A state-of-the-art review of Geographic Information System applications, the main criteria of selection, and available data that may be used in the process of site selection for floating offshore wind farms

Un état de l'art des applications du système d'information géographique, des principaux critères de sélection et des données disponibles pouvant être utilisées dans le processus de sélection de sites pour les parcs éoliens offshore flottants

Krzysztof Szczepaniec[1], Fergal O'Rourke[2], Peter Ryan[3]

[1] Centre for Renewables and Energy at Dundalk Institute of Technology, School of Engineering, Dundalk, Ireland, krzysztof.szczepaniec@dkit.ie
[2] Centre for Renewables and Energy at Dundalk Institute of Technology, School of Engineering, Dundalk, Ireland, fergal.orourke@dkit.ie
[3] Centre for Renewables and Energy at Dundalk Institute of Technology, School of Engineering, Dundalk, Ireland, peter.ryan@dkit.ie

ABSTRACT. The energy crisis, global warming, and rising energy consumption have positioned renewable energy as a priority from national and international planning perspectives. Not only to reach the goals of the renewable energy mix, but also as part of overall energy security strategy. Rising energy prices and supply concerns have made the need for energy changes tangible for society and have increased public awareness of renewable energy. To achieve its renewable energy targets, Ireland has placed a focus on the development of offshore wind energy projects, due to its massive potential in the region. Other regions have already commenced the deployment of large-scale offshore wind farms and the technology is now competitive with fossil fuels. This work presents a comparison of Geographic Information System (GIS) applications and Multi-Criteria Decision-Making (MCDM) methods applied in the process of multicriteria site selection for Floating Offshore Wind Farms (FOWF) and highlights current trends in FOWF site selection and characterisation. This work is an objective review of the methodologies applied by researchers and a discussion of their adequacy to find the answer to the research questions posed by industry. Furthermore, it outlines the limitations of the methods and comments on the chosen criteria in the context of reaching the researches objectives. It also highlights the suitability of the industry standards methods and best practices. Finally, the work attempts to map the next steps that shall be taken to improve the methodology for criteria selection.

KEYWORDS. Geographic Information System (GIS), Floating Offshore Wind Farm (FOWF), Multi-Criteria Decision-Making (MCDM), Analytic Hierarchy Process (AHP), Fuzzy Analytic Hierarchy Process (FAHP), Monte Carlo Analytic Hierarchy Process (MAHP), Evidence Reasoning (ER), Multiple Attribute Decision Analysis (MADA), ECOS Conference.

1. Introduction

The energy crisis, global warming, and rising energy consumption have prioritised renewable energy from national and international planning perspectives. Not only to reach the goals of the renewable energy mix but also as part of the overall energy security strategy. Rising energy prices and supply concerns have made the need for changes tangible for society and have increased public awareness of renewable energy. In order to achieve its renewable energy targets, Ireland has begun to shift its attention to offshore wind developments, for a number of reasons. The legislative changes that will help to unlock the Irish offshore wind energy potential have already been made. The government has introduced the new Maritime Area Planning Act [1] that streamlines the planning process. Other regions have already begun to deploy large-scale offshore wind energy projects. In January 2023, the Crown Estate signed Lease Agreements for six offshore wind projects, with a total capacity of 8.0 GW located in the waters around England and Wales [2]. The Scottish Government has even more progressive plans. The Net-Zero target has been set to 2045, five years before the consensus reached under the Paris Agreement [3]. To reach this ambitious target, in 2022 the Crown Estate Scotland conducted the ScotWind Leasing auction of 17 offshore projects with a total capacity of 24.8 GW, ten of those projects involve floating technology with a total capacity of 14.6 GW [4].

The energy crisis has accelerated the legislation and set new objectives dictating the pace of offshore wind development. In May of 2022, The European Commission defined the steps leading to independence from Russian fossil fuels before 2030. The Esbjerg Offshore Wind Declaration [5] signed in May of 2022 by representatives of Denmark, Belgium, Netherlands and Germany set out new targets of at least 65 GW by 2030 and 150 GW by 2050. The European region is not the only one to put offshore wind energy in the spotlight, ambitious objectives have been set out by the USA, China, South Korea, Vietnam, India and Brazil [6].

In 2021, 21.1 GW of offshore wind turbines was connected globally to the grid [6] setting a new record. However, according to [7] to achieve Net-Zero before 2050, annual installations should increase to 28 GW by 2030 and then to 45 GW by 2050. The unprecedented shift towards offshore wind technology as one of the main renewable energy sources in the energy mix, and the new technology that must be implemented on a commercial scale to reach the targets, will bring new challenges that must be addressed. The vast majority of wind resources, estimated at about 80%, are located in waters deeper than 60 m [8]. From a technological development perspective, fixed-bottom offshore wind turbine deployment is constrained to a water depth of approximately 60 m [7,9]. Hence, to unlock the offshore wind potential and reach the ambitious objectives, the deployment of floating wind turbines on a commercial scale is inevitable.

The rapid growth of installed offshore wind turbines may, however, come at a price. Pressure to act quickly could potentially compromise stakeholders' interests and harm the natural environment, leading to conflicts and negative perceptions of offshore wind by society. In order to mitigate these potential issues, an efficient methodology and toolset to extract the most suitable locations for development projects is crucial. Site selection for the deployment of floating offshore wind farms off the Irish coast requires careful analysis. Careful site selection requires adequate techniques that allow data integration with geographical location, analysis of data, and results visualisation. The Geographic Information System (GIS) addresses all of these requirements. Furthermore, it is widely used in spatial environmental studies since it supports the decision-making process by linking it with multicriteria evaluation methods [10]. Environmental and maritime spatial studies are complex and many interests must be considered. Therefore, sufficient criteria prioritisation and alternative comparison methods are highly desirable to implement alongside GIS.

