Development of a model for the identification of suitable areas for the development of wave energy projects in the European Atlantic region in the context of maritime spatial plann...

Technical Report · October 2022

DOI: 10.13140/RG.2.2.29874.07360

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SAFE WAVE

STREAMLINING THE ASSESSMENT
OF ENVIRONMENTAL EFFECTS
OF WAVE ENERGY

Development of a model for the identification of suitable areas for the development of wave energy projects in the European Atlantic region in the context of maritime spatial planning and its implementation into a Decision Support Tool

Co-funded by the European Union

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WP 6

Development and implementation of Decision Support Tools for wave energy development in the context of maritime spatial planning

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SUBMISSION DATE
27| September| 2022

DISSEMINATION LEVEL

PU	Public	X	
CL	Classified – EU classified (EU-CONF, EU-RESTR, EU-SEC) under Commission Decision No 2015/444		
CO	Confidential, only for members of the consortium (including Commission Services)		

DOCUMENT HISTORY

Issue Date	Version	Changes Made / Reason for this Issue
27/09/2022	0.1	Ibon Galparsoro and co-authors. Final version
06/10/2022	1	Juan Bald. Reviewed version

CITATION

Galparsoro, I., G. Mandiola, G., R. Garnier, I. de Santiago, E. Villarín, G. Iglesias, I. Machado, T. Soulard, E. Le Bourhis, L. Zubiate, I. Menchaca and J. Bald, 2022. Development of a model for the identification of suitable areas for the development of wave energy projects in the European Atlantic region in the context of maritime spatial planning and its implementation into a Decision Support Tool. The corporate deliverable of the SafeWAVE Project co-funded by the European Climate, Infrastructure and Environment Executive Agency (CINEA), Call for Proposals EMFF-2019-1.2.1.1 - Environmental monitoring of ocean energy devices. 50 pp + Annexes.

This Project is co-funded by the European Climate, Infrastructure and Environment Executive Agency (CINEA), Call for Proposals EMFF-2019-1.2.1.1 - Environmental monitoring of ocean energy devices.

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1. SAFE WAVE project synopsis

The European Atlantic Ocean offers a high potential for marine renewable energy (MRE), which is targeted to be at least 32% of the EU's gross final consumption by 2030 (European Commission, 2020(European Commission, 2020). The European Commission is supporting the development of the ocean energy sector through an array of activities and policies: the Green Deal, the Energy Union, the Strategic Energy Technology Plan (SET-Plan) and the Sustainable Blue Economy Strategy. As part of the Green Deal, the Commission adopted the EU Offshore Renewable Energy Strategy (European Commission, 2020) which estimates to have an installed capacity of at least 60 GW of offshore wind and at least 1 GW of ocean energy by 2030, reaching 300 GW and 40 GW of installed capacity, respectively, moving the EU towards climate neutrality by 2050.

Another important policy initiative is the REPowerEU plan (European Commission, 2022) which the European Commission launched in response to Russia's invasion of Ukraine. REPowerEU plan aims to reduce the European dependence amongst Member States on Russian energy sources, substituting fossil fuels by accelerating Europe's clean energy transition to a more resilient energy system and a true Energy Union. In this context, higher renewable energy targets and additional investment, as well as introducing mechanisms to shorten and simplify the consenting processes (i.e., 'go-to' areas or suitable areas designated by a Member State for renewable energy production) will enable the EU to fully meet the REPowerEU objectives.

The nascent status of the MRE sector and Wave Energy (WE) in particular, yields many unknowns about its potential environmental pressures and impacts, some of them still far from being completely understood. Wave Energy Converters' (WECs) operation in the marine environment is still perceived by regulators and stakeholders as a risky activity, particularly for some groups of species and habitats.

The complexity of MRE licensing processes is also indicated as one of the main barriers to the development of the sector. The lack of clarity of procedures (arising from the lack of specific laws for this type of projects), the varied number of authorities to be consulted and the early stage of Marine Spatial Planning (MSP) implementation are examples of the issues identified that may delay the permitting of the projects.

Finally, there is also a need to provide more information on the sector not only to regulators, developers and other stakeholders but also to the general public. Information should be provided focusing on the ocean energy sector technical aspects, effects on the marine environment, role on local and regional socio-economic aspects and effects in a global scale as a sector producing clean energy and thus having a role in contributing to decarbonise human activities. Only with an informed society would be possible to carry out fruitful public debates on MRE implementation at the local level.

These non-technological barriers that could hinder the future development of WE in EU were addressed by the WESE project funded by EMFF in 2018. The present project builds on the results of the WESE project and aims to move forward through the following specific objectives:

1. Development of an **Environmental Research Demonstration Strategy** based on the collection, processing, modelling, analysis and sharing of environmental data collected in WE sites from different European countries where WECs are currently operating (Mutriku power plant and BIMEP in Spain, Aguçadoura in Portugal and SEMREV in France); the SafeWAVE project aims to enhance the understanding of the negative, positive and negligible effects of WE projects. The SafeWAVE project will continue previous work, carried out under the WESE project, to increase the knowledge on priority research areas, enlarging the analysis to other types of sites, technologies and countries. This will increase information robustness to better inform decision-makers and managers on real environmental risks, broad the engagement with relevant stakeholders, related sectors and the public at large and reduce environmental uncertainties in consenting of WE deployments across Europe.
2. Development of a **Consenting and Planning Strategy** through providing guidance to ocean energy developers and to public authorities tasked with

consenting and licensing of WE projects in France and Ireland; this strategy will build on country-specific licensing guidance and on the application of the MSP decision support tools (i.e. WEC-ERA[1] by Galparsoro et al., 2021[2] and VAPEM[3] tools) developed for Spain and Portugal in the framework of the WESE project; the results will complete guidance to ocean energy developers and public authorities for most of the EU countries in the Atlantic Arch.

Development of a **Public Education and Engagement Strategy** to work collaboratively with coastal communities in France, Ireland, Portugal and Spain, to co-develop and demonstrate a framework for education and public engagement (EPE) of MRE enhancing ocean literacy and improving the quality of public debates.

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[1] https://aztidata.es/wec-era/;

[2] Galparsoro, I., M. Korta, I. Subirana, Á. Borja, I. Menchaca, O. Solaun, I. Muxika, G. Iglesias, J. Bald, 2021. A new framework and tool for ecological risk assessment of wave energy converters projects. Renewable and Sustainable Energy Reviews, 151: 111539. https://doi.org/10.1016/j.scitotenv.2022.156037

[3] https://aztidata.es/vapem/

2. Executive summary

The present report describes the process undertaken during the development of a model for the identification of suitable areas for the development of wave energy projects in the European Atlantic in the context of maritime spatial planning and its implementation into a web-based Decision Support Tool.

The approach implemented is based on the previous work developed by Galparsoro *et al.* (2020) in the framework of WESE project (Wave Energy in Southern Europe; Project funded by the European Commission. Agreement number EASME/EMFF/2017/1.2.1.1/02/SI2.787640). The scope of such project was the development of a model and a decision support tool for the identification of the most suitable areas for the development and deploying of wave energy projects in the Portuguese and Spanish Atlantic area. As the objective of SafeWAVE is equivalent to that of the WESE project, the same approach was adopted, but modifications, adaptations and improvements were applied to fit with the objectives of SafeWAVE. In addition, the adaptation and improvement of the model was enriched by the consultation and discussion with WEC industrial developers and scientists. The objective of the workshop was to share and discuss the approach and assumptions made during the development and operationalisation of the site suitability model. The main focus was put on the structure and technical factors considered within the model. There was a general agreement on that the main factors were already considered but additional feedback was obtained in relation to information sources and the way such factors could be integrated into the model. In particular, regarding the wave energy resource and the estimation of the production capacity, the oceanographic conditions for construction and maintenance of the devices, the calculation of the levelized cost of energy (LCOE), as well as the other aspects related to the deployment of the farms such as depth, slope, seafloor type, distance to substation and distance to port.

The conceptual model was then operationalized in a Bayesian Network. The spatial data to feed the model were obtained from different publicly available datasets. The geographical scope of the model is the European Atlantic region which covers the EEZs of Ireland, the UK, France, Spain and Portugal. Accounting for a total area of 3,676,970 km^2.

The model developed was implemented into a web-based decision support tool called VAPEM (https://aztidata.es/vapem/) and which was previously described by Galparsoro *et al.* (2020).

The model presented here is still subjected to modifications and improvements. Preliminary results of the suitable areas for development of WEC farms will be contrasted with WEC developers and scientists to reach a consensus and a final model that will be used to produce the final suitability maps under Task 6.3.

3. Glossary

WEC – Wave Energy Converter

DST – Decision Support Tool

MSP – Maritime Spatial Planning

4. Introduction

The EU has adopted the determination to achieve the climate neutrality by 2050 (European Commission, 2020), by fast forwarding the clean transition and joining forces to achieve a more resilient energy system (European Commission, 2022). To achieve such an objective a massive speed-up and scale-up in renewable energy in power generation is being promoted (European Commission, 2022). In this context, the marine renewable energy can become a key player. During the last decades new technologies have been developed to obtain energy from wind, currents, tides, and waves. In particular, the global wave energy resource is calculated to be 2.11±0.05 TW (Gunn and Stock-Williams, 2012), and part of such energy can be harvested by wave energy converters (WECs) (Sang *et al.*, 2018; Xu *et al.*, 2020), transforming the kinetic and/or potential energy of waves into electricity (Lehmann *et al.*, 2017; Mustapa *et al.*, 2017; Stratigaki, 2019). WECs will need to be deployed in large-scale arrays, forming so-called *wave farms* (Stratigaki, 2019; Veigas *et al.*, 2015).

Main barriers preventing the development of wave energy converters (WECs) are: (i) the early stage of development of these technologies, (ii) the uncertainties regarding the coastal and marine impacts and the risks of wave farms (Copping *et al.*, 2016; Copping *et al.*, 2020; Hanna *et al.*, 2016), (iii) the need for a Marine (or Maritime) Spatial Planning (MSP) approach to overcome the potential competition and conflicts between wave energy sector and other marine users (O´Hagan, 2016), (iv) the fact that they have been considered uneconomical (Astariz and Iglesias, 2015), and (v) the slow and complex consenting process, which is still generally regarded as a non-technological barrier caused by the complexity and the lack of dedicated legal frameworks (Apolonia *et al.*, 2021; European Commission, 2022; Simas *et al.*, 2015).

In order to support an acceleration of permitting procedures for renewable energy projects and related infrastructure, the Commission is amending its proposal on the Renewable Energy Directive[4]. The revised proposal operationalises the principle of renewable energy as an overriding public interest, introduces the designation of ‘go-to’ areas and other ways to shorten and simplify permitting while also minimising potential risks and negative impacts on the environment (European Commission, 2022). The renewables ‘go-to area’ means a specific location, whether on land or sea, which has been designated by a Member State as particularly suitable for the installation of plants for the production of energy from renewable sources, other than biomass combustion plants. Technical, environmental and socioeconomic aspects should be taken into account when identifying suitable areas for future development of marine renewable energy projects, which in turn requires the adoption of integrative management approaches. The Maritime Spatial Planning Directive (MSPD) (Directive 2014/89/EU) establishes a framework aimed at promoting the sustainable growth of maritime economies, the sustainable development of marine areas and the sustainable use of marine resources. Marine Spatial Planning (MSP) provides a platform for holistic assessments and may facilitate the establishment of the marine renewable energy sector (Hammar *et al.*, 2017; Yates and Bradshaw, 2018). Several approaches have been proposed in the framework of MSP for the identification of suitable areas for the development of wave energy projects (Galparsoro *et al.*, 2012; Maldonado *et al.*, 2022). Basically, they are geo-spatial multi-criteria evaluation approaches to identify optimal locations to install a wave energy farm, while minimising potential ecological risks and conflicts with other coastal and offshore users (Azzellino *et al.*, 2013; Bertram *et al.*, 2020; Castro-Santos *et al.*, 2019; Flocard *et al.*, 2016; Galparsoro *et al.*, 2012;

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[4] Proposal for a Directive of the European Parliament and of the Council amending Directive (EU) 2018/2001 of the European Parliament and of the Council as regards the promotion of energy from renewable sources, COM (2022)222, (18.5.2022)

Vasileiou *et al.*, 2017). Such approaches aim to assist planners, decision-makers, industry stakeholders and investors when identifying feasible areas, based on environmental, technical and socioeconomic criteria.

In this context, the objective of WP6 of SafeWAVE project is the wave energy development site selection under Maritime Spatial Planning framework. In a first stage the gathering, editing and management of relevant information was performed (Task 6.1) (Galparsoro *et al.*, 2021c); while, the present report focuses into the development of a model for the identification of suitable areas for the establishment of wave energy projects in the European Atlantic region in the context of maritime spatial planning and its implementation into a Decision Support Tool (Task 6.2).

5. Objective

The main objective of the present deliverable is to describe the process of development of a model for the identification of suitable areas for the establishment of wave energy projects in the European Atlantic region in the context of maritime spatial planning and its and implementation into a web-based Decision Support Tool (DST).

For the achievement of such purpose, the subsequent steps were conducted.

1. Adoption of a model that was previously developed in the framework of the Wave Energy in Southern Europe (WESE) project (Galparsoro *et al.*, 2020).
2. Adaptation of the model to fit with the objectives of SafeWAVE project, mainly the expansion of the model to the whole European Atlantic region.
3. Interactions with wave energy converters developers and scientists to discuss potential improvements of the adopted model.
4. Collation and edition of information layers needed to feed the model.
5. Model feeding.
6. Model runs and evaluation of the results.
7. Integration of the model into a web-based DST, namely VAPEM tool (https://aztidata.es/vapem/).

6. Adoption of a model for the identification of suitable areas for the development of wave energy projects

The approach implemented in the present task is based on the previous work developed by Galparsoro *et al.* (2020) in the framework of WESE project (Wave Energy in Southern Europe; Project funded by the European Commission. Agreement number EASME/EMFF/2017/1.2.1.1/02/SI2.787640). The scope of such project was the definition of a conceptual model and development of a decision support tool for the identification of the most suitable areas for the deployment of wave energy projects in the Portuguese and Spanish Atlantic area. As the objective of SafeWAVE is equivalent to the one of WESE project, we adopted the same approach, but modifications, adaptations and improvements were applied to fit with the objectives of Safe WAVE.

Basically, the approach is based on a conceptual model that considers all the most relevant technical, environmental and conflicting parameters to be considered when identifying most suitable areas for the development of wave farms (Galparsoro *et al.*, 2012). The environmental dimension of the model was defined considering the Marine Strategy Framework Directive (MSFD; Directive 2008/56/EC) for the integrated consideration of the 16 types of pressures and 27 ecosystem elements that could be affected by such technologies (Galparsoro *et al.*, 2021a). It also takes into consideration other aspects, such as potential of wave energy resource in the Atlantic area, distribution of other potentially conflicting maritime activities, legally excluded areas, important areas for relevant environmental components, and other suitability parameters (Figure 1).

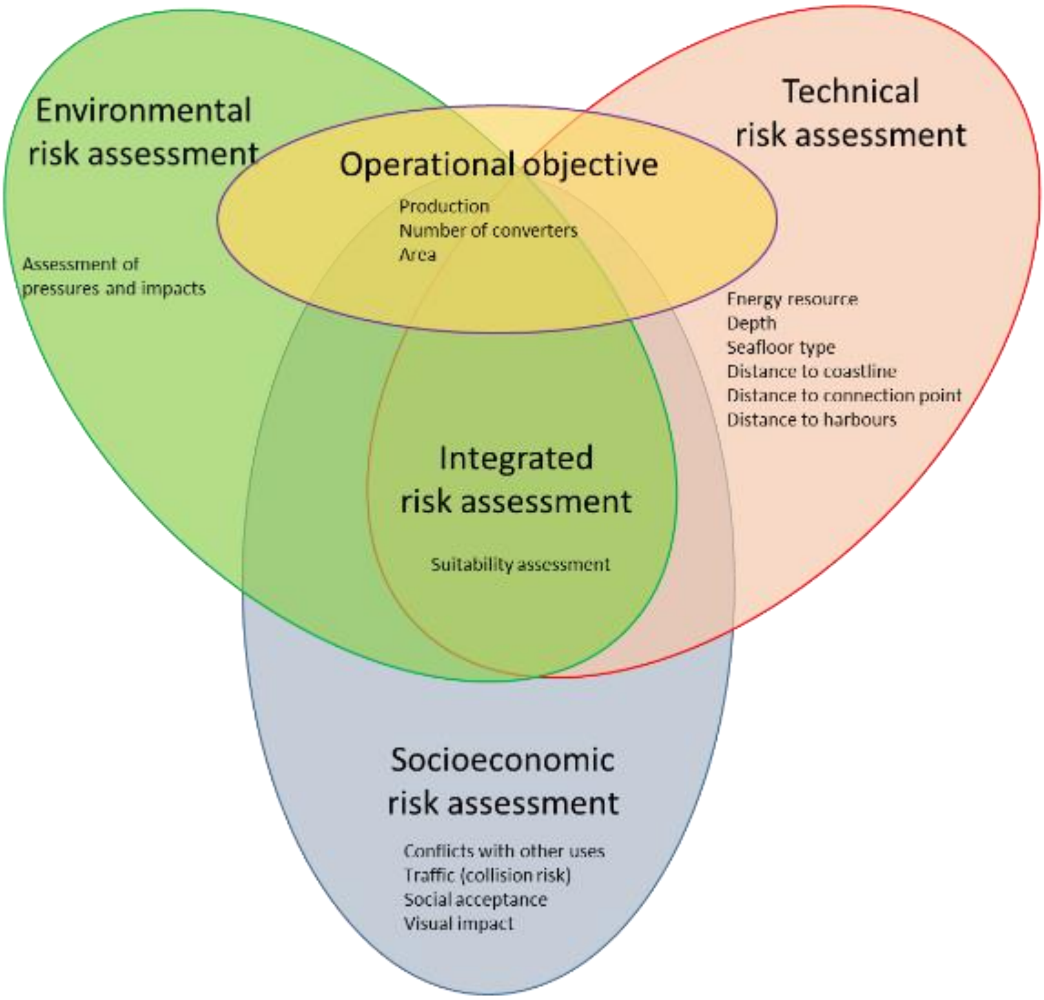

Figure 1. Conceptual model adopted for the identification of most suitable areas for the development of wave farms. Adopted from Galparsoro *et al.* (2020).

7. Model development

7.1 Integration of expert knowledge

The adaptation and improvement of the model was enriched by the consultation and discussion with WEC industrial developers and scientists.

On the 25th of May 2022 an online workshop was organized by AZTI. The objective of the workshop was to share the advances made and to discuss with the industrial partners of SafeWAVE project and other WEC developers the approach and assumptions made during the development and operationalisation of the site suitability model. A total number of 10 people attended to the workshop:

- Patxi Etxaniz (IDOM)
- Enric Villarín (CORPOWER)
- Ines Machado (WAVEC)
- Thomas Soulard (Ecole Centrale de Nantes)
- Enored Le Bourhis (Ecole Centrale de Nantes)
- Laura Zubiate (BiMEP)
- Gotzon Mandiola (AZTI)
- Roland Garnier (AZTI)
- Juan Bald (AZTI)
- Ibon Galparsoro (AZTI)

A presentation was made to guide the discussion (accessible in Annex I of the present report). During the presentation, discussions were held regarding the approach, structure and indicators.

7.1.1 Main outputs of the meeting

7.1.1.1 Model structure and factors considered

First aspect that was presented to the attendees was the structure of the model that was adopted for further improvement (Figure 2 and Figure 3). There was an agreement among the attendees that the model suggested, was considering all the most relevant factors when assessing site suitability.

