA.	Condition of the barrage Access to the site Plant layout Grid connection Actual head Actual discharge Days of energy generation Amount of energy generated.	Spatial maps were used to give a clear vision of the possibility of exploiting different sites and the priority of implementation. The most suitable turbines from the conventional and non-conventional types for every site are determined, and their efficiencies are estimated. The applicability of the proposed turbines under various operating conditions remain to be investigated in the future to evaluate their accurate				✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
				performance with an analysis of uncertainty.				
Hagos, Y. G., Andualem, T. G., Mengie, M. A., Ayele, W. T., & Malede, D. A. (2022). Suitable dam site identification using GIS-based MCDA: a case study of Chemoga watershed, Ethiopia. *Applied Water Science*, *12*(4), 69.	Identify potentially suitable sites for dam construction in Chemoga, Ethiopia, in an area with burgeoning demand from irrigation, hydropower, fisheries and freshwater for drinking	Use of remote sensing and GIS techniques (ArcGIS) to create a dam suitability stream model	Topography Climate Hydrology Soils Agronomy Socioeconomics Six influencing thematic layers: stream order/drainage density, slope, runoff potential, land use/cover, geology, and distance to the road	The most important features in identifying a suitable dam site were stream order/drainage density (39%), slope (26.2%), and runoff potential (17.9%). Stream order was found to be important among the other features because it ensures that enough water is available to be stored in the dam. Finally, based on the two output suitability maps (Suitability of streams and Overall suitability), six potential dam sites were proposed.	✓	✓		✓
John, B., & Naharudin, N. (2022, October). Potential Sites for Micro-Hydropower Station by using Spatial-MCDA. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1067, No. 1, p. 012038). IOP Publishing.	An assessment of the optimal sites for micro-hydropower generation based on the case study of Sarawak, Malaysia	Spatial-MCDA, which combines Spatial Analysis and Multicriteria Decision Analysis (MCDA). Site Suitability Analysis was carried out using Weighted Overlay Analysis (Spatial Analysis).	Criteria: Slope Water velocity Accessibility Once the criteria had been identified, the weightage for	The results of this analysis found several potential sites in the case study region, in particular the areas that are close to villages and small vegetable gardens. Although the study showed the possibility of using Spatial-MCDA in finding potential sites for micro-hydropower stations, in the future, it is				✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
			each of the criteria was derived using AHP based on expert choice.	recommended that suitable criteria is adopted for other study areas, rather than using those specific to Malaysia.				
Moshe, A., & Tegegne, G. (2022). Assessment of run-of-river hydropower potential in the data-scarce region, Omo-Gibe Basin, Ethiopia. *International Journal of Energy and Water Resources*, 1-12.	Suitability of potential hydropower projects in the Winike River, Omo-Gibe Basin, Ethiopia	Hydropower potential was assessed using GIS and a Soil and Water Assessment Tool	The following sequential procedure was applied: (1) the stream network for the Winike river basin was generated; (2) the hydraulic head of second-order and above streams was estimated; (3) the hydropower potential sites with the hydraulic head of 20 m and above were identified; (4) the SWAT parameters were calibrated, validated, and regionalised in the study basin; (5) the flow duration curve was developed; and (6) finally, the hydropower	Based on the analysis, 103 potential sites were found to be suitable in the study region based on the available discharge and hydraulic head ranging between 20 and 81 m. The run-of-river hydropower potential of the identified sites was determined by integrating the results of the hydraulic head and dependable flow. In general, the overall analysis showed that the total hydropower potential of the Winike river was found to be 183.16, 125.96, and 33.03 MW at 50, 75, and 90% dependability, respectively. Moreover, the GIS-based MCDA was able to rank the potential sites based on their suitability in the study region, albeit that this analysis was limited to an assessment of potential production capacity.	✓			✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
			potential of each site was estimated.					