A good example of how critical the preliminary site selection might be is the 400 MW offshore wind farm Anholt, located off the Danish coast on the Baltic Sea. This location was prioritised by authorities in the planning procedure. However, the risk of construction of the wind farm assessed by three potential bidders was so high, that two bidders gave up the race. As a result, only one offer was submitted with the price per kWh twice as high as for other offshore projects at the time [11]. Floating offshore technology is at a relatively early stage of commercialisation, the first commercial-scale floating wind farm, Hywind Scotland has been in operation since 2017; The farm consists of five floating wind turbines with a total capacity of 30 MW [12]. Another project of 3 wind turbines and total capacity of 25 MW called Windfloat Atlantic has operated since 2020 [13]. The largest operating floating wind farm is the Kincardine Offshore Windfarm located off the east coast of Scotland, consisting of five Vestas V164-9.5MW wind turbines and one Vestas V80-2.0MW wind turbine with a total capacity of nearly 50 MW [13].

2. Geographic Information System

2.1. *Methods of spatial analysis*

The Geographic Information System (GIS) is a data management and processing tool in the spatial domain. Hence, most researchers use GIS as the primary tool because it allows for the convenient organising of data in a spatial grid and its complex processing capability. It is also a flexible tool allowing advanced users to programme new features. Today, due to the large amount of available data, GIS plays an important role in many aspects of the modern economy. In principle, the vector or raster system of data analysis may be used in GIS. The chosen approach depends on the objectives, the results will differ depending on the chosen method [10]. The first common method of vector-based analysis is the conversion of the criteria to true or false values and then using Boolean operators. This approach leads to the results of a crisp spatial mapping of areas that are either included or excluded from a designated set [10]. This method is suitable to process hard constraints as an exclusion area. The second method is based on raster-based analysis where quantitative criteria are processed as continuous variables rather than simplified to a Boolean's true or false approach [10]. Very often two methods are applicable in one study. Examples of vector and raster methods application can be found in [10,14]. The constraints may have a form of exclusion areas like military zones or designated wildlife areas where offshore wind farm development is prohibited. Criteria can also be a continuous factor where development is not prohibited but less or more favourable because of other factors like wind speed, water depth, distance to the port and many others [10,11].

The key to effectively achieving the objectives is a proper definition of criteria that form the attractors and set the boundaries of the study. Criterion is the basis of decision-making; it represents the objectives and methodology and also serves as evidence of the reasoning behind the decision [15]. Hence, diligent criteria selection is a crucial part of the spatial assessment. Furthermore, the selection should also concern the appropriateness and quality of data they are based on.

2.2. *State-of-the-art GIS applications*

Due to open access to many valuable data sets and GIS tools, the usage of geographical information system in marine spatial planning has gained momentum. The importance of spatial planning is also acknowledged by authorities. In 2014 the European Commission adopted the directive establishing a framework for maritime spatial planning [16]. The main objectives of the directive are to support the sustainable development of the marine sector by considering economic, social and environmental aspects and applying the ecosystem-based approach to ensure the coexistence of various activities and uses. Moreover, the marine spatial plans shall contribute to the sustainable development of the energy sector on the sea, transportation and fisheries concerning the preservation and protection of the environment.

For the region of the Celtic Sea off the southwest coast of England and Wales, [14,17] have conducted an extensive GIS spatial analysis to identify project development areas to be offered on tender for Floating Offshore Wind Farm (FOWF) deployment. The central axis of the study was the engagement of the stakeholders at an early stage of the study to participate in the process. The study has a discrete structure that could be divided into five steps. In the first step, the authors defined the area of study and defined the main assumptions that were implemented in GIS and visualised. In the second step, the hard constraints were defined. The hard constraints consist of nineteen criteria where only nine of them effectively influence the analysed area, and ten of them don't contribute to the model. Despite not ultimately contributing to the model it is important to acknowledge that they were considered in the study. 0 twenty-six criteria with only two of them not affecting the analysed area. Soft and hard constraints have been listed in Table 1 and Table 2.

Study	[14, 17]		[18, 19]		[20]		[21]	
Criterion	**Applied**	**Exclusion**	**Applied**	**Exclusion**	**Applied**	**Exclusion**	**Applied**	**Exclusion**
Exclusive Economic Zone	Yes	-	Yes	-	No	-	No	-
Distance	Yes	>200 km from grid connection	Yes	>200 NM from shore	No	-	No	-
Protected Wrecks / Heritage	Yes	-	Yes	-	No	-	Yes	-
Environmental protected areas	No	-	Yes	-	Yes	-	Yes	-
Nuclear Power Stations	Yes	Buffer 1NM	No	-	No	-	No	-
Navigational Dredging	Yes	-	No	-	No	-	No	-
Cables agreements	Yes	-	No	-	No	-	No	-
Infrastructure Oil and Gas Agreements	Yes	-	No	-	No	-	No	-
Meteorological Equipment Agreements	Yes	-	No	-	No	-	No	-
Minerals and Aggregates Agreements	Yes	-	Yes	-	No	-	No	-
Minerals Capital and Navigation Agreements	Yes	-	Yes	-	No	-	No	-
Natural Gas Storage Agreements	Yes	-	No	-	No	-	No	-
Pipelines Agreements	Yes	-	Yes	-	No	-	No	-
Tidal stream, wave, wind agreements	Yes	-	Yes	-	No	-	No	-
Aquaculture agreements	Yes	-	Yes	-	Yes	-	Yes	-
Outfall leases	Yes	Buffer 250 m	No	-	No	-	No	-
Active cables Infrastructure	Yes	Buffer of 250 m	Yes	Buffer 500 m	No	-	No	-
Active Pipelines Infrastructure	Yes	-	Yes	Buffer 500 m	No	-	No	-
Traffic Separations Schemes	Yes	Buffer 1.77 NM	Yes	Buffer 500 m	Yes	-	Yes	-
Platform Helicopter Safety Zones	Yes	-	No	-	No	-	No	-
Military areas	No	-	Yes	-	No	-	No	-
Wind Velocity	Yes	<9.5 m/s @ hh	Yes	Excluded <4 m/s @	No	-	Yes	<4 m/s and >25 m/s

