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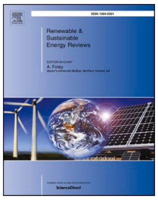

A novel framework for sustainable decision-making on reusing Oil & Gas offshore platforms with application to the Adriatic Sea

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ABSTRACT

Many Oil and Gas offshore platforms will likely end their operational life in the near future and enter a decommissioning phase, which is a relevant process from both an economic and environmental viewpoint. As an alternative to decommissioning "as is", these platforms could be optioned for repurposing to support different economic activities, a. o. energy, tourism, aquaculture, transportation, greenhouses. This paper presents a methodological framework to facilitate the identification of the repurposing activities and the decision between reuse and decommissioning of Oil and Gas platforms. The selection of the most promising combination of reuse activities is performed through a multi-criteria assessment, while the decision between reuse and decommissioning consists of the quantitative evaluation of the sustainability of the reuse, based on economic, social and environmental Key Performance Indicators. These indicators represent the most significant issues posed by the reuse such as the creation of new jobs, investment and operation costs, production, marine footprint, CO_2 reduction, social awareness of ecosystem services. The relevance of the responsibility of the decommissioning cost in case of reuse is also discussed. This new framework is applied to an Oil and Gas platform in the Northern Adriatic Sea, Italy, in a hypothetical decommissioning scenario. The results of this application show that a large marine area would be required to make the reuse a sustainable alternative to decommissioning.

List of abbreviations

CBA	Cost-Benefit Analysis
CV	Coefficient of Variation
DCF	Discount Cash Flow Analysis
EIA	Environmental Impact Assessment
GIS	Geographic Information System
KPI	Key Performance Indicators
LCA	Life Cycle Assessment
MCA	Multi Criteria Analysis
MUP	Multi-Use Platform
O&G	Oil and Gas
O&M	Operation and Maintenance
PBP	Payback Period
PTO	Power Take-Off
PV	Photovoltaic
R&D	Research and Development
RE	Renewable Energy
RES	Renewable Energy Sources
SUP	Single-Use Platform
TRL	Technology Readiness Level
WEC	Wave Energy Converter
WTP	Willingness To Pay

1. Introduction

Seas and oceans have immense – still under-exploited – resource wealth and great potential for boosting economic growth, employment and innovation.

Marine Renewable Energy (RE) is insufficiently harvested, especially offshore coastlines with great depths where fixed wind towers cannot be deployed. A few floating wind farms do exist and wave energy arrays have not been yet systematically demonstrated. Furthermore, the combination of different Renewable Energy Sources (RES), which may increase the active operational time and the economic feasibility of these installations, has been poorly tested so far [1].

Aquaculture is an increasingly significant sector worldwide, with a twofold benefit: food security and contribution to biofuel technologies. Offshore aquaculture [2] reduces the anthropogenic pressures on the coast [3] and the anthropogenic factors that can influence the product

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quality. However, it is still an emerging sector and the technologies for smart aquaculture systems including remediation and using eco-compatible materials are not widely adopted.

The increasing tourist pressures in coastal areas and the novelty of offshore installation is making new frontiers for offshore tourism [4,5], such as offshore information centres, helicopter flights and diving around offshore wind farms, sea mammals watching. These initiatives are very promising in terms of new job opportunities, but are fragmented, due to physical barriers (such as geographical and environmental conditions at the sites) and policy barriers (absence of a specific permitting system).

Overall, the further growth of ocean-based industries implies increasing transportation needs and growing pressures on ocean resources and demand for ocean space, while conflicts among maritime uses are also intensifying, calling for a multi-actor marine use planning [6,7] and for the reduction of the carbon footprint of offshore operations and transport. As pointed out already by the H2020 MUSES project [8], the permissions and policy barriers for multi-use of marine areas are still hard to be overcome, and industrial parties do not have secure and clear legal rights in tenure in order to promote long-term investment opportunities.

The offshore Oil and Gas (O&G) infrastructures are ending their operational life in most areas of the world, and the impact of decommissioning activities is still largely unknown. According to IHS Markit's proprietary database Petrodata™ FieldsBase ([9]), nearly 2′800 fixed platforms and 160 floating platforms could be decommissioned during the 2021-30 period, that represents 33 % of fixed platforms and 43 % of floating platforms currently in operation. Additionally, more than 32′000 O&G platforms in the US are already permanently or temporarily abandoned: poorly decommissioned and orphaned wells are a direct threat to our environment, society, and economy. Most nations require complete removal of obsolete structures according to UNCLOS regulation, which presents substantial engineering challenges and extremely high costs >100 bln of euros in Europe, including UK [10]. Decommissioning means removal of tons of materials to be dismantled and re-cycled on land and environmental impacts on the local ecosystem that already changed at the platform installation, decades ago. Policies of complete removal are based on the assumption that 'leaving the seabed as you found it' represents the most environmentally-sound decommissioning option. However, O&G structures can support abundant and diverse marine communities, in some cases of regional significance [11,12]. Materials, structures, power connection to shore can be reused and become an advantage for new multi-use installations.

A full review of the rig-to-reef experience has been recently performed in the USA and in Mexico [13], with information also about Australia, Asia and Europe. The authors synthesised the practice, the environmental impact and the policies of platform (partial) removal and reuse as artificial reefs. The surveys revealed that the fish and invertebrate populations beneath platforms compared to natural reefs nearby, with the tendency to a higher abundance of large fishes in proximity to platforms. Kaiser et al. [14,15] highlighted that the reuse for mariculture in the Gulf of Mexico would be attractive only in case it is carried out on previously decommissioned platforms. Nugraha et al. [16] demonstrated that the conversion of the abandoned rig structures into artificial reefs in Indonesia would be beneficial both for oil companies and for coastal communities because it would create new ecosystems to support marine and fisheries and it would raise the tourism sector. The unclear liability of the existing platforms and the missing common regulatory framework for decommissioning and reuse are perceived as the more significant barriers to the reuse [14,16].

A comprehensive framework for sustainability assessment of reuse or decommissioning of O&G platforms nowadays does not exist. The only Decision Support Tool available to date, the PLATFORM Oil & Gas Platform Decommissioning tool [17], is based on the best practices gained in the USA and includes partial or full removal of the platforms and reef enhancement option [18]. Martins et al. [19] proposed to apply a multi-criteria framework to select the most suitable decommissioning scenario without considering the reuse opportunity. Leporini et al. [20] compared the reuse of O&G platforms for the production of RE against standard decommissioning scenarios, including total removal or partial removal with the possibility to use the sub-structure as an artificial reef. More alternatives should be nowadays considered to promote Blue Growth [21].

In this context, the PlaCE project, a national project funded by the Italian Ministry of Research, aimed at investigating cutting-edge technologies and solutions for the eco-sustainable reuse of offshore platforms, starting from a demonstrator located in the Adriatic Sea in front of the Abruzzo region coastline, the Viviana O&G platform [22]. In particular, in view of the reuse of offshore platforms to boost Blue Economy, a life-extension strategy was tested in the area close to Viviana platform, based on mineral deposition technology under low voltage electrolysis of seawater to protect the structures from corrosion [23]. Other activities included experiments of innovative eco-sustainable strategies of aquaculture based on integrated shellfish and holothurians farming, design and development of innovative systems for RE