Munir, B. (2022). Assessment of hydropower potential of Neelum River using remote sensing and GIS techniques, *Pakistan Journal of Science*, *74*(1).	GIS-based methods were applied to investigate the relative assessment of hydropower potential of the Indus and Jhelum streams of Pakistan	GIS data was utilised involving neighbourhood stream datasets. The information was then handled utilising various spatial analysis apparatuses, accessible in ArcGIS, to distinguish the optimal areas for creating hydropower plants, and to assess the specific hydropower potential in those locations.	Stream datapoints were generated at specific locations, facilitating an interpolation of average stream flow values at these points. The interpolation of stream flow data was accomplished using the ratio proportion technique in GIS. The elevation values at these points were extracted from a Digital Elevation Model to obtain the hydraulic head. Knowing the average annual stream and hydraulic head values, the theoretical hydropower potential at these previously defined points was evaluated.	This type of investigation can help decision-makers, such as the Water and Power Development Authority (WAPDA) of Pakistan, to determine optimal power generating sites in the largely overlooked river basins of Pakistan. This is particularly important, given that the nation is heavily fossil fuel reliant and has been afflicted with energy security challenges for many years.	✓			✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
Prakasam, C., & Saravanan, R. (2022). Application of GIS Techniques and Environmental Flow Norms to Assess Hydropower Impact on the Environment: A Case Study of Binwa and Larji Hydropower Projects in Himachal Pradesh, India. In *Environmental Change in South Asia: Essays in Honor of Mohammed Taher* (pp. 121-137). Cham: Springer International Publishing.	Identify a suitable location for the construction of a dam in the Beas River basin in Himachal Pradesh, India, using overlay analysis to identify appropriate environmental strategies for hydropower generation.	A site suitability map and location of a potential hydropower project were generated using the weighted overlay method in a GIS environment. The map was compared with the currently proposed location maps for validation. A land use land cover (LULC) map and precipitation data were additional variables used in the analysis.	The analysis was based on terrain characterisation factors such as elevation, slope, stream order, stream number, and other related indices relating to land use and precipitation data.	A site suitability map showing locations of potential hydropower projects was generated using the weighted overlay method. Environmental flow guidelines that are currently adopted in numerous countries around the world were reviewed to evaluate and recommend the best strategy for the Beas River basin. The outcome of this study provides recommendations for better planning and management of the environment and ecosystem of the Beas River basin. Such analysis and planning strategies can be applied to other river systems where similar types of terrain are present.	✓	✓		✓
Laks, I., Walczak, Z., & Walczak, N. (2023). Fuzzy analytical hierarchy process methods in changing the damming level of a small hydropower plant: Case study of Rosko SHP in Poland. *Water Resources and Industry*, *29*, 100204.	An evaluation of the optimal variant of increasing the damming level at Rosko SHP.	Fuzzy AHP.	Economic: Increase in revenue; increase in maintenance costs; costs of obtaining permits and preparing documentation. Legal:	The authors of the article proposed a methodology for assessing the operation of SHPs and supporting decision-making processes when it is necessary to change the operation regime of a small hydropower plant due to, for instance, changes in its hydrological conditions. When performing such analyses, it is important to not only consider	✓	✓	✓	✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
			Environmental agreements; claims of farm owners and entrepreneurs. Technical: Required development of technical infrastructure; impact on damming structure; susceptibility to failure. Socio-environmental: Possible social opposition; impact on the environment; impact on tourism and water transport; protests of environmental organisations; predicted reduction in CO_2 emissions.	the economic aspects of projects, but also other values that are often difficult to measure i.e., the value of natural resources, legal conditions and requirements or the social situation. The proposed criteria and sub-criteria can be easily adapted to the specificity of a given facility, and the use of fuzzy AHP logic can successfully eliminate the emerging difficulties by developing a pairwise comparison matrix. Consequently, it is possible to overcome the difficulties with identifying evident, clearly defined preference values by experts, which will make evaluation results more reasonable and comprehensive. The authors additionally proposed a sensitivity analysis procedure that enables the estimation of model stability and the resulting ranking of alternatives. When deciding on the construction and operation, as well as the modernisation of facilities, especially where the safety of both the facility and the associated infrastructure and surroundings this is				

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
				crucial, and economic criteria should not be decisive. When making decisions, MCDA tools and methods should be used to solve complex and complicated decision-making problems, in which both the quantitative and qualitative aspects of the problem are considered.				

