



# A Sustainability Index of potential co-location of offshore wind farms and open water aquaculture



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## ABSTRACT

This paper presents the definition of a Sustainability Index for the co-location in marine areas of offshore wind farms and aquaculture plans. The development of the index is focused on the application of MCE technique based on physical constraints and biological parameters that are directly linked to the primary production. The relevant physical factors considered are wind velocity and depth range (which directly governs the choice of the site for energy production and for offshore technology), the relevant biological parameters are SST, SST anomaly and CHL-a concentration (as a measurement of the productivity). The further development of the technique, already used in open water aquaculture localization, consists in converting raw data into sustainability scores, which have been combined using additive models, in order to define the overall sustainability. The study area used to implement the computation of the Sustainability Index (SI) was identified in the Danish portion of the Baltic Sea and in the western part of the Danish North Sea. Results on the spatial distribution of the SI underline different responses as a function of the physical and biological main influencing parameters.

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## 1. Introduction

Offshore wind farms allow for increased availability of wind power and wind persistence, as well as lower visual impact of the turbines (EWEA, 2009). Compared to onshore wind, offshore wind farms are more costly to install and maintain but also have a number of key advantages: stronger and more stable wind; larger wind turbines; less conflict with neighbouring citizens and other stakeholders unless they interfere with competing maritime activities or impact negatively on important marine environmental interests (Bilgili et al., 2011). Moreover, enhanced current velocity due to the presence of the piles and to the air fluxes of the turbines may increase the environmental sustainability of aquaculture plans in these areas (Moland et al., 2013).

On the other hand, the expansion of the offshore wind industries in recent years is likely to result in high spatial competition (Buck et al., 2008; Mee, 2006). The focus for co-location has inevitably been on wind farms and aquaculture as these activities has

some common traits and possible synergies. They both claim large areas at sea in relatively shallow areas, have restrictions for other types of activities (e.g. ship traffic and fishing) and have logistics and infrastructures that to some degree can benefit from a co-use (Benassai et al., 2011). Furthermore, they may provide an alternative livelihood for fishermen faced with losing their traditional fishing grounds (Michler-Cieluk and Krause, 2008).

The advantage of moving aquaculture further away from coastal waters consists in an enhanced water quality. Open ocean waters are in general less exposed to anthropogenic impacts and might provide a continuous supply of clean water having satisfactory levels of dissolved oxygen and less pollutants like pesticides and near-surface agents (Buck, 2004). On the other hand, significant alterations to the technologies may be required, e.g., to the turbine foundations to withstand the additional mechanical load of aquaculture equipment. In addition, open ocean hydrodynamic conditions can represent further challenges for aquaculture infrastructures and require resistant species that can withstand strong currents and large wave heights.

The identification of sustainable aquaculture sites among those already devoted to offshore wind farms requires therefore a deep knowledge of the marine environment in view of the mooring optimization (Benassai et al., 2014) as well as an understanding of the numerous conflicting uses and constraints (Longdill et al.,

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2008). The spatial decision making process begins with the recognition and definition of the problem, e.g., identifying suitable and sustainable sites for the open coastal culture of shellfish. Once defined, the Multi-Criteria Evaluation (MCE) technique (Nath et al., 2000), focuses on specifying, creating and aggregating comprehensive sets of evaluation criteria.

The development of the technique, already used in open water aquaculture localization (Longdill et al., 2008), consists in converting raw data of physical and biological parameters into sustainability scores, combined using additive models, in order to define the overall sustainability.

In order to overcome the complications arising from the variety of scales and units involved, the MCE technique requires each criterion to be transformed to comparable units (Longdill et al., 2008). Data are generally converted to standardised sustainability scores (normalised values between 0 and 1) through the use of Parameter Specific Sustainability Functions (PSSFs) (Vincenzi et al., 2006).

In Denmark several sites were used or planned to be used for offshore wind farms installations (Stenberg et al., 2010). In this paper we have computed a spatial distribution of the SI, and then we have verified if some of those sites appear to be suitable locations for a multi-use purpose combining wind energy and aquaculture activities.

The paper is structured as follows: in Section 2, the factors influencing the sustainability of offshore aquaculture are described; in Section 3 the analytic framework of MCE and of PSSF is presented, while in Section 4 the study area and data source are illustrated. Finally, the experimental results and the discussion are given in Sections 5 and 6, together with some conclusions on the robustness and the limits of the method in Section 7.

## 2. Factors influencing the sustainability of aquaculture in offshore wind farms installations

The first step of the MCE technique is the identification of the relevant factors influencing aquaculture sustainability, among them the main physical and biological factors are wind velocity and persistence, current velocity as a function of water depth, depth range (which directly governs the choice of offshore technology) and both SST and SST anomaly, dissolved oxygen, CHL-a concentration, (which govern the productivity).