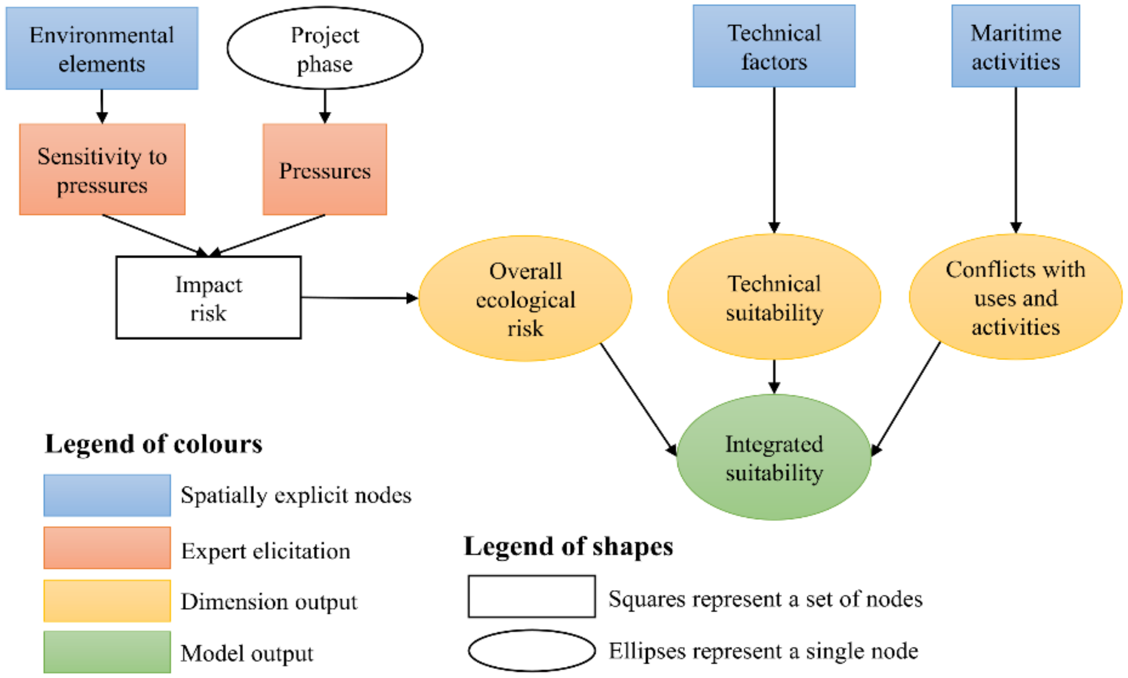

Figure 2. Simplified representation of the model adopted for the identification of suitable areas for the development of wave farms. Adapted from Maldonado *et al.* (2022).

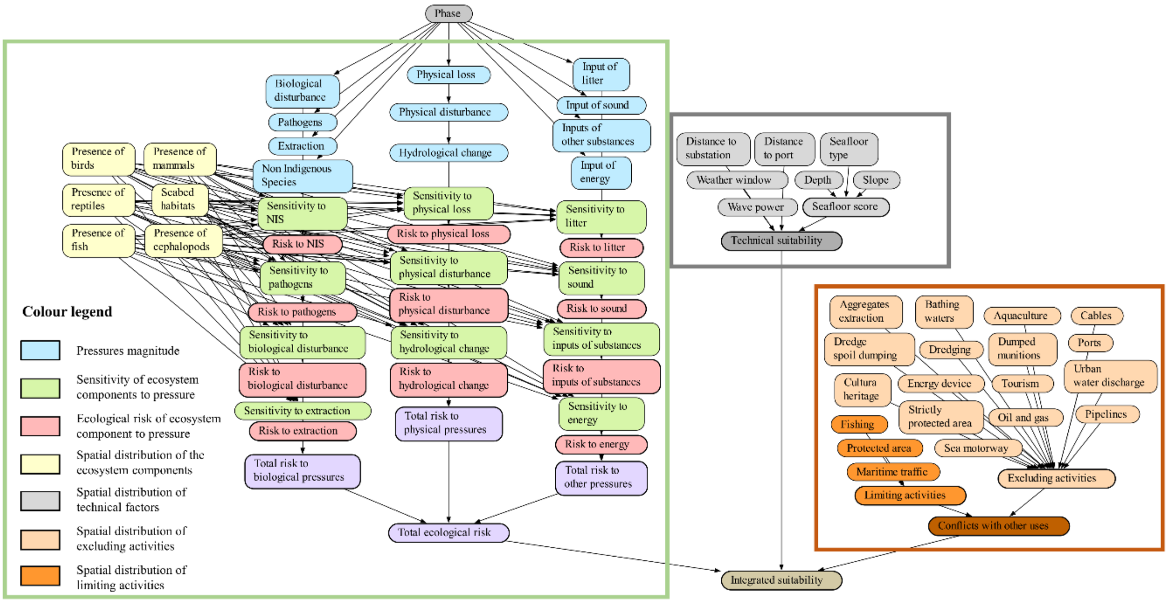

Figure 3. Bayesian belief model defined for the identification of suitable areas for the development of wave energy projects. The green box contains all the "environmental dimension" of the model and considers the environmental pressures (stressors) that might be produced by wave energy converters, the ecosystem elements that are sensitive to those pressures (receptors), and corresponding ecological risk. The yellow boxes represent nodes for which the model is fed with spatially explicit information. The grey box contains the factors considered under "technical dimension"; and the orange box accounts for the marine activities that potentially conflict with the establishment of wave farms. The conflicts are classified as being limiting or excluding activities with the development of wave energy farms. Adapted from Maldonado *et al.* (2022).

7.1.1.2 Technical considerations

The main focus was put on the structure and technical factors within the model (Figure 4). There was a general agreement on the fact that the main factors were already considered but additional feedbacks were obtained, which are further developed in the next subsections.

Wave energy resource

The wave energy resource and climatic characteristics are key factor when identifying suitable areas for the development of wave energy projects. Originally, the wave energy resource was calculated from data obtained from

Copernicus Marine Service[5]. The variables used were wave height (Hs) and peak period (Tp) for a period from 1992 to 2018.

In addition, it was suggested to check the numerical estimation of energy delivery from a selection of wave energy converters by Todalshaug *et al.* (2015). Details on resource code toolbox could be found at: https://resourcecode.ifremer.fr/tools (with weather windows, wave energy production and extremes estimations).

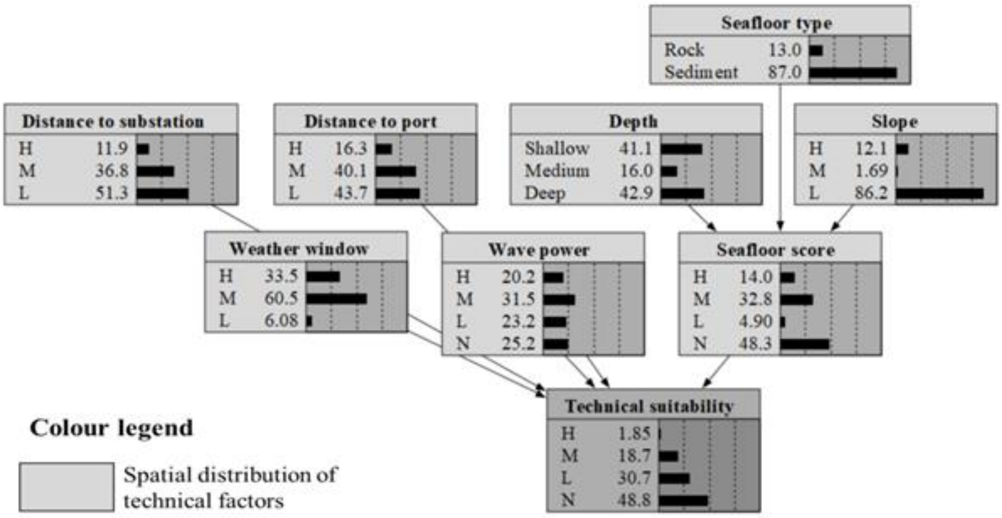

Figure 4. Technical factors considered in the Bayesian belief model for the identification of suitable areas for the development of wave energy projects. Adapted from Maldonado *et al.* (2022).

Production capacity

The most important thing is the minimum and maximum energy that can be obtained at a particular site. It is very difficult to calculate the conversion capacity of the converter at a site until the device is designed and constructed according to the characteristics of the selected site. For the model development perspective, ranges, orders of magnitude of power matrix or capacity factors for different WECs would be needed.

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[5] https://marine.copernicus.eu/

The capacity factor estimation is complex. It is calculated specifically for a device and the location in which the device will be deployed.

For the model production, it would be very useful to access to annual energy production (AEP) and capacity factor (CF) for the whole European Atlantic region.

For wave energy potential, it is need to take time-series of (Hs,Te) over at least an entire year, convolve it with the power matrix and take the yearly sum. CorPower agreed to share the CF of their device.

Good weather windows

When considering suitable areas for WECs, one must take the good weather windows into account to accomplish construction and maintenance works. Initially, we defined a weather window as the period of five consecutive days (from 6 am to 6 pm) with significant Hs lower than 1.5 m. Thus, the variable included in the model is the mean number of weather windows in a year. The higher the number of weather windows, the greater the technical suitability.

It was suggested that in most cases for maintenance activities, 1 day is enough and needs to be in daylight. Main issue is that the devices are experimental. And thus, there is high uncertainty regarding the number of times and frequency that it is necessary to visit the device. In principle, if everything works well, it is almost not necessary to go, if it is giving problems, it is necessary to go periodically, almost every week. It would be interesting to add the probability per year of having to visit the device, but at this stage of technical development of the devices, this is a difficult factor to be included in the model.

It was suggested to check the operation and maintenance characteristics and costs of offshore wind farms, as this is the sector that is more advanced and a good reference for wave energy sector. It was suggested to check Rinaldi *et al.* (2018).

Extreme events

Oceanographic extremal events play a relevant role both in the survivability of the devices, as well as in their performance, but is not considered as a critical factor to be considered. It could be considered as an economically limiting factor. WECs are designed considering extremal conditions. It is expected that extreme events will occur once or twice during the life cycle of a device. If extreme events occur during the life cycle of the device, it may break down and stop producing. But if they do not break, they continue to operate normally. It is not possible at this stage to establish a threshold and the duration of the extreme conditions.

Levelized Cost of Energy (LCOE)

Due to the nascent state of wave technology, with a wide variety of wave energy converters (WECs) under development, it is not straightforward to give a general figure for the WEC cost (Iglesias *et al.*, 2018).

De Andres *et al.* (2016) investigated the optimum size of WEC for a 20 MW array based on the CorPower Ocean technology, and a Levelized Cost of Energy (LCOE) model was created. One plausible option would be a power matrix that could consider the Aguçadoura testing site.

A recent work by Vanegas-Cantarero *et al.* (2022) provides a multi-criteria analysis of CorPower technology that could be used for the model.

Main issue when calculating the LCOE is that the information that is needed to feed the model needs to be spatially explicit. A good example is provided by Castro-Santos *et al.* (2015).

Depth

According to the developers the distance to coastline (or electricity connection point onshore), is more relevant than the depth itself (in terms of economic cost). This is because technically, the installation at deep zones is possible but involves a higher economic expense. Thus, in principle, there is no depth limitation. At the current status of development of WECs and WEC projects, it seems unrealistic to go beyond the 100 m depth. Site suitability according to depth could be classified according to three depth classes: 20-30, 30-60, 60-100.

Slope

Seafloor slope was considered in the adopted model. The idea was to avoid high slope seafloor due to potential instabilities and areas close to continental shelf break. Seafloor with higher slope than 3 degrees would be avoided. No comments and no objection to the approach was made.

Seafloor type

The model prioritizes sedimentary seafloor, because the installation is easier and cheaper, using gravity or drag anchors. Nevertheless, it should be considered that there are different designs and solutions also for rocky seafloor (thus, it is mainly an economic factor). Due to present status of development and other costs associated to the WECs installation, for the present version of the model, rocky seafloor will be avoided but not excluded.

Seafloor score

The seafloor score is obtained as the combination of to the bathymetry, slope, and seafloor type (rock or sediment). Sedimentary seafloor is preferred to rocky ones; however, the latter are not automatically excluded. Deep locations (depth > 200 meters) are not directly excluded but are less preferable due to higher potential costs of farm construction. Therefore, since the seafloor characteristics are determinant when identifying suitable locations, the proposed seafloor score can be used to filter unfeasible locations (too shallow or too steep). The seafloor score is used to prioritise sedimentary seafloor, but if the slope is low, rocky seafloor could also be suitable.

Onshore network connection

The model takes the distance to the nearest onshore electric network connection into account since this factor is of high relevance when estimating the cost of construction of the wave energy farm. Therefore, the nearer the connection, the greater the technical suitability. Distance higher than 60 km should be high.

Distance to port

The distance to port is a relevant factor that impacts on the installation and maintenance costs of the farm. Distance to different types of ports should be considered according to the project phase:

- For manufacturing and construction, the port should be large and equipped with major loading and unloading systems. It should have a shipyard.
- For maintenance operations, a small port is more than enough. Considering the high number of small ports in European coastline and that we do not have a full list of ports, a good proxy might be to consider the distance to coastline.

As an example, in Portugal, the current farms are 4 to 5 km away, and the first one was 6 km away.

CO_2 intensity

It was suggested adding CO_2 intensity as a technical factor in the next version of the tool. It might not yet be a criteria used for WECs but it is expected that it will by the time WEC become commercial. A low score could be close to CO_2 intensity of nuclear or wind, and high compared to gaz.

7.2 Operationalisation of the model

The conceptual model was then operationalised using the Bayesian Belief Network (BBN) approach. The BBN approach is suitable for the integration of the conceptual model, as it makes it possible to integrate empirical information and expert knowledge when empirical information is not available (Maldonado *et al.*, 2022).

The model integrates environmental, technical, and social dimensions (Figure 1). Figure 2 shows a simplified representation of the wave energy model, in which the type of node regarding the origin of the data (expert or real) is specified. Real data was used to feed the spatially explicit nodes, whereas expert knowledge was intended to determine the non-spatial nodes.

7.2.1 Ecological Risk Assessment

The ecological risk dimension of the model was adopted from Galparsoro *et al.* (2021a), which was operationalised by Galparsoro *et al.* (2021b) and Maldonado *et al.* (2022).

Ecological risk can be described as the likelihood and magnitude of adverse effects from stressors to ecological receptors (Figure 5). ERAs (Hope, 2006) could be used to link a certain operational activity with the vulnerability of ecosystem components and with the occurrence and magnitude of pressures that such activity could pose in the environment. To assess the total risk and the identification of management measures that could be adopted for minimising the potential environmental impact.

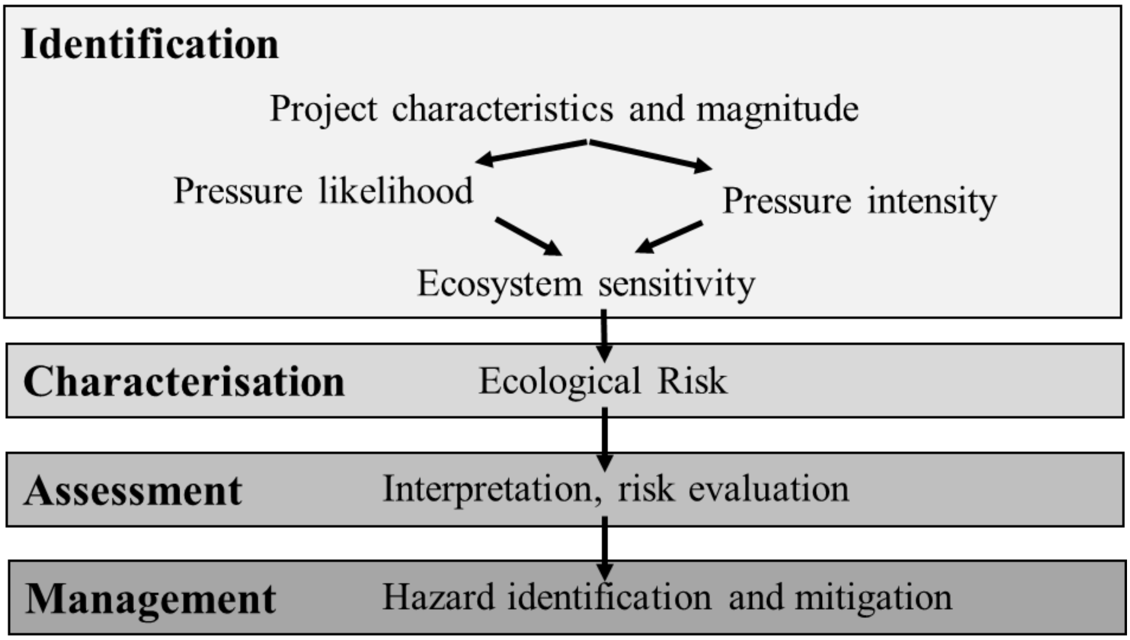

Figure 5. General framework implemented for the Ecological Risk Assessment. From Galparsoro *et al.* (2021a).

Figure 6 shows the piece of BBN involving the environmental dimension, i.e., the pressures produced by each technology, the sensitivity of different environmental components (e.g., mammals, marine birds, seafloor, etc.) to these pressures and their risk.

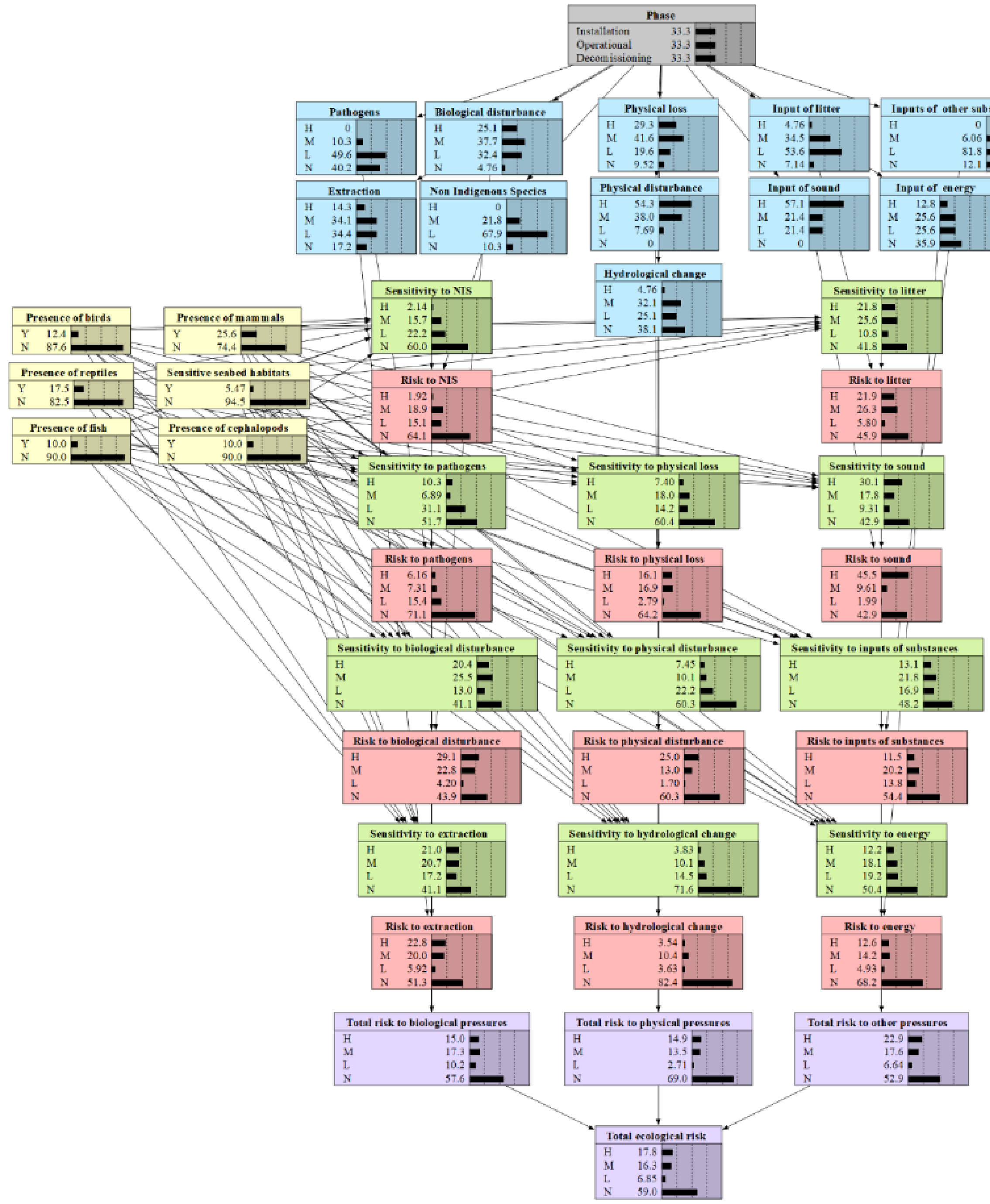

Figure 6. Environmental dimension of the Bayesian model implemented for the identification of suitable áreas for the development of wave farms. Blue nodes represent each of the pressures potentially produced by a wave energy converter, while the green nodes represent the sensitivity of each of the ecosystem components to each pressure and the estimated risk (red). The model calculates the total pressures and the total environmental risks (violet). Adapted from Maldonado *et al.* (2022).

