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(Review Article)

Integrating Aquaculture Production with Offshore Energy: The Role of GIS Innovation and Marine Spatial Planning (MSP)

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Abstract

Globally, growing human activity in coastal and offshore waterways has led to increasingly complex disputes between many industries vying for ocean resources, including space, use, and conservation. Advocates of aquaculture consider mainly the biological and technical feasibility of potential offshore locations, as well as their economic consequences. Marine Spatial Planning has also been promoted as a way of attaining ecosystem-based management of water spaces. Multi-use and industry-specific planners are predominantly relying on spatially referenced datasets, GIS-related aids to analysis, and the Decision Support Systems to have alternatives analyzed and to balance cost and benefit implications. The exploration of the possibility of co-locating wind farms and aquaculture facilities rewards that the shrinking of the cumulative human footprint in sea areas is a feasible path. It simultaneously creates the issue of economic synergies between the production of renewable energy and aquaculture, which, in turn, requires strict analysis and strategic planning. This form of integration will overcome the hurdles facing the two industries and will at the same time provide clean energy and sea food for the country in an environment-sustainable way.

Keywords: Marine Spatial Planning; Offshore Wind Energy; Offshore Aquaculture; Geographic Information System; Decision Support Systems; Co-location strategies

1 Introduction

The use of technological changes in aquaculture has made the production of high-in-premium, nutrient-rich sea food easy to grow in coastal and offshore areas. The advantages of these changes include the possibility of developing aquaculture, increasing the production of proteins, reducing human hostility, and decreasing the risks of being exposed to pollution on land. Increasing demand on American-made seafood and changes in technology in the field of open-ocean farming contribute to the resulting benefits (Riley et al., 2021). The new strategy is seafood production, which is between sustainable aquaculture and renewable energy. This idea also implies the provision of a strategic interconnection of offshore energy infrastructure and facilities of seafood manufacture to create synergies that would help overcome the environmental challenges, enhance the economic growth, and help to create a more sustainable future (Pace et al., 2023).

Aquaculture in the Gulf Coastal Plain (GCP) plays an essential role in the economic and social welfare of the coastal areas for aquacultural conservation, coastal intelligence, and coastal resilience (De Meulder & Shannon, 2018). Oyster production depends on selecting the appropriate aquaculture areas to ensure sustainability and richness. Sustainable metrics have improved technology, policy, management, and responsible siting through innovative spatial modeling and artificial intelligence techniques (Wang et al., 2021). The population of the world is growing; more than 40 percent of people inhabiting it are less than 100 km away from the coasts of the world (United Nations, 2017). The Global Coastal Population (GCP) is particularly exposed to the increased threats of extreme events such as floods and droughts capable of modifying the hydrological processes and posing more profound uncertainties to ecosystem services (Talbot et al.

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2018; Woodward et al. 2016). It is expected that the future climatic conditions of this region will differ significantly with the historical patterns. Extreme conditions can have significant effects, but their magnitude cannot yet be determined. Heavy fishing on wild fish populations, along with the increasing global demand for aquatic products, highlights the possible importance of the offshore aquaculture production as the key food security provider (Einarsson and Óladotir, 2020). This is an alternative solution that can ease the strains on wild stocks and is a viable solution to meet the increasing demands of the increasing population.

However, to maximize the implementation of these promises and achieve long-term feasibility of production, special attention should be paid to some key issues. It is imperative to balance this obligation with sustainable water-management activities and mitigation of climate change to prevent degradation of the environment and competition of other industries with water resources that are limited (Sahoo and Goswami, 2024). Offshore aquaculture involves complicated operations in distant marine settings, where the technical innovations are critical to sustainability and productivity increase.

The realization that our seas can function as a multipurpose resource to suit various requirements is at the core of this investigation. It is imperative that offshore energy, whether from wind, solar, or other renewable sources, replace conventional, environmentally taxing energy generation (Osman et al., 2023). The benefit of having wind turbines or solar panels close to the aquaculture sites is twofold. To begin with, the turbines utilize clean energy that can service the world and reduce the consumption of fossil fuels (Holmane, 2024). Second, the energy platforms allow a fish and shellfish farm to thrive in the water beneath the energy platforms. The most developed and the tested type of ocean power is wind energy. There is already technology available that can serve the two industries, and most people believe that ensuring our food and energy supply is a national priority.