The wind climate information is the most important part of the data base. The wind speed has to be related to the rated power of the wind mill, which is reported in Fig. 1 for a 3.6 MW turbine, particularly suited for offshore sites. It is noted that the majority of the power percentage is obtained for a wind speed range between 8 and 14 m/s.

The sensitivity of the economic performance of the wind farm to reliable wind speed data claims for precise wind measurement. The

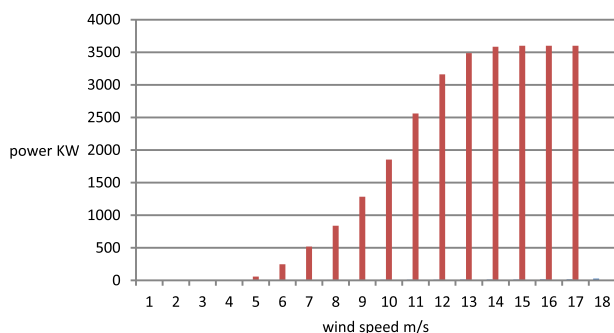


Fig. 1. Rated power of turbine as a function of the wind speed.

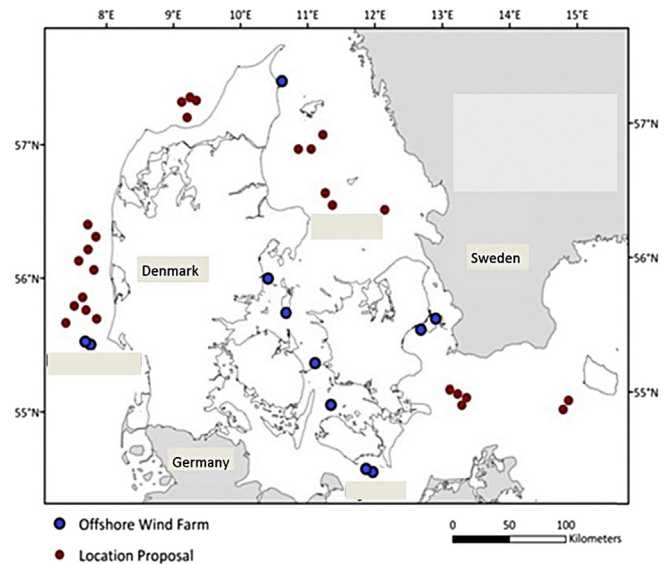


Fig. 2. Distribution of offshore wind farms (red = operational/blue = proposed) in Denmark. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

approach followed in this paper is the use of real measured data, which is obtained by remote sensing techniques.

Current speed is another important parameter, because increased current speed can act to decrease flushing times through aquaculture developments, thus enabling the support of denser populations than if water exchange was more limited. Further, several authors have correlated bivalve growth directly to current speeds (Longdill et al., 2008).

The depth range is crucial for offshore wind farm installations, because of the robustness and economy of the monopile solution, which is suitable for depths not higher than 30–40 m. For higher depths, the structures are totally different and much more expensive. So the most important factor influencing the feasibility of an offshore wind farm is the favourable depth condition (lower than 40 m).

Optimal sites for a sustainable offshore aquaculture are characterized by conditions leading to relatively enhanced growth rates, which are largely controlled by food availability and phytoplankton dynamics (Winter, 1978; Soniat and Ray, 1985). Several studies have identified strong direct linkage ( $R^2 = 0.77$ ) between upwelling indices and cultured shellfish production and quality (Espinosa-Carreón et al., 2004). In fact upwelling typically provides a rich source of nutrients to enhance phytoplankton growth and large volumes of shellfish are cultured in areas of high phytoplankton concentrations.

An upwelling index, associated to high productivity areas, is considered an increase in sea surface CHL-a concentrations (Valavanis et al., 2004). In fact areas with high CHL-a concentrations are associated with an increase of available nutrients to photo-synthesisers. The oceanographic processes such as upwelling, gyres or eddies, which can transport cold, nutrient-rich water from below the pycnocline to the euphotic zone where photosynthesis of autotrophs organisms takes place are typically associated with low SSTs. The spatial integration of normalized SST and CHL-a anomalies indicates areas of productive processes such as upwelling, gyres, etc. (Valavanis et al., 2004). The use of climatological (long-term) datasets allow the identification of persistently productive regions, independent of short-term variability.

Coastal monthly mean SSTs were obtained for each coastal segment as the mean temperature of the entire coastal segment

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