APPENDIX C – WIND POWER, GIS AND MCDA STUDIES

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
Ali, S., Lee, S. M., & Jang, C. M. (2017). Determination of the most optimal on-shore wind farm site location using a GIS-MCDM methodology: Evaluating the case of South Korea. *Energies*, *10*(12), 2072.	The current study deals with optimum site selection for an onshore wind farm development in the territory of South Korea using GIS. Using the thematic layers of the criteria and GIS software commands, such as Euclidean distance, slope, spatial analysis, area, intersection, erase, and buffers, the study obtained the global thematic raster layers for an on-shore wind farm suitability map.	The AHP coupled with fuzzy triangular numbers (FTN) was utilised as a MCDM tool to obtain criterion weights and estimate the optimum site selection decision.	Production: Average wind speed Land use restrictions: Airports Military zones Wetlands, rivers, lakes and streams Protected areas Tourism, historical cultural and religious places Natural and federal areas Railways and subways Public and community interest sites Locational: Distance to electricity sub-stations Distance to powerlines Distance to roads Distance to cities and towns Distance to railways	Restricted areas, such as military zones, federally protected areas, wetlands, etc., were excluded from the study zone. Then the remaining areas were evaluated based on seven criteria, which were assigned relative weights using the fuzzy-analytical hierarchy process (FAHP). Six scenarios were considered in this study and wind farm suitability maps (scaled from 1 to 8: with 1 being the least suitable site and vice versa for 8) were constructed for all the scenarios. It was found that the eastern part of South Korea has the highest potential for hosting future on-shore wind farms, whereas north-western areas are the least suitable region for this purpose.		✓	✓	✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
Anwarzai, M. A., & Nagasaka, K. (2017). Utility-scale implementable potential of wind and solar energies for Afghanistan using GIS multi-criteria decision analysis. *Renewable and Sustainable Energy Reviews*, *71*, 150-160.	Determination of most suitable location for wind energy and solar power in Afghanistan	ArcGIS was used to apply the MCDA system according to the following process: (1) selection of data layers and union of polygons; (2) selection by attributes and location; (3) aggregate polygons; and (4) intersection. The National Renewable Energy Laboratory developed the Geospatial Toolkit (Gst) for Afghanistan, containing the GIS-based wind related information	Production: Wind energy capacity Land use restrictions: Protected areas and lakes Land beyond 10 km road access Sand dunes and permanent snow areas Marshland (permanent and seasonal) Irrigated land Natural forest Fruit trees, gardens, vineyards etc. Settlement or urban areas	The MCDA system was designed to use the available input databases considering technical, economic, environmental, topography, and social aspects. The authors claim it is possible to enrich the database and introduce more criteria for optimal selection. The obtained result shows huge wind potential areas; despite the west part being popular for wind in the country, there is considerable potential near existing hydropower plants, such as Kajaki and Naghlo, and in Zabul, Nangarhar, Baghlan, Takhar, Sari Pul, Faryab provinces.	✓	✓		✓
Gigović, L., Pamučar, D., Božanić, D., & Ljubojević, S. (2017). Application of the GIS-DANP-MABAC multi-criteria model for selecting the location of wind farms: A case study of Vojvodina, Serbia. *Renewable energy*, *103*, 501-521.	Development of a hybrid MCDA-GIS-MABAC spatial model for the selection of locations of wind farms, tested on the case study of Vojvodina, Serbia	The proposed model is based on the combined application of Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA) using the multi-criteria technique of Decision-Making Trial and Evaluation Laboratory (DEMATEL), the Analytic Network Process (ANP) and	Production: Wind speed average Land use restrictions: Land cover/use Urban areas Protected areas Relief: Slope Locational:	This model broadens the theoretical framework of knowledge in the field of location problems. The existing problem is considered using new methodology, which creates the basis for further theoretical and practical improvement. In addition, this model highlights new and modified criteria and constraints which until now other models have not considered, and which are of	✓	✓	✓	✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
		Multi-Attributive Border Approximation Area Comparison (MABAC). ANP is a generalization of the AHP method, in that it replaces the hierarchy with a network by means of feedback. ANP, unlike hierarchically-structured problems, takes into consideration different forms of dependence and feedback. The DEMATEL-ANP (DANP) method is used to determine the weight coefficients of the evaluation criteria, and the MABAC method is used to rank the selected viable locations. The final map of benefits is presented using raster cells (alternatives), which are evaluated in the range of 1 (least suitable) to 7 (most suitable).	Distance to electricity network Distance to roads Distance to telecommunications network Distance to airports Distance to tourist sites Distance to military facilities Population density	significance to this issue. It is important to note that the criteria applied for the selection of sites for the development of wind farms vary in different regions and depend on the governing socio-economic and natural resources. Therefore, this procedure allows the inclusion of other criteria that were not included in this study. This is primarily related to the requirements of investors, municipal and non-governmental agencies and environmentalists, as well as limitations in terms of their visibility in relation to settlements and facilities for sport and recreation. All these criteria can have an additional role in selecting the best solution. The practical significance of this model is the possibility of its application in solving location problems in various fields, including the environment, transport, risk and others. The main recommendations for the further use of this model are its accessible mathematical apparatus and the stability (consistency) of its solution, as well as the possibility of combining it with other				

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
				methods, especially in the section related to determining the weight criteria. Directions for future improvement of the GIS-DANP-MABAC model should be based on the application of classical fuzzy sets and the intervals of fuzzy numbers in the process of determining the parameters of the criteria/clusters.				
