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Qualitative modeling for representing the social-ecological system of the Groix–Belle-île offshore wind farm project

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Abstract

The increasing numbers of offshore wind farm (OWF) projects question the impacts of such infrastructures on the social-ecological system (SES) in which they are to be constructed. Some answers can be given using qualitative modeling and loop analysis. We used participatory modeling to co-construct a qualitative model of the socio-ecosystem together with stakeholders of the APPEAL project. The goal of the project was to evaluate the potential impacts of the pilot OWF in the Groix–Belle-île region. Then, loop analysis was used to study the characteristics of the SES created by the setting-up of an OWF. We focused on the impacts of SES variables on each other by evaluating their effects through direct and indirect pathways. Pleasure boating appeared as one of the SES components prone to suffer from the OWF construction, whereas industrial tourism was likely to benefit from it. This article presents the methodology used to obtain such results, for it to be used in spatial planning or in citizen-science processes.

Keywords: loop analysis; participatory modeling; sensitivity analysis; qualitative modeling

Introduction

Anthropogenic development and environmental protection are often conflicting (Vitousek et al. 1997, Rands et al. 2010): humans are constantly expanding their activities and living spaces, so that wildlife and humans interact in more and more territories, and it is essential to evaluate the impacts of such expansion. To do so, research is developing to better understand the dynamics of the relationships between humans and the natural environment (Ostrӧm 2009). This field of research studies social-ecological systems (SESs) (Berkes and Folke 1998, Olsson et al. 2014). It sees human and non-human systems as one entity, with balanced human and non-human variables composing it. The social and ecological subsystems are taken as one complex entity characterized by intertwined dynamics and feedbacks (Lansing 2003).

Marine SESs act as catalysts for debates between advocates of anthropogenic activities and ecosystem protection because they are highly complex. One example is the development of offshore wind farms (OWFs). In 1991, the world's first offshore wind turbine was built in Denmark, and this new type of energy production system has expanded around the world ever since. In 2019, 110 OWFs had been built in Europe (GWEC 2020; https://gwec.net/gwec-in-2020/)). OWF energy is estimated to reach 234 GW in 2030 (GWEC, 2020, https://gwec.net/gwec-in-2020/) with the lead in Asian-Pacific regions and continuing expansion in Europe. OWFs are one response proposed to global warming (Esteban et al. 2011, Zhang et al. 2015). The space and wind available in marine ecosystems make them a resourceful location for OWFs (Perveen et al. 2014). However, this development arises questions. Marine ecosystems are already under multiple stresses all over the world (Li and Dag 2004, Halpern et al. 2008, Crain et al. 2009), and reluctance to OWF projects has emerged because of their impacts on the environment and on local human activities.

It is important to understand the implications of OWF construction in light of those concerns. This was the objective of the APPEAL project led by France Energies Marine (FEM), the Laboratoire des sciences de l'environnement marin (LEMAR) and the Université de Bretagne Occidentale (UBO). This project was focused on the pilot OWF (three turbines) that will be constructed in the Groix–Belle-île territory in Brittany (France) in 2024 and 2025. The goal of the project was to understand implications and changes resulting from the construction of an OWF on the local SES.

The work presented here is part of this project. It follows the work of Fofack-Garcia et al. (2023) on the local governance processes of the Groix–Belle-île OWF, which analyzed the perception of the impacts of floating OWFs by decision-makers involved in the validation process of the Environmental Impact Assessment. Our work also follows that of Le Marchand et al. (2022) on the trophic web of the Bay of Biscay where Groix and Belle-île islands are located. The local governance process helped us understand the dynamics between the actors and their different interests in the ecological system. The trophic web was our base for the ecological part of the SES. The combination of actors, humans and non-humans presented by those two studies was the starting point for our work. Our objective was to describe the SES of Groix–Belle-île in the presence of the OWF, and to determine (i) the indirect effects influencing the SES, and (ii) whether human activities would be in conflict, whose maximization could not be reached at the same time? To have the most accurate SES model possible, we organized a participatory workshop with APPEAL collaborators. Participatory approaches have been described as a good way of involving actors in decision processes (Arnstein 1969, Bacqué and Gauthier 2011). The various actors all belong to different fields of expertise, this is why it was important to collect their opinions and suggestions to build a model as close to reality as possible. Stakeholders' engagement through participatory processes has been recognized as a powerful tool to reduce conflicts, promote stakeholders' views and knowledge, improve acceptance of policy decisions, and support social learning in natural resource issues (Voinov and Bousquet 2010, Squires and Renn 2011). A stakeholder can be defined as an individual, a group or an organization that has an interest (a stake) and the potential to influence the actions and aims of an organization, project or policy direction (Crosby 1992, Walt 1994). We co-constructed our model with stakeholders engaged in the APPEAL project for it to be based on stakeholder expertise. We gathered a variety of stakeholder types around the table to collect different views and generate discussions. Thanks to this method, we also made sure that the model was understood and validated by the stakeholders.

The model was built based on loop analysis (Levins 1974, Puccia and Levins 1985), using positive and negative direct relationships between variables (actors) to describe the dynamics characterizing the Groix–Belle-île socio-ecosystem. Qualitative modeling has already proven useful for management purposes (Dambacher et al. 2015). Our work falls into the scope of those of Dambacher et al. (2015) and Haraldsson et al. (2020). The latter was a starting point on the reflection about building socio-ecosystems for an OWF. We embraced its philosophy and methodology, while adding actors' participation.

Materials and methods

Study area

The Groix–Belle-île pilot wind farm will be situated in the Bay of Biscay (Fig. 1). This gulf is located on the eastern side of the North Atlantic Ocean. It is bordered by the French and Spanish coasts to the south and the English Channel to the north. The wind farm will occupy a 14-km^2 area, 14 km away from Groix Island and 19 km from Belle-île Island, and will consist of three floating turbines. This technique implies that the turbines are placed on floats allowing small movements following the waves. They will be linked together by dynamic cables and to the shore by a static 28-km long cable (ENGIE). Many anthropogenic activities are found in this area, which is important for tourism and pleasure boating. Moreover, the Bay of Biscay is the first fishing area in Europe, with about 100 000 tons of fish and shellfish extracted every year by French and European fishermen (http://ices.dk/marine-data).