				10 m				
Water Depth	Yes	<50 m >250 m	Yes	<50 m >1000 m	Yes	<62 m >1000 m	Yes	<100 m
Significant wave height	Yes	Not excluded but 2 groups identified: <14 m >14 m	No	-	No	-	Yes	>8 m
Islands / Rocks	No	-	No	Unkonwn	Yes	-	Yes	-
Seismic fault lines	No	-	No	-	Yes	-	No	-

Table 1. *Hard constraints, exclusion zones*

Step four is based on the application and processing data applied to models in previous steps. As a result of running the exclusion and restriction models in the GIS, the final map presenting more or less favourable locations for FOWFs deployment was created. The soft constraints criteria were organised into groups and subgroups and then pairwise compared. The analytic hierarchy process (AHP) was used to assess their relative importance and to calculate the weights of soft constraints. Finally, the weights were applied to the soft constraints model. The combined output has been normalised from 0 to 100 to reflect the percentage of constraints. Then the considered area has been divided into equal cells of the seabed. The constraints have been organised into ten groups ranging from the least constraints of 10% to the most constraint 90% and 100%. Cells constrained in 50% or less were chosen for further proceedings. Then neighbouring cells were organised forming five large areas representing 11,000 km^2, of potential FOWF sites, which will be the subject of a detailed study in step five which has not been completed yet. The selection of the project development areas (PDAs) is based on the assessment of technical risks, cost of energy and environmental and social impact. This step will identify smaller areas of the PDAs that will be offered on public auctions for particular FOWF projects. Therefore, a detailed study of technical risks and the cost of energy is required. To fully understand the technical challenges and cost of the energy the authors are aiming to:

– study wake effect to shape project parameters and forecast energy yield;

– recognise the relationship between the energy density, turbine layout and mechanical fatigue loading;

– analyse mooring and anchoring systems and their limitation in terms of geotechnical and met-ocean site characteristics;

– recognise energy export options and related costs as well as onshore grid reinforcement.

– Finally, based on the information above fine tune Levelised Cost of Energy (LCOE) layer will be used in the final PDAs ranking.

Ref.	General Criteria Tier 1	Weight	Basic Criteria Tier 2	Weight	Basic Criteria Tier 3
[14]	**Economic**	0.5	Navigation	0.1	AIS density (Tier 4)
					Harbor authorities
					Anchorage areas
					Open disposal sites
			Sub-surface infrastructure	0.225	Evaporites agreements
					CCUS agreements
					O&G Fields
					O&G awarded blocks
			Infrastructure	0.175	Out of service pipelines
					Out of service cables
					Wells
			Fisheries	AIS data, linear weight	AIS density (Tier4)
	Environmental	0.2	Environmental designations	0.11	SACs
					SPAs
					Ramsar
					MCZ & NNRs
					SSSIs
			Environmental features	AIS data, linear weight	Fish spawning & nursery areas (Tier 4)
			Contamination	0.09	Closed disposal sites
	Social	0.3	Leisure	0.045	AIS density (Tier 4)
					Recreational Yachting Training Areas
					Marinas
			Visual	0.075	Visibility
			Historic	0.075	Wrecks (unprotected)
					World Heritage Sites
			Bathing	0.09	Bathing beaches
[18]	**General Criteria**	Weight	Basic Criteria		Weight
	Met-ocean	0.295	Wind velocity		0.073
			Wind potential		0.094
			Water depth		0.038
			Wave conditions		0.051
			Marine currents		0.028
			Temperature		0.01
	Viability	0.104	Technical feasibility		0.066

			Sufficient study times	0.038
	Logistics	0.102	Distance to local electrical grid	0.053
			Distance from coastal facilities	0.048
	Facilities	0.237	Distance from shore	0.033
			Distance from residential areas	0.032
			Distance from the maritime routes	0.03
			Distance from underwater lines	0.042
			Distance to marine recreational activities	0.035
			Distance from airport	0.065
	Marine environment	0.148	Distance from protected areas	0.064
			Proximity to migratory bird paths	0.043
			Proximity to migratory marine life paths	0.041
	Techno-economic	0.114	Area of the territory	0.035
			Proximity to the area of electric demand	0.031
			Population served	0.017
			Multiple resources	0.031
[21]	**Met-ocean**	0.515	Wind velocity	0.3697
			Potential power output	0.3344
			Significant wave height	0.2441
			Tidal range	0.0518
	Logistics	0.1756	Vicinity to ports maintenance	0.3212
			Sub-station vicinity	0.2384
			Depth range	0.4404
	Facilities and environment	0.3094	Minimum distance to land	0.0669
			Proximity to fisheries	0.0688
			Proximity to shipping lanes	0.2722
			Proximity to shipwrecks	0.0424
			Proximity to MPAs	0.2774
			Proximity to aquatic habitats	0.2722