Pamučar, D., Gigović, L., Bajić, Z., & Janošević, M. (2017). Location selection for wind farms using GIS multi-criteria hybrid model: An approach based on fuzzy and rough numbers. *Sustainability*, *9*(8), 1315.	The study presents a spatial mathematical model to identify sites for wind farm instalment which can provide significant support to the planners in strategy and the management of wind energy use.	The model is based on the combined use of GIS with multi-criteria techniques of Best-Worst method (BWM) and Multi Attributive Ideal-Real Comparative Analysis (MAIRCA).	Production: Average wind speed Land use restrictions: plant cover, pasture, arable land, agricultural, cropland, protected areas, water areas, industry, urban areas, forests	Ranking of alternatives using the MAIRCA method was carried out based on the total value of the gap, whereby the best alternative is taken to be one that has the lowest value of the gap, or the one that is closest to the ideal alternative. An alternative that is the worst is the one that has the highest value of the gap, or the one that is farthest from the ideal alternative.		✓		✓
Villacreses, G., Gaona, G., Martínez-Gómez, J., & Jijón, D. J. (2017). Wind farms suitability location using geographical information system (GIS), based on multi-criteria decision making (MCDM) methods: The case of continental Ecuador. *Renewable energy*, *109*, 275-286.	Nationwide assessment of the most suitable locations in Ecuador for onshore wind energy projects.	The MCDM methods applied to this research were the AHP method that was implemented for calculating the weights, the (OWA) Occupational Repetitive Actions (OCRA), VIKOR and TOPSIS. An Overall Performance Index (OPI) was applied to	Production: Average wind speed Air density Relief: Slope Location: Distance to electricity sub-stations Distance to roads	The study demonstrates the practical use of expert validation in GIS-based renewable energy suitability studies. This was the first Ecuadorian research to specifically evaluate the most suitable wind farms using GIS-MCDM. The results support future decision making to the government of Ecuador, when building more renewable	✓	✓		✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
		evaluate the results. Finally, the mutual correspondence between MCDM methods was evaluated by Pearson correlation coefficient.	Distance to urban areas Distance to transmission lines Distance to charging ports Environmental: Vegetation coverage	energy infrastructures based on wind power plants in relation with the energy mix change. The results of the Pearson correlation coefficient for each MCDM method show that for the OWA, VIKOR and OCRA method, the correlation of the results is above 93%. While in the case of the TOPSIS method, the correlation of the results is about 53%.				
Sheng, X., Zeng, P. P., Xing, H., Lienhart, P., & Dai, Q. (2018, November). A GIS+ MCDA based assessment method of potential onshore wind power development sites in Mongolia. In *2018 International Conference on Power System Technology (POWERCON)* (pp. 1465-1471). IEEE.	Use of GIS-MCDA analysis to inform decision-makers about the optimal location of wind farms in Mongolia.	Using the ArcGIS software, combined with basic geographic information data such as land use, and based on the reasonable numerical simulation of the distribution of wind energy resources, the areas where wind energy resources cannot be developed can be located, with the area for wind energy resources development finally being identified. Study utilises a GIS-Ranking methodology based on the weighted linear combination (WLC) technique. This technique can be summarised as a map (raster) combination	Production: Annual average wind speed Locational: Distance to road network Distance to city and village areas Distance to available electricity substations	This study provides results that can be used as a reference for pre-assessing potential new wind farm investments, providing useful advice for spatial planning at the regional level in Mongolia. However, this work is still a high-level strategic assessment focused on technical potential, and site-specific issues (e.g., soil characteristics) or local constraints (e.g., social acceptability and/or land use conflicts) are not considered. The authors admit that the results are also very dependent on the heterogeneous quality of the input GIS data.				✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
		procedure where each evaluation criterion is multiplied by a weight and the results summed, all the individual satisfaction degrees of the selected factors should be aggregated using spatial multi-criteria decision making, to produce a composite map with ranked sites.						
Harper, M., Anderson, B., James, P., & Bahaj, A. (2019). Assessing socially acceptable locations for onshore wind energy using a GIS-MCDA approach. *International Journal of Low-Carbon Technologies*, *14*(2), 160-169.	Assessment of the suitability of various locations for wind farms in the UK, with focus on social acceptability and social license	Firstly, input parameters covering environmental, technical, and social are selected. For example, ideal sites are typically identified as having high average wind speeds; not being close to urban areas; not in protected landscapes (e.g., National Parks); not close to airports (to minimise radar interference); close to roads for access; and finally, close to powerlines for grid connection. Each location is then scored	Social acceptability: Perceived likelihood of winning planning permission based on location factors and political affiliation of municipality) Economic: Cost-effectiveness (deriving from wind capacity, distance from national grid, site access, and ground clearance) Legal: Exclusion zones (presence of	The layered approach used within this methodology allows the results to be more easily interpreted and reduces the concerns surrounding standardization of parameters. Rather than assessing sites using a single parameter, we can understand whether a site is likely to be acceptable to the three different stakeholders, i.e., government (legislative), developers (economic) and local population (planning acceptance). On a national level, it is important to consider the distribution of potential sites and the consequent impact this may have on the electricity transmission network. Geospatial models	✓	✓	✓	✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
		against these input parameters, and incompatible areas are excluded from further analysis, such as areas that have already been developed (roads and buildings). Whilst traditional MCDA methodologies have combined different types of parameters (e.g. *economic*, *environ mental*) into a single scoring parameter, this study proposes a multi-level approach whereby parameters are grouped into commensurate groups. In doing so, this reduces the subjectivity that is often introduced into parameter weighting used within the Weighted Sum Method and AHP methods.	airports, roads, protected areas etc.)	are highly influenced by the availability and quality of the data provided for the analysis. In this case, wind speed is only available at 1 km resolution and does not account for roughness of surface caused by urban developments of varying land cover, such as forests. The errors from any dataset would have propagated through the analysis, and combined with errors from other layers, may cause inaccuracies in the output map. The authors state that future work will, therefore, expand upon the sensitivity analysis of the results to better capture such error.				