Marine spatial planning (MSP) is one of the methodological approaches that supports the idea of ecosystem-based marine governance, which aims to balance various goals in an integrated approach (Winslow, 2023). This paradigm shift makes the implementation of spatially referenced data, Geographic Information System (GIS)-based analysis platforms, and Decision Support System (DSS) indispensable, and the point of GIS development cannot be overstated in the evaluation of the co-location prospects of offshore energy and aquaculture facilities. In compliance with the potential benefits of reducing the anthropogenic footprint of the aggregates in the marine environment, MSP proposes an extensive analysis of the site features, the possible conflicts, and structural or functional synergies (Hosseinzadeh et al., 2023). Future research proposed would assess the practicality of the co-location of renewable energy generation plants and sustainable aquaculture within the Gulf of Mexico.

2 Reconciling Ocean Uses Through Marine Spatial Planning (MSP)

The offshore aquaculture industry has existed globally as a commercial and experimental enterprise over two decades and is notably active in Mexico, Australia, the United States, Puerto Rico, and Japan (Lester et al., 2018; Naylor et al., 2021). The marine environmental challenges have become increasingly complex over the past decades. Meanwhile, the relationships among energy production, resource use, security, fishing, and conservation present a complex nexus of interests; hence, a more coordinated and integrated policy is required (Stelzenmuller et al., 2017).

Co-location of offshore energy production with marine food production represents a paradigm shift toward sustainable utilization of the marine space, where future large regions of blue waters may be transformed into multifunctional platforms. These platforms would not only enhance energy security but also support aquaculture production (Braun, 2020). The realization of the negative environmental impacts of conventional sources, which have become more evident in recent years, has initiated a global transition to cleaner energy sources (Omer, 2008; Saleh and Hassan, 2024). Meanwhile, overfishing, habitat destruction, and biodiversity loss in marine ecosystems have increasingly drawn scrutiny to the seafood.

Moreover, the coastal areas are now monitored using aerial and satellite imagery, enabling the detection of illegal or environmentally harmful activities. Sound recordings are analyzed using artificial intelligence (AI) to monitor marine life, while spatial data on marine conservation are tracked through AI-integrated Geographic Information Systems (GISs) (Bakker, 2022).

Applications of such decision-making techniques as multicriteria decision analysis (MCA) have also been reported (Tahri et al., 2021l; Voskamp et al., 2023). MCA assists in balancing unequal protection objectives, including the protection of non-target species and entire ecosystems. Consumer activism has enhanced sustainable practices by encouraging technological innovation, effective governance, improved management, and responsible site selection, achieved through the adoption of advanced spatial-modeling methods.

Geographic Information Systems (GIS) are a key tool to analyze the availability of aquaculture sites, since they combine relevant spatial data, enables a systematic examination, and generates cartographic products that influence the policies (Ghobadi et al., 2021; Bandira et al., 2021). Moreover, GIS is essential in demarcating and mapping Areas of Interest (AOI) and in demarcating species-specific permitting procedures regarding aquaculture (Bakker, 2022).

Additionally, ecosystem-based aquaculture requires the ability to introduce the strategies of Marine Spatial Planning (MSP), that delivers equal sovereignty in resource utilization and facilitates the incorporation of environmental features into the planning apparatus (Riley et al., 2021). The unique aspect of MSP is its integrative capacity that allows coordinating the spatial and time dimension of various maritime operations in a single decision-making process.The objectives of MSP are to simplify the process of spatial and resource distribution with the help of mapping marine zones and allocating the necessary tasks according to ecological, social, and economic standards (Gambino et al., 2024).