7.2.2 Technical Assessment

The technical dimension of the model is also based on Galparsoro *et al.* (2021b) and Maldonado *et al.* (2022), but it was adapted according to feedbacks obtained from wave energy converters developers.

The current wave energy technology has a number of requirements to select a suitable location, including the depth or seafloor type. Moreover, the wave power (resource) is an important factor to consider when determining technically feasible locations. Other factors considered in this model are the distances to coast, nearest port, and nearest electrical substation. Figure 7 shows the piece of BBN that reflects this technical assessment.

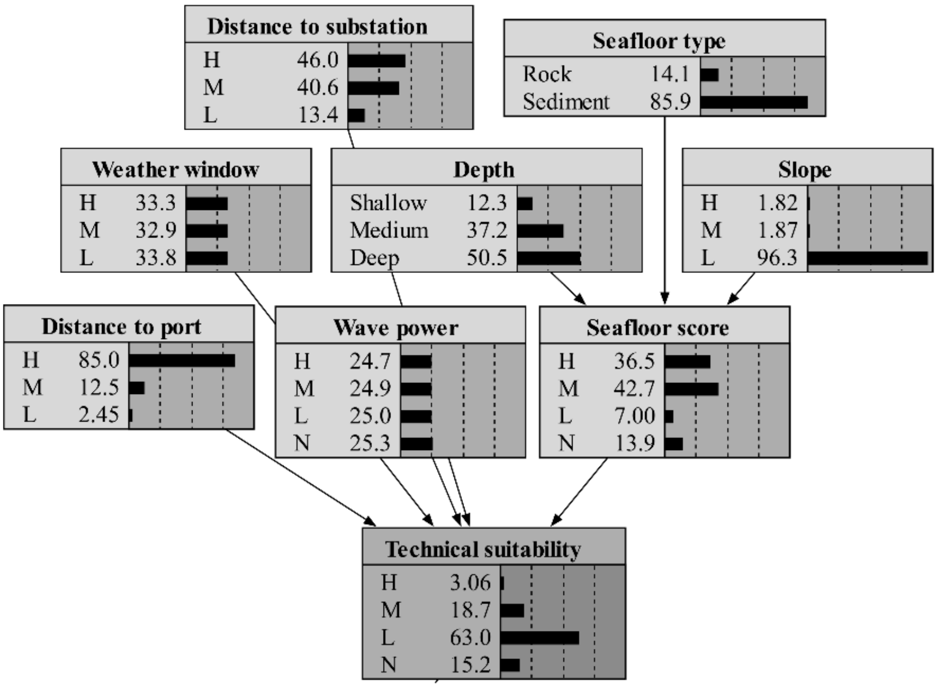

Figure 7. Technical dimension of the Bayesian model implemented for the identification of suitable areas for the development of wave farms.

7.2.3 Conflicts with other uses

The interaction of different activities taking place in the same location is a challenge that needs to be tackled when planning suitable locations for new wave energy farms. In this regard, 18 excluding and 4 limiting factors are considered in the model (Figure 8). Excluding factors are incompatible activities or uses of the space, such as marine protected areas, bathing waters or dredging areas. Limiting factors are compatible but limiting activities, such as maritime traffic or fishing. Figure 8 shows the piece of BBN that represents possible conflicts between the infrastructure of WECs and the economic activities considered.

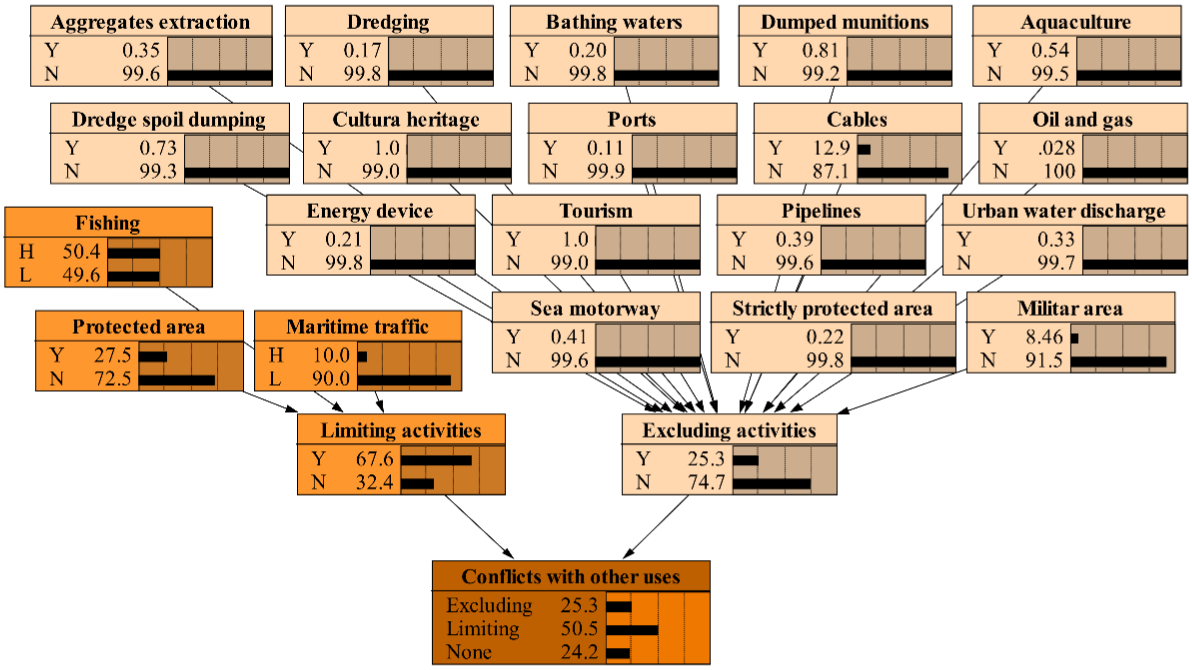

Figure 8. Bayesian model that considers the potential conflicts of wave energy farms with other marine uses.

Finally, Figure 9 shows the full BBN model constructed. Interactions between multiple stressors are combined using several pathways. Blue nodes represent the pressure types potentially produced by a WEC. Green nodes represent the sensitivity of different ecosystem components to such pressures; while the red nodes, represent the ecological risk of the project to each individual ecosystem element. All of these result into the total ecological risk (violet boxes).

Besides, the grey-coloured nodes represent the risks associated to the technical dimension based on seven parameters. The orange nodes represent the conflicts with other sectors classified as being limiting or excluding. Finally, the final integrated feasibility is obtained as a result of the combination of the environmental, technical feasibility and conflicts with other uses.

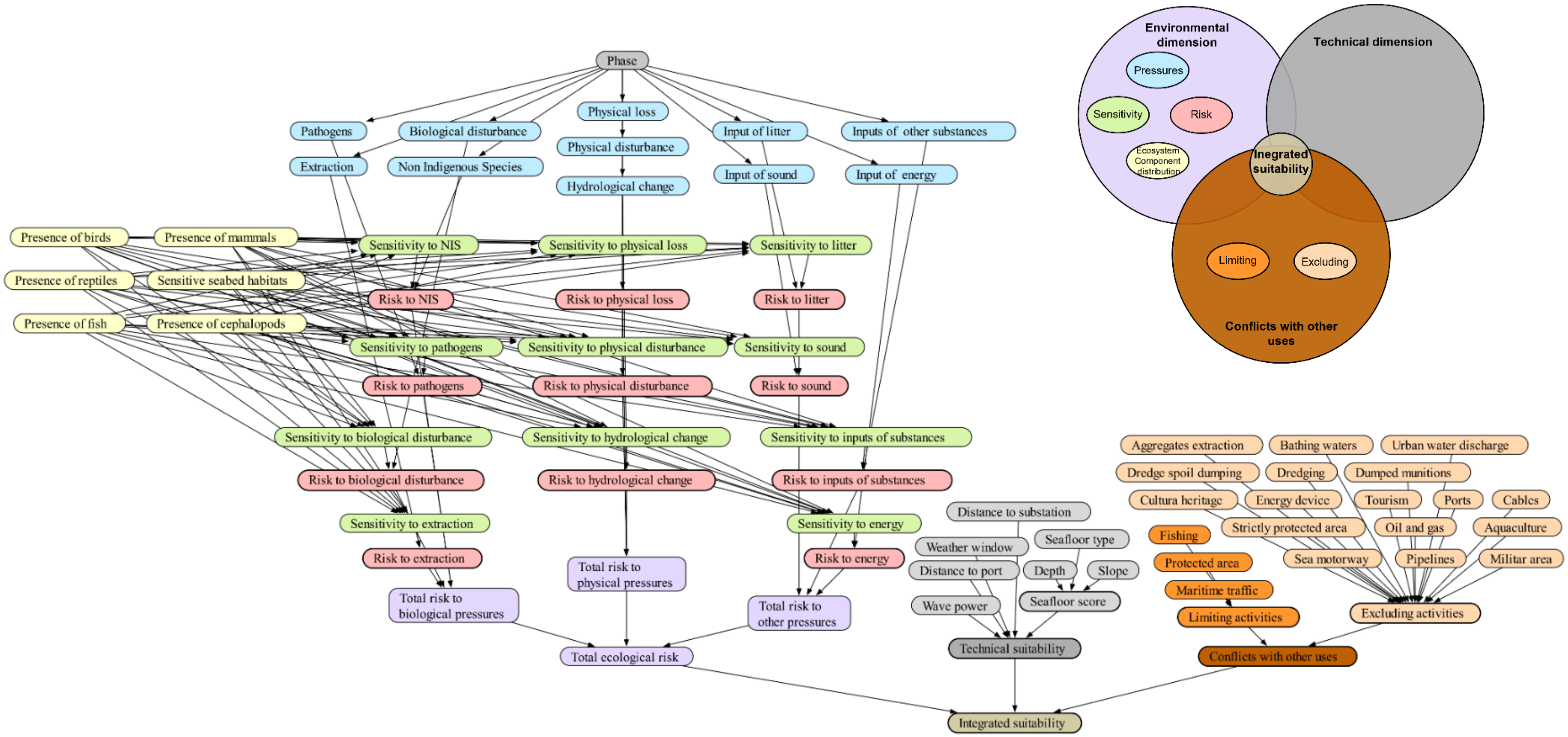

Figure 9. Structure of the full Bayesian network model for the identification of suitable areas for the development of wave energy farms. The final node, integrated feasibility results from the combination of the total environmental risk, technical feasibility, and conflicts with other (limiting or excluding) activities. Adapted from Maldonado *et al.* (2022).

7.3 Model feeding

All the variables in the wave energy model are discrete, or have been discretized, and both real data and expert knowledge were used. Real data was used to feed the spatially explicit nodes, for instance, the wave power, whereas expert knowledge was intended to determine the non-spatial nodes, such as the pressures produced by a WEC.

7.3.1 Description of spatial data

The spatial data were obtained from different publicly available datasets. The geographical scope of the model is the European Atlantic region which covers the EEZs of Ireland, UK, France, Spain and Portugal (Figure 10)[6]. The total area of the study area is 3,676,970 km^2. A reference grid of 1 km resolution is used as the unit of observation, which is based on the ETRS89 Lambert Azimuthal Equal Area coordinate reference system. The first stage of the WP6 was the identification, gathering, editing and management of relevant information for identifying suitable areas for the development of wave energy projects (Galparsoro *et al.*, 2021c). The identified sources of information dealt with:

- Technical aspects such as wave energy resource, depth, seafloor type distribution, distance to ports and good weather windows. Those factors are of high relevance for the identification of suitable areas in terms of their technical viability.
- Legal constraints representing the spatial distribution of areas that could be under different management and legal restrictions that could affect the development or establishment of wave energy facilities.
- Environmental aspects for the consideration of the potential ecological risk that the establishment or development of a wave farm may have.

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[6] Obtained from https://www.marineregions.org/

- Maritime activities and uses that potentially could conflict or pose limitations to the development or establishment of marine wave energy facilities.

The full list of spatially explicit variables, description and discretization values used for the Bayesian Network development is shown in Table 1.

It should be noted that the process of generation of relevant information for site suitability will be a continuous process throughout the SafeWAVE project.

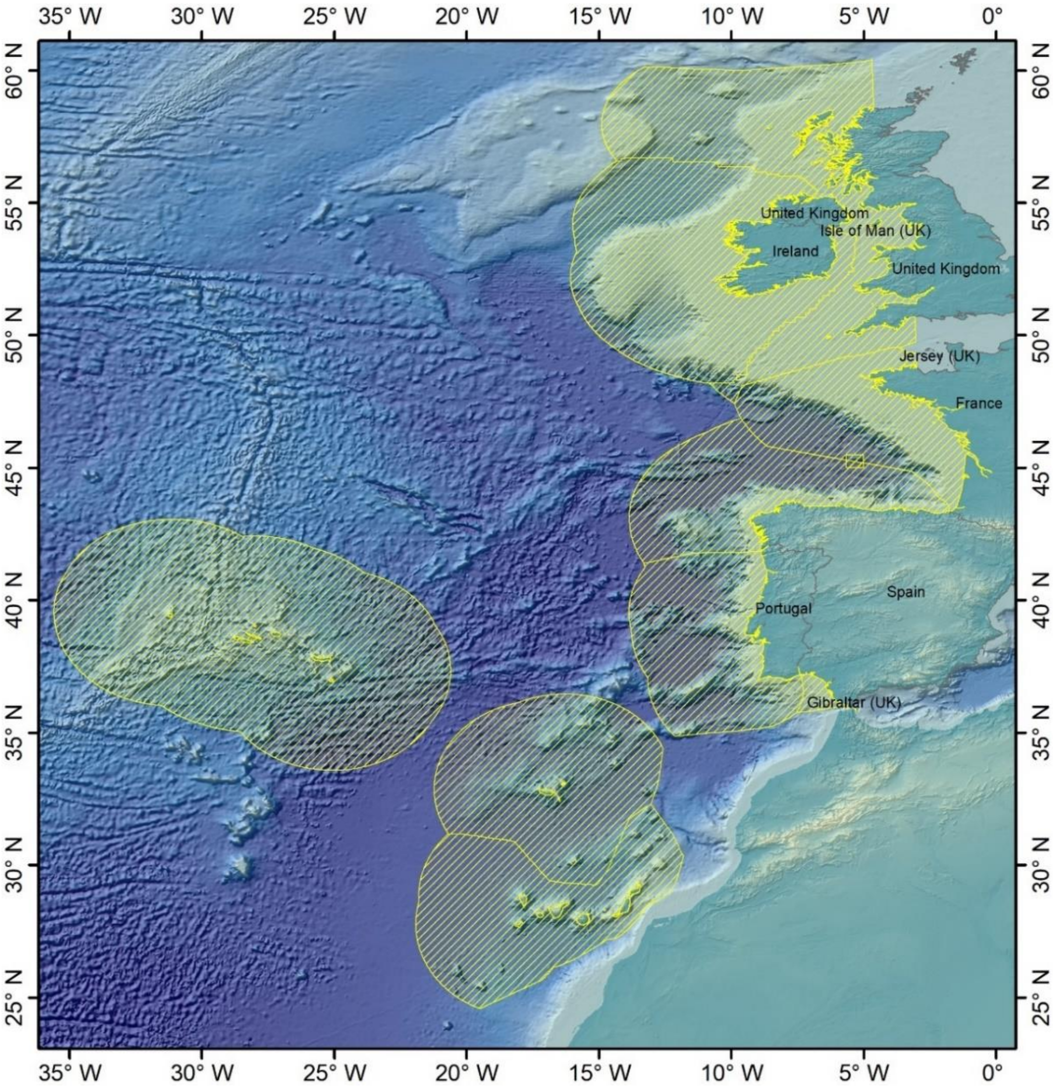

Figure 10. Spatial extension of the analysis area in the European Atlantic region which considers the exclusive economic zones of Ireland, UK, France, Spain and Portugal[3].

Table 1 List of spatially explicit variables, description and discretization values used for the Bayesian Network development.

Node set	Node name	Description	Discretization
Environmental component	Fish presence	Species (elasmobranchii and actinopterygii) richness (n° of species per square kilometre), based on predictions of occurrence. Source Aquamaps.org	Computed as quantile 90 H: [475, 800] L: [54, 475)
Environmental component	Mammal presence	Species richness (n° of species per square kilometre), based on predictions of occurrence of mammal species. Source Aquamaps.org	Computed as quantile 90 H: [9, 13] L: [0, 9)
Environmental component	Reptile presence	Species richness (n° of species per square kilometre), based on predictions of occurrence. Source Aquamaps.org	Computed as quantile 90 H: [3, 4] L: [0, 3)
Environmental component	Bird presence	Breeding bird species richness (n° of species per square kilometre), based on predictions of occurrence. Source Aquamaps.org	Computed as quantile 90 H: [18, 25] L: [0, 18)
Environmental component	Cephalopod presence	Species richness (n° of species per square kilometre), based on predictions of occurrence. Source Aquamaps.org	Computed as quantile 90 H: [67, 78] L: [16, 67)
Environmental component	Seabed presence	Presence of sensitive habitats	Y: Presence of sensitive habitats N: otherwise (or unknown)
Technical component	Seafloor type	Most frequent seabed substrate type in a cell	Rocky: Rock or other hard substrate majority Sedimentary: Non rocky substrate majority
Technical component	Wave power	Mean wave power (MWh/m) in a cell	N: [0, 217) L: [217, 282) M: [282, 331) H: [331, 401]

Node set	Node name	Description	Discretization
Technical component	Depth	Mean depth in a cell (meters)	Deep: [-200, -100) Medium: [-100, -30) Shallow: [-30, 0]
Technical component	Distance to port	Distance from centre of cell to nearest port, avoiding land (km)	L: [0, 10) M: [10, 30) H: [30, 600]
Technical component	Distance to electrical substations	Straight distance from centre of cell to nearest electrical substation	L: [0, 30) km M: [30, 100) km H: [100, 600] km
Human activities	Cable	Presence/absence of cables (buffer 500 m)	Y: presence of cables N: otherwise (or unknown)
Human activities	Dredging	Presence/absence of dredging sites (buffer 500 m)	Y: presence of dredging sites N: otherwise (or unknown)
Human activities	Aggregates extraction areas	Presence/absence of aggregates extraction areas (buffer 500 m)	Y: presence of aggregates extraction areas N: otherwise (or unknown)
Human activities	Ports	Presence/absence of ports (buffer 1 km)	Y: presence of ports N: otherwise (or unknown)
Human activities	Ocean energy devices	Presence/absence of "in development" or "operational" ocean energy devices (buffer 500 m)	Y: presence of devices N: otherwise (or unknown)
Human activities	Oil and gas	Presence/absence of areas of "exploitation" or "exploration" of oil or gas	Y: presence of oil or gas areas N: otherwise (or unknown)
Human activities	Pipelines	Presence/absence of pipelines (buffer 500 m)	Y: presence of pipelines N: otherwise (or unknown)
Human activities	Dredge spoil dumping	Presence/absence of dredge spoil dumping sites (buffer 500 m)	Y: presence of dredge soil dumping sites N: otherwise (or unknown)
Human activities	Dumped munitions	Presence/absence of dumped munitions sites (buffer 500 m)	Y: presence of dumped munition sites N: otherwise (or unknown)

Node set	Node name	Description	Discretization
Human activities	Urban waste discharge	Presence/absence of urban waste discharge sites (buffer 500 m)	Y: presence of urban waste discharge points N: otherwise (or unknown)
Human activities	Bathing waters	Evaluation of bathing waters. Possible values are excellent, good, sufficient, poor and not evaluated	Y: bathing waters have been evaluated N: otherwise
Human activities	Aquaculture	Presence/absence of fish or shellfish aquaculture sites (buffer 500 m)	Y: presence of aquaculture sites N: otherwise (or unknown)
Human activities	Protected areas	Presence/absence of marine protected areas (MPAs) incompatible with other activities	Y: presence of MPAs N: otherwise (or unknown)
Human activities	Strictly protected areas	Presence/absence of marine strictly protected areas (strictly MPAs) incompatible with other activities	Y: presence of strictly MPAs N: otherwise (or unknown)
Human activities	Sea motorway	Presence/absence of sea motorways	Y: presence of sea motorways N: otherwise (or unknown)
Human activities	Cultural heritage	Presence/absence of cultural heritage sites	Y: presence of cultural heritage sites N: otherwise (or unknown)
Human activities	Militar area	Presence/absence of military area	Y: presence of military area N: otherwise (or unknown)
Human activities	Tourism	Presence/absence of touristic sites	Y: presence of touristic sites N: otherwise (or unknown)
Human activities	Fishing effort	Number of fishing vessels above 15 m length	L: [2, 7) H: [7, 1690]
Human activities	Maritime traffic	Vessel density (Hours/km^2*moth)	L: [0, 2.8) H: [2.8, 2.2*10^4)

7.3.2 Mean Annual Energy Resource

Wave data:

The wave reanalysis data presented by Maldonado *et al.* (2022) have been extended to the new domain covering the European Atlantic region. Furthermore, the data have been updated with the 2022 database, that contains data for the period 1993-2020 (Maldonado et al., 2022 used data for the period 1993-2019). Another improvement with respect to the Maldonado et al., 2022 study, is about the spatial resolution.