Qualitative modeling

We used qualitative modeling with loop analysis to build the SES of the Groix–Belle-île wind farm project. This technique is based on a signed digraph allowing to model the system by describing the network of interacting variables. Loop analysis was first developed to study the role of feedback loops in networks (Levins 1974, Puccia and Levins 1985). It consists in first identifying all the variables (e.g. human and non-human ones) that compose a system, and then linking them together according to their direct relationships in a signed digraph (Fig. 2). The relationships are described by (+1), (0), and (−1) values; (+1) represents a positive link between two variables, meaning—one's growth rate will benefit from the level of the other, (−1) represents the opposite, and (0) the absence of a direct relationship between the two variables. For example, in a predator (X_2)–prey (X_1) relationship, X_2 will exert a negative effect (−1) on X_1 while a positive interaction (+1) will be used for the link from X_1 to X_2. Each variable has a negative (−1) self-effect, e.g. corresponding to the carrying capacity (Fig. 2). The dynamics of the n variables of the system is driven by a system of differential equations as in the Lotka–Volterra model (Metcalf et al. 2014):

$$\frac{dNi}{dt} = fi\left(N_1, N_2, \ldots, N_n, c_1, c_2, \ldots, c_n\right). \tag{1}$$

Where n = number of variables,
N_i, f_i = growth function, and
c = growth parameters.
The a_{ij} coefficient is the partial derivative of fi:

$$a_{ij} = \frac{\partial f_i}{\partial N_j}. \tag{2}$$

This equation computes the community matrix A composed of a_{ij} coefficients. In the matrix, the entry in the ith row and the jth column displays the magnitude (a_{ij}), and the sign of this coefficient is the direct effect of variable j on i (Hosack et al. 2008). The idea is then to test how the model will react to press perturbations, i.e. sustained changes in the magnitude of the growth parameter of a variable (Raymond et al. 2011). This can be done using the negative inverse of A: $-A^{-1}$ (Dambacher et al. 2002, 2005, Hosack et al. 2008, Forget et al. 2020):

$$-A^{-1} = \frac{adj\ (-A)}{\det\ (-A)} \tag{3}$$

With $adj\ (-A)$ = adjoint of −A, and $det\ (-A)$ = determinant of −A. The matrix $-A^{-1}$ outlines direct and indirect effects ensuing from press perturbations. The long-term directions of change can be identified using the adjoint matrix (Dambacher et al. 2002, 2005), which summarizes the total numbers of direct and indirect effects between input and response variables. In other words, loop analysis predicts the direction of changes of the variables in response to variation in the growth parameter of a targeted variable. The results are summarized in a table of predictions. This calculation was performed using the R software tool (ver. 3.6.1) and the code developed by Bodini et al. (2018), which implements a simulation approach to circumvent ambiguities in the net effect triggered by perturbations on target variables when linked to response variables through an even number of positive and negative paths. In such a way, the effects that travel through short pathways are stronger than those conveyed by longer chains.

Once the qualitative model is built, its stability must be checked. If the model is to be representative of a real system, its stability conditions are needed so that the variables can persevere when a perturbation occurs. For a qualitative model to be stable, it has to meet the two Hurwitz criteria

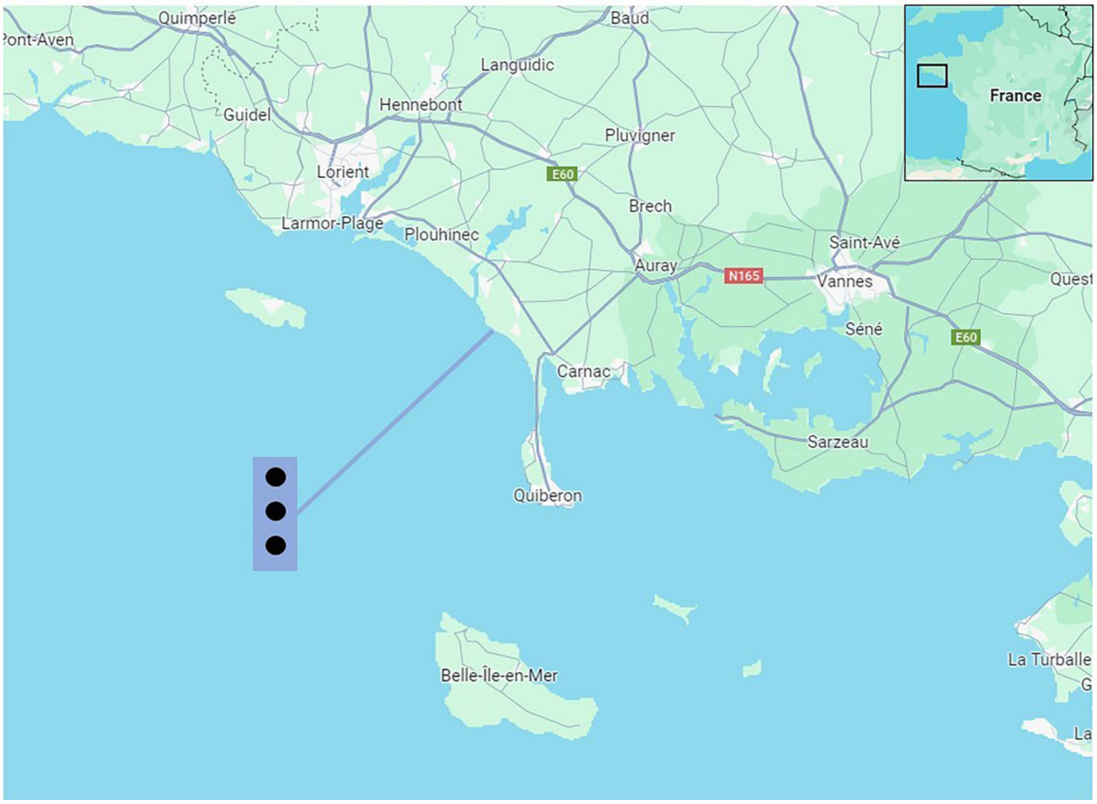
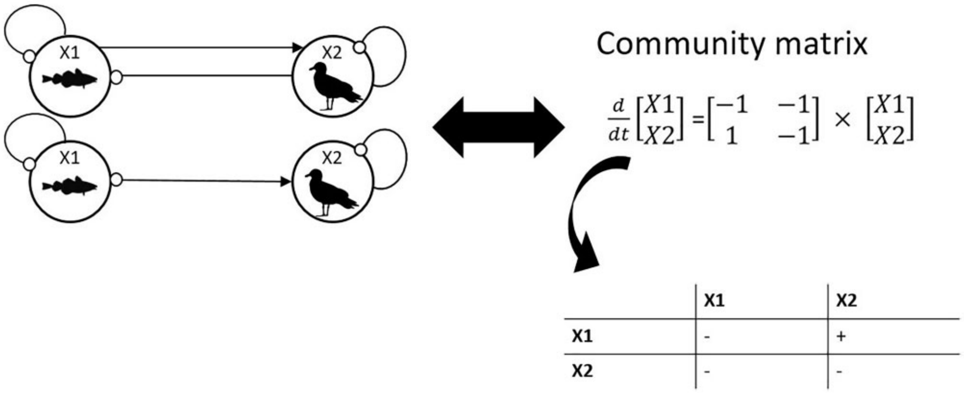