The shift of MSP as an ad-hoc initiative to a statutory framework is a significant step to the strategic management of marine spaces (Rafael et al., 2024). The trend here can be seen to be more strategic ocean planning and incorporation of new ideas like offshore co-location. In turn, MSP is no longer an experimental or voluntary project but a part of the governance structures that are intended to control and coordinate human activities in the seas (Zuidema and Faaiz, 2020).

3 Potential Benefits of MSP to Aquaculture

The idea of spatial configuration as the primary defining factor of green aquaculture changes in non-traditional, ad-hoc operational schemes began to gain traction (Agúndez et al., 2022; Engle and van Senten, 2022). Marine Spatial Planning (MSP) plays a crucial role in conserving the marine ecosystem because it allows the introduction of evidence-based decision making, resource management, and governance of the ecosystem. The combination of machine-learning methods with Multi-Criteria Evaluation (MCE) frameworks grounded in Geographic Information Systems will enable the planners and policymakers to create data-driven and sustainable approaches to the ocean-area utilization (Aspen, N., 2022; Gambino et al., 2024).

The fisheries and aquaculture stakeholders in the process of Marine Spatial Planning (MSP) have been on the journey of reluctance and involvement in the process, as a reflection of increased benefits of strategic spatial governance in these sectors (Gee and Mikkelsen, 2023). The future development goals include the development of large offshore facilities in combination with offshore wind farms. The niche production industry like sturgeon rearing, feed production, nutrient removal, and bioenergy production using micro- and macroalgal growth are the spheres where MSP can have a decisive and beneficial effect (V. Stelzenmuller et al., 2017).

With the diversification of marine activities and the extending of the operations of aquaculture activities to new geographic areas, MSP will become an inseparable instrument of establishing the harmonization of the conflicting interests, of maximizing the spatial distribution, and of ensuring the long-term sustainability of new aquaculture activities.

4 Potential Benefits of MSP to Offshore Energy

Renewable energy minimizes greenhouse gas (GHG) emissions significantly, and mitigates the effects of climate change (Suman, 2021). As the planet has shifted to the low-carbon energy mix, offshore wind energy has become one of the highest priorities, with vast and steady wind sources offered in open oceans taking the energy sector to higher levels of sustainability (Gusatu et al., 2020). The strong potential of power generation in the offshore wind is due to the long-term and continuous exposure of wind conditions that are common to the offshore environments, and thus the offshore wind can be a compelling proposal to address the large electricity demand that is being registered globally.

The implementation of offshore wind system has therefore emerged as a key factor in augmenting the rising energy needs, at the same time helping in cutting climate change shortcomings and lessening reliance on fossil fuels (Shields et al., 2023).

Offshore wind energy is an intersection of innovativeness, strength, and capability. It surpasses the traditional fixed installations and makes use of floating turbines that are deployed in efficient locations around load centers in the coast to maximize the energy-capturing and delivery efficiency (Hassan et al., 2024).

Marine Spatial Planning (MSP) is an appropriate model of effective management of offshore resources. There is a need to integrate MSP in the current offshore renewable energy industry and in wind and other offshore based power systems to realize full potential of renewable solutions and reduce environmental and space conflicts. Transparent and inclusive discussions form the foundation of effective marine resource governance, particularly when reconciling environmental priorities with industrial development goals.

In co-location initiatives, such as the integration of offshore aquaculture and wind farms, potential spatial conflicts may arise with existing industries (Stelzenmuller et al., 2021). However, open stakeholder engagement promotes collaboration and ensures that MSP strategies are designed to balance conservation objectives with the needs of offshore energy development (García et al., 2021).

Despite the growing number of offshore wind farm projects and rising investment in the U.S. offshore wind industry, the current installed capacity remains limited (approximately 30 MW). There is, therefore, a pressing need to assess existing offshore wind resources and forecast future changes, as substantial growth is expected within the next decade (Costoya et al., 2020). The global ambition to achieve 100% clean and renewable energy, as outlined in the United Nations 2030 Agenda for Sustainable Development, places offshore wind energy at the heart of the future green energy landscape (Beiter et al., 2016).