Most of the wave data were collected from the IBI-MFC Multi-Year (MY) high-resolution wave reanalysis product provided by CMEMS (IBI_REANALYSIS_WAV_005_006, hourly data). The reanalysis is based on the MFWAM model developed by Meteo-France (MF), fed by the ERA 5 reanalysis wind data from ECMWF. and has a horizontal resolution of 0.05° (the reanalysis used by Maldonado *et al.* (2022) had a resolution of 0.1°). This dataset covers the IBI (Iberian Biscay Irish) area (latitude [-19°, 5°], longitude [26°, 56°]). It includes the offshore islands of Spain and Portugal, except Azores (Canary Islands, Balearic Islands, Madeira). For Azores, wave data were downloaded from the global wave reanalysis product provided by CMEMS (WAVERYS, GLOBAL_REANALYSIS_WAV_001_032), obtained with the same MFWAM model forced by the ERA5 wind field, with a horizontal resolution of 0.2° and a temporal resolution of 3 hours (like Maldonado et al., 2022). The following spectral sea state parameters have been used: significant wave height (*Hs*), mean period (*Tm*), peak period (*Tp*), mean direction (*Dm*) and peak direction (*Dp*). Similarly, to Maldonado *et al.* (2022), only the points located at depth lower than 200 m were used.

Energy resource:

The energy resource is obtained by means of linear wave theory. The wave power (*P*) reads:

$$P = Ec_g$$

where the wave energy (*E*) is expressed as:

$$E = \frac{1}{16}\rho g {H_s}^2$$

where ρ (Rho) is the density of seawater (assumed to be 1025 kg/m^3) and *g* is the gravitational acceleration.

The wave group celerity (c_g) is expressed as:

$$c_g = \frac{L}{T_e}\frac{1}{2}\left(1 + \frac{2kh}{\sinh 2kh}\right)$$

where *L* is the wavelength, *Te* is the energy period, *k* is the wave number and *h* the water depth.

Te can be estimated by means of the spectral moments if available. However, if the spectral shape is unknown (as in the present case) approximations should be used. In the present study, it is assumed that the sea states follow a standard JONSWAP spectrum with a peak enhancement factor of γ = 3.3, which allows to simplify the following relation *Te ≈ 0.9Tp* representative of regions with combined presence of sea and swell sea states (Cornett, 2008; Gonçalves *et al.*, 2014; Sierra *et al.*, 2016). Despite that this assumption introduces some uncertainty in the estimation of *P*, it should be taken into account that it is proportional to *Te* and to the square of *Hs*, so the errors induced by inaccurate *Te* are less significant than the errors induced by inaccurate Hs.

Finally, the annual energy resource (AER, in MWh/m) for a given year is obtained by the following expression:

$$AER = \sum_{i=1}^{N_H}\sum_{j=1}^{N_T} f\big(Hs(i), Te(j)\big)\, P\big(Hs(i), Te(j)\big)\, 10^{-6}$$

where *f* is the occurrence of the corresponding bin at the locations of interest. Then, we obtain the mean annual energy resource (MAER, in MWh/m), by averaging AER over the period of analysis (1993-2020):

$$MAER = \overline{AER}$$

Figure 11 shows MAER obtained with the global reanalysis WAVERYS (0.2° resolution, left, this covers the whole European Atlantic region) and with the IBI-MFC reanalysis (0.05° resolution, right).

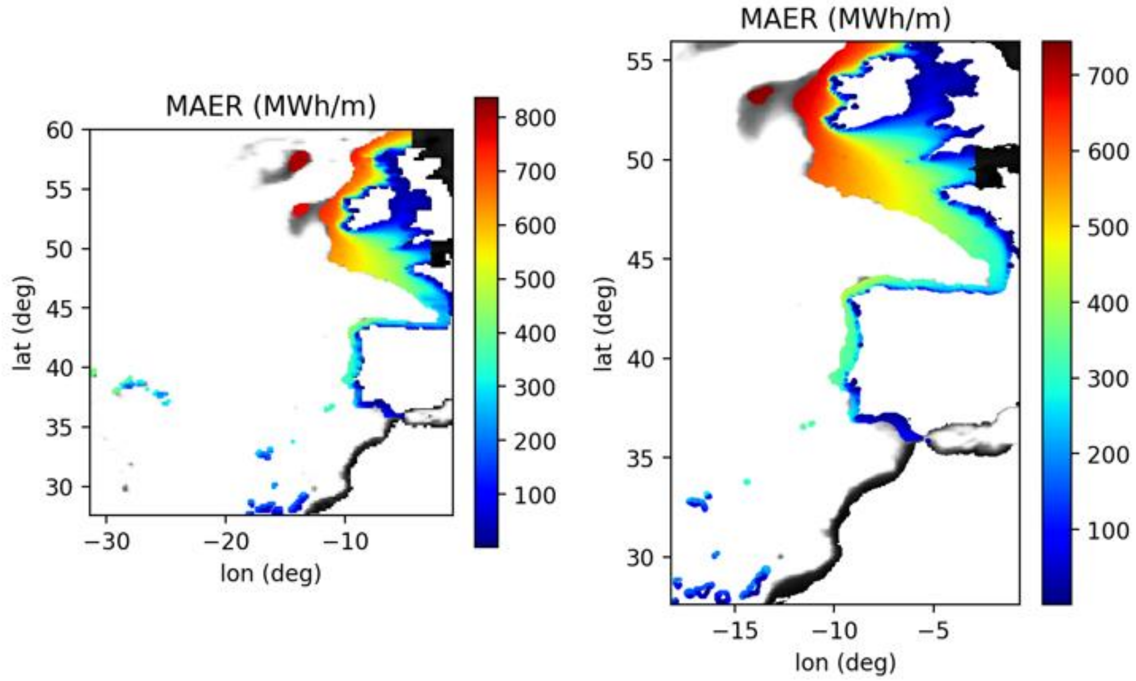

Figure 11. Mean annual energy resource (MAER, in MWh/m).

7.3.3 WEC performance

In this study, we give information of the performance of a specific device through the computation of the mean power production (MPP, in kW), the capacity factor (CF, in %) and the capture width (CW, in m).

The mean power production (MPP, in kW) is defined as follows:

$$MPP = \overline{\sum_{i=1}^{N_H}\sum_{j=1}^{N_T} f\big(Hs(i),Te(j)\big)\,PM\big(Hs(i),Te(j)\big)}$$

where PM is the power matrix of the specific device and represents the power that can be delivered for different wave conditions (Hs, Te), where the power is given in kW.

The capacity factor (CF, in %) relates the mean power production with the nominal power given of the device given by the constructor (Pmax):

$$CF = 100\,\frac{MPP}{P_{max}}$$

The capture width (CW, in m) relates the power production and the energy resource and is defined as:

$$CW = \frac{MAEP}{MAER}$$

where MAEP (in MWh) is the mean annual energy production defined as:

$$MAEP = \overline{\sum_{i=1}^{N_H}\sum_{j=1}^{N_T} f\big(Hs(i),Te(j)\big)\,PM\big(Hs(i),Te(j)\big)\,10^{-3}}$$

The following figures show the variables of interest obtained with the global reanalysis WAVERYS (0.2° resolution, left, this covers the whole European Atlantic region) and with the IBI-MFC reanalysis (0.05° resolution, right). They show preliminary results obtained for a generic power matrix. In the next steps, we will use real power matrix provided by our partners.

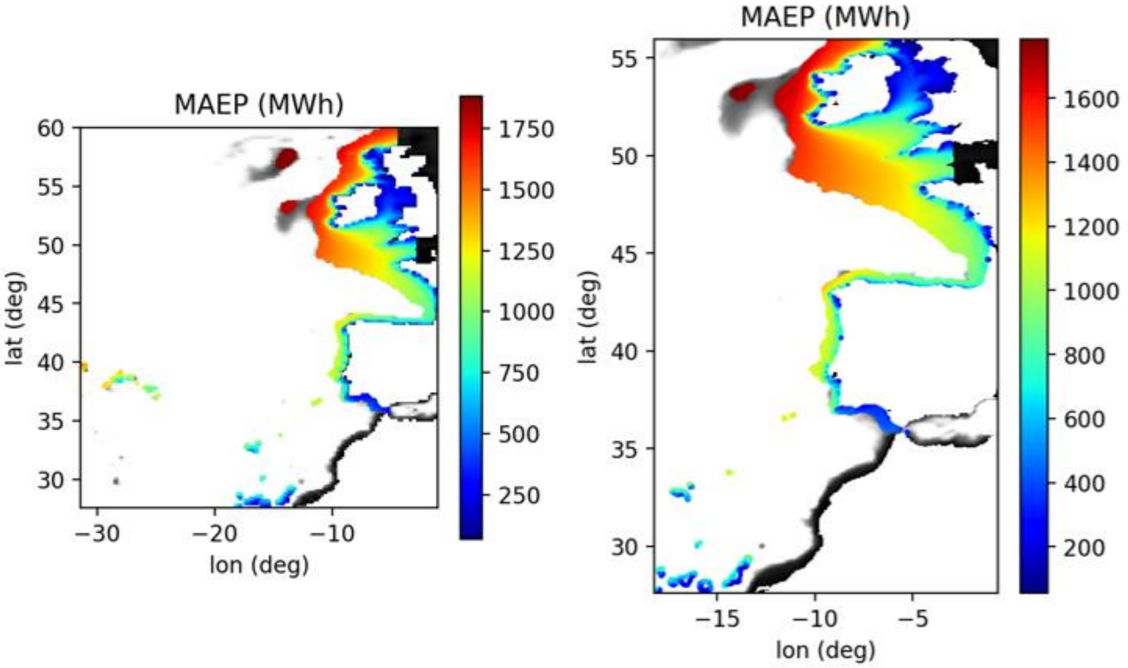

Figure 12. Mean annual energy production (in MWh)

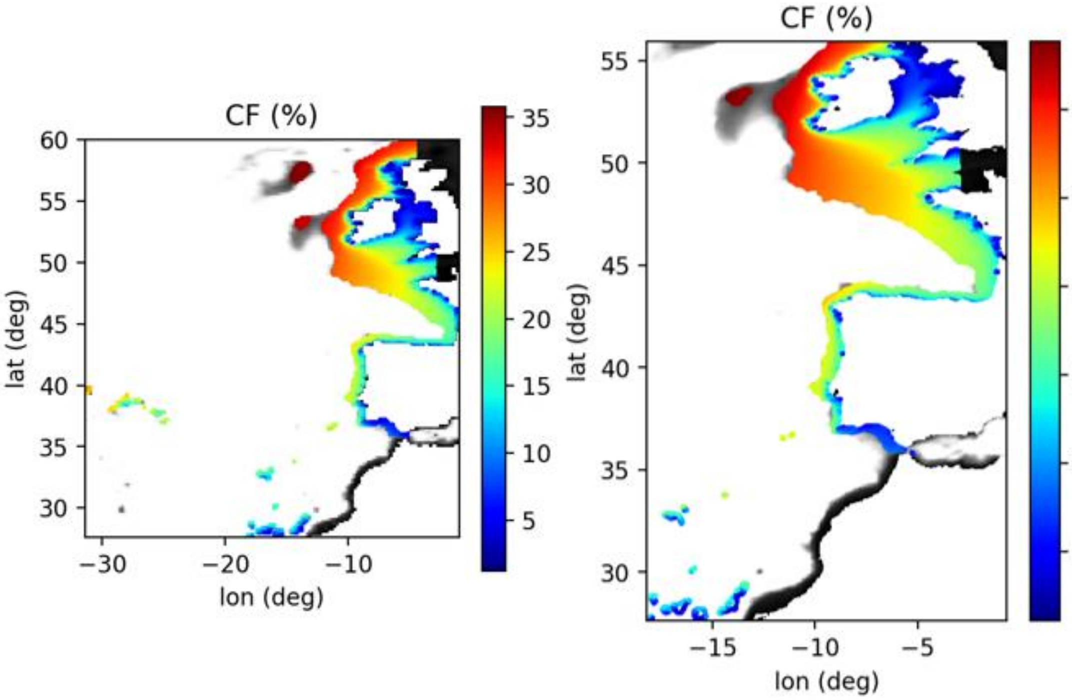

Figure 13. Capacity factor obtained for generic device (CF, in %).

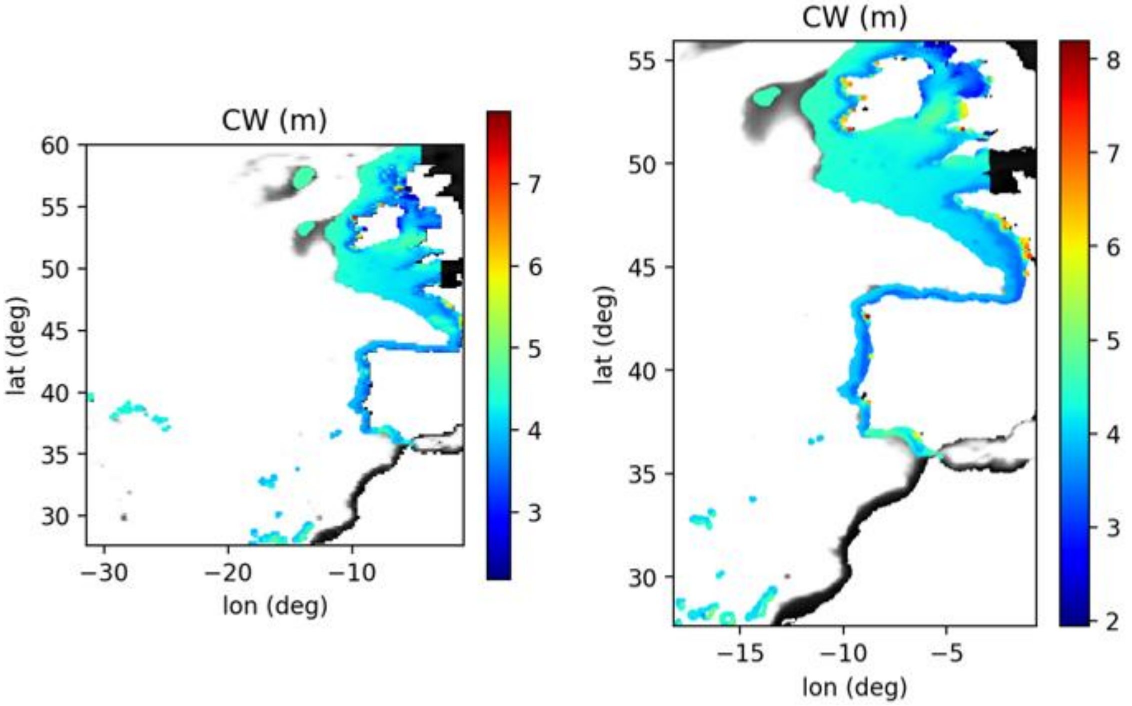

Figure 14. Capture width of a generic device (CW, in m).

8. Implementation of the model into a web-based decision support tool

The model developed and described in this report was implemented into a web-based decision support tool called VAPEM and that was previously described by Galparsoro *et al.* (2020).

The tool was developed in Shiny (https://shiny.rstudio.com), a package of R (https://cran.r-project.org) programming open source language that facilitates the creation of interactive web applications. This tool represents an interactive interface between the model and the user. The tool permits the user to define, explore and visualise the results of different scenarios, being a spatially explicit tool.

Within the main menu of the tool, the WECs feasibility model developed in SafeWAVE project is accessible by the user (Figure 15).

Once the WECs feasibility model has been selected, the user can explore different pre-defined scenarios which define different environmental, socio-economic or technical factors that could influence in the feasibility of different geographical locations for the development of wave energy projects (Figure 16), or the user can generate their own scenario by assigning different values to the parameters of the wave energy model that define the feasibility for the development of wave energy projects (Figure 17).

The user can also visualize and explore the full model and analyse the consequences of changing values (evidence) of the different factors influencing the final feasibility of the development of wave energy projects (Figure 18). Finally, the user can visualize the results of its own scenario as bar charts (Figure 19) or as a map representing the geographical distribution of the feasibility for wave energy projects development (Figure 20). The user has the option of visualising the final feasibility map and the background maps of factors influencing the final feasibility value. The tool also provides some visualisation modifications options (map colours, etc.), as well as the option of downloading the final map as a GIS layer.

Move towards an integrated understanding of maritime activities and their links to the ecosystem

This tool provides a user-friendly environment to explore complex models, define management scenarios and visualize maps, making it [illegible]

1. Select a theme of interest.
2. Pick a scenario from the list, or build your own.
3. Explore the scenario from the map viewer, how things would look under it.
4. Download the data, or go back and tweak the scenarios as you like.

If you are an experienced user, you may jump to the Full Model section, to interact directly with the models underneath.