Figure 1. Groix–Belle-île wind farm project. The three turbines are represented by the dots and the wind farm by the rectangle. The line represents the electrical connection to the coast. The turbines and wind farm area have been enlarged for the benefit of the figure.



Community matrix

$$\frac{d}{dt}\begin{bmatrix} X1 \\ X2 \end{bmatrix} = \begin{bmatrix} -1 & -1 \\ 1 & -1 \end{bmatrix} \times \begin{bmatrix} X1 \\ X2 \end{bmatrix}$$

	X1	X2
X1	-	+
X2	-	-

Figure 2. Illustration of a signed digraph (case of predator–prey dynamics). The predator impacts the prey population negatively by feeding on it. The prey influence the predator population positively by supplying energy and then increasing its growth rate, thereby by contributing to the survival and expansion of the population. The community matrix shows these dynamics and is illustrated by the signed digraph.

(Dambacher et al. 2003, 2015, Metcalf et al. 2014), namely:

criterion (i): the system is not dominated by positive feedbacks

criterion (ii): the system is not dominated by higher-level feedbacks

The potential of a model to fail one of those criteria will determine if it is a class-I model (failing criterion i) or a class-II model (failing criterion ii). The weighted feedback w*F*n and the weighted determinant w*D*n (Dambacher et al. 2003) are computed to test stability according to criterion (i) and criterion (ii), respectively.

Model building

We started from the works of Le Marchand et al. (2022) and Fofack-Garcia et al. (2023) to identify the variables. Le Marchand et al. developed the trophic model of the Bay of Biscay using the Ecopath with Ecosim software program. Fofack-Garcia et al. (2023) described the network of actors through the degree of concern of the human actors for the ecological compartments. Based on these works, we drew a list of 102 variables for human and non-human components. Then, we grouped and selected variables to attain a trade-off between complexity representation and computational tractability. The variables were selected by first describing the activity sectors and ecological groups, and ranked within each group. For the sociological variables, the groups were based on the human activities occurring in the area and the emotional relationship of humans toward the ecological system. Then, we selected variables and groups of variables directly impacted by the OWF. For example, fisheries and pleasure boating were considered as directly impacted, and selected. We aimed to assemble a balanced model with comparable numbers of sociological and ecological variables (Haraldsson et al. 2020) to stress that they both have major roles in governing system's dynamics. This lines with the conceptual work of Berkes and Folke (1998) that promotes the equilibrium between social and ecological components in SES.

Participatory workshop

A first draft model was built to be presented in a participatory workshop that took place in January 2021 and was composed of collaborators of APPEAL. It involved fifteen participants from different domains of expertise. The majority were researchers from Brittany and Normandy, in addition to an engineer from the SHOM (Marine Service of Hydrography and Oceanography), one representative from RTE (the transportation network in charge of installing the electrical cables), an elected member of the fishery committee and a project manager from EOLFI, the company in charge of the project. A version of the stable model and the methodology were presented. Each link and variable was explained. An open discussion was initiated, and each participant expressed their opinions, concerns and suggestions. These discussions resulted in a consensus about what to change in the model. The workshop took place in videoconference because of the COVID-19 pandemic and lasted half a day.

Table of predictions

We tested the stability of the model built during the participatory workshop several times until we reached a stable version, with a sufficient number of variables. Then, we studied its table of predictions, which gave the expected direction of change for each variable in response to positive press perturbations. The default is that responses are expressed considering positive press perturbations; consequences of a negative input along each row of the table of predictions can be obtained by simply reversing the signs. In a model with a high number of variables, predictions tend to be ambiguous, so that we are not sure about their accuracy. To solve this problem, a numerical routine randomly assigned values in the interval [0,1] to the coefficients a_{ij} of the community matrix from a uniform distribution (Bodini et al. 2018). This was run $n \times 1000$ times, with $n =$ number of variables. Stable matrices only were selected and combined to produce the final table of predictions. The directions of change were determined based on the percentage of identical signs in each $n \times 1000$ matrices. The conversion from percentages of sign to predictions was based on Bodini *et al.* (2018, Supplementary Information).

Results

Assessing model stability

The initial model was composed of 23 variables, eight ecological and 15 socioeconomic. Yet, as explained in the methodology section, it had to be stable for the loop analysis to be performed, and this one was not. In order to stabilize it, we first removed the links that appeared weak compared to the others, e.g. the (−1) links from Benthic Fishes, Pelagic Fishes and Demersal Fishes to Plankton because eating of plankton by planktivorous fish is not going to drastically reduce the plankton population, and both benthic and demersal fish do not primarily feed on plankton. We then changed other links to connect variables in a more realistic way and removed those isolated. Figure 3 shows the final version of the model and Table 1 described the model variables.

We added Table A to the Supplementary Material for explaining the meaning of the links used to build the digraph. For instance, the dynamic link from wind farm turbine (WFT) to PW indicates that: an increase in the number of WFT decreases the perception of wildness as it corresponds to an expansion of human activities and infrastructure in the marine environment.