AIS - Automatic Identification System, CCUS - Carbon Capture Utilisation and Storage, O&G - Oli and Gas, SACs - Special Areas of Conservation, SPAs - Special Protection Areas, MCZ - Marine Conservation Zone, NNRs - National Nature Reserves, SSSIs - Sites of Special Scientific Interest

Table 2. *Soft constraints, evaluation criteria*

The case study [22] of site selection for floating offshore wind off the coast of Ireland is focused on the LCOE as the main criterion. Researchers have employed the GIS software to conduct the study. The study can be divided into two parts. The first part is focused on identifying exclusion zones, i.e. the places where development is not possible. In this part, only a few basic exclusion criteria have been considered that are in line with the initial version of the Offshore Renewable Energy Development Plan (ORDEP). As the the plan considered only areas up to approximately 100 km from the coast, the area of search has been extendend to the Irish Exclusive Economic Zone (EEZ). As the study pre-dates the publication of ORDEP II the researchers could not refer to it. The list of exclusion zones has been supplemented by bathymetry, near-shore protected areas, aquaculture reserves, routes of cargo and passenger ships, a minimum distance from shore of 10 km and natural offshore parks. In the second part of [22], researchers identified the main inputs to model the LCOE. The main project cost drivers at the pre-operational stage, are capital expenditure (CAPEX) and operational expenditures (OPEX), it is unclear if project development costs were also included in the study. Finally, the annual energy yield has been estimated based on the reference offshore 10 MW wind turbine developed by the Technical University of Denmark (DTU). To estimate annual energy yield, researchers based their work on a layout consisting of one hundred wind turbines with a total installed capacity of 1 GW. However, the wind turbine technical specifications, including hub height and rotor diameter, have not been included in the study. Therefore it is unclear what area is needed to accommodate 1 GW of installed capacity, the total installed capacity potential in Irish waters, and the base to calculate wake losses, the factor that is directly related to FOWF layout. To calculate annual energy output the 20 years long-term time series spatially distributed layout in the search area has been used in the case study [22]. The exact procedure of annual energy yield calculation, based on long-term time series, using the turbine's power curve and GIS software has not been described in the reviewed study. The ERA5 wind speed data that are available to download from the Copernicus Programme requires processing before it can be used in the energy yield assessment. This procedure has not been described in the reviewed study. The aim of the [22] is the site selection for FOWF through LCOE. Due to the relative immaturity of floating offshore wind technology, no operating floating wind farms on Irish waters, and persisting problems with the supply chains related to the global trend of post-pandemic deglobalisation, the estimation of CAPEX and OPEX is subject to large uncertainty. Therefore it would be expected that more emphasis will be placed on forecasting the energy yield where the uncertainty of the assessment is largely dependent on methodology and input data therefore it can be managed and mitigated.

For the region of the European Atlantic coast of Portugal, Spain and France the [18] has proposed an integrated GIS approach of multicriteria site selection for floating offshore wind farms. Researchers conducted the literature review in the field of offshore wind farms site selection based on GIS and Multi-Criteria Decision-Making (MCDM) methods and proposed their proprietary approach of an integrated GIS tool built using the Phyton language. The site selection is performed in three stages. In the first stage data from various regulatory bodies, like national marine spatial plans and issued concessions are collected and processed to feed the GIS model. The second stage is narrowing the area of search by the addition of hard constraints as a result of step one. The hard constraints or in other words exclusion zones can be divided in this study into two main categories. The first is the regulatory, infrastructural and maritime usage while the second is related to social-economic aspects reflected in wind speed, water depth and distance from shore. The locations with an average wind speed below 4 m/s at 10 m height are considered as not suitable therefore form the exclusion zone. As a suitable area to deploy FOWF the water depth range between 50 m to 1000 m has been considered as well as a minimum distance from shore in case of the regions where such regulations are in place. The third step of the study aims to assess the feasible locations defined in the previous step. Each site may have a different characteristic that shall be recognised and represented by the quantitative, objective measure to allow for choice of the best alternative from a technical and socio-economic perspective. To rank sites, a set of evaluation criteria or in other words soft constraints have been proposed by the researchers. With the help of industry experts and as per a review of existing studies, the twenty-three evaluation criteria grouped into six categories have been chosen and applied to the model. Soft and hard constraints have been listed in Table 1 and Table 2. As a result of the study, the forty-two locations suitable for floating offshore farms have been identified and evaluated. The area of potential FOWF development covers 7230 km^2. To ease site comparison, each site has been characterised by a fixed set of evaluation criteria like: average wind speed, wind potential, water depth and others. The researchers have also estimated the number of wind turbines and annual energy yield together with CO_2 and SO_2 reduction as well as direct and indirect job creation. There are just a few examples of operating small-scale floating wind farms, there is no reliable operational data that includes the power curve changes and availability factors. Also, wind turbine layout due to wake effects and impact on energy yield requires a detailed investigation. Finally, applied FOWT power curves and detailed long-term wind conditions should be used in the energy yield estimation. Therefore, presented performance estimates have a large component of uncertainty and shall be treated just as an indication factor. In [18], no MCDM methods have been implemented.