Vavatsikos, A. P., Arvanitidou, A., & Petsas, D. (2019). Wind farm investments portfolio formation using GIS-based suitability analysis and simulation procedures. *Journal of environmental management*, *252*, 109670.	An evaluation of the optimal formation of an investment portfolio focused on onshore wind energy projects, using GIS-MCDA and based on	Use of AHP in tandem with a MCDM-based portfolio formation, which aims to select a subtotal of alternative investments that produce the highest sum of gained suitability under the	Production: Average wind speed Design considerations Social: Landscape perceptions Aesthetics	Due to the spatial nature of renewable energy sector-related decisions, the synergy of GIS and MCDA models can enrich the quality of the related decisions given their ability to effectively support land management considerations. Traditional NPV-based	✓	✓	✓	✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
	spatial and non-spatial factors. Case study of the Thrace region in north-eastern Greece.	standard constraints that underlie capital rationing methods. Creation of a Portfolio Selection Index and Portfolio Alternative Selection Index.	Land use considerations Environmental impacts	analysis aims to maximise investors' opportunities in monetary terms. Alternately, MCDA-based portfolio formation takes into consideration a variety of decision-making dimensions and thus reduces possible risks that are usually spatially related. Moreover, their implementation significantly enriches the performance of the traditional capital projects evaluation methods (CPEM) by providing physical data to the sizing process in a quick and accurate manner. Thus, decision-making frameworks that combine GIS-based suitability analysis with traditional financial evaluation techniques can significantly enrich the planning phase to achieve efficient installations in terms of required area reduction, power generation maximisation and local characteristics examination. With respect to the realisation of wind energy projects, the paper at hand proposes a framework capable of expanding the use of the traditional GIS-based derived suitability index to establishing portfolios. Moreover, the proposed framework is				

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
				enriched by robust analysis using Monte Carlo Simulation, which provides significant insights regarding the stability of the derived portfolios and the projects that they comprise.				
Elmahmoudi, F., Abra, O. E. K., Raihani, A., Serrar, O., & Bahatti, L. (2020). Elaboration of a wind energy potential map in Morocco using GIS and Analytic Hierarchy process. *Engineering, Technology & Applied Science Research*, *10*(4), 6068-6075.	Optimal siting of wind energy projects in Morocco.	AHP study using QGIS.	Production: Average wind speed Relief: Slope Locational: Land use Distance from powerlines Distance from roads Distance from populated areas	As a result of this study, the areas having very high wind potentiality have been identified and a best wind farm location map has been prepared. The map, using the overlay function in GIS, exhibits the most and least suitable areas for the location of wind farms in Morocco. The approach could help identify suitable wind farm locations in other areas using their geographic information.	✓	✓		✓
Peri, E., & Tal, A. (2020). A sustainable way forward for wind power: Assessing turbines' environmental impacts using a holistic GIS analysis. *Applied Energy*, *279*, 115829.	Use of a GIS-MCDA approach to evaluate optimal turbine design with focus on minimising environmental impact. Case study of northern Israel.	These criteria are divided into three types of layers: (1) the benefit layer, reflecting the energy potential; (2) anthropocentric layers, characterising the environmental impact on neighbouring residential areas, such as noise, shadow flickers and visual impact; and (3) ecological layers, expressing the impact on biodiversity and the	Production: energy generation Environmental and social impacts: Noise Shadow flicker Visual impact Birds Bats Land cover Open lands Topography Settlement populations	The results indicate that 0.5% of possible sites in the study area are suitable for wind turbine development according to the strictest environmental constraints. Anthropocentric environmental impacts from turbines were found to be significant whenever sites were located less than 750 m from settlements. Ecological impacts, however, were not found to be correlated with the distance from natural protected areas. The authors contend that future studies should	✓		✓	✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
		ecosystems, such as the sensitivity of damage to birds and bats, land cover and estimation of continuity for open lands. Regarding visibility analysis, this was carried out individually for each cell using WindPro ZVI calculations. A quantitative model was built based on the key factors presented in the literature. This facilitated a comparison of turbine visibility levels in nearby settlements. Due to the ambiguity as to whether individual spatial perception is negative or positive, it was decided *not* to include roads and riding or walking routes as visibility points. Rather, only the visibility effect on the neighbouring settlements continually exposed to the turbines was characterised.		combine the environmental impact results with other MCDA approaches such as WSM and AHP. Converting such analyses to monetary values can aid in a designing more holistic cost / benefit analyses for renewable energy that include the full external costs. The study's literature review of GIS-MCDA studies reveals a tendency to avoid quantification and the contrasting of environmental impacts from renewable energy facilities, as many other studies simply resort to buffer zones around settlements or NPAs to avoid wind energy's negative environmental effects. In a country as small as Israel, this highly conservative strategy essentially means that wind energy will never make a meaningful contribution to the country's renewable energy portfolio.				
