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Multi-criteria selection of offshore wind farms: Case study for the Baltic States

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ABSTRACT

This paper presents a multi-criteria selection approach for offshore wind sites assessment. The proposed site selection framework takes into consideration the electricity network's operating security aspects, economic investment, operation costs and capacity performances relative to each potential site. The selection decision is made through Analytic Hierarchy Process (AHP), with an inherited flexibility that aims to allow end users to adjust the expected benefits accordingly to their respective and global priorities. The proposed site selection framework is implemented as an interactive case study for three Baltic States in the 2020 time horizon, based on real data and exhaustive power network models, taking into consideration the foreseen upgrades and network reinforcements. For each country the optimal offshore wind sites are assessed under multiple weight contribution scenarios, reflecting the characteristics of market design, regulatory aspects or renewable integration targets.

1. Introduction

The European Union (EU) has set ambitious goals with respect to energy and environmental impact, the renewable energy directive sets a target of reaching 20% of final energy consumption from renewable energy sources by 2020 (Official Journal of the European Union, 2009). The European Commission (EC), in their 2030 impact assessment for climate and energy policy framework, identified the need for renewable energy shares in the final energy consumption ranging from 25% to 27% in 2030 and from 30% to 51% in 2050, translated in the mid-term in a renewable electricity share between 43% and 47% in 2030 (European Commission, 2014). Considering these projections, at least 21% of the renewable shares is expected to be provided by wind power generation (European Commission, 2014). The total installed capacity in the EU has seen an increase of 3.8% compared to 2013 levels and 29.4% since 2000, representing a compound annual growth rate of 9.8% (THE EUROPEAN WIND ENERGY ASSOCIATION, 2015). On the other hand, the offshore installed capacity still accounts only for 7% of installed capacity in the EU,[1] median projection of new capacities in 2030 are mostly located in the Nordic and Baltic Seas with respectively 45 GW and 8 GW of total installed capacity (European Wind Energy Association, 2015).

Cavazzi and Dutton (2016) proposed a Geographical Information System (GIS) based tool for assessing the UK's offshore wind energy potential, the tool provide a stakeholder neutral evaluation considering economic factors such as the development cost, maintenance and production yield - derived from average wind speed. Atici et al. (2015), proposed an AHP based multiple criteria decision making for wind farms site selection, the proposed site selection methodology relies on two stages namely pre-elimination and evaluation of the remaining alternatives. Several criteria have been identified to reflect the interest of three stakeholders: investors, regulators and civil society - the identified criteria reflect mainly the financial impact in terms of connection costs and energy yield. Sánchez-Lozano et al. (2016), proposed a Fuzzy AHP to obtain weights relevance for the identified criteria consisting of the wind site distance to cities, power lines/substations, telecommunication infrastructures and energy yield based on average wind speed. The proposed approach had the advantage of processing both quantitative and qualitative criteria. Fetanat and Khorasaninejad (2015) proposed a hybrid multi-criteria decision making tool using fuzzy logic derived processes for offshore wind sites selection based on depth, environmental, technical resources and economic aspects. In fact, optimal selection of wind site projects has been extensively addressed in the literature, with the aim to identify the

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[1] The Wind Energy Association (EWEA) projects in their most conservative scenario the doubling of the installed capacity by 2014 (129GW) to 251GW in 2030, 66GW of which is offshore wind resulting in an expected 19% share of the EU electricity demand.

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Nomenclature

A	Wind turbine's blade swept area [m^2]
B'_s	Normalized Balancing criteria at a site s
c	Weibull function scale parameter
$C'g_s$	Normalized congestion criteria for the site s
$C'r_s$	Normalized correlation criteria at a site s
Cf'_s	Normalized capacity factor criteria at a site s
C_p	Wind turbine power coefficient
f_s	Wind speed Weibull distribution function for a site s
I'_s	Normalized investment cost criteria
k	Weibull function shape parameter
L_i	the load at the hour i within a control area
N	Number of points
NL_i	the net load at the hour i within a control area
OC_s	Cost objective at a site s
OP_s	Performance objective at a site s
OR_s	Reliability objective at a site s
P_C^{Sys}	Aggregated Contingency Overload
$Pmax_s$	Aggregated wind power generation at a site s
P_s	Aggregated wind power generation at a site s
Pw_i	the wind power generated at the hour i within a control area
R_s	Reliability criteria at the site s
$Tl_{j,k}$	Thermal limit of the line connecting the bus j to the bus k [MW]
T_s	Final score for the aggregated criteria at the site s
$\bar{u}$	Average measured wind speed
u_i	Wind speed measurement
u_r	Wind speed at a reference height z_r
v_m	Wind meridional velocity component
v_z	Wind zonal velocity component
V'_s	Normalized volatility criteria at the site s
W_{CB}	Weight adapting the balancing criteria
W_{CI}	Weight adapting the investment criteria
W_{PC}	Weight adapting the correlation criteria
W_{PCF}	Weight adapting the capacity factor criteria
W_{RC}	Weight adapting the Congestion criteria
W_{RV}	Weight adapting the Volatility criteria
z	Height of the estimated wind speed
z_r	Reference height for the measured wind speed
α	Atmospheric stability empirical factor
$\Delta Ld_{j,k}$	Overloading in % of line connecting the bus j to the bus k
μ	Wind speed expected mean value
ρ	Air density [kg/m^3]
σ_L	Load standard deviation
σ_{NL}	Net load standard deviation
σ_w	Wind power generation standard deviation.