In the follow-up article [19] written by the same authors, the site selection of forty-two potential floating wind sites has been supplemented with the MCDM method to ease and streamline the multi-criteria decision-making process. In that research, scholars utilised the twenty-three evaluation criteria formed in the previous study. The relative importance of each criterion has been estimated in a pairwise comparison process with the AHP methodology. The criteria's weights were assigned based on the opinions of five industry experts representing different fields of the offshore wind industry. The pairwise comparison method was used not only to weight criteria but also to evaluate alternatives which are in this case forty-two locations grouped by region. All feasible locations were compared concerning each criterion therefore with known criterion weight derived in the previous step the most suitable location in each group could be identified. Researchers have applied two evaluation criteria related to wind speed. One is the wind velocity and the second is wind potential reffered to in the wind industry, Full Load Equivalent (FLE). The FLE is defined as the theoretical number of hours in the year of operating by the wind turbine at the rated power. The wind speed itself is a useful indicator however does not reflect in full the wind conditions on site. Nonetheless, if the wind speed is used as an evaluation criterion, then cubed weighting is typically applied to capture the nonlinear relation between wind speed and energy output from wind turbine. Using wind potential seems to be preferable, however, usage of the power curve and wind distribution in the form of Weibull or time series is inevitable.

Castro-Santos et al. [20] have proposed the application of GIS for selecting the site for the floating offshore farm in the North-West of Spain. The GIS method is similar to the above studies and comprises two steps. The first is defining the exclusion zones, and the second step defines the soft constraints. As a hard constraint where development is not permitted or desirable the following restrictions are considered: fishing banks and grounds, navigation areas, Spanish marine development plans, environmental protection areas, underwater rocks and seismic fault lines. Noteworthy is the application of bathymetry as a hard constraint that can be adjusted to the given platform technology addressing different draft requirements. The area of the search will vary depending on the considered technology.

The soft constraints are based on local ports and shipyards' characteristics. The draft, storage area and lifting capability have been considered. In the case study described in [20], the ports and shipyards draft has been set between 3.0 m to 12.5 m which is suitable for installation vessels and tugboats but may not be for semisubmersible platforms where the draft is dependent on chosen installation and towing strategy, operational draft oscillates around 20 m [23].

The final areas of interest are shaped based on hard and soft constraints as per desirable water depth or port and shipyard characteristics. As an output not only feasible areas of development are plotted but also the distance to the suitable port or shipyard and the economic indexes of internal rate of return, levelised cost of energy and others. The economic indexes are presented in the form of a heat map covering only areas that are resultant of the application of exclusion zones and soft constraints. The input parameters that are used to calculate the economic indexes have not been presented in [20]. No MCDM method has been applied in the study, however, the estimation of economic factors and depicture results on maps support decision-making based on economic criteria.

Nonetheless, due to the immaturity of floating wind farm technology, and other factors that have a significant impact on costs and energy yield, it is expected that large uncertainty is assigned to these factors. Therefore, they shall be considered as indications rather than precise values. Due to large uncertainty related to economic estimates at this stage of the high-level study, it would be worth considering usage normalised, unitless economic factors.

For the western part of the Irish coast, [21] has outlined a multiple attribute decision-analysis methodology for selecting the most suitable location to deploy the floating offshore wind farm. To limit the search area, researchers conducted a literature review, identified sites that are either developed or in planning procedure, investigated the grid connection possibilities and held meetings and consultations with experts in the renewable and legislation field. This procedure led to the selection of the area of interest of Shannon Foynes Bay off the coast of Galway. Instead of dedicated GIS software typically used in spatial analysis, researchers utilised Microsoft Excel. The Excel cells play the same role as the raster cells in GIS assessments. It allows the assignment of multiple attributes reflecting criteria to each cell and the application of Excel formulas. Here also criteria are divided into two main groups of hard and soft constraints. The nine hard constraints and thirteen soft constraints organised into three main groups have been identified. It is unclear if all of the listed constraints have contributed to the final output. After the limitation of the search area by the application of hard constraints the researchers with the help of five experts in the offshore wind industry prioritised soft criteria in the pairwise comparison procedure as a part of the AHP method. Then the MCDM method of Evidence Reasoning (ER) was applied. Soft and hard constraints have been listed in Table 1 and Table 2

It is unclear why Excel has been used since there is GIS software that provides better accuracy, data management and processing as well as built-in and programmable tools dedicated to spatial analysis. Also, some of the GIS software is free and could be used in this study without extra costs.

3. Multi-Criteria Decision Making

The Multi-Criteria Decision Making (MCDM) methods are used to support the decision-making aiming to achieve the objective by choosing the best alternative among all alternatives under multiple evaluation criteria. The increase in the number of MCDM methods took place in the 1970s, while the origins of modern MCDM date back to the 1950s [24]. Over one hundred MCDM methods have been developed, moreover, recently hybrid and modular methods are frequently used to eliminate the basic methods' drawbacks. An example is an application of fuzzy set theory to the Analytic Hierarchy Process (AHP), implemented in [25,26]. The MCDM methods are widely used in the financial sector, medical diagnostic, engineering, spatial planning, management and other fields where multiple criteria must be handled in the decision process. The choice of the method depends on the scenario that is analysed. Some of the methods are suitable for certain problem-solving, but there is no single universal method to address all scenarios [27].

3.1. *MCDM methods used in site selection*

A floating offshore wind farm site selection requires detailed consideration of multiple criteria in order to achieve the objectives. In FOWF site selection one of the most popular methods is the AHP introduced by Saaty in 1971 [28]. Application of AHP requires deconstructing problems in a hierarchical or network structure followed by the Pairwise Comparison (PC) of elements regarding their importance. To score relative importance, Saaty’s fundamental scale has been applied as presented in Table 3. In the typical AHP process of site selection, the criteria would be pairwise compared to reaching the goal and separately the alternatives (feasible sites) concerning criteria.