Barzehkar, M., Parnell, K. E., Mobarghaee Dinan, N., & Brodie, G. (2021). Decision support tools	Determination of the most productive and	MCDA based on the AHP, GI), fuzzy logic, and a weighted linear	Production: Average wind speed	The application of an MCDA based on the AHP, fuzzy logic, the WLC method, and GIS	✓	✓		✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
for wind and solar farm site selection in Isfahan Province, Iran. *Clean Technologies and Environmental Policy*, *23*, 1179-1195.	environmentally friendly sites for wind energy projects in the Isfahan Province, Iran.	combination (WLC) approach to determine optimal locations for renewable energy generation infrastructure.	Locational: Distance from transmission lines Distance from population centres Distance from wetland and protected areas Distance from roads Flooding Distance from rivers Slope Distance from fault lines Land related restrictions: Land use Soil texture Geological formations	models helped to formulate a meaningful evaluation that incorporates the environmental and socioeconomic data associated with site selection for wind energy projects. The authors note that it may be possible to incorporate a wider variety of parameters including further ecological, social, and economic indicators to improve site selection even further.				
Nasery, S., Matci, D. K., & Avdan, U. (2021). GIS-based wind farm suitability assessment using fuzzy AHP multi-criteria approach: the case of Herat, Afghanistan. *Arabian Journal of Geosciences*, *14*(12), 1091.	An evaluation of the best locations for siting wind energy projects in the Herat province of Afghanistan	Integration of the fuzzy AHP MCDA method and GIS techniques. The data used in this study were at different scales and raster resolutions; therefore, all data were resampled to the exact raster resolution. The vector data was converted to raster format after buffer analysis. These data layers were then classified into sub-criteria categories and	Production: Annual average wind speed Relief: Slope Locational: Distance from residential areas Distance from electricity transmission lines Distance from roads Land use restrictions:	The authors claim that this paper is an example for other researchers to conduct further investigations in this geographical area. The study used the most important and effective factors, weights, and methods for this specific area, considering the environmental and economic situation. The results may be different for other regions in Afghanistan; therefore, various factors, methods, and weights for these areas should be applied. Although fuzzy sets logic		✓		✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
		ranked accordingly. The weighted overlay technique was used to integrate all factors to generate a wind farm suitability map. Sensitivity analysis was performed on the wind speed criterion.	Land cover/land use conflicts	provides great support to the decision-maker with complex problems, user opinion still dramatically affects the decision process. In future studies, studies are planned to identify renewable energy areas in the region with fuzzy AHP and other methods such as M-AHP and hesitant fuzzy, aiming to reduce the user impact. The limitations of the study are the unavailability of high-resolution DEM and large-scale maps and data on the area.				
Sotiropoulou, K. F., & Vavatsikos, A. P. (2021). Onshore wind farms GIS-Assisted suitability analysis using PROMETHEE II. *Energy Policy*, *158*, 112531.	This paper introduces a new decision-making framework that combines GIS and PROMETHEE II, a multi-attribute decision making (MADM) method, to enable the GIS-assisted wind farm suitability analysis. Case study of the Thrace region in north-eastern Greece.	Constraint maps identify suitable (1) and non-suitable (0) alternative locations by creating Boolean raster datasets. Constraint map multiplication results in a binary dataset of feasible and non-feasible locations. The derived raster dataset provides a combined result with a graduated suitability index mapping restricted to the feasible location area.	Production: Average wind speed Relief: Terrain slopes Locational: Distance from high voltage electricity lines Distance from third level road network Distance from antennas, radars, and telecommunication stations Distance from industrial areas and mining zones	The proposed framework is the first to combine GIS and PROMETHEE II with a spatial interpolation model to assist wind farm suitability mapping. Thus, this method has the benefit of outranking relation methods, where candidate locations are not evaluated according to their absolute performance according to the analysis criteria but to their differences in pairs. Thus, the analysis results in a graduated score of suitability which balances descending (cost) criteria performance deviations, to gain and exceed performance to the analysis ascending (benefit) criteria. The latter is	✓	✓		✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
			Distance from livestock plants Distance from high-productivity agricultural land Distance from urban areas Distance from energy transmission lines Environmental protection: Natura 2000 network areas Tourism-related: Distance from significant cultural heritage areas Distance from coastline Distance from other non-compatible land uses Civil protection: Distance from water bodies, lakes and rivers Distance from airports	quite common in everyday decision-making, where a choice is made according to the principle of not paying more for an alternative unless justified in terms of quality and availability. The absolute suitability analysis performance revealed locations that satisfied the analysis constraints. The PROMETHEE II assisted relative suitability analysis indicating the a) outranked locations (negative net flow), b) those that outrank them (positive net flow), and c) sites with a neutral preference attitude (zero net flow). The combined results compared with the actual wind turbine locations proposed by wind developers indicate that the proposed model captures the private sector decision-making perspective. However, a significant number of locations suitable for wind farm implementation with respect to pre-existing land use types have been indicated. The latter comprises a vital issue for land use planners and policymakers when trying to reach consensus among different groups of interest. Moreover, the method ensures				

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
				transparency in the decision-making process because stakeholders (i.e., policy makers, planners, wind developers) express their preferences by defining threshold values and criterion weights.				