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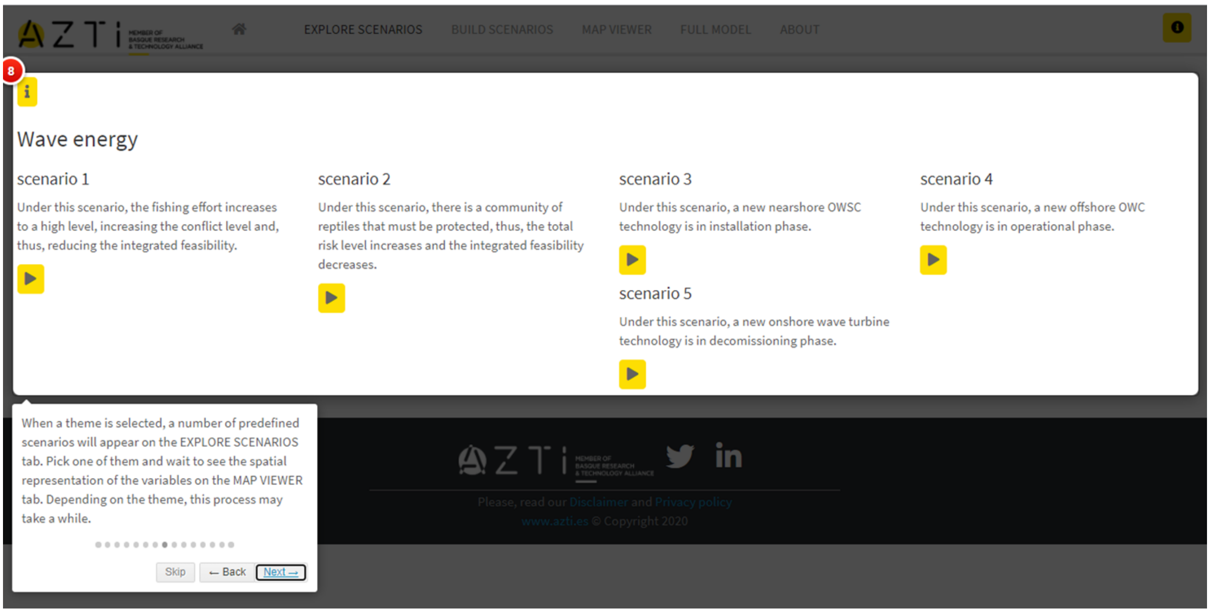
Figure 15. Front page of the VAPEM tool in which the Wave Energy Converters feasibility model has been integrated (marked with the yellow box).



Wave energy

scenario 1

Under this scenario, the fishing effort increases to a high level, increasing the conflict level and, thus, reducing the integrated feasibility.

scenario 2

Under this scenario, there is a community of reptiles that must be protected, thus, the total risk level increases and the integrated feasibility decreases.

scenario 3

Under this scenario, a new nearshore OWSC technology is in installation phase.

scenario 4

Under this scenario, a new offshore OWC technology is in operational phase.

scenario 5

Under this scenario, a new onshore wave turbine technology is in decomissioning phase.

When a theme is selected, a number of predefined scenarios will appear on the EXPLORE SCENARIOS tab. Pick one of them and wait to see the spatial representation of the variables on the MAP VIEWER tab. Depending on the theme, this process may take a while.

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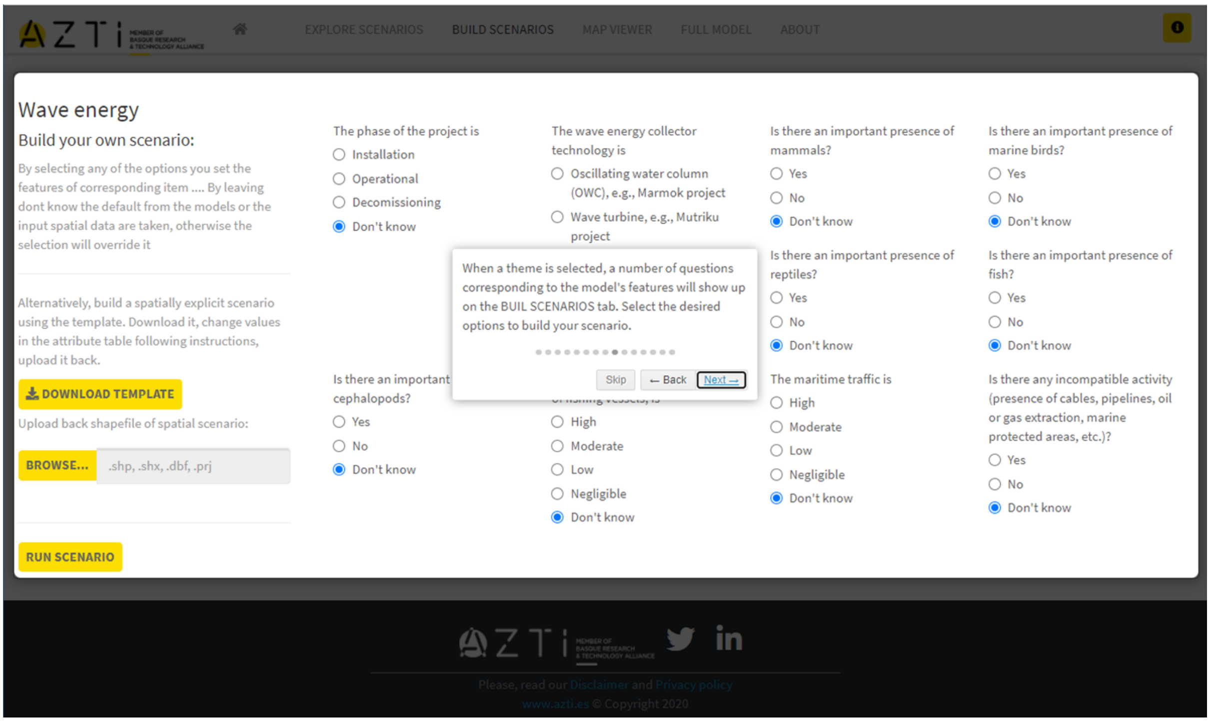
Figure 16. Screenshot with the pre-defined scenarios when running the Wave Energy Converters feasibility model.



Wave energy

Build your own scenario:

By selecting any of the options you set the features of corresponding item .... By leaving dont know the default from the models or the input spatial data are taken, otherwise the selection will override it

Alternatively, build a spatially explicit scenario using the template. Download it, change values in the attribute table following instructions, upload it back.

Upload back shapefile of spatial scenario: .shp, .shx, .dbf, .prj

The phase of the project is
○ Installation
○ Operational
○ Decomissioning
● Don't know

The wave energy collector technology is
○ Oscillating water column (OWC), e.g., Marmok project
○ Wave turbine, e.g., Mutriku project

Is there an important presence of mammals?
○ Yes
○ No
● Don't know

Is there an important presence of marine birds?
○ Yes
○ No
● Don't know

Is there an important presence of reptiles?
○ Yes
○ No
● Don't know

Is there an important presence of fish?
○ Yes
○ No
● Don't know

When a theme is selected, a number of questions corresponding to the model's features will show up on the BUIL SCENARIOS tab. Select the desired options to build your scenario.

Is there an important cephalopods?
○ Yes
○ No
● Don't know

○ High
○ Moderate
○ Low
○ Negligible
● Don't know

The maritime traffic is
○ High
○ Moderate
○ Low
○ Negligible
● Don't know

Is there any incompatible activity (presence of cables, pipelines, oil or gas extraction, marine protected areas, etc.)?
○ Yes
○ No
● Don't know

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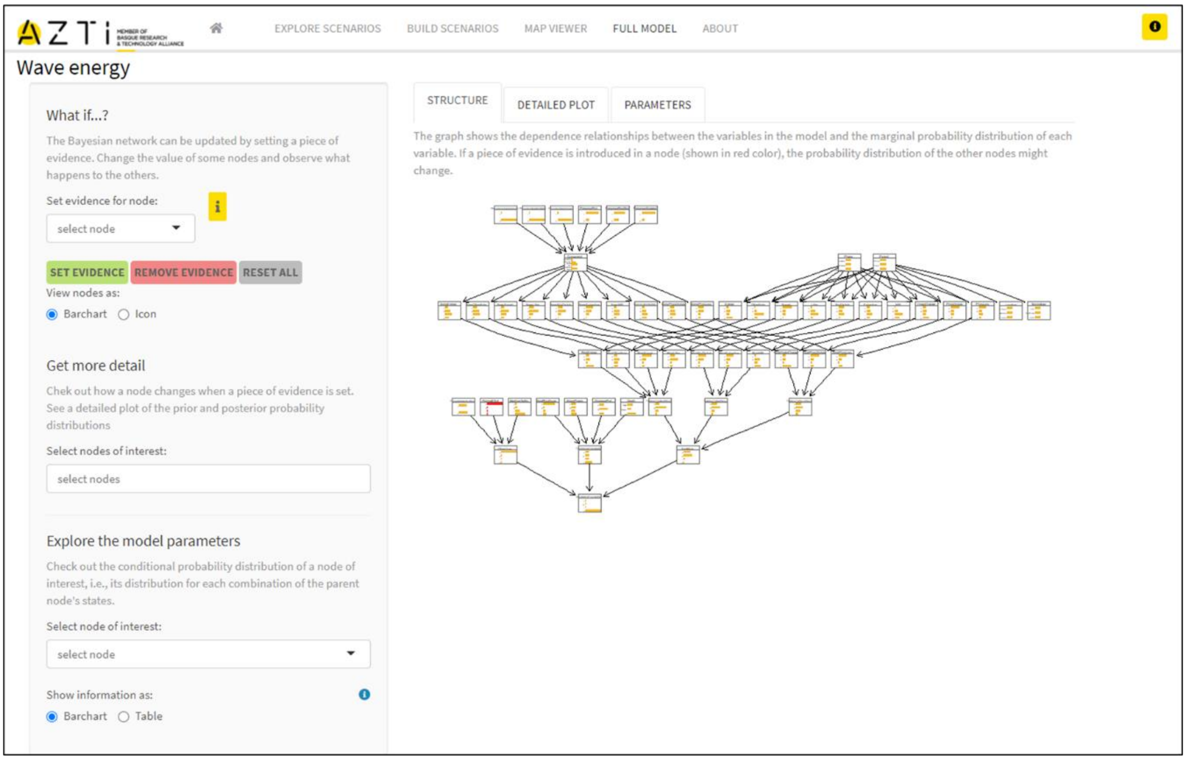
Figure 17. Screenshot of the panel in which the user can define its own scenarios for the identification of feasible areas for the development of wave energy projects.



Wave energy

What if...?

The Bayesian network can be updated by setting a piece of evidence. Change the value of some nodes and observe what happens to the others.

Set evidence for node: select node

View nodes as:
● Barchart ○ Icon

Get more detail

Chek out how a node changes when a piece of evidence is set. See a detailed plot of the prior and posterior probability distributions

Select nodes of interest: select nodes

Explore the model parameters

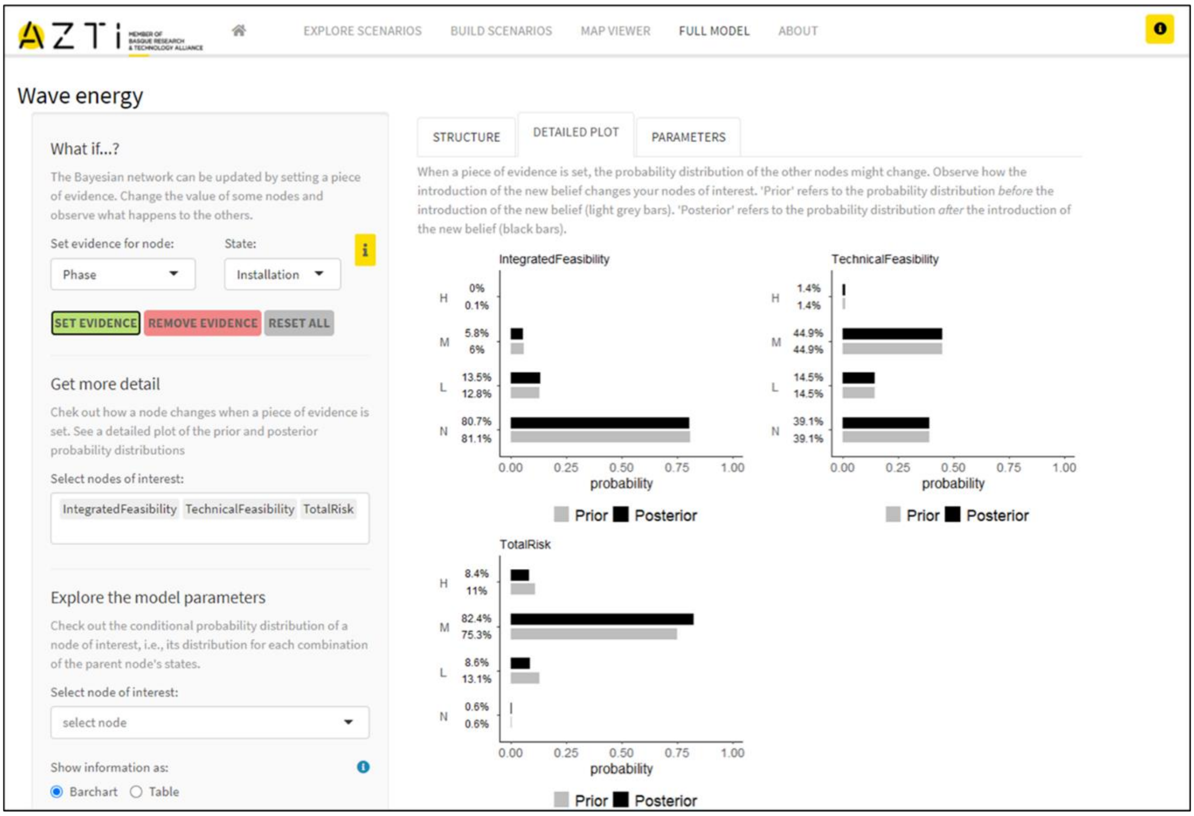
Check out the conditional probability distribution of a node of interest, i.e., its distribution for each combination of the parent node's states.

Select node of interest: select node

Show information as:
● Barchart ○ Table

The graph shows the dependence relationships between the variables in the model and the marginal probability distribution of each variable. If a piece of evidence is introduced in a node (shown in red color), the probability distribution of the other nodes might change.

Figure 18. Visualization of the full Wave Energy Converters feasibility model. The user can change the values of the factors influencing the feasibility of wave energy projects.



Wave energy

What if...?

The Bayesian network can be updated by setting a piece of evidence. Change the value of some nodes and observe what happens to the others.

Set evidence for node: Phase

State: Installation

Get more detail

Chek out how a node changes when a piece of evidence is set. See a detailed plot of the prior and posterior probability distributions

Select nodes of interest: IntegratedFeasibility TechnicalFeasibility TotalRisk

Explore the model parameters

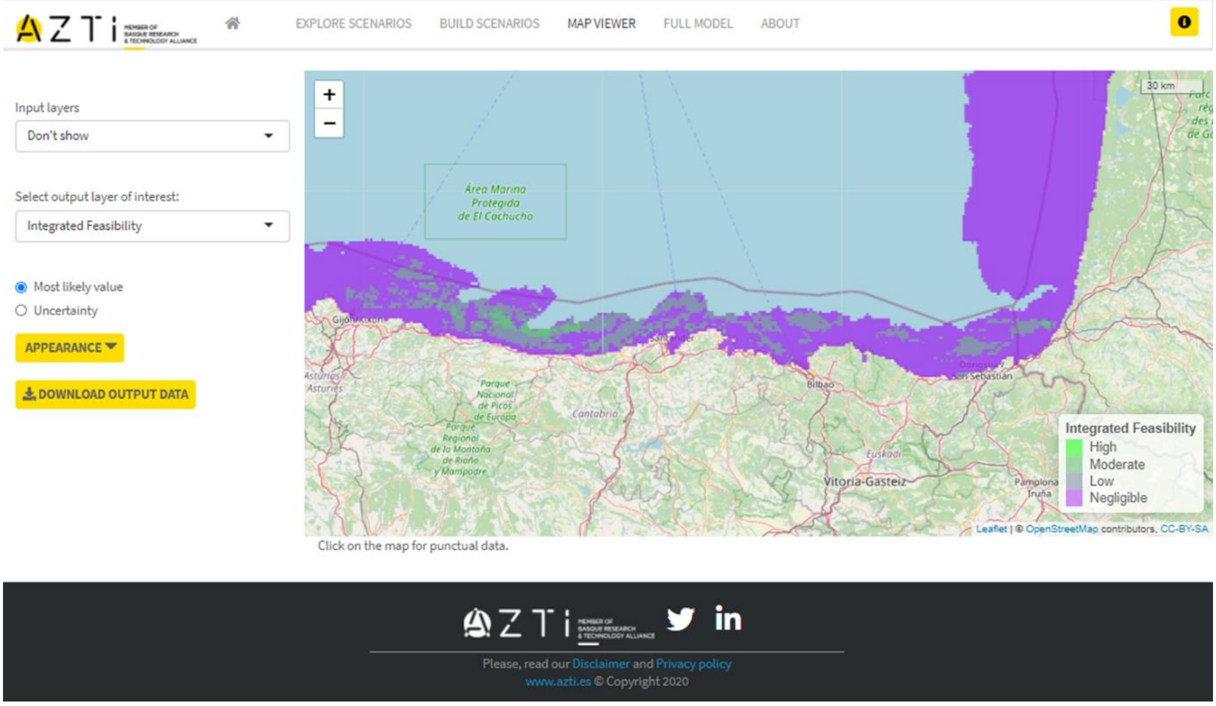
Check out the conditional probability distribution of a node of interest, i.e., its distribution for each combination of the parent node's states.

Select node of interest: select node

Show information as: ● Barchart ○ Table

When a piece of evidence is set, the probability distribution of the other nodes might change. Observe how the introduction of the new belief changes your nodes of interest. 'Prior' refers to the probability distribution *before* the introduction of the new belief (light grey bars). 'Posterior' refers to the probability distribution *after* the introduction of the new belief (black bars).

Figure 19. Bar chart visualization of the feasibility for wave energy projects development based on input values and definition of scenarios.



Input layers: Don't show

Select output layer of interest: Integrated Feasibility

● Most likely value
○ Uncertainty

Click on the map for punctual data.

Figure 20. Integrated feasibility map for wave energy projects development.

9. Conclusions and future works

The main objective of Task 6.2 was the development of a model for the identification of suitable areas for the construction of wave energy projects in the European Atlantic region in the context of maritime spatial planning and its implementation into a Decision Support Tool.

The developed model is based on previous work but adapted to cover the whole European Atlantic region and has been improved by the incorporation of modifications proposed by wave energy converters developers and scientists of the SafeWAVE partnership.

The final objective of WP6 is the identification of suitable areas for the development of wave energy projects, and thus, the expected final product of this WP is a set of maps that could be used for the identification of the most suitable locations. The next months will be dedicated to the production of the maps (Task 6.3), which will require to continue working on potential adjustments of the model according to the feedback of scientist and wave energy converters developers. The present version of the model will probably require additional modifications to reach a consensus and a final model that will be used to produce the final suitability maps.