The final version of the model was composed of 20 variables, twelve social and eight ecological. The relationships between the ecological variables were of the predator-prey type and were established from the work of Le Marchand et al. (2022). The links between social variables and ecological and other social ones were based on the environmental impact study by Fofack-Garcia et al. (2023) and discussions with experts and APPEAL collaborators. Our model was built around the building of an OWF that we divided into Wind Farm Surface (WFS) and WFT as the impacts were described as very different by the stakeholders. As an illustration, the alteration of the farm's overall surface area will affect boat circulation, whereas the quantity of turbines will have an impact on the local sea bird population. Given that our research pertains to a pilot farm, we have hypothesised that an increase in surface area will result in a corresponding increase in the number of turbines. The time frame of our work embraces some decades, under the assumption of a progressive, future growth and expansion of the OWF sector. For this reason, we included both the WFS and WFT as variables in the loop model rather than considering them as constant parameters. Most of their links are influencing other variables but our interest was in modeling the sequences of interactions that may lead the approval process to alter the expansion of areas occupied by OWFs. Increasing growth rates of WFS and WFT can be more easily conceived rather than decreasing ones, which would correspond to the decommissioning of infrastructure. However, since the present study focuses on a time horizon of 20/30 years, which corresponds to and even exceeds the expected lifetime of an OWF, it gets plausible that some changes in the whole system might also result in a decrease of the number of turbines and, consequently, of the sea surface occupied by the infrastructure.

We computed weighted feedback (wFn) and weighted determinant (wDn) to evaluate the stability of the model:

Criterion (i): $\mathrm{wFn} = -0.011$
Criterion (ii): $\mathrm{wDn} = 0.86 \times 10^{-30}$

The result obtained for criterion (i) was very close to 0. Consequently, our model had a low to moderate stability scope. The second criterion classified our model as "class I," meaning that it was likely to fail criterion 1. Our model was considered stable as such.

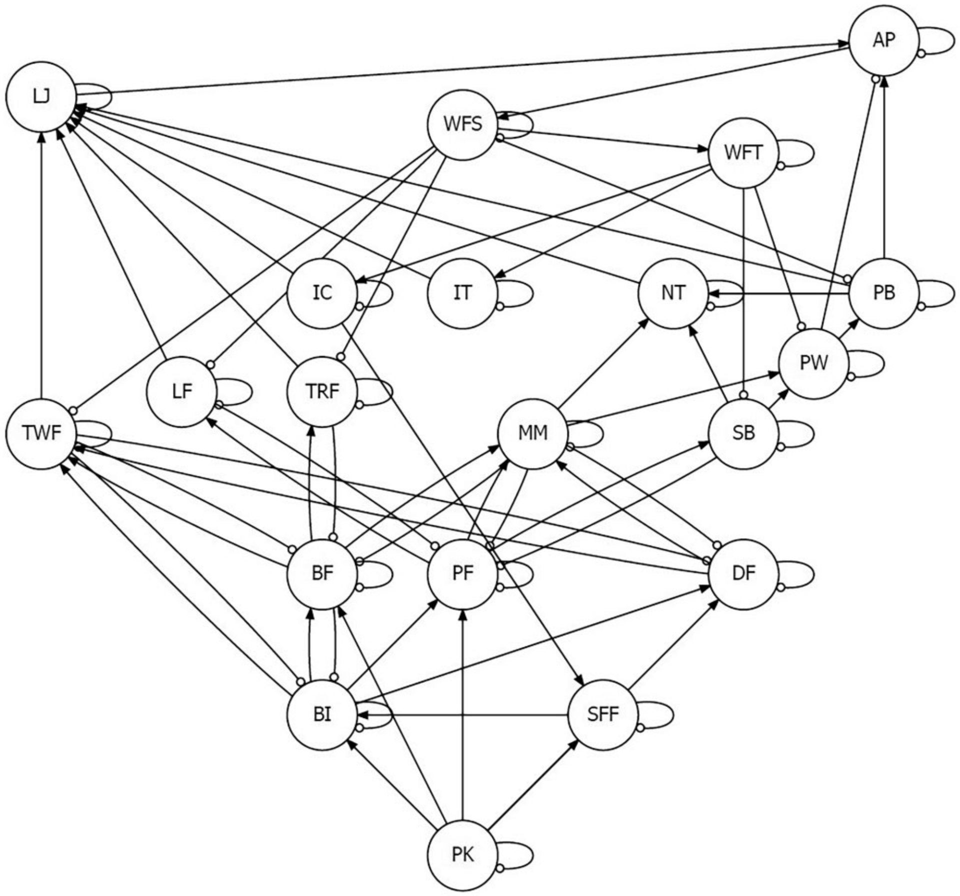


Figure 3. Stable version of the Groix–Belle-île SES model obtained following the participatory workshop and stability analysis.

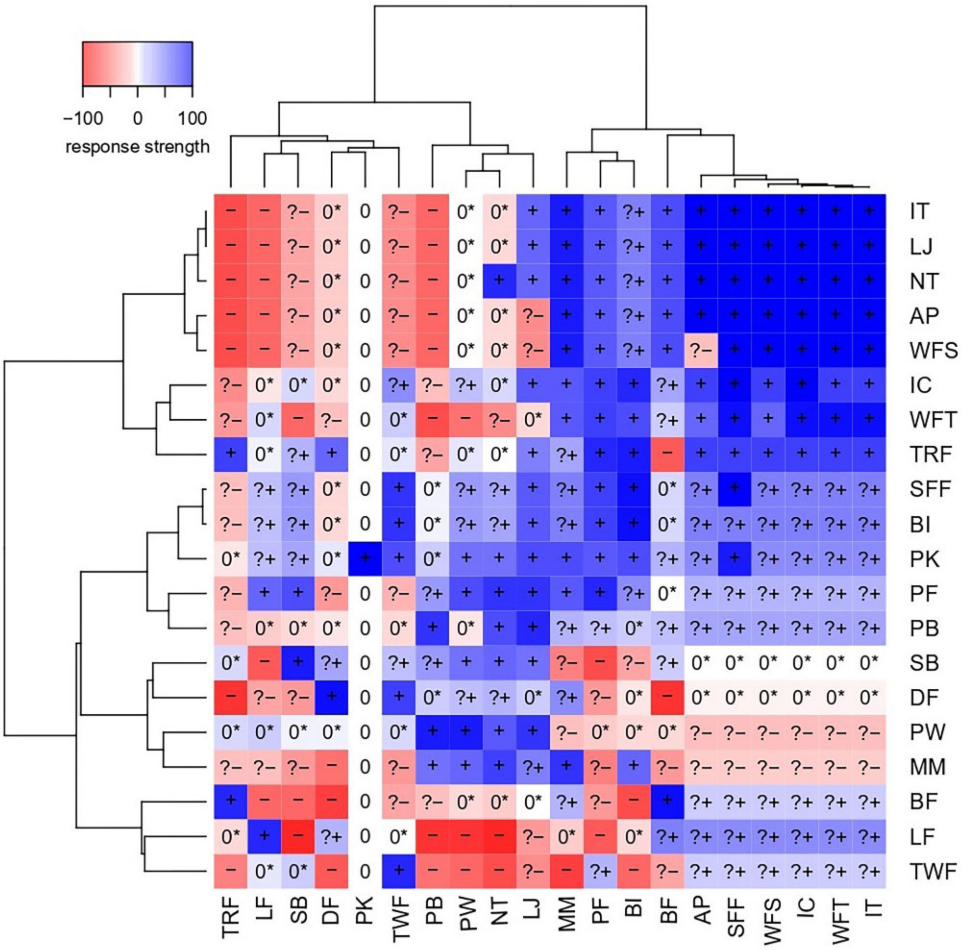
Table 1. Human and non-human variables used to draw the final version of the SES model.