The U.S. National Renewable Energy Laboratory (NREL), under the Department of Energy (DOE), has published several offshore wind resource assessments across U.S. territorial waters. Additionally, numerous academic studies have examined the potential of U.S. offshore wind energy using various wind speed datasets (Wang et al., 2019). Wind power potentialities directly belong to wind speed, where even slight alterations in the circulation or strength may highly impact estimated output of the energy (Wang and Liu, 2021). Wind power, thus, can be regarded as essential in reducing climate change yet it is subject to the change in climatic conditions (Moradian et al., 2024). Other transfers of wind movements besides the mean wind velocity consist of turbulence, the vertical shear, and their directional stability, which influence the productivity and dependability of the offshore wind power generation (Carvalho et al., 2017).

5 Decision Support Systems for Aquaculture Siting and Offshore Energy Siting

Marine Spatial Planning (MSP) is a vital system of marine governance, which rests on the need to balance the environmental, economic and social goals. It is a paradigm shift that needs to incorporate spatially referenced information, Geographic Information System (GIS)-based tools to analyze as well as Decision Support Systems (DSS) to support evidence-based making decisions as well as strategic ones (Ocón, 2023). The processing and management of spatial data are generally performed in the GIS platforms where the various data sets are resolved into the integration of common analytical processes (Stelzenmuller et al., 2012).

MSP accommodates the connections between the offshore energy systems and the aquaculture, therefore creating an active interface that informs strategic decision making with reference to sustainable maritime development. Alternative planning scenarios are indispensable and introduced to the planners and decision affair assistants when developing the MSP as spatial data layers provide the opportunity to query, calculate as well as visualize the alternative planning scenario (Stelzenmuller et al., 2012; Vaitis et al., 2022).

Over time, when the pressures on marine environments continue to rise, MSP is a top technology used to enhance ecosystem-driven practices of marine management (Depellegrin et al., 2021; Ocón, 2023). The implementation of the Decision Support Systems supports this paradigm shift with multidimensional and systematic interventions to eliminate the complexity characteristic of the aquaculture and offshore energy initiatives (Drennan, 2020).

The selection of appropriate sites of such projects is beyond the physical, chemical, and biological factors, the political, economic, and social variables are becoming incredibly dominant, which makes the decision-making process more complex by nature (Ntona and Schroder, 2020).

DSS in MSP are represented by the photosynthesis of the variety of software packages and sophisticated frameworks of analytical tools, which include variables associated with ecosystem services and the conditions related to stakeholders (Aporta et al., 2020; Depellegrin et al., 2021). This ability highlights the importance of DSS tools in explaining the complex units of interdependence existing in the marine systems.

Since there are numerous types of DSS tools, it is possible to distinguish at least four major classes: 1) data-based, 2) model-based, 3) knowledge-based, 4) communication-oriented systems (Aporta et al., 2020). In combination, the tools are instrumental in breaking down the intricacies of the MSP, knowing opportunities and limitations, outlining the economic and environmental worth of marine actions in the maritime areas. Therefore, DSS is an indispensable part of comprehensive ocean management and sustainable distribution of resources.

5.1 Integration of DSS into GIS-Based System:

The integration of Decision Support Systems (DSS) into Geographic Information System (GIS)-based framework is a fundamental progressive milestone enabling the enhancement of aquaculture sustainability and the offshore energy production (Shaginimol et al., 2020). The stream of integration facilitates process of spatial based decision making to the extent that it allows the concurrent review of numerous environmental variables, economic variables, and social variables through a single framework of computation.

Spatial analytical tools such as suitability models are used to identify and rank the possible sites according to stipulated criteria regarding environmental and operational suitability. These models are important in the decision-making process in relation to the positioning of the aquaculture and marine energy infrastructure. GIS suitability modeling is one of the most used applications of DSS in this sphere According to which it is possible to systematically assess the potential sites of aquaculture use via the method of overlaying, spatial weight, and scenario analysis.