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11. ANNEX I. Presentation of DST MSP approach

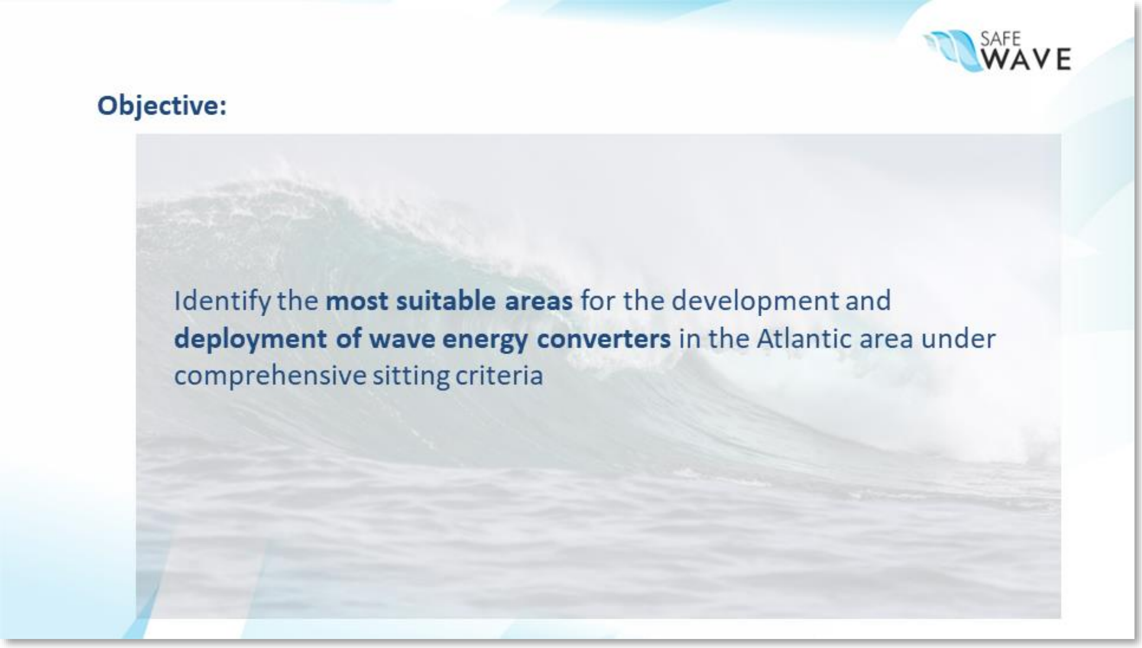
SAFE WAVE

STREAMLINING THE ASSESSMENT OF ENVIRONMENTAL EFFECTS OF WAVE ENERGY

WP6: Wave energy development site selection under Maritime Spatial Planning framework

Ibon Galparsoro Iza
Gotzon Mandiola
Roland Garnier

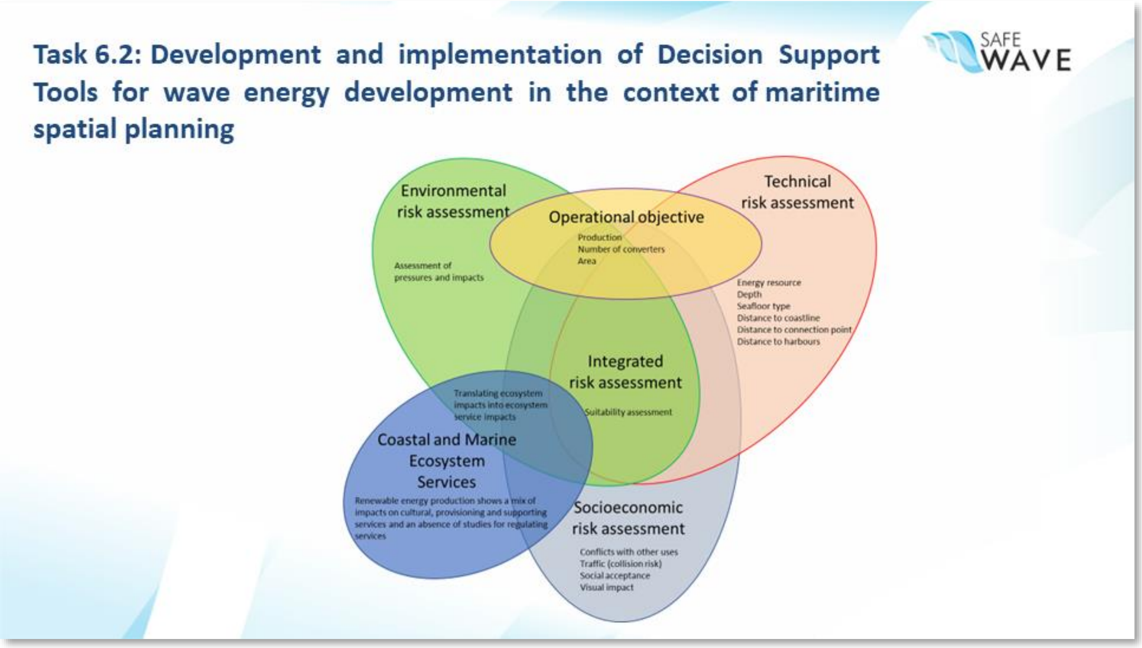
AZTI
25th May 2022



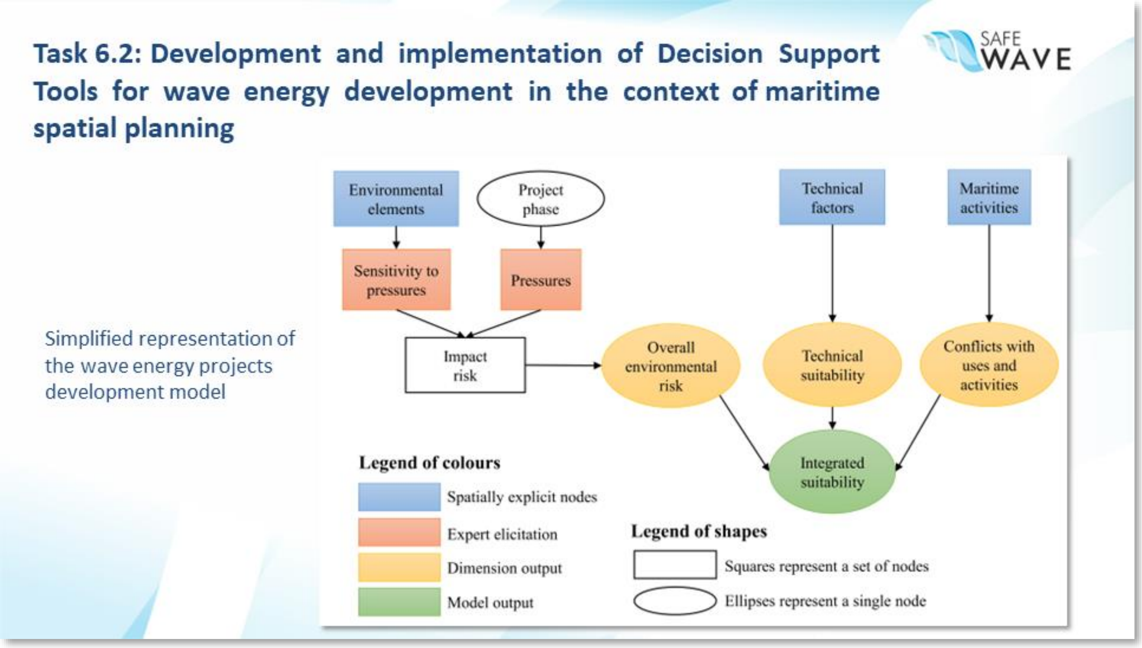
SAFE WAVE

Objective:

Identify the **most suitable areas** for the development and **deployment of wave energy converters** in the Atlantic area under comprehensive sitting criteria

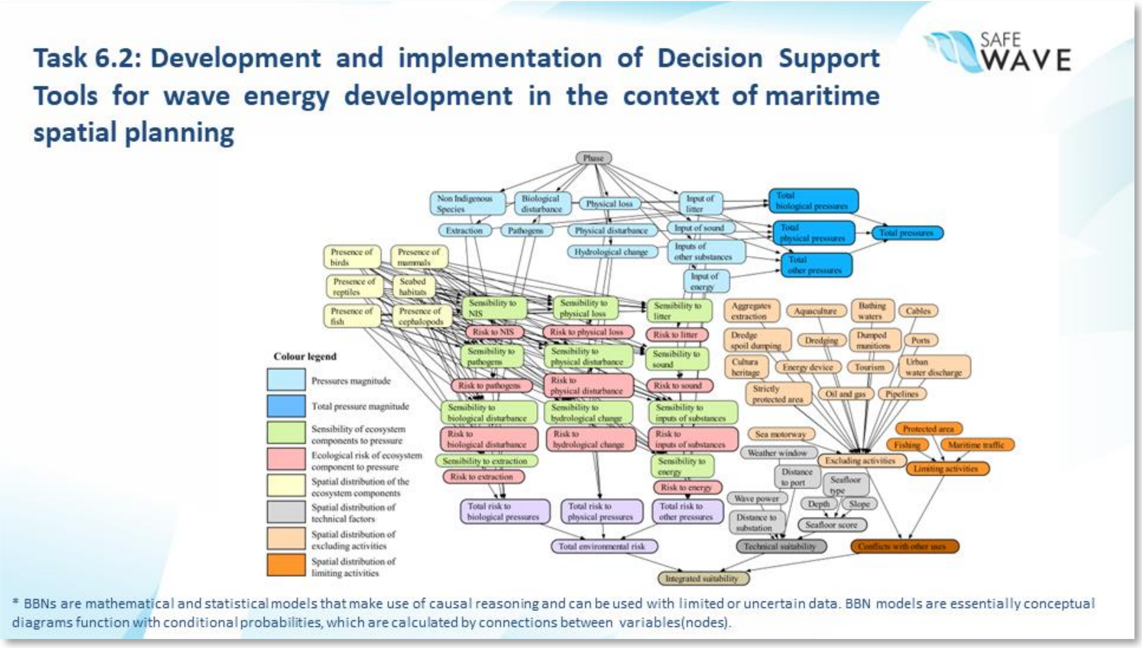


Task 6.2: Development and implementation of Decision Support Tools for wave energy development in the context of maritime spatial planning



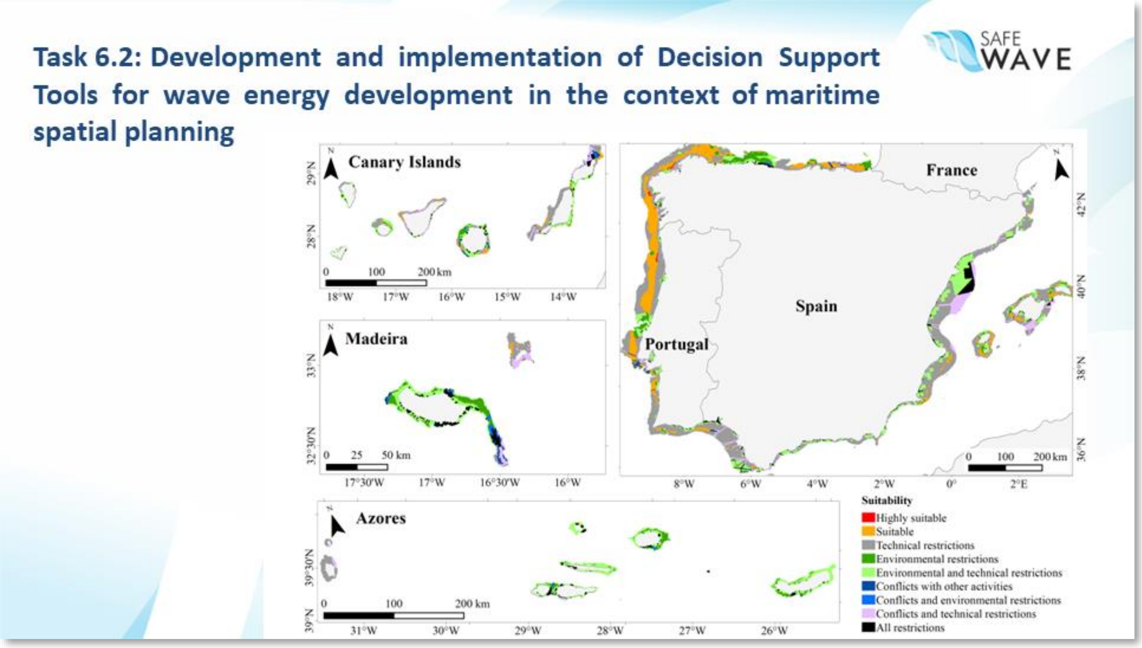
Task 6.2: Development and implementation of Decision Support Tools for wave energy development in the context of maritime spatial planning

Simplified representation of the wave energy projects development model

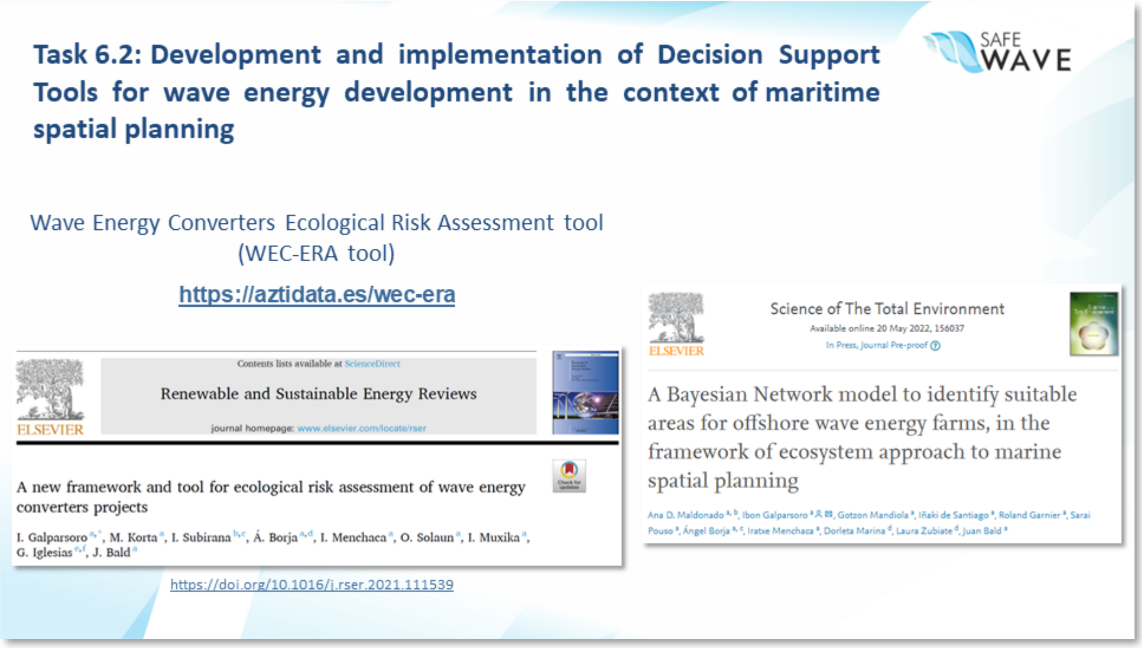


Task 6.2: Development and implementation of Decision Support Tools for wave energy development in the context of maritime spatial planning

* BBNs are mathematical and statistical models that make use of causal reasoning and can be used with limited or uncertain data. BBN models are essentially conceptual diagrams function with conditional probabilities, which are calculated by connections between variables(nodes).



Task 6.2: Development and implementation of Decision Support Tools for wave energy development in the context of maritime spatial planning



Task 6.2: Development and implementation of Decision Support Tools for wave energy development in the context of maritime spatial planning

Wave Energy Converters Ecological Risk Assessment tool
(WEC-ERA tool)

https://aztidata.es/wec-era

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A new framework and tool for ecological risk assessment of wave energy converters projects

I. Galparsoro [a,*], M. Korta [a], I. Subirana [b,c], Á. Borja [a,d], I. Menchaca [a], O. Solaun [a], I. Muxika [a], G. Iglesias [e,f], J. Bald [a]

https://doi.org/10.1016/j.rser.2021.111539

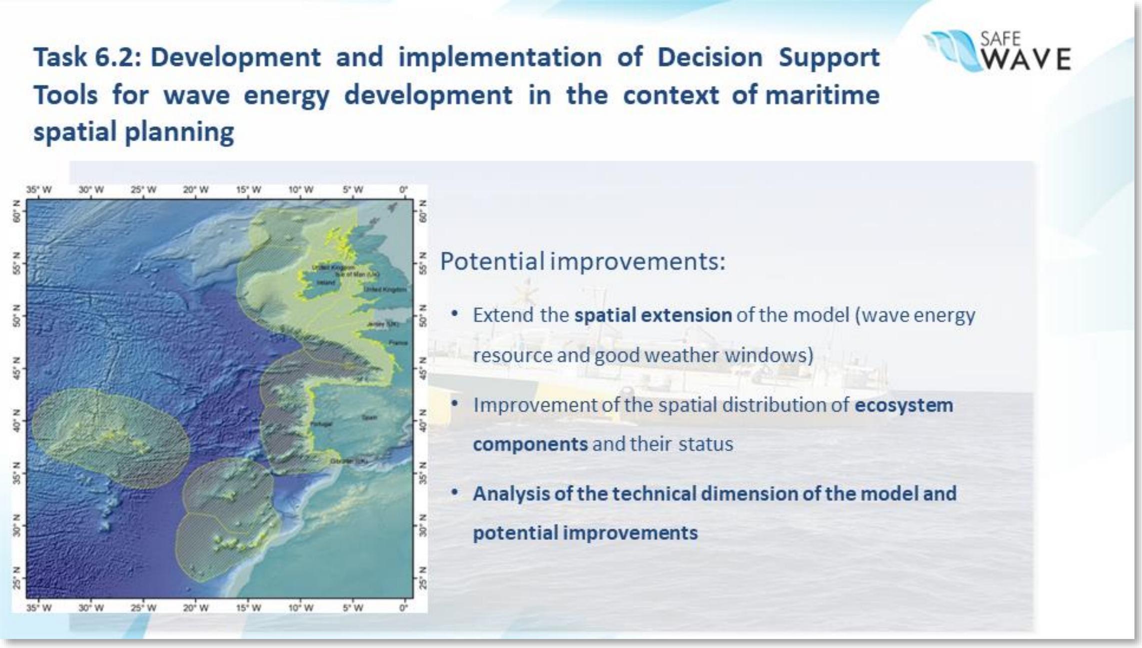
Science of The Total Environment

Available online 20 May 2022, 156037

In Press, Journal Pre-proof

A Bayesian Network model to identify suitable areas for offshore wave energy farms, in the framework of ecosystem approach to marine spatial planning

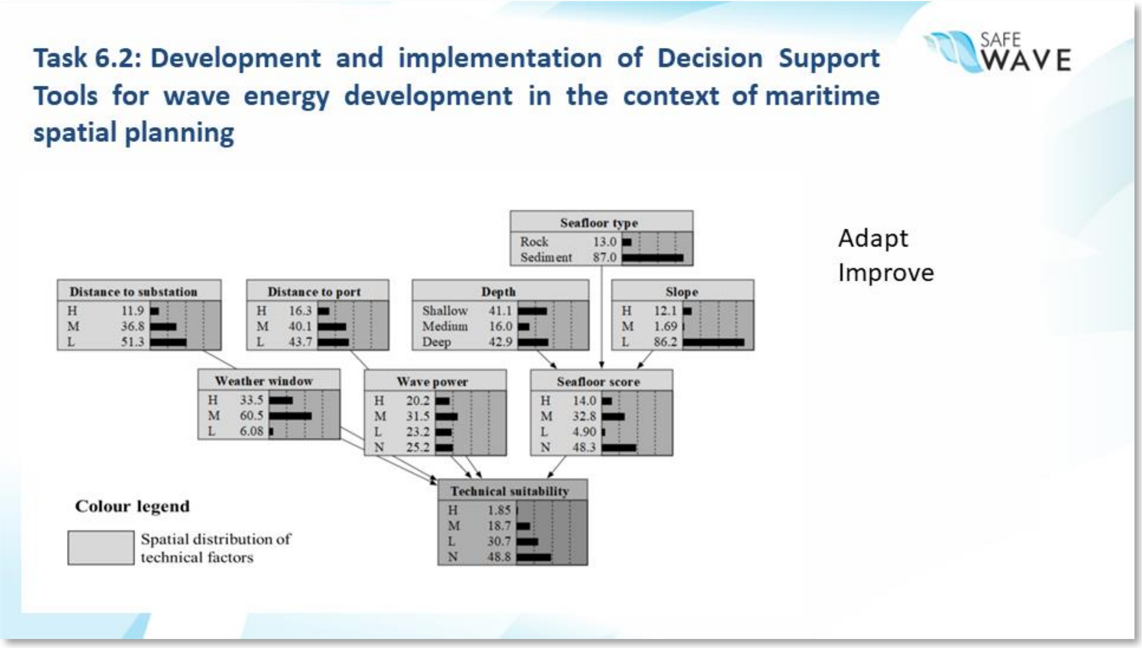
Ana D. Maldonado [a, b], Ibon Galparsoro [a], Gotzon Mandiola [a], Iñaki de Santiago [a], Roland Garnier [a], Sarai Pouso [a], Ángel Borja [a, c], Iratxe Menchaca [a], Dorleta Marina [d], Laura Zubiate [d], Juan Bald [a]



Task 6.2: Development and implementation of Decision Support Tools for wave energy development in the context of maritime spatial planning

Potential improvements:

- Extend the **spatial extension** of the model (wave energy resource and good weather windows)
- Improvement of the spatial distribution of **ecosystem components** and their status
- **Analysis of the technical dimension of the model and potential improvements**