Variables	ID in the digraph	Description and representative species (ecological nodes)
Wind farm surface	WFS	Area occupied by the farm
Wind farm turbines	WFT	The three turbines and their floating structure in the farm
Infrastructures and cables	IC	Floating structures and submarine cables
Local jobs	LJ	Jobs created by the establishment of the OWF
Industrial tourism	IT	New type of tourism originating from the project
Natural tourism	NT	Traditional tourism interested on biodiversity and landscape
Pleasure boating	PB	Private boating activities
Perceived wildness	PW	Individual perceptions of the ecosystem wildness[a]
Approval processes	AP	Governmental decision processes
Line fishery	LF	Fishing activities using lines and hooks
Trap fishery	TRF	Fishing activities using traps
Trawl fishery	TWF	Fishing activities using nets pulled out from the water
Sea birds	SB	*Laridae* spp., *Alcidae* spp.
Marine mammals	MM	*Delphinus delphis, Tursiops truncatus*
Demersal fishes	DF	*Scophthalmus maximus, Solea solea*
Pelagic fishes	PF	*Clupea harengus, Sardina pilchardus*
Benthic fishes	BF	*Lophius piscatorius, Pleuronectes platessa*
Sessile filter feeders	SFF	*Pecten maximus, Glycymeris* spp
Benthic invertebrates	BI	*Cacinus maenas, Maja brachydactyla*
Plankton	PK	

[a] Ecosystem wilderness understood here in the broad sense of the living and non-living environment such as elements of the visual landscape and cultural heritage.

Table of predictions—expected variables' direction of change when exposed to a perturbation

The heatmap is the result of simulated matrices predicting the direction of change of variables in case of perturbation(s) (Fig. 4). The variables were clustered on the *y*-axis according the similarities of responses they trigger. They were grouped on the *x*-axis according to similarities in their responses to positive inputs acting on the *y*-axis variables. The



	TRF	LF	SB	DF	PK	TWF	PB	PW	NT	LJ	MM	PF	BI	BF	AP	SFF	WFS	IC	WFT	IT
IT	−	−	?−	0*	0	?−	−	0*	0*	+	+	+	?+	+	+	+	+	+	+	+
LJ	−	−	?−	0*	0	?−	−	0*	0*	+	+	+	?+	+	+	+	+	+	+	+
NT	−	−	?−	0*	0	?−	−	0*	+	+	+	+	?+	+	+	+	+	+	+	+
AP	−	−	?−	0*	0	?−	−	0*	0*	?−	+	+	?+	+	+	+	+	+	+	+
WFS	−	−	?−	0*	0	?−	−	0*	0*	?−	+	+	?+	+	?−	+	+	+	+	+
IC	?−	0*	0*	0*	0	?+	?−	?+	0*	+	+	+	+	?+	+	+	+	+	+	+
WFT	?−	0*	−	?−	0	0*	−	−	?−	0*	+	+	+	?+	+	+	+	+	+	+
TRF	+	0*	?+	+	0	0*	?−	0*	0*	+	?+	+	+	−	+	+	+	+	+	+
SFF	?−	?+	?+	0*	0	+	0*	?+	?+	+	?+	+	+	0*	?+	+	?+	?+	?+	?+
BI	?−	?+	?+	0*	0	+	0*	?+	?+	+	?+	+	+	0*	?+	?+	?+	?+	?+	?+
PK	0*	?+	?+	0*	+	+	0*	+	+	+	+	+	+	?+	?+	+	?+	?+	?+	?+
PF	?−	+	+	?−	0	?−	?+	+	+	+	+	+	?+	0*	?+	?+	?+	?+	?+	?+
PB	?−	0*	0*	0*	0	0*	+	0*	+	+	?+	?+	0*	?+	?+	?+	?+	?+	?+	?+
SB	0*	−	+	?+	0	?+	?+	+	+	+	?−	−	?−	?+	0*	0*	0*	0*	0*	0*
DF	−	?−	?−	+	0	+	0*	?+	?+	0*	?+	?−	0*	−	0*	0*	0*	0*	0*	0*
PW	0*	0*	0*	0*	0	0*	+	+	+	+	?−	0*	0*	0*	?−	?−	?−	?−	?−	?−
MM	?−	?−	?−	−	0	?−	+	+	+	?+	+	?−	+	?−	?−	?−	?−	?−	?−	?−
BF	+	−	−	−	0	?−	?−	0*	0*	0*	?+	?−	−	+	?+	?+	?+	?+	?+	?+
LF	0*	+	−	?+	0	0*	−	−	−	?−	0*	−	0*	?+	?+	?+	?+	?+	?+	?+
TWF	−	0*	0*	−	0	+	−	−	−	?−	−	?+	−	?−	?+	?+	?+	?+	?+	?+

Figure 4. Table of predictions of the final model. This heatmap shows how variables are impacted by press perturbations (i.e. the default considers positive inputs on row variables). All variables are on both axes. *Y*-axis, input variables; *X*-axis, variables impacted by the inputs.

dendrogram classified the variables based on their impact (on the left of Fig. 4) and response (top of Fig. 4). Variables responding in similar ways were clustered together. The percentages of the outcomes of the simulations (the "response strengths") were classified as follows: "strong" if >80%, weak if 60% < effect ≤80%, and ambiguous if ≤60% (Sobocinski et al. 2018, Forget et al. 2020). A strong effect was a measure of the confidence in the type of impact/response. For example, TRF impacted BF negatively and the effect was strong, which illustrates the high likelihood of such a cause–effect relationship. On the contrary, Trap Fishery had an ambiguous positive effect on marine mammals, suggesting this impact may occur under specific and circumstances only. Variables with ambiguous responses were those more likely reacting differently to perturbations.