Ajanaku, B. A., Strager, M. P., & Collins, A. R. (2022). GIS-based multi-criteria decision analysis of utility-scale wind farm site suitability in West Virginia. *GeoJournal*, *87*(5), 3735-3757.	This study provides a GIS-MCDA modelling approach that incorporates expert opinions of the siting criteria in determining potential locations for wind farms in the state of West Virginia.	AHP-based MCDA.	Production: Average wind speed Relief: Slope Elevation Locational: Distance to transmission lines Distance to nearest paved road Distance to airports Distance from residential development Distance to lakes and rivers Land use restrictions: Protected areas Wildlife habitats (especially bird and bat areas, which were an elimination criteria)	This research builds upon previous studies and contributes to the literature by incorporating two important components: (1) inclusion of critical wildlife habitat for birds and bats as an elimination criterion within the AHP, and (2) the participation by wind power experts in the AHP decision-making process for the utility-scale wind farm suitability modelling. By incorporating expert opinions with weighing of ten siting factors, about 70,000 hectares of land are identified as 'highly suitable' for wind power development throughout the state of West Virginia. This area represents the potential to yield an estimated 29,000 MW of future utility-scale wind power capacity, which is larger than the current coal dominated electricity generation capacity in West Virginia.	✓	✓		✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
			Note that bird and bat data is related to presence, not impacts to migratory routes.					
Arca, D., & Keskin Citiroglu, H. (2022). Geographical information systems-based analysis of site selection for wind power plants in Kozlu District (Zonguldak-NW Turkey) by multi-criteria decision analysis method. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *44*(4), 10720-10732.	Study reviews geographic factors and applies GIS-MCDA approach to determine best sites for wind power projects in the Kozlu district of Turkey.	The AHP approach was applied, as described elsewhere in relation to other studies. Maps based on these data were produced in raster format through the application of ArcGIS software and with significance/weight values assigned as per expert opinions. A compatibility result map, displaying the best sites for wind power projects, was obtained by using the Weighted Linear Combination (WLC) through the combination of criterion maps categorised on the basis of weighted sums.	Production: Average wind speed Relief: Elevation Slope Aspect Lithology Locational: Distance to power distribution centres Distance to roads Land use restrictions: Land use trade-offs	GIS-based MCDA methods, which make it possible to make fast and reasonable decisions, offer an important mechanism of support for decision-making processes intended for the selection of the best locations. Irrespective of the power of the methods to be applied, the most important factor affecting the result is to correctly ascertain the criteria which influence the issue. If the criteria which are likely to bring about erroneous results due to subjective judgments associated with expert opinions utilised in specifying the criteria are identified properly, then the results can be evaluated more accurately.	✓	✓		✓
Ifkirne, M., El Bouhi, H., Acharki, S., Pham, Q. B., Farah, A., & Linh, N. T. T. (2022). Multi-Criteria GIS-Based Analysis for Mapping Suitable Sites for Onshore Wind Farms in Southeast France. *Land*, *11*(10), 1839.	An assessment of the optimal location of wind farms in south-east France using GID-MCDA.	AHP-based approach. The spatial database was generated using ArcGIS and QGIS software; the pairwise comparison in the AHP	Production: Average wind speed Relief: Slope Elevation	According to the findings, many sites were identified as suitable for wind farms. Visual and manual analyses were performed on these sites to choose those with an area larger than 400 hectares, a	✓			✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
		was computed using Excel.	Land use restrictions: Protected areas Locational: Distance to electricity sub-stations Distance to roads	high average wind speed, accessibility by roads, proximity to electrical substations, and a distance from protected areas. Four sites with an average installed capacity of 45 MW were selected, which must be confirmed by the appropriate state authorities. The decision tool provided in this article may be utilised in any part of the world by adapting it to the specific characteristics of each territory, as well as the distinct needs and policies. Despite the quality and reliability of the IGN database used, the methodology followed (including the choice of the MCDA method), and the analysis performed in this work, the authors recommend several undertakings for future projects, such as taking into account knowledge of the study area and the regulations put in place by the government concerned, and the relevant choice of determination (decision) criteria and their weightings, which often vary between experts' opinions and from one country to another.				
