ICOE 2018 12 / 14 JUNE CHERBOURG FRANCE

Development of an iterative spatial assessment for regional grid connection for floating wave and wind energy arrays.

Thomas van Lanschot[#1], David Forehand[#2], Henry Jeffrey[#3]

Institute for Energy Systems, University of Edinburgh, West Mains Road, Edinburgh EH9 3JN, UK

[1]T.van-Lanschot@ed.ac.uk,

[2]D.Forehand@ed.ac.uk,

[3]henry.jeffrey@ed.ac.uk

***Abstract*- The offshore energy industry has long been dominated by fixed wind devices often located in shallower water. However, recently floating technologies in wind and wave energies have shown the commercial ability to operate in resource rich deeper more distant waters. The development in these fields is often ahead of policy, regulation and infrastructure. Previous studies often utilise spatial analytics to make assessments but often overlook grid requirements. In order to address this issue a series of spatial analytic and electrical power flow models have been established to form a novel assessment method. First an analytical hierarchical model was developed to identify possible. Second, clustering analysis was used to create a topology suitable for modelling needs. Finally the two models have been integrated in an optimal power flow dispatch model. It was found that sensitivity analysis was needed at each stage of the modelling process. However, it forms the basis of strategic development tool that could be used to highlight development impacts in multiple scenarios.**

***Keywords*-**Spatial Analytics, Site Selection, Power modelling, Cluster analysis

1. INTRODUCTION

In the last 20 years, offshore wind has developed into a valued part of the energy mix of countries around Europe. Recently a move away from fossil fuels due to climate change and security of supply issues has been increasing [1]. This move to localise more power generation within Europe has led to developments in wind and recently nascent wave energy. The previous developments for wave and wind were primarily focused on shallow water [2]. With large areas of wind and wave resources being located in deeper water, floating technologies have become more considered [3]. Due to these technologies being at the forefront of the state-of-the-art, regulation and infrastructure often lags behind. When regulators and government bodies issue site development leases, multi criteria site assessments must be made. Spatial analytics has been utilised extensively in the past to carry out such work. However, in national and international spheres, the complexities of integrating what site assessments highlight as attractive is often unfeasible due to grid restraints and are often over looked or considered a certainty. This problem is exacerbated when considering international cross border flow. Therefore pertinent questions include: How to identify sites with particular spatial requirements for these technologies and how estimates can be made for the development of electrical infrastructure in synergy.

Therefore it is the objective of this paper to establish a series of interlinked, tailored models based on the requirements of the technology. A spatial analytical model will highlight where the likely sites may be within the Exclusive economic zone (EEZ) of the Atlantic coast and North Sea. Due to large scale interconnection and large scale energy plans being on a pan-European scale modelling the European system is key.

A second spatial analytical model will aggregate the European transmission network and create a topology with regional clusters based on wave and wind energy (WWE) requirements. This topology will be used to establish the optimal power flow (OPF) for current and future scenarios. It is therefore by creating a model designed for the needs of WWE that the impact of grid infrastructure can be assessed on a national and international scale. This will aid in policy development but the work will also define for developers the viability of certain sites based on cost effective grid integrated large scale arrays. The models will focus in detail on the coastlines of: Portugal, Spain, France, Belgium, Germany, Denmark, Norway, Ireland and the UK. Nomenclature of territorial units for statistics (NUTS) economic territory regional level 1 polygons where used to represent the boundaries of study. With external European grid regions represented at national level. The 1 level representing the smallest granularity standard of socio economic regional research.

2. METHOD

A. Modelling process

A geographical information system (GIS) was used to perform spatial reductions in an analytical hierarchy process (AHP). A spatial clustering algorithm was used to group NUTS regions for the transmission network node points, lines and generation and demand data. This data feeds into power flow models solved in analytics software AIMMS. Figure 1 illustrates the modelling flow process. The dispatch OPF and topology iteration are greyed out as, although the model has been designed to function within this work, it has not been fully explored and results not yet established.

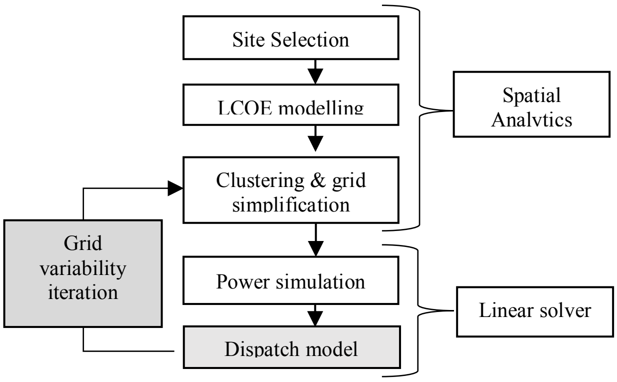

Figure 1 : Flow Chart of modelling approach.