The dendrograms highlighted which variables had similar impacts and responses. Two groups were clearly distinct in terms of responses (*x*-axis). The first group ranged from industrial tourism to marine mammals includes variables that reacted in similar ways to perturbations. This was especially true for the subgroup from industrial tourism to approval processes. In the second group, ranging from local jobs to trap fishery, responses changed more depending on the variable. This highlighted the most sensitive variables, i.e. those that responded differently to each other: whenever an input variable was modified, the response was different.

An increase of the OWF socio-economic sector determines comparable responses in the entire system, as shown by the variables WFS, IC, WFT, LJ, and IT that are grouped together along the rows of the table of predictions (Fig. 4). It is relevant to note that also Trap Fishery (TRF) shows similarities with this set of variables, indicating that analogies in the impacts caused at system level transcend the boundaries of specific economic sectors. Conversely, a more mixed clustering characterizes the columns of the table of predictions (Fig. 4) where ecological (SFF) as well as socio-economic (IT, WFS, WFT, and IC) and governance (AP) variables related to OWFs display similar responses to press perturbations. This outcome indicates that management decisions concerning the OWF sector can be hardly taken without triggering analogous directions of change (SFF) or tradeoffs/conflicts (SB and DF) with ecosystem variables.

The table of predictions clearly describes that the net, overall impact of the wind farm (both WFS and WFT nodes) on Pleasure Boating (PB) is negative. Such a net impact is obtained by considering all pathways linking WFS and WFTs to Pleasure Boating. This means that a prevalence of negative paths stronger than the positive ones determines a net negative response of Pleasure Boating following an increase in the area occupied by the wind farm and the number of turbines. Nevertheless, some pathways carrying a positive impact from WFS and WFTs exist and, if the strength of these pathways is such that exceeds the magnitude of the negative pathways, then a beneficial impact of OWFs on PB emerges. We listed in the Supplementary Materials (Table B) all of the pathways from WFS to Pleasure Boating and from WFTs to Pleasure Boating. Although in both cases the number of positive and negative pathways is the same (25/25 from WFS to PB, and 103/103 for WFT to PB), the average strength of the negative pathways is higher compared to the average strength of the positive (−0.0283 vs. 0.0096 for the net impact from WFS to PB, and −0.0044 vs. 0.0009 for the net impact from WFT to PB). For this reason, the net effect simulated by the loop analysis for a positive press perturbation on the OWF-variables WFS and WFT on PB is negative. However, this result was obtained by randomly simulating the strength of links as no quantitative information was available. This means there might also exist combinations of interaction strengths that lead to net positive effects to prevail over the pathways carrying negative impacts. If the strength of the positive pathways would prevail due to certain combinations of link strength, then the predictions obtained from random simulations would even be reverted, determining a stronger overall positive impact from OWF variables to PB. Table B with details on pathways linking WFS and WFT to PB were added to the Supplementary Material. In each line of the tables, we summarized the sequence of nodes composing the pathway, its strength, the total number of nodes included, and the net effect over PB (either positive or negative).

Trap fishery and Line fishery seemed to be more negatively impacted than the other variables by the OWF. The offshore windfarm area was close to fisheries thus halting directly the chance of any fish extraction. The contrary was observed with Trawl fishery: negative impacts were ambiguous, so that the OWF might have a negative effect under specific conditions.

The Approval Process was negatively impacted by WFS in specific conditions. The increasing surface area of the OWF decreased the approval processes. This can be explained by the role played by Perceived Wildness and Pleasure Boating in those processes. These two variables were both negatively linked with the wind farm: WFS and WFTs for Pleasure Boating and with WFTs for Perceived Wildness. As Pleasure Boating and Perceived Wildness impacted Approval Process, that the resulting feedback resulted in a (weak) net negative effect of WFS on Approval Process. These variables illustrate the perception and opinion of local actors, whose feeling towards the project grew less welcoming with an increasing OWF surface area.

No variable was impacted only negatively or only positively. Thanks to indirect paths, unexpected responses emerged when constructing the model. For example, our expectation was that Pleasure Boating would only be negatively impacted by the OWF. However, marine mammals had a positive impact on Pleasure Boating (through Perceived Wildness) and the variable marine mammals itself responded favorably to several variables such as WFS. By extension, the overall negative response of Pleasure Boating was alleviated by this positive impact. The indirect effect of the variable marine mammals reduced the negative impact of the OWF on Pleasure Boating.

Discussion

The setting-up of OWFs in marine systems disrupts the settled organization of the SES. Many actors are impacted by this new source of energy generation that is being introduced very rapidly in numerous places. These sudden changes create debates and opinions diverge, e.g. about the economic opportunity vs. the threat to local fisheries. We simulated a system with a constructed OWF to understand the social-ecological implications. We produced a model with a large number of different actors that not only described human activities and the present marine species, but also integrated the perception of individuals. Conflicts between certain activities and unpredicted relationships between social and ecological variables were highlighted.

A new SES

The building of a wind farm created a new SES (Mazé 2020, Niquil et al. 2021) in which the infrastructure interacted with most of the system's components (Fig. 4). These new connections created various feedback reactions thus affecting many variables.

The methodology used in the present work allowed us to model the SES of Groix–Belle-île following the construction of an OWF. The workshop with the project partners representing a wide variety of actors was a way of confronting the ideas of specialists from different fields and ranges of expertise to draw as realistic a model as possible. This approach is important when building an SES model because it gathers variables related to non-human/human activities and human perceptions.

The building of an OWF in a territory like the Bay of Biscay is going to bring about important perturbations in a region where tourism, fishing activities and pleasure boating are important. The construction of an offshore structure in the area will create a new dynamic of the SES (Olsson et al. 2014). Thanks to the public debate, the establishment of the OWF was negotiated with local actors, fishermen, and other private actors representing various social-ecological interests to find consensus on the most acceptable options. Inhabitants of the region were afraid that their environment would be drastically changed (Devine-Wright 2007, Fournis and Fortin 2015, Oiry 2015). Simulations were run to predict the landscape seen from the shore at different distances and viewpoints to visualize to what extent the turbines would be visible. However, reactions and feelings of local dwellers cannot be predicted, and it will be interesting to collect their opinions once the farm is built because their perception may change (Bush and Hoagland 2016). Although they are not included to our model, it is nevertheless worth mentioning landowners among the stakeholders potentially impacted by OWF. For this category of stakeholder, two possible ways to address potential OWF impacts: (i) their involvement in the approval process and their capacity to influence the decision-making concerning infrastructures and cables; and (ii) their perceptions of impacts of these infrastructures on their property values.