Task 6.2: Development and implementation of Decision Support Tools for wave energy development in the context of maritime spatial planning

Seafloor type

Rock	13.0
Sediment	87.0

Distance to substation

H	11.9
M	36.8
L	51.3

Distance to port

H	16.3
M	40.1
L	43.7

Depth

Shallow	41.1
Medium	16.0
Deep	42.9

Slope

H	12.1
M	1.69
L	86.2

Weather window

H	33.5
M	60.5
L	6.08

Wave power

H	20.2
M	31.5
L	23.2
N	25.2

Seafloor score

H	14.0
M	32.8
L	4.90
N	48.3

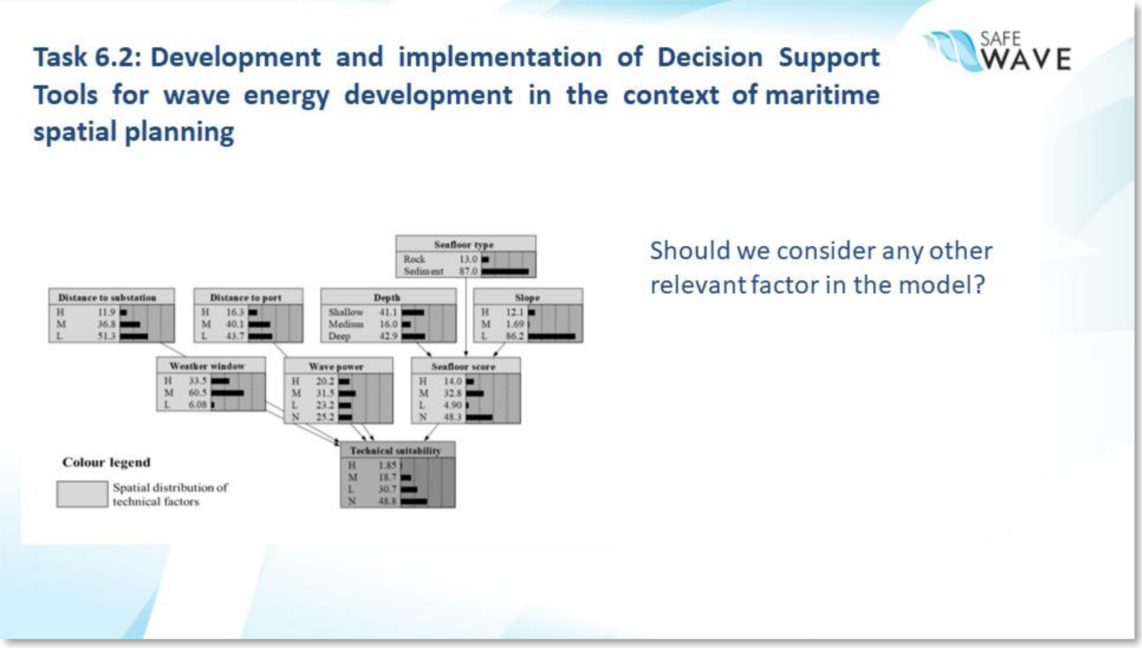
Technical suitability

H	1.85
M	18.7
L	30.7
N	48.8

Colour legend

▭ Spatial distribution of technical factors

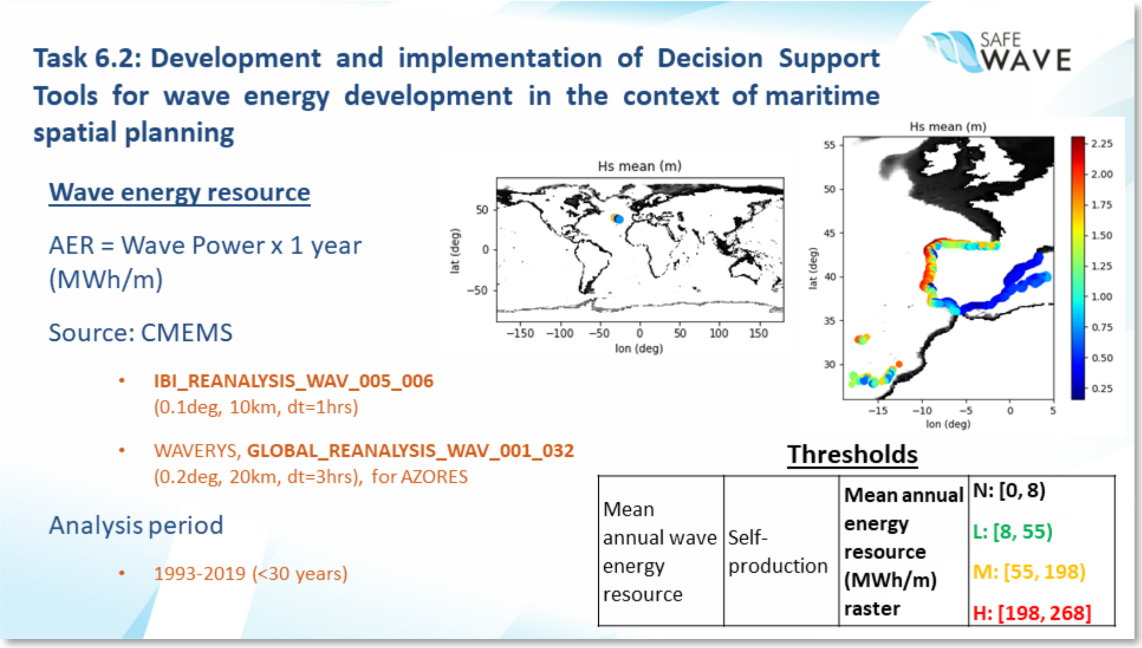
Adapt
Improve



Task 6.2: Development and implementation of Decision Support Tools for wave energy development in the context of maritime spatial planning

Seafloor type: Rock 13.0; Sediment 87.0
Distance to substation: H 11.9; M 36.8; L 51.3
Distance to port: H 16.3; M 40.1; L 43.7
Depth: Shallow 41.1; Medium 16.0; Deep 42.9
Slope: H 12.1; M 1.69; L 86.2
Weather window: H 33.5; M 60.5; L 6.08
Wave power: H 20.2; M 31.5; L 23.2; N 25.2
Seafloor score: H 14.0; M 32.8; L 4.90; N 48.3
Technical suitability: H 1.85; M 18.7; L 30.7; N 48.8
Colour legend
Spatial distribution of technical factors

Should we consider any other relevant factor in the model?



Task 6.2: Development and implementation of Decision Support Tools for wave energy development in the context of maritime spatial planning

Wave energy resource

AER = Wave Power x 1 year (MWh/m)

Source: CMEMS

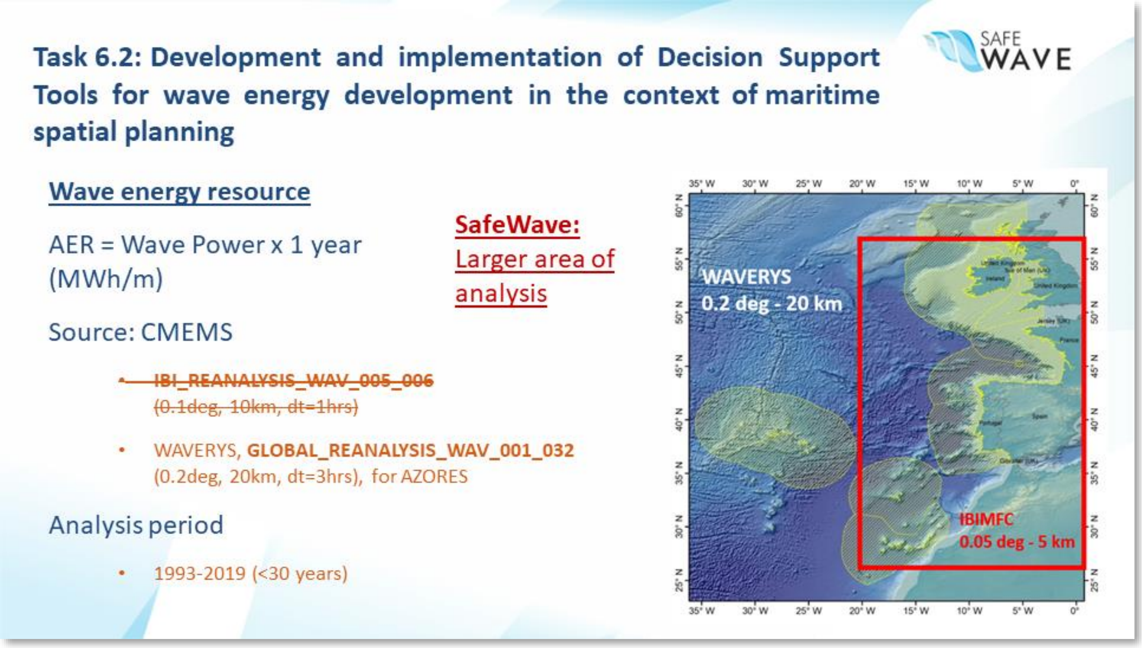
- **IBI_REANALYSIS_WAV_005_006** (0.1deg, 10km, dt=1hrs)
- WAVERYS, **GLOBAL_REANALYSIS_WAV_001_032** (0.2deg, 20km, dt=3hrs), for AZORES

Analysis period

- 1993-2019 (<30 years)

Thresholds

Mean annual wave energy resource	Self-production	**Mean annual energy resource (MWh/m) raster**	**N: [0, 8)** **L: [8, 55)** **M: [55, 198)** **H: [198, 268]**



Task 6.2: Development and implementation of Decision Support Tools for wave energy development in the context of maritime spatial planning

Wave energy resource

AER = Wave Power x 1 year (MWh/m)

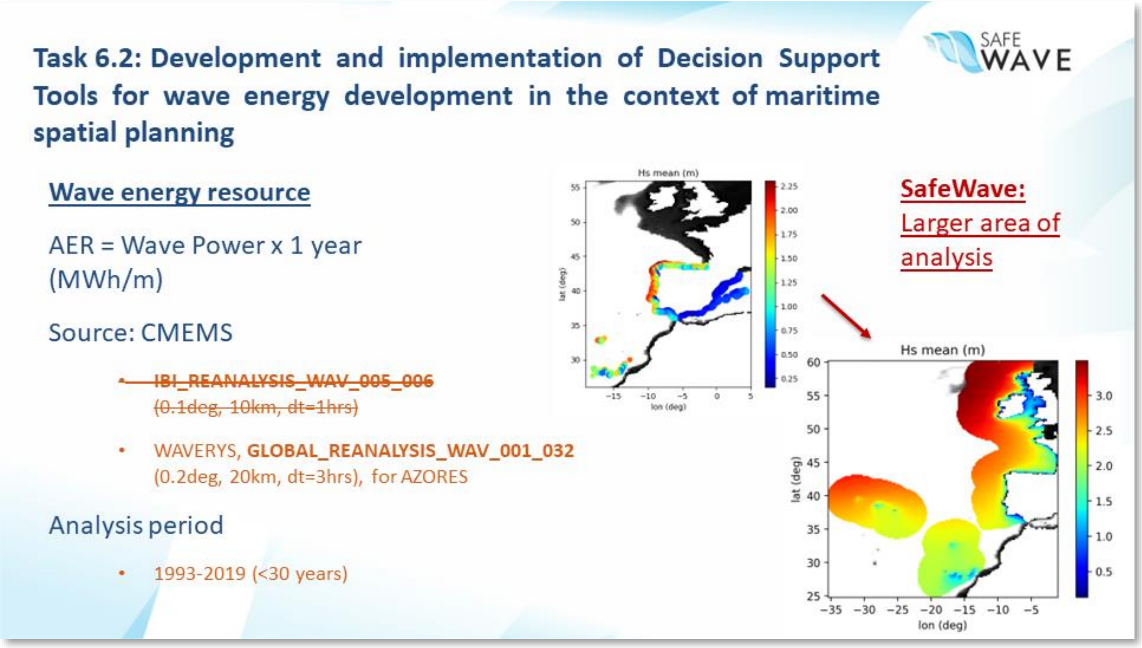
SafeWave: Larger area of analysis

Source: CMEMS

- ~~**IBI_REANALYSIS_WAV_005_006** (0.1deg, 10km, dt=1hrs)~~
- WAVERYS, **GLOBAL_REANALYSIS_WAV_001_032** (0.2deg, 20km, dt=3hrs), for AZORES

Analysis period

- 1993-2019 (<30 years)



Task 6.2: Development and implementation of Decision Support Tools for wave energy development in the context of maritime spatial planning

Wave energy resource

AER = Wave Power x 1 year (MWh/m)

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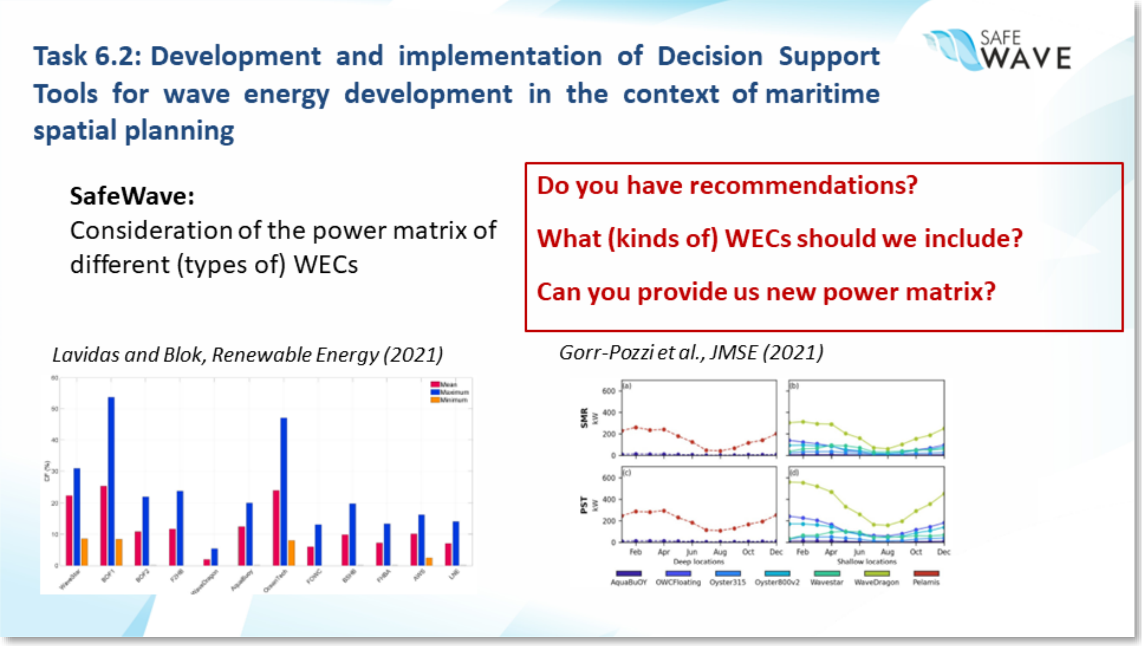
- WAVERYS, **GLOBAL_REANALYSIS_WAV_001_032** (0.2deg, 20km, dt=3hrs), for AZORES

Analysis period

- 1993-2019 (<30 years)

SafeWave: Larger area of analysis



Task 6.2: Development and implementation of Decision Support Tools for wave energy development in the context of maritime spatial planning

SafeWave:
Consideration of the power matrix of different (types of) WECs

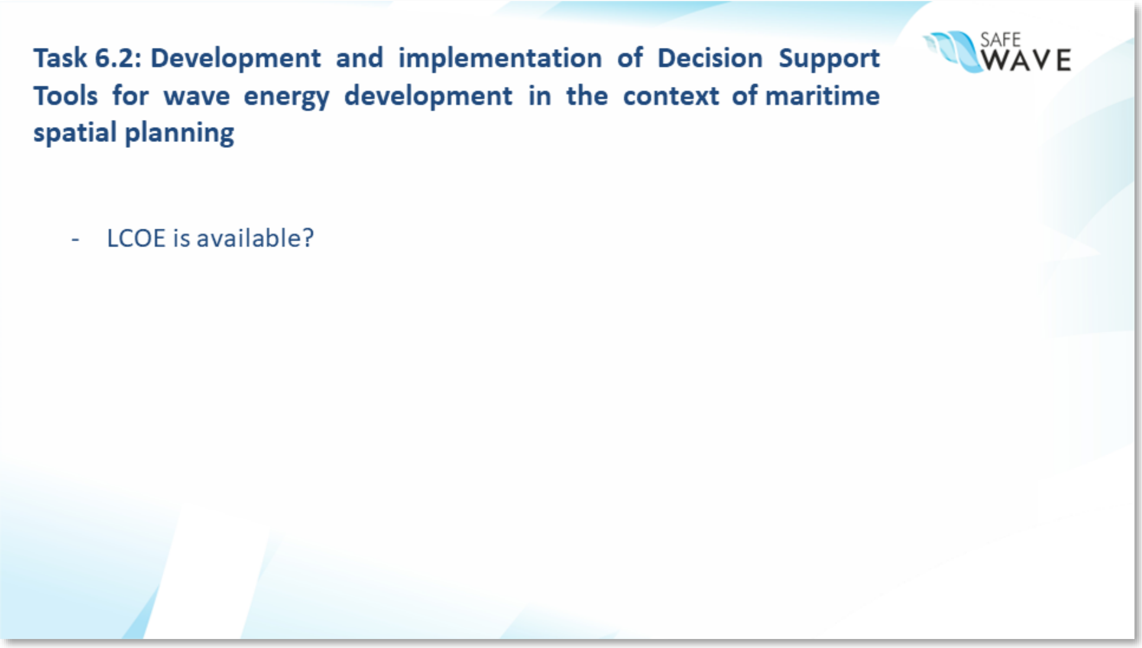
Do you have recommendations?

What (kinds of) WECs should we include?

Can you provide us new power matrix?

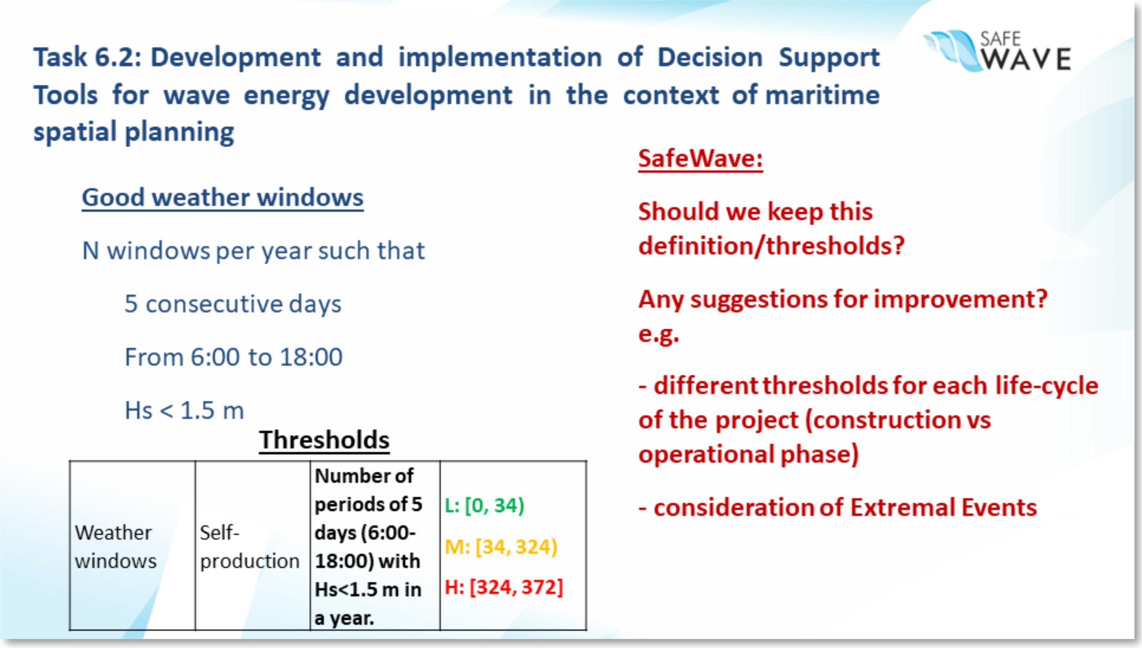
Lavidas and Blok, Renewable Energy (2021)

Gorr-Pozzi et al., JMSE (2021)



Task 6.2: Development and implementation of Decision Support Tools for wave energy development in the context of maritime spatial planning

- LCOE is available?