The relative intensity of importance	Name	Explanation
1	Equal importance	Equal contribution
3	Moderate importance	Experience and judgment strongly favour one over another
5	Essential importance	Experience and judgment strongly favour one over another

7	Very strong importance	One is strongly favoured and its dominance is verified in practice
9	Extreme importance	Strong evidence exists in favour of one over another
2,4,6,8	Intermediate values	The comprise solution
Reciprocal	-	If *i* has one of the importance numbers when compared with *j*, then *j* has a reciprocal value of *i*

Table 3. *The Saaty's fundamental scale* [28]

The AHP is a relatively easy and transparent method, it introduces a structural and logical division of complex problems and a pairwise comparison of its elements step by step. It also allows for group decision-making and evaluation of quantitative and qualitative criteria as well as an application of subjective and objective measures.

Among the weaknesses of the method is a rapid increase in pairwise comparisons with criteria and alternatives to be considered [28]. The number of pairwise comparisons needed for a particular matrix of order *n,* is *n(n-1)/2* because it is reciprocal as well as its diagonal elements are comparisons of the same elements and therefore equal to one [28]. Let the A_1, A_2,…, A_n, be the set of criteria. The comparison of criteria is represented by n-by-n matrix $A = (a_{ij}),\ ij = 1,2,\dots,n$. The quantified pairwise comparison on pairs of $(A_{i,}A_j)$ is represented by numerical entries a_{ij} in matrix A [28]. The entries a_{ij} to (1) follow two general rules:

if $a_{ij} = a$, then $a_{ji} = 1/a,\ a \neq 0$;

and,

if relative importance intensity $A_i = A_j$, then $a_{ji} = 1,\ a_{ji} = 1$, as well as $a_{ii} = 1$.

The comparison matrix *A* has the form:

$$A = \begin{bmatrix} 1 & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ \frac{1}{a_{1n}} & \cdots & 1 \end{bmatrix} \text{ (1) [29]}$$

Besides human error, bias, or subjectivity, the final result will also be influenced by the presentation of Saaty's scale, the number of degrees used (eg. five instead of nine) and their form of verbal degrees or numerical as well as the graphical presentation of scale. Also, the method of obtaining the judgments is important, whether as an administrated interview or without the influence of the researcher [30]. The main advantages and disadvantages of the AHP method are listed below.

Among the main advantages of the AHP method are:

– Relative simplicity and transparency [28];

– Useful for organising the complex problem into a structured hierarchy [28];

– Offer the possibility of application of quantitative and qualitative criteria as well as an objective and subjective evaluation of each on one scale [19];

– Support of group judgments [28];

– Consistency check allows for verification of errors in the pairwise comparison process [28,29].

However, the AHP method does have some disadvantages:

– It is based on experts' opinions therefore it may be subjective [31];

– Each group of elements that are pairwise compared should not exceed seven, therefore in the case of many criteria division in many subgroups is required [29];

– The number of pairwise comparisons increases rapidly with the number of criteria [28] ;

– Presentation of Saaty's fundamental scale and form of gathering expert's opinions may influence results [30];

The AHP procedure supported by GIS was used by The Crown Estate [14]. The pairwise comparison of criteria concerning their risk of achieving the objective was introduced. The criteria selection and weighting are a result of consultations with stakeholders and industry experts. Twenty-six soft constraints were identified and organised in the logic hierarchy. The soft constraints were relatively compared concerning the risk posed to achieve a goal. Therefore, the higher the weight of the criterion the higher the risk is. In the next step, weights were applied to soft criteria and the overlay analysis was performed. The combined output was normalised from 0 to 100 and then divided into ten groups. Finally, they were fed to the GIS model as the attributes of raster cells, where weights were summed up as an overlay of multiple data layers of each soft constraint. The higher the score the more constraint the raster cell is. The cells with a score of 50% or less were chosen for further proceedings followed by grouping neighbouring cells to form larger areas. In that manner, the areas with the lowest development risk were identified, so further assessment with the concern of the performance and costs of the FOWF can be conducted.

For the Atlantic coastal region of Spain, France and Portugal, Diaz and Guedos Soares [19], conducted an extensive multicriteria floating site evaluation. Their work comprises not only criteria weighting but also an evaluation of forty-two sites that have been outlined as a result of the GIS procedure conducted in the preceding study [18]. The pairwise comparisons of constraints were conducted by five experts experienced and competent in broad offshore energy areas. Nonetheless, the evaluation of the importance of certain criteria varied between experts. To reflect the central tendency of the results of pairwise comparisons conducted by the experts, their judgments were averaged throughout the geometric mean. Unlike in [14] the criteria weights calculated in [19] reflect risks by minimising weight with the proximity to certain elements (eg. maritime routes) and the opportunities by maximising weight where higher wind speed occurs. The higher the combined weight the better the location is from an economic and risk perspective.

The AHP method assumes that the decision maker in the pairwise comparison process can select a clear winner which may not be the case in many situations. In these cases, the probabilistic approach would provide additional information [26]. Therefore, the AHP is not recommended for scenarios with high uncertainty of judgments. Also, if the final rank of alternatives is convergent, there are no statistical measures to differentiate alternatives and support decision-making [32].