Moreover, if we were to observe reef and reserve effects, they could bring back marine mammals' prey and favor their survival in the territory. A reef effect occurs when a structure is built and creates a new habitat that is rapidly colonized by marine species (Wilhelmsson et al. 2006, Wilhelmsson 2010, Wilhelmsson and Malm 2008), often increasing the biomass of sessile organisms (Raoux 2017). This process also affects fish biomass positively (Bergström et al. 2013, Reubens et al. 2014) by increasing their prey availability. Moreover, a decreased solicitation of a marine area creates an area that exhibits the characteristics of a marine protected area (reserve effect) (Wilhelmsson et al. 2006). This effect can bring about biomass increases and a drastic change in the structure of the ecological community (Lindeboom et al. 2011). Decreasing the fishing pressure and/or boat access in the windfarm area could increase fish biomass, which in turn would increase the stock available to fisheries (Gill et al. 2020) and preserve the ecological populations from ship-induced stress. Our model predicted mainly positive impacts on Sessile Filter Feeders because they will be able to colonize the new structures (a direct link included in our model). We also observed a majority of positive impacts on the variable benthic fishes. Demersal fishes will not be impacted or may be negatively impacted by the OWF variables; and for pelagic fishes, the results are in-between: the variables related to the wind farm will have a positive impact, but those including predation (sea birds, fisheries) will have a negative impact. The responses described here illustrate reserve and reef effects, even if they are difficult to differentiate for fish. However, positive effects on sessile filter feeders and on benthic and pelagic fish are highlighted. These impacts will change the structure of the local food web. Follow-up studies will be needed to investigate the potential spillover effect (i.e. increase of benthic and pelagic fishes), to corroborate the positive consequences predicted for fisheries outside the windfarm area. Reserve and reef effects may increase the acceptation by local communities, which tend to fear for marine mammals decline.

The closing of the windfarm area to fisheries is one of the main reasons for opposition to such projects (Gray et al. 2005). Our simulation results have to be considered with caution with respect to this aspect. The model showed that the fishing sector highly impacted by the OWF was the trap fishery (TRF). As Trap fishery is a static fishing technique, with smaller boats and in restricted fishing areas (https://www.bretagne-peches.org/) compared with trawling, a higher impact was expected. The effects on trawling were smaller, likely explained by the species targeted by this technique, which are more numerous than those extracted using traps or by line fisheries, and can be found in a broader area browsed by larger vessels. In our model, this was represented by the links from Trawl fishery to the fish groups; the potential positive impact of offshore windfarms on benthic and pelagic fishes could be a step towards sustainable fisheries.

Renewable energy sources are a new attractive element of industrial tourism (Beer et al. 2018). That is why we made the hypothesis that a positive relationship will exist between the wind farm and Industrial Tourism. The table of predictions showed no indirect link changing this dynamic, and all the strong impacts on Industrial Tourism were positive. As a consequence, we suggest that a new kind of tourism can emerge from the building of the offshore windfarm, thus attracting tourists and creating favorable conditions for new employment opportunities.

This model illustrates that the OWF tends to have a more negative impact on social components than on ecological ones, this is also shown in the work of Haraldsson et al. (2020). Our objective was not to provide an all-encompassing portrayal of the dynamics that arise from the construction of the Groix–Belle-Île OWF. Rather, our aim was to demonstrate how this methodology can enhance comprehension of the interplay between social and ecological factors, and how engaging stakeholders can result in a more realistic SES model. The motivation behind constructing an SES is to explore the intricate connections between ecological and social systems, rather than viewing them in isolation. In pursuit of this objective, we strived to strike a balance between ecological and social variables (Haraldsson et al. 2020).

Emergence of unpredicted links in the SES

The table of predictions showed unpredicted cause–effect relationships. Direct relationships were drawn in the digraph, and the heatmap revealed unexpected effects due to indirect links (Fig. 4). For example, an increase in phytoplankton stimulated local employment growth even though those two variables were not directly linked.

The table of predictions evidenced synergistic and antagonistic effects. When looking at a response variable (i.e. a column in the table of predictions), the cells showing the same qualitative impact are exhibiting synergistic effects of different press perturbations (i.e. the rows in the table of predictions), while opposite signs indicate antagonistic effects. Antagonistic effects can illustrate conflicts of interest. For example, when there was a positive input on WFS, the direction of change was negative for Pleasure Boating but positive for marine mammals. This illustrated a conflict between pleasure boating (an important activity in the Groix–Belle-île region) and the potential positive impact of the OWF on marine mammals. Moreover, antagonistic effects were seen between the fisheries and pleasure boating variables on one hand, and the wind farm, construction sector and sessile filter-feeders variables on the other. Existing conflicts can persist once the farm is built and operating. However, the ambiguity of some results showed that the system may find a new equilibrium. Variables like benthic fishes, pelagic fishes, and Sessile Filter Feeders showed in fact a positive reaction to the windfarm. As those groups are interesting for fisheries, they could compensate for the ban on fishing in the area. Compensation can come from the spillover effect resulting from the growing fish population in the windfarm area (Halouani et al. 2020). Synergies and antagonistic responses between human activities were also interesting to look at, as they illustrate the social actors' interactions with the SES. There were synergies between the sectors that will benefit from the OWF—construction (e.g. infrastructures and cables variable) and industrial tourism, whereas they were antagonistic with the fishery sectors when responding to WFS and WFTs. Therefore, it is unlikely these sectors will thrive together. The modeling of the SES using loop analysis is a way of anticipating possible emerging conflicts.

Limitations of our work and perspectives

The participatory approach helped us to create a model that made consensus among the stakeholders. By organizing and holding the workshop, we made sure that APPEAL collaborators were comfortable with our approach and the resulting model. As our domain of expertise was different from theirs, all information collected during the workshop were complementary. However, our methodology had a few limitations, as the model requires a few nuances to be considered. First, we held one workshop only and with an online format due to restrictions imposed by COVID-19. Our goal was to ask the stakeholders their opinions about the draft model and complete it with their knowledge, but it might have been relevant to hold several workshops and construct the model with them step by step, as proposed by Etienne (2010). Then, there was no stakeholder representing local dwellers, who would have brought their vision and knowledge of the territory. Different degrees of participation exist (Arnstein 1969, Basco-Carrera et al. 2017), but they are mostly related to decision making in management. Our project did not consist in decision making but only in modeling of the SES. Therefore, we can consider we were in a collaborative type of participation as we took the stakeholders' remarks into account and validated the model with them (Luyet et al. 2012). Yet, we could have taken one step further and started a discussion with them about the results of our model, and collected their opinion on the management measures to be proposed to mitigate the impacts of the OWF.