Task 6.2: Development and implementation of Decision Support Tools for wave energy development in the context of maritime spatial planning

Good weather windows

N windows per year such that

5 consecutive days

From 6:00 to 18:00

Hs < 1.5 m

Thresholds

Weather windows	Self-production	**Number of periods of 5 days (6:00-18:00) with Hs<1.5 m in a year.**	**L: [0, 34)** **M: [34, 324)** **H: [324, 372]**

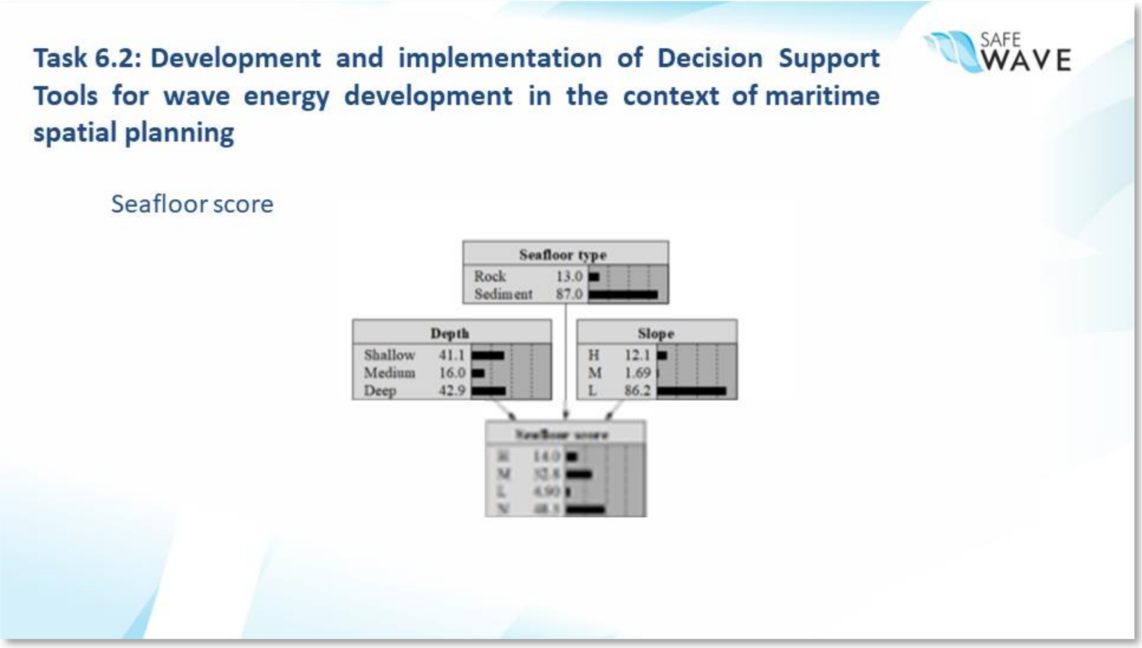
SafeWave:

Should we keep this definition/thresholds?

Any suggestions for improvement? e.g.

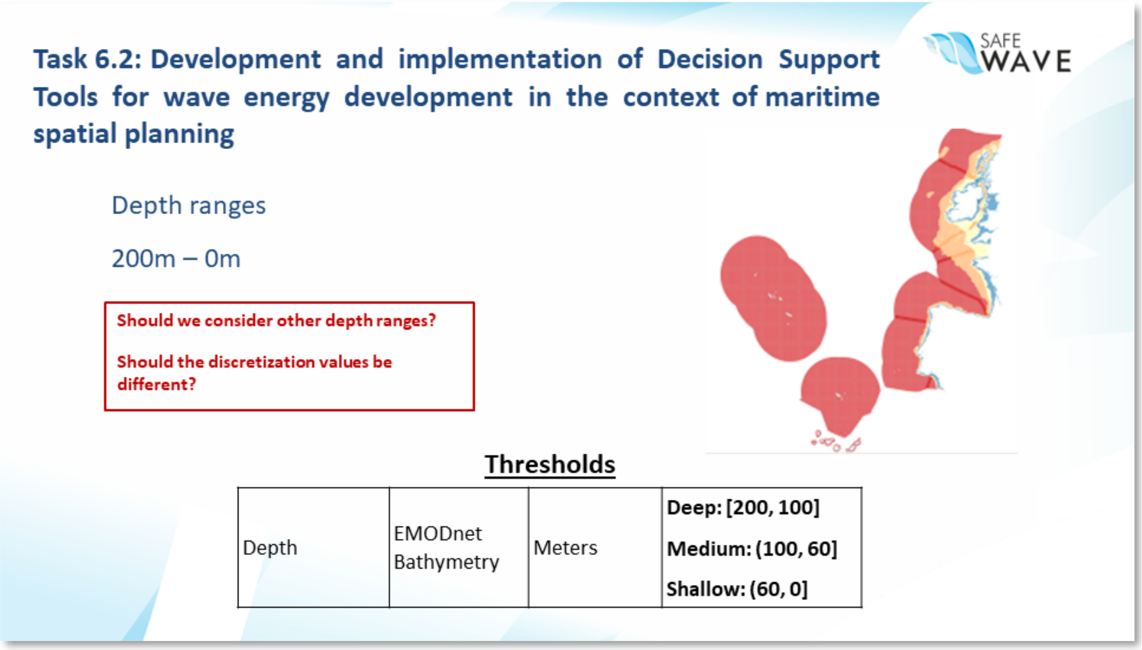
- different thresholds for each life-cycle of the project (construction vs operational phase)

- consideration of Extremal Events



Task 6.2: Development and implementation of Decision Support Tools for wave energy development in the context of maritime spatial planning

Seafloor score



Task 6.2: Development and implementation of Decision Support Tools for wave energy development in the context of maritime spatial planning

Depth ranges

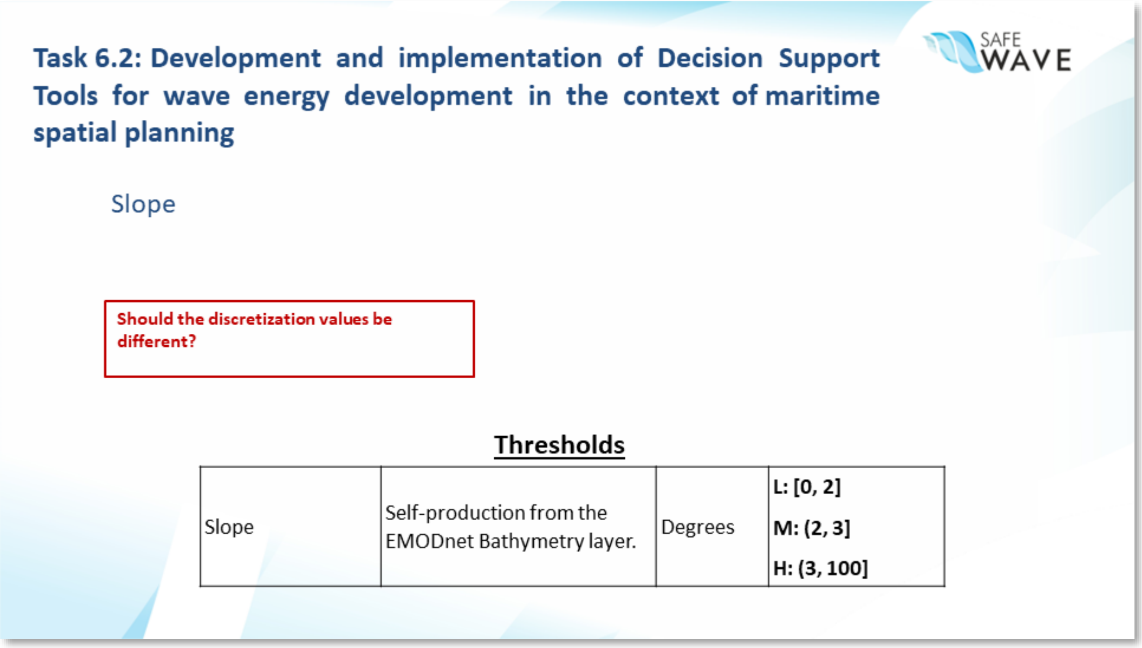
200m – 0m

Should we consider other depth ranges?

Should the discretization values be different?

Thresholds

Depth	EMODnet Bathymetry	Meters	**Deep: [200, 100]** **Medium: (100, 60]** **Shallow: (60, 0]**



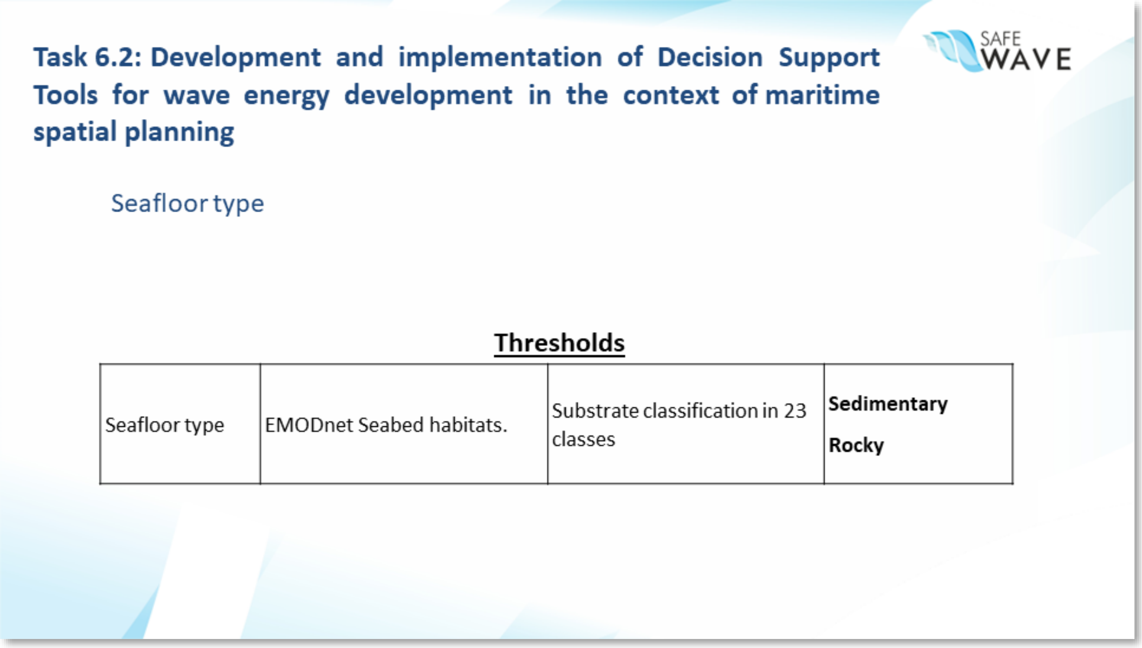
Task 6.2: Development and implementation of Decision Support Tools for wave energy development in the context of maritime spatial planning

Slope

Should the discretization values be different?

Thresholds

Slope	Self-production from the EMODnet Bathymetry layer.	Degrees	**L: [0, 2]** **M: (2, 3]** **H: (3, 100]**

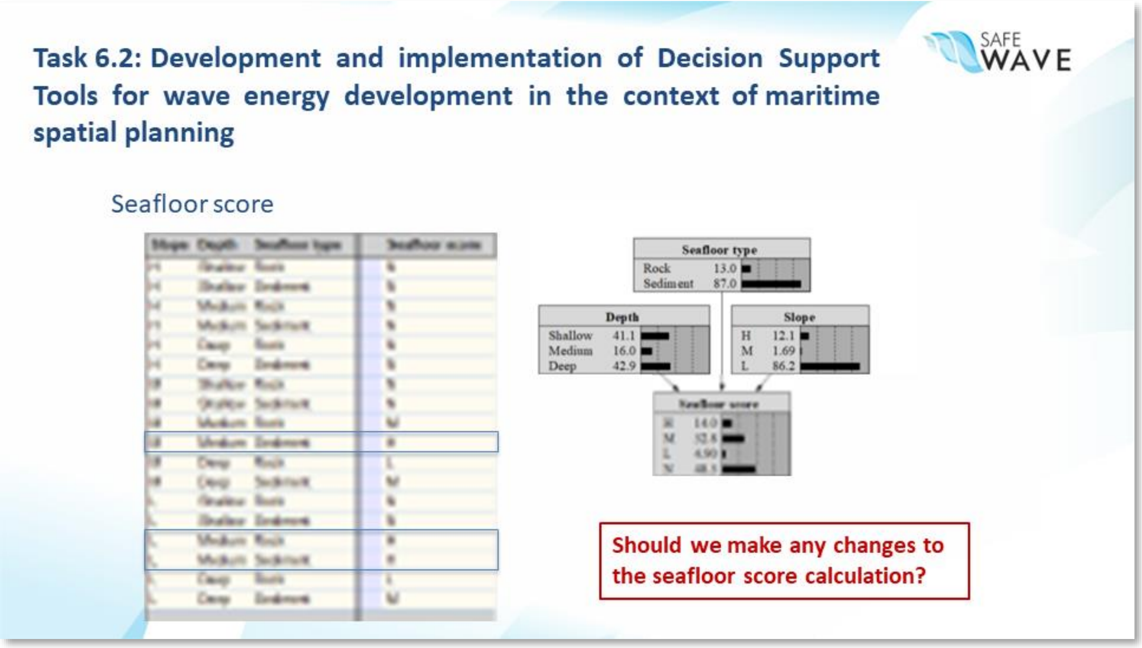


Task 6.2: Development and implementation of Decision Support Tools for wave energy development in the context of maritime spatial planning

Seafloor type

Thresholds

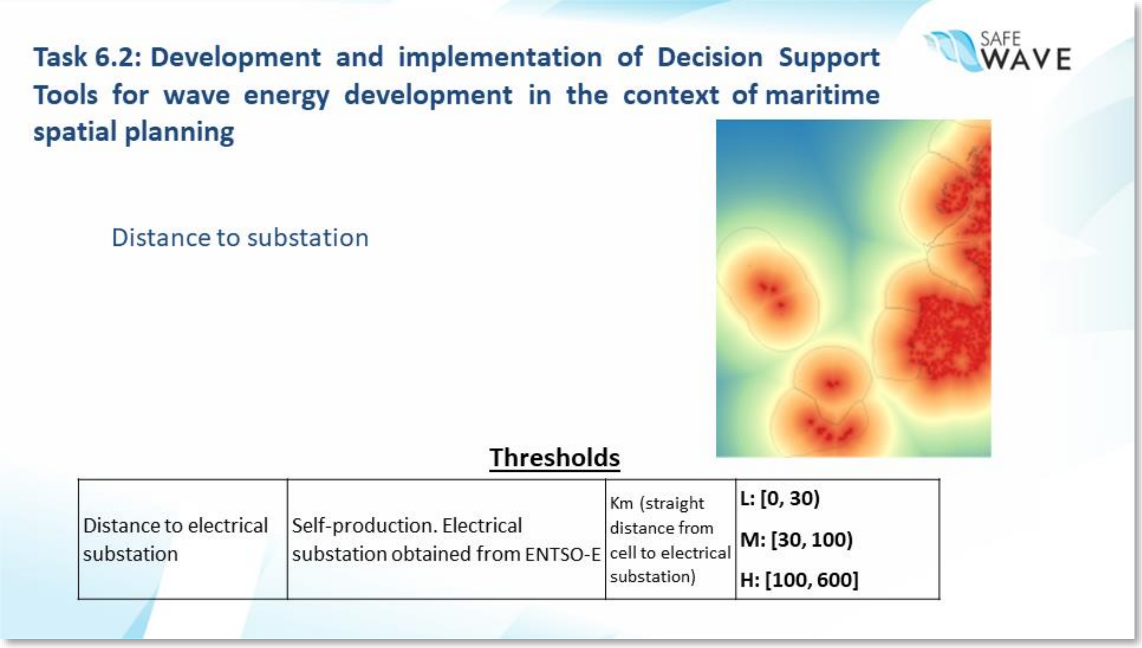
Seafloor type	EMODnet Seabed habitats.	Substrate classification in 23 classes	**Sedimentary** **Rocky**



Task 6.2: Development and implementation of Decision Support Tools for wave energy development in the context of maritime spatial planning

Seafloor score

Should we make any changes to the seafloor score calculation?

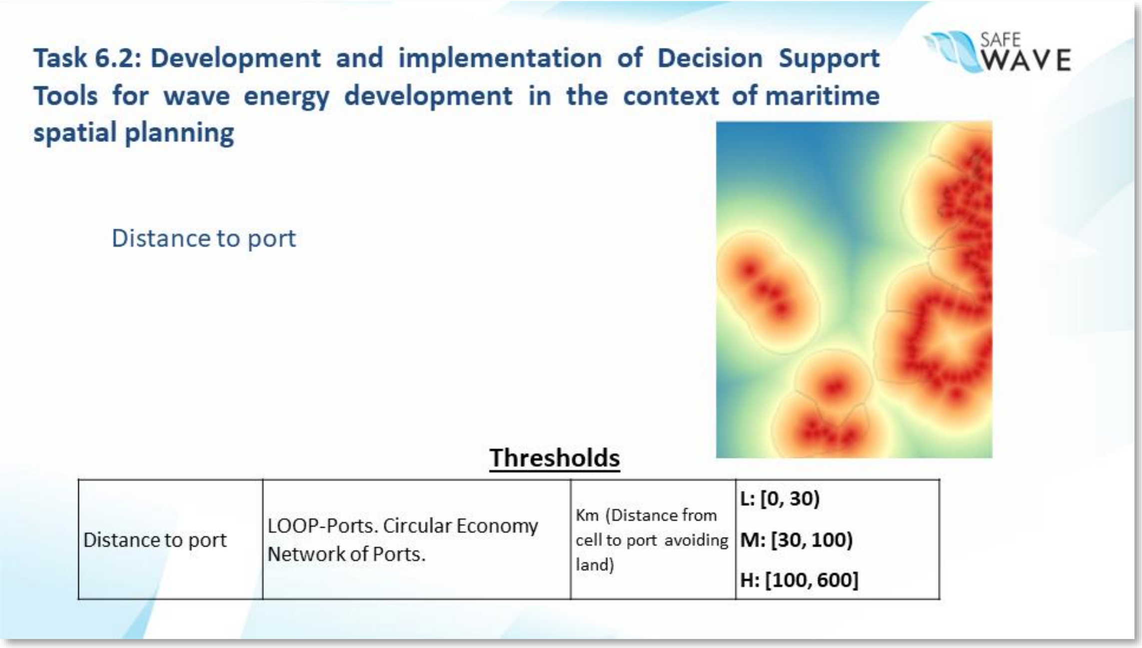


Task 6.2: Development and implementation of Decision Support Tools for wave energy development in the context of maritime spatial planning

Distance to substation

Thresholds

Distance to electrical substation	Self-production. Electrical substation obtained from ENTSO-E	Km (straight distance from cell to electrical substation)	**L: [0, 30)** **M: [30, 100)** **H: [100, 600]**



Task 6.2: Development and implementation of Decision Support Tools for wave energy development in the context of maritime spatial planning

SAFE WAVE

Distance to port

Thresholds

Distance to port	LOOP-Ports. Circular Economy Network of Ports.	Km (Distance from cell to port avoiding land)	**L: [0, 30)** **M: [30, 100)** **H: [100, 600]**

SAFE WAVE

STREAMLINING THE ASSESSMENT OF ENVIRONMENTAL EFFECTS OF WAVE ENERGY

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