Mokarram, M., Pourghasemi, H. R., & Mokarram, M. J. (2022). A multi-criteria GIS-based model for	Identification of wind farm sites with lowest	Analytical Network Process (ANP), with the Ordered Weighting	Production: Average wind speed	Depending on the economic situation and the importance of the project in the study area,	✓	✓	✓	✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
wind farm site selection with the least impact on environmental pollution using the OWA-ANP method. *Environmental Science and Pollution Research*, *29*(29), 43891-43912.	impacts on human health and highest performance.	Averaging (OWA) method used to prepare land suitability maps and assess levels of risk.	Relief: Elevation Slope Land use restrictions: Distance from protected areas Distance from rivers Distance from fault lines Land use (other) Locational: Distance from communication roads Distance from rural areas Distance from urban areas Environmental: Noise pollution	one of the land suitability maps with a level of risk could be used. Additionally, due to the noise pollution caused by the installation of these turbines, the authors recommend that they are built further away from residential areas (rural and urban). Economically viable power plants can be built in high and sloping areas if there are winds of high speed, density, and stability. Ultimately, it is suggested that using predictive algorithms, such as Monte Carlo and artificial intelligence algorithms, it is possible to determine optimal locations for building wind farms. In future studies, a combination of methods such as neural networks and the OWA method may be used to prepare land use maps with different levels of risk. With this method, the best management decision for the study area can be determined based on the situation of the region and the budget allocated for it.				
Shafiee, M. (2022). Wind Energy Development Site Selection Using an Integrated Fuzzy ANP-TOPSIS Decision Model. *Energies*, *15*(12), 4289.	Evaluation of optimal locations for onshore wind energy projects, seeking to address the subject of	MCDA applied by integrating the fuzzy analytic network process (FANP) and the fuzzy technique for order performance by	Economic: Economic security Job creation Profit Social:	There is substantial scope for future research in optimal site selection for renewable energy systems. The following are some possible extensions suggested by the author:	✓	✓	✓	✓

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
	uncertainty. Case study of a hypothetical 25 MW onshore wind energy project in Iran.	similarity to ideal solution (TOPSIS) to evaluate and prioritise the potential sites for wind power development. The results are discussed and compared with those obtained using the traditional AHP, ANP and ANP-TOPSIS decision-making approaches. The required information was collected from a literature review, Delphi and on-site interviews with key stakeholders involved in the renewable energy sector of the country, GIS platforms, and Iran's wind energy resource atlas.	Social acceptance Regional reputation Technical: Wind efficiency Readiness of domestic technologies Geographical: Land suitability Environmental friendliness (visual, noise, bird mortality, interference with radar)	(a) The proposed decision model can be extended to determine suitable sites for the development of hybrid renewable energy systems (e.g., wind-solar or wind-wave) (b) Although the proposed methodology was shown to be efficient from an accuracy point of view, it was found to be computationally intensive. In order to address this issue, some other new MCDM models can be developed. (c) A sensitivity analysis can be carried out to support the decision-making process. This will help decision-makers to establish how robust the results are. (d) Designing an interactive and web-based dashboard to use for the site selection of renewable energy projects could be very beneficial to industries.				

Study	Objectives	Methods	GIS-based criteria	Selected discussion points	Relevance to Master Plan WG			
					WG1	WG2	WG3	WG4
Raza, M. A., Yousif, M., Hassan, M., Numan, M., & Kazmi, S. A. A. (2023). Site suitability for solar and wind energy in developing countries using combination of GIS-AHP; a case study of Pakistan. *Renewable Energy*, *206*, 180-191.	Optimal site selection for wind and solar energy projects. Case study of Pakistan.	AHP approach involving eight criteria. Restriction criteria were applied to filter out potential sites where construction of wind projects is not possible due to laws and regulations. This included protected areas, forests, airports, croplands, water bodies, regularly flooded areas, and residential areas.	Production: Wind speed Wind power density Relief: Slope Elevation Locational: Land cover Distance to roads Distance to cities Distance to power lines	For future studies, the authors state that the research can be broadened by the inclusion of existing power. Direct input of stakeholders and policymakers in decision making process can streamline proposed methodology. The study's approach and results can provide investors and policy makers with information relating to planning aspects, specific to energy planning in Pakistan.	✓	✓		✓