most appropriate location for investment while considering mainly the benefits in term of energy yield, environmental impact and cost using GIS tools and techniques (Atici et al., 2015; Cavazzi and Dutton, 2016; Gorsevski et al., 2013; Latinopoulos and Kechagia, 2015; Lee et al., 2009; Mekonnen and Gorsevski, 2015; Sliz-Szkliniarz and Vogt, 2011; Van Haaren and Fthenakis, 2011).

It is clear that in order to reach the expected targets, within a reliable fully integrated EU electricity network, necessary infrastructure investment has to be foreseen, as well as the allocation of extra costs to mitigate the intermittency effect of such resources (i.e. ancillary services, network reinforcement, demand side management etc.). Against this background, it is critical for policy makers to take into consideration all the parameters affecting electricity networks operators, investors, utilities and consumers. This has to be achieved by capturing the interaction between the different actors and determining where capacity can be developed in the most cost-effective way.

While the economic aspect has been exhaustively assessed as a key factor for wind sites selection - reflecting mainly the producer surplus in term of energy yield and investment costs - the economic consumer surplus has not been adequately evaluated by considering the impact of a candidate project in term of subsequent operational expenditure (OPEX) cost. In fact, whereas a site can present optimum characteristics in term of energy yield or environmental impact, its integration at a certain network location can result in substantial higher OPEX costs to preserve the overall reliability and security of supply levels. In that perspective, the Transmission System Operators (TSO) shall be considered as a relevant stakeholder for a comprehensive evaluation taking into consideration the power system component in gauging the impact of each potential site in term of risks and operational costs.[2]

In this paper, we propose an Analytic Hierarchy Process (AHP) for the multi-criteria evaluation of offshore wind site prioritization. In addition to the performance evaluation (expected energy yield), the proposed approach takes into consideration the technical impact of the candidate wind sites in term of security of supply as well as integrated energy efficiency (demand and supply conjunction, balancing needs).

The proposed approach is applied for a case study in the Baltic Sea, using a transmission simulation model for the 2020 year horizon. In Section 2, we introduce the proposed general framework starting from the preselection phase which is based on a predefined set of GIS layers to identify a limited set of candidate sites. Once the preselection phase is defined, we introduce the AHP evaluation criteria, the corresponding calculation methods, as well as a pairwise comparison methodology to define their contribution to the prioritization process. Section 3, describes in detail the implementation of the proposed site selection framework for the three Baltic States. Finally, in the Section 3.5, we present the results for each Baltic State based on the pairwise comparison to illustrate the impact of the criteria weighting in the prioritization process.

2. Site selection framework

The proposed site selection framework aims to investigate in systemic approach the interrelationship of criteria affecting an optimal selection of offshore wind sites taking into consideration relevant decision maker's priorities and preferences which are aggregated to reach a consensus prioritization. Fig. 1 illustrates a high-level flowchart of the proposed site selection framework consisting in three main steps: prerequisite data processing (depends on the local characteristics therefore addressed in detail in the Section 3), pre-selection phase, and finally the sites evaluation and ranking. The pre-selection process aims to constrain the potential candidates list taking into consideration effective boundaries confined by territorial, regulatory or technological limitations. The proposed selection criteria are identified into three objectives: (i) Reliability objective: impact on the electricity network security of supply in term of congestions and volatility, (ii) Cost objective: impact in term of investment cost and balancing reserves (TSO OPEX), (iii) Performance: expected energy yield and the correlation of wind profile patterns with coincident load demand. The interrelationship and relevance of each of the defined criteria are evaluated based on pairwise comparison to derive priority scale taking into consideration all the stakeholder's perspectives. It is important to underline that the proposed framework aims to investigate a prerequi-

[2] Such costs could involve congestion management or balancing costs that are ultimately socialized in the final consumer tariffs, therefore affecting the customer surplus.