B. Technology

The purpose of this work was not to appraise certain technologies but to focus on the key factors impacting site selection. However, the two elements are interlinked therefore the following reference technologies were chosen: Heaving plate wave energy converter rated at 1MW and a Spar buoy floating structure with a 6MW wind turbine.

C. Site Selection

Exclusion zones were removed entirely with a buffer of 500 m in accordance with regulations [6]. The zones include: Ferry routes, subsea pipes and cabling, offshore structure and geotechnical fault zones. Site restrictions considered to impact cost and feasible installation included: Depth. Slope and wave and wind resource parameters. Site sensitive factors can be dictated by government policy and are therefore carried through the modelling process. The site sensitive factors being, shipping and fishing density (scored 1–5) and environmentally sensitive zones (scored 1–5, representing a 0–50% percent infringement).

D. LCOE Modelling

A uniform mesh of cells based on array spacing was established. While known to be sensitive, wake affects between cells have not been included in the model, work is ongoing in this field. Resource characterisation was established from data [4] at a spatial resolution of 5km. As an approximation of resource, an annual average was estimated to calculate power and subsequent energy production per cell. The levelised cost of energy (LCOE) was established from a cell value for operational expenditure values (OPEX) and capital expenditure CAPEX based on assumptions from [11][5][6]. Distance and depth from the spatial model were used to approximate the installation, cabling, mooring CAPEX. The partial LCOE cell values were grouped in a spatial clustering analysis. Significant clusters of arrays where grouped. Then linked to shore to evaluate the final CAPEX value for connection was established as the cost per distance from site to the substation locations within coastal NUTS regions from open source SciGRID database. The cable is assumed DC due to the efficiency over distance [7].

E. Regional clustering

Due to the complexity in modelling the entire European transmission system and inherent computational problem it was decided to simplify a regional European grid. Regional Simplification being common practise methods as seen in [8] [9]. To reflect the requirements of WWE infrastructure placement granularity was kept at a coastal level. Regional clusters reduces the number of nodes, substations and generators, and links, transmission lines, connecting the system. A grouping analysis was performed to spatial resolve the clustering of NUTS polygons which is outlined in figure 2.

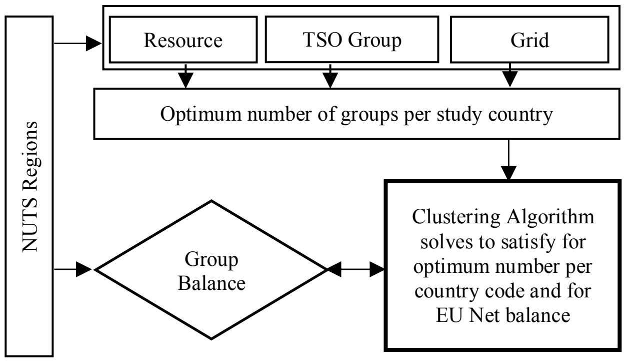

Figure 2: Algorithm process solving regional clustering

Resource bins were characterised as a radial distance of 400 km from a coastal connection point. Each bin represents the location and value of the regional mean value for wave and wind. Transmission system operation (TSO) groups within national networks represent the operators that govern transmission networks. This is included in order to ensure that the aggregation is representational. The grid connection uses SciGrid data to ensure that only regions with a link to the high voltage transmission network are included.

The demand values for the model were established from the NUTS regional distribution of a European population dataset from Eurostat and the European network transmission operator electricity (ENTSOE) groups demand data sets. Due to winter and summer fluctuations in electrical demand [10] mean seasonal values were established for 2016. Generation, type and capacity were established by combining the data sets of ENTSOE and Enipdeia, an open source electrical database, and geo locating each generation station over 10 MW capacity. The demand data and installed capacity were scaled to sub national values with a pre normalisation mean of 76% and 82% respectively. With a 92 % and 88 % representation post normalisation. Variation in values were found across regions due to difference data output.

The SciGRID cross region line data was cross referenced with the ENSTOE atlas to ensure a closer representation of actual line location. The ENTSOE future development plans were used to establish future generation, demand and topology scenarios for 2020 and 2030. Future topology in these time periods were digitised from under construction and approved projects for grid expansion and interconnection which could impact power flow. This is of high importance in this work as future developments in WWE also lie in these time frames.