The dominant paradigm of a methodology followed at Food and Agriculture Organization (FAO) is a continuation of the initial applications of GIS and remote sensing presented in the mid-1980s, which were among the first attempts of utilizing generalized spatial analysis in the selection of aquaculture sites (Stelzenmuller et al., 2017). These antecedent models form the basis on which modern technologies of spatial decision-making are based, technologies which currently encompass DSS algorithms, predictive models and stakeholder-oriented evaluations to maximize ecological sustainability, together with production efficiency.

5.2 Combining Offshore Wind Energy and Aquaculture

The spatial relations between offshore wind energy plants and aquaculture activities have gained growing academic interest, which can be explained by the growing dearth of traditional natural resources and the rise of competition in the ocean-space. In New England and the larger United States, there has been efforts to redefine the industrial synergies in generation of electricity and fish production (Hopkins et al., 2021; Langan, 2009). This situation has consequently made the process of assessing the viability and practicability of co-locating fish and shellfish farms close to offshore wind turbines a new area of interest in sustainable marine resource management.

Advocates of co-location believe that co-location of the aquaculture systems with the wind farms would ensure that the cumulative human impact on the marine environment is minimized through space conflicts and use of ocean-space. Nevertheless, opponents point out that duplicate regulation systems, jurisdictional confusion, and lengthy permitting processes complicate such integration so much that it is difficult to effectively put it into practice. Therefore, to support evidence-based marine spatial planning, the technical, environmental, and socio-economic parameters that affect co-location should be evaluated in depth (Stockbridge et al., 2025).

To ascertain the benefits or viability of co-location of wind farms and aquaculture plants, there is a need to use multi-criteria analysis which would cross-reference spatial, operational as well as environmental characteristics of the two industries. Indicatively, wind farms, as well as mussel aquaculture locations need to be located close to other infrastructure facilities on land, including mussel markets, and transportation hubs (Paulson, 2022). Other physical variables such as water level, wave regime, tidal flow, and substrate of the bottom area, should also have the same environment to facilitate operational safety and sustainability (Stelzenmuller et al., 2017). Comparison of these parameters will enable the planners to identify feasible areas to integrate and evaluate the technological feasibility of combined offshore operations.

Other than the physical and economic factors, the co-location debate is also influenced by ethical and social factors. According to Malcorps et al. (2021), the growth of open-ocean aquaculture poses challenging questions of food equity and environmental justice all over the globe. Most of the seafood eaten in Western countries is imported, and most of their production is exported domestically (Harrison et al., 2023). The imbalance comes at the cost of further pressure on the developing countries that rely on aquaculture, with industrialization, pollution, and loss of habitats threatening food security even before (Naylor et al., 2021a). It is in this light that industrialized countries have a moral duty to come up with sustainable offshore aquaculture infrastructures that will enhance the production of food locally besides averting overreliance in ecologically prone areas.

At the same time, the ongoing use of fossil fuels as the energy source further contributes to the vulnerability of the climate and marine life ecosystem. The future implementation of renewable energy infrastructures within the aquaculture sectors can be considered a part of the broader change of the blue economy, during which the maritime industries will conform to the environmental sustainability and economic circularity purpose (Buck and Langan 2017). Integration is a good example of a substantive movement toward a more sustainable and fairer exploitation of marine resources.

6 Conclusions and Future Needs

Offshore energy production co-location of aquaculture is a possible solution to socio-economic and environmental issues witnessed in the Gulf of Mexico. This paper highlights the importance of Geographic Information Systems (GIS), GIS-based decision support system (DSS), and Marine Spatial Planning (MSP) in ensuring solutions to these issues. The document also expounds on the value of thorough study and implementation of DSS and GIS response tools to determine suitability of co-location keeping in mind environmental sustainability and economies of scale. The authors assume that MSP should be part of the decision-making process, thus reducing the anthropogenic effects, overcoming the spatial competition in the marine resources, as well as aligning business activities with the aims of marine ecosystems.

In this section, the possible advantages of MSP are outlined, and a strategic framework suggested that will improve the spatial allocation of co-sited offshore energy and aquaculture development to create an environment of sustained sustainability in the long term.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict-of-interest to be disclosed.

Author Contributions

The author only prepared this manuscript and is entirely accountable to its content.

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