To address issues inherently related to the application of AHP, the study [19] has been extended by Diaz et al. [25] with the addition of the Monte Carlo simulations and Fuzzy Set theory to determine the relative preference of wind farm locations. The fuzzy set theory applied to AHP forming the FAHP allows for ambiguity in decisions, where there are no clear boundaries therefore the decisions are closer to natural human decisions [25,26]. The application of the fuzzy set is executed by replacing the standard Saaty's scale with Triangular Fuzzy Numbers (TFNs).

The AHP and FAHP do not provide a measure for the imprecision and disagreement between decision-makers. The Monte Carlo Analytic Hierarchy Process (MAHP) provides information about the influence on results of judgment variability of decision-makers. The application of Monte Carlo simulation is recommended when there is a large uncertainty associated with the ranking of alternatives. However, the exact level of uncertainty over which the Monte Carlo Analytic Hierarchy Process (MAHP) outperforms the AHP is not clearly defined [32,33]. In [25] nine different locations were ranked based on twenty-three criteria resulting in twenty-three separate sets of pairwise comparisons for each location. Finally, the ranking of each location was performed with three methods: AHP, FAHP and MAHP. The same results were derived for locations ranked at first, second and third place. Seven out of nine locations were ranked the same by AHP and MAHP, the only differences being locations ranked as seven (Bilbao) and eight (Mutriku). Five out of nine locations were ranked the same by AHP and FAHP, where the highest difference in ranking is by two places, the location ranked by AHP is in seventh position while using the FHAP method is in ninth position. In All three methods, changes by one to two locations in the ranking occurred between Bilbao, Mutriku and San Vicente sites. The probability distribution derived from MAHP shows that the probability of ranking those three locations at the place of seventh, eighth and ninth is very close oscillating around 30%. That explains slight differences in final results between the three methods. Convergent results especially between the AHP and MAHP and slight variance between AHP and FAHP indicates that in the given example, the AHP method itself performs equally or if not better considering its simplicity than FAHP and MAHP. Table 4 lists the results of the [25].

No.	**Site name**	**Ranking**			**Probability of occurrence at a given ranking place**					
		AHP	**FAHP**	**MAHP**	**Ranking No.**	**Probability**	**Ranking No.**	**Probability**	**Ranking No.**	**Probability**
1	Ribadeo	1	1	1	1	87%	2	6%	3	4%
2	Navia	2	2	2	2	40%	3	36%	4	10%
3	A Guarda1	3	3	3	3	35%	4	24%	2	21%
4	Huelva	4	5	4	4	24%	2	21%	6	20%
5	A Guarda2	5	4	5	5	33%	4	25%	6	22%
6	Santander	6	6	6	6	43%	5	29%	4	13%
7	Bilbao	7	9	8	9	32%	7	28%	8	28%
8	Mutriku	8	8	7	8	31%	9	30%	7	29%
9	San Vicente	9	7	9	8	32%	9	30%	7	29%

Table 4. *Comparison of AHP, FAHP and MAHP results from [25]*

A slightly different approach to multi-criteria site selection of FOWF is presented in [21]. Researchers applied the AHP method to calculate weights of general and basic criteria and then employed the Evidence Reasoning (ER) method to rank the sites. The AHP method combined with ER is also named Multiple Attribute Decision Analysis (MADA). The ER is an evidence-based primary MCDM method developed in the early nineties. It applies to solving problems having quantitative and qualitative criteria [21]. Unlike in the AHP, the ignorance and uncertainty of decision-makers can be assessed. The downside of this method is its complexity, therefore non specialists may not be able to apply it or interpret results [34]. In [21] the MADA method was applied to rank forty-three sites of Shannon Foynes Bay off the coast of Galway. The utility ranking derived in the MADA method vary in the range of 0.6193 for the site ranked at first place to 0.5421 for the site at forty-third place which results in an average step per rank of 0.002. As a result of the study, the most suitable site has been determined along with other sites where five of the most suitable sites are adjacent. The site named F16 is the most favourable site among all forty-three sites explored. Furthermore, this site was ranked high in all three general criteria. However, site G14 ranked third position was ranked twelve and nineteenth in terms of the general criteria of met-ocean and facilities and environment but first in general criteria of logistics. The general criteria weighting has been distributed in [21] as follows: met-ocean 51.50%, facilities and environment 30.94% and logistic 17.56%. It is seen that combination weighting has a profound effect on the final assessment of site suitability [21].

In [35] the researchers compared AHP and MADA methods. The comparison has been performed based on the case study of twenty-two feasible sites off the coast of Scotland and three sites off the Madeira Islands. The locations used in the case study were derived from other studies performed by Loughney et al. [36] and Diaz and Guedes Soares [18,19]. The final results of ranking sites off Scotland's shore show no substantial differences in location suitability assessment. Results up to eight in rank vary by one place. Results of ranking sites off the Madeira Islands are the same for the first place in ranking however the second and third places are reversed between AHP and MADA.

The weights range for the ranking of the Scottish sites is very narrow for the AHP method ranging between 0.9984 for the site ranked at first place to 0.9866 for the site ranked at the twenty-second place. It means that the average step of weight per place in the ranking is 0.0006. The range of weights derived in the MADA method vary in range of 0.7565 for the site ranked at first place to 0.6325 for the site at twenty-second place which results in an average step per rank of 0.006. The range of weights in the ranking of the Madeira Islands is wider than for Scottish sites the weights range from 0.697 to 0.567 in the AHP method and from 0.392 to 0.300 in the MADA method. Respectively the average step of weight per place of rank is then 0.065 and 0.046. The relatively narrow weight range in the case study of Scottish sites and Irish sites as in [21] which were also grouped in a relatively small area is probably the result of lower differentiation of sites' characteristics.