The first clustering process was to establish the optimum number of groupings per study country relative to the input variables, resource, TSO group and grid connection. A spatial constrained grouping, Euclidean K-nearest neighbour, analysis was used with variable initialisation seeding location.

The 'regional transfer capacity' (RTC) in MW was established by approximating the Surge Impedance Loading (SIL). This value is an estimation of the MW loading on the lines in question. SIL was established from the following:

$$SIL\ (MW) = 0.927 * \left(\frac{kV^2}{Z_0}\right) \quad (1)$$

Where, *kV,* represents the transmission Line voltage rating from the SciGRID database, Z_0, the surge impedance on the line and cable inductance, L_c, by:

$$Z_0\left(\frac{\Omega}{\text{km}}\right) = \sqrt{\frac{\frac{L_C}{1000}}{C*10^{-6}}} \quad (2)$$

$$L_c(mH) = \frac{X_L}{2\pi f*1000} \quad (3)$$

Where, *f*, system operating frequency (Hz), is established from the national grid database. Inductive reactance, X_L, is established from the following:

$$X_L = \frac{2\pi f(0.1404*log_{10}\frac{\sqrt[3]{A*B*C}}{d}}{2\pi f*1000} * k * L \quad (4)$$

A, B and C represent a series of approximations on representative line configuration and dimension, d, diameter of the conductor, for the line type. A database of line configuration estimations from each national grid was established ranging from 220 kV to 700 kV. *L* (km) is the length of the section and *k* is the correction factor for installation type assumed as 1, the factor for air (overhead powerline installation). Capacitance, *C*, the ability for the line to carry charge was established as:

$$C\ (\mu f) = \frac{7.35*SIC}{log\frac{D}{d}} * \frac{L}{10^6} \quad (5)$$

Where SIC is the Dielectric constant of the cable insulation established from the database as another representative value. Diameter over the insulation, *D*, is also estimated from a representative value from the line configuration database.

After (RTC) based on SIL values the second clustering analysis was performed. It solves for two rules. One, the adjoining regional balance as RTC must be greater than the aggregated sum difference of demand not met by generation. Two, the cluster must stay as close to the national regional grouping values established. By solving for these two rules a reduced network is created representing the NUTS regional granularity favouring WWE requirements but also providing a balanced network.

F. Power flow Analysis

The purpose of the power flow analysis was to establish the viability of the aggregated system. Secondary analysis will indicate where space for new generation lies and to what extent curtailment will take place in offshore renewables. The model will also iterate across varying levels of LCOE inputs established as well as regional capacity. This will provide a basis for the spatial relevance of infrastructure upgrades within NUTS regions.

The initial power flow model simulates a hypothetical scenario for the new clustered system. This establishes the coherency of the network and where failure points lie within the grid due to conditional constraints of demand and line limits. The transmission network will then solve the dispatch problem. This model finds an optimal solution to an economic problem in an optimal power flow under electrical constraints. The OPF solves for the minimal 'cost' value for power generation dispatch. The term DC OPF is a linearized approximation for an AC OPF and not a DC power line representation. Within this approximation it is assumed that: line resistance is zero, the voltage magnitude is equal to the base voltage, phase voltage difference is minimal, and power is unimpaired across borders in a free flowing market. Links between nodes represent bidirectional flow and the nodal junction network system applies Kirchhoffs law within the application of the OPF theory. It is the principle that the sum of power generated at node x, and the total inflow into node x must equal the demand at x. This applies to all nodes within the system.

For the purposes of this work assumptions for cost values were made based on [11] as an approximate indication. It is the purpose of further work to run multiple simulations to improve model outcomes by using more local values as well as the availability of units which were assumed from [12]. At this stage the injection site outputs identified in the spatial model, LCOE and impact, will be included into the dispatch model. The availability of other 'green' renewable sources also factored into the dispatch model through a ranking system matched with their cost. It is here where the sensitivity of impact values carried through the analysis are evaluated as well as the levels of new WWE being accepted.

It is also within further work that variations from the clustering analysis will be assessed in the OPF model. This will allow for the comparative analysis of this method in regional NUTS level grid aggregation. Within this iteration the sensitivity of the reduction method can be represented in the overall dispatch OPF results.

3. RESULTS AND DISCUSSION

The research has highlighted the link between the spatial analytical components and the development of an aggregated grid model. A vast amount of work was required for data collection and processing. The results in this section are an indication of what the model could be used for. Figure 3 represents 3 sites identified by the model as theoretical injection tranches, the geo location of these represented in figure 4. It is apparent that the outcomes are sensitive to certain aspects, notably distance. Research is underway to improve on the evaluation of site related cost drivers.