Some relationships need to be better covered by the model to address economic tipping points for tourism and pleasure boating for instance. By potentially modifying marine landscapes, user practices and, more generally, the relationship between coastal societies and their environment, offshore wind energy can be seen as both a threat and an opportunity for a large local maritime economy, including tourism and pleasure boating. One of the main questions raised is how coastal tourism and perceptions can evolve in the context of offshore wind energy by considering for instance the emergence of offshore wind tourism (Cabanis 2018, Glasson et al. 2022). Based on an analysis of tourist activities, practices, and flows at the sites where OWF are located, trends in tourist services, and economic tipping points can be identified during the construction phase of the wind farms, but especially during the operational phase (Mangi 2013, Gusatu et al. 2020, Glasson et al. 2022).

Moreover, in perspective, a variable that could be interesting to integrate into the model is the attraction behavior of tourists and recreational fishermen/users to areas occupied by the OWF. An attraction that sometimes stems from the curiosity (Fortin et al. 2017) or arises from the increase in the abundance and diversity of target species for recreational fisheries and species of patrimonial interest (Brink and Dalton 2018, Smythe et al. 2020). This accumulation of effects (reef and reserve) associated with a policy of opening the park area thus tends to reinforce recreational fisheries and tourist uses (Carr-Harris and Lang 2019).

As far as the model is concerned, a limitation of our work is that we used a static architecture where all links coexist at the same time, which is not the case in reality. Even if the study of feedback loops allowed us generating nonlinear responses, due to the combination of synergistic and antagonistic effects via pathways of different lengths (Hosack et al. 2008), the digraph is still assembled using simple, linear interactions, which is a simpler view than what really happens in a SES. For example, the noise caused by the OWF construction is a major source of stress for species in the area. As we used a static model, we modelled interactions that follow the construction phase of an OWF, without considering previous perturbations such as those caused by the noise during the construction phase. The stability of our model was not optimal, resulting in ambiguity in the table of predictions, but this was because we aimed at producing the most complete representation possible of our system. This choice resulted in the use of a great number of variables, and stability conditions were less likely to be achieved. Furthermore, we did not include bats among the ecological variables, which is a limitation as they might be affected by the windfarm (turbines and light) (Lehnert et al. 2014).

Conclusion

The present study identifies indirect relationships that play important roles in the SES dynamics of an offshore windfarms. The construction and operation of an OWF positively impact sectors such as construction and industrial tourism, but are in conflict with some of the fishery activities and pleasure boating. This study highlights the relevance of participatory modeling and SES models appear as a good way of addressing complex human and non-human relationships.

In the future, it would be interesting to test press perturbations and management scenarios to anticipate further modifications of the system. This is the case for a compensation measure that was decided in the project to reduce the impact of turbines on seabirds, especially *Larus* spp.

In order to appreciate how the OWF will impact human activities, it would be relevant to investigate how fishermen will adapt to the new conditions. The first OWF in France (Saint-Nazaire, 80 bottom-fixed OWTs) will be commissioned in 2024. Fishing inside the area will be authorized under certain conditions set by the public authorities, in consultation with fishermen and the OWF developers. Given that Saint Nazaire is going to be the first example of OWF-fishing co-uses, it will be a unique opportunity to model the transformations of the fishermen's living conditions. A comparative analysis could also be conducted on the adaptations as two other OWFs (Fécamp and Saint Brieuc in the English Channel) are going to be commissioned. What insights and lessons can be drawn from this co-use experience in-the-making, which is rarely observed in Europe (Belgium, for instance, prohibits fishing in OWFs in operation)? Will aquaculture develop in the OWF areas? What issues of area sharing (co-uses) between fishing, aquaculture, and OWF will the setting-up of aquaculture arise? How will tourism concretely address and adapt to OWFs? All these questions are relevant because we can monitor the evolution of the SES, the onset of new actors, the emergence of new issues, and the adaptation to the each other's conditions of living. In future research studies, it will be important to investigate who will be impacted and how these sectors can recover, typical questions that can be addressed with participatory workshops. The present loop model could be used in the future to explore alternative job opportunities for fishermen: would they switch to another activity? Would they still go fishing in the OWF area? Scenarios could be developed, tested in the model and evaluated. Loop analysis has in fact the merit of combining the fast testing of alternative hypotheses, through the construction of signed digraphs that require simple input data and no knowledge on the mathematical formulations that describe interactions between variables (Scotti et al. 2020). Fishermen and other stakeholders could be involved in the discussion of alternative management options, enabling the quick testing of their consequences and potentially increasing their acceptance.

This model can be used to inform policy goals such as marine spatial planning of areas for offshore wind turbines. In France in particular, the burning news of the revision of the strategic seafront documents is part of a wide national public debate covering each of the four metropolitan maritime façades, from November 2023 to April 2024. The aim of this public debate, entitled "La mer en débat" ("the sea in debate"), is to determine where the 45 GW deployment target, set by the French government for 2050, should be installed. This debate takes into account other parallel issues such as the definition of strong protection zones for marine species and habitats and potential conflicts of co-use (fishing, pleasure boating, perceived wildness of landscapes, etc.). This model, used at the level of each maritime seafront for public debates, would be a relevant, pragmatic tool for engaging stakeholders in practical planning work in order to bring forward concrete proposals of OWF locations to the State. Such an approach would have the effect of increasing trust and understanding amongst stakeholders in the final public decision on future siting areas.

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Author contributions

All authors developed the ideas, conceptualized, and participated to the writing the manuscript. MT was the lead author and write the original draft. NN, MS and RFG reviewed and edited the manuscript. MT, MS, RFG conceptualized and built the model and analyzed it, with the help of Jeffrey M. Dambacher and Marie Le Marchand. NN. initiated and supervised the work and secured funds, together with François Le Loc'h.

Supplementary data

Supplementary data is available at *ICES Journal of Marine Science* online.

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Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

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