The comparison shows that both methods AHP and MADA are suitable to support multi-criteria decision-making and allow for the engagement of the industry experts and stakeholders considering all interests because both methods support group-decision making. The inherent subjectivity of preferences between criteria is one of the disadvantages of the AHP method. Limited involvement of experts in the final steps of the MADA method, which requires a detail study of criteria by the methodology developer, may reduce the influence of the subjectivity of the experts [35]. One of the advantages of the MADA method is its ability to measure ignorance, however this factor has not been estimated in reviewed studies [21,35].

The AHP method requires less computations, is easier to implement, and more intuitive, therefore in this regard, it outperforms the MADA method. Because of this the AHP may be the preferred method to be applied where stakeholders and non-specialists are engaged. Results indicate that the value of the weight across all sites is very similar, therefore there is no clear winner. In this case, the uncertainty of the results is high. This can raise confusion among stakeholders that no clear information for decision-making has been obtained as a result of the study.

4. Discussion and Conclusion

Finding the best locations for deployment of FOWF is crucial for further development of this technology, reaching its technological maturity and proving reliability. This step is required to achieve commercial readiness, set a standard and create efficient supply chains that would streamline development and decrease costs and project finance risk. There is a consensus that GIS methods are the most suitable for spatial analyses, including site selection of FOWF. Among the reviewed studies, there is only one, where the GIS software was not employed [21]. The choice of Microsoft Excel instead of the proper tool dedicated to spatial analysis is unclear. Some GIS tools are available for free and are far more versatile than Excel to perform spatial analysis.

The key to achieving desired results is by defining a detailed research question therefore setting clear objectives of work. The objectives then shape the criteria through which the specific problem is reflected. The criteria set the boundaries and attractors of the study. Each criterion is a base for decision-making and reflects methodology as well as objectives. In reviewed studies, sets of criteria chosen by researchers is adequate for a general policy-making approach, suitable for maritime development spatial planning that aims to draw up the broad areas of sea where the development of FOWF is feasible. A good example is a study conducted by The Crown Estate [14]. Some of the criteria chosen by researchers do not fully represent the specifics of wind turbine operation and the industry approach to site condition assessment. An example is setting an annual average wind speed of 4 m/s at 10 m a.s.l. as an exclusion criterion whereas FOWF projects with an average wind speed close to 4m/s are not economically feasible. The assumed minimum wind speed shall be approximately twice as high and extrapolated to the hub height of the wind turbine as in [14,17]. Also doubling criteria of the twin nature like wind speed and wind potential is limited to one, otherwise this factor might be overrepresented and dilute weights of other criteria. To stress the nonlinear relation between wind speed and energy, cubed weighing is applied to this criteria, as the potential power output is the factor of interest. Criteria reflecting the extreme met-ocean conditions were not considered therefore some operational risks were not addressed. In [18,20,22,26] researchers based site selection results on estimates including the potential installed power capacity, annual energy yield, capacity factor and economic factors. Estimation of CAEX and OPEX is subject to large uncertainty that is beyond the control of forecasting for researchers. Nevertheless, the uncertainties of annual energy yield estimates can be controlled in the process because they are related to methodology, input data and data processing.

Solving the multi-criteria problems in many cases requires the application of one of the MCDM methods. In reviewed studies, researchers utilised various MCDM methods. Their pros and cons have been described in the body of this paper. The main aim of those methods is to derive weights of the criteria that lead to support the multicriteria decision. In most of the reviewed studies, researchers implemented weights to all of the evaluation criteria and then conducted the overlay analysis using GIS software. Some of the criteria represent a risk or cost, for instance, distance to a protected area or distance to a grid connection, whereas others reflect opportunities, like wind speed. Mixing these two types of contrary-in-nature criteria in one overlay analysis may lead to non-optimal results. To limit the negative impact of possible overweighting or underweighting risk, costs and opportunities among criteria, conducting a separate overlayer analysis may be a solution.

The main drawback of the methods is their subjectivity and the fact that the results are sensitive to human errors, ignorance, ambiguity and even the method of obtaining the expert’s judgments. It means that by using the same tools and even the same group of experts the results may not be repeatable. Therefore it falls outside of one of the basic science rules that the scientific experiment shall be repeatable. Researchers admitted that the evaluation of criteria importance significantly varied between industry experts and as a result, the judgments were averaged. That indicates that each of the competent and experienced experts was prone to their discipline bias. The subjectivity is inherent to described MCDM methods therefore it cannot be fully eliminated, but only mitigated by implementing other methods like fuzzy set theory or Monte Carlo simulations or by including a large number of experts and stakeholders. The presented results and comparison of MCDM methods indicate that they are not suitable for assessing sites that are relatively close to each other or adjacent at least using a set of criteria applied in those studies. This leads to the conclusion that the methodology from choosing the set of criteria through the application of the MCDM method is well suited for high-level maritime spatial development planning, so the very early stage where usually a policy-maker is involved, rather than an approach that could be implemented by developers and investors to assess site conditions and site potential in terms of energy yield and project risks.

Further research on site selection for floating wind farms should be focused on finding the objective methods of site selection and characterisation and a set of criteria that represent the developmental and operational challenges of a given technology. Furthermore, it should also reflect the industry expectations, best practices and standards. With the maturity of the technology, once more data is available the method shall be supplemented by the technical specifications of floating platforms supported by operational data. Future research will be conducted towards the economic aspects concerning the LCOE from floating offshore wind farms. The success and pace of implementation of this technology are strongly correlated with this factor.

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