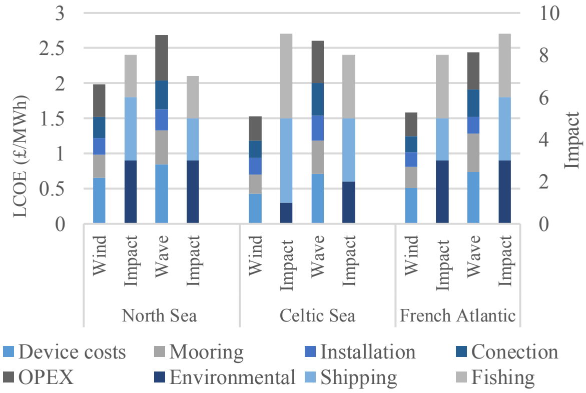

Figure 3: LCOE representative tranche output with impact scoring.

The scores carried through analysis also illustrate the impact high level marine policy can have on development. The spatial weightings of these can impact tranche scoring greatly and therefore sensitivity testing is underway to establish representative national values. The impact noted in the French Atlantic and the Celtic sea showed large impacts on fishing grounds for both wind and wave technology and it these considerations that would need to be tested in future. Further the wind and wave energy production estimates for the Celtic sea and the French Atlantic had significant impact on LCOE values when comparing the values against the North Sea which has greater access to port facilities and the grid. The comparative distance impact on OPEX which uses the same port fee values highlights the impact on scores across the 3 sites with difference access to facilities, the same can be said for connection CAPEX.

The grouping and cluster analysis results are represented in table 1. These values represent a grouping of data for 3 variables, resource, connectivity and TSO group but could be expanded to more. It was found that the difference between wave and wind resource on the topology as well as the optimal number of representative nodes was negligible. Therefore one topology was used in analysis. However, the standard deviation variability across counties showed a sensitivity for resource values and grid connection. Germany for example has a well-connected grid but low resource access therefore was clustered more uniformly to its TSO regions. Conversely the UK has a higher deviation due to high dispersion of resource and grid connection. The secondary balancing

	Primary analysis			Second Analysis		
Country	NUTS	n	Std. Dev.	Balance	n	Std. Dev.
NO	19	5	0.1	0.38	5	0.33
BE	11	4	0.56	0.25	2	0.38
DE	40	11	0.12	0.23	8	0.45
FR	96	14	0.39	0.15	13	0.24
GB	192	15	0.32	0.19	16	0.11
DK	14	4	0.15	0.14	3	0.22
NL	14	5	0.47	0.07	5	0.37
ES	47	14	0.26	0.04	10	0.19
PT	18	6	0.23	0.1	4	0.27
IE	26	8	0.28	0.48	4	0.25
Sum:	477	86			70	

Table 1: Summed national values for grouping primary analysis to identify the optimal number of groups and the reduced values for nodes (n) after grid balancing. Standard deviation in primary analysis represents the 3 input variables.

The nodal reduction from 477 to 86 was balanced to a final 70 which combined with the 20 external countries created a 90 node network connected with 324 connecting lines. This was used to solve the initial baseline, 2016 winter peak. A dispatch simulation for the input values solved for 3098 constraints with 2178 variables. The model first solves for thermal generation types identified with lower LCOE values. An initial model output is represented in figure 4.

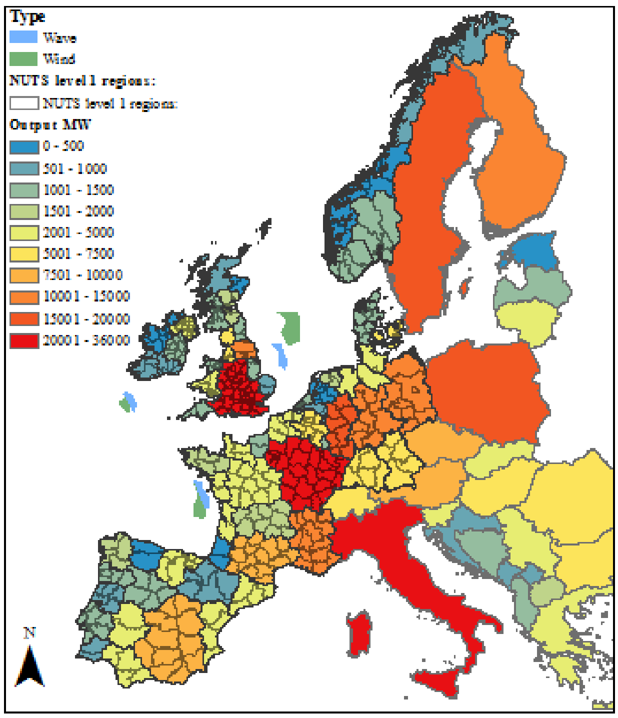

Figure 4: Distributed instant dispatch across the study zone. Granularity in NUTS zones demonstrates the regional simplification. The LCOE test case sites are included as reference however they did not factor into the dispatch model.

As can be seen in figure 3 the levels of power produced by the Italian and eastern European countries are relatively high. This is due to large levels of thermal generation capability. The south of England contains the densest distribution of power generation in the UK, this also corresponds with the high generation capability and immediate high local loading. Although just an indication of results, the visualisation of Figure 3 highlights the uses the model can have in spatial analytics. The location of the LCOE tranches highlight potential links to NUTS regions that could host increased capacity.

Direct comparison with the historic outputs found from the ENTSOE database will be used in future to develop the iterative correlation parameter. This will allow for analysis on the impact regional clustering has had on the grid network. However, it is pertinent to note that many factors, including; political pressure, costing parameters and variability of availability have great influence on this type of modelling. Due to this sensitivity the model outputs were not intended for a direct comparison. However, it suggests a theoretical system for Europe.

4. CONCLUSION

The work conducted in this paper achieved the following objectives. First, develop a spatial analytics database and AHP process to identify possible sites for floating offshore wind and wave arrays. Second, to develop a clustering analysis based on electrical grid regional simplification methods tailored to the needs of the technology. Third to integrate the two model outputs in an OPF dispatch model using the reduced grid topology. Finally the model was used to test the topology but not run the full OPF dispatch.

It was established at each level of modelling that sensitivity would need to be evaluated prior to the OPF dispatch outputs could be used as a valid comparison. Further to this the LCOE evaluation must be expanded to reduce estimates in calculations based on distance and depth.

The model will in future highlight the potential for floating array injection levels and locations on a near term, 2020 and longer term, 2030, basis. In order to satisfy the development of arrays a key feature of the work revolved around NUTS regions and transmission infrastructure within them. The work highlighted how regional clustering would reflect the needs of the technology with regards to infrastructure. In modelling this the location of array curtailment due to constraints will be highlighted and the impact of upgrades established to demonstrate the need for partnered development.

REFERENCES

[1] A. Stegman, A. De Andres, H. Jeffrey, L. Johanning, and S. Bradley, "Exploring Marine Energy Potential in the UK Using a Whole Systems Modelling Approach," 2017.

[2] WindEurope, "The European offshore wind industry," *Key trends Stat. 2016*, no. January, p. 33, 2017.

[3] European Wind Energy Association, *Deep water*, no. July. 2013.

[4] C. Kalogeri, G. Galanis, C. Spyrou, D. Diamantis, F. Baladima, M. Koukoula, and G. Kallos, "Assessing the European offshore wind and wave energy resource for combined exploitation," *Renew. Energy*, vol. 101, pp. 244–264, 2017.

[5] A. Myhr, C. Bjerkseter, A. Ågotnes, and T. A. Nygaard, "Levelised cost of energy for offshore floating wind turbines in a life cycle perspective," *Renew. Energy*, vol. 66, pp. 714–728, 2014.

[6] S. Cavazzi and A. G. Dutton, "An Offshore Wind Energy Geographic Information System (OWE-GIS) for assessment of the UK's offshore wind energy potential," *Renew. Energy*, vol. 87, pp. 212–228, 2016.

[7] Red Penguin Associated Ltd, "Submarine cables and offshore renewable energy installations: Proximity study," p. 100, 2012.

[8] T. Anderski, Y. Surmann, P. V. A. N. Roy, and T. Anderski, "Modular Development Plan of the Pan-European Transmission," 2014.

[9] A. Seack, J. Schwippe, U. Häger, and D. Panasetsky, "Load Flow and Dynamic Model," 2014.

[10] D. J. Brayshaw, H. E. Thornton, A. A. Scaife, B. J. Hoskins, and D. J. Brayshaw, "The relationship between wind power , electricity demand and winter weather patterns in Great Britain The relationship between wind power , electricity demand and winter weather patterns in Great Britain."

[11] Fraunhofer, "Electricity Costs of Energy Intensive Industries An International Comparison Electricity Costs of Energy Intensive Industries An International Comparison."

[12] G. Doucet, "Performance of Generating Plant : Managing the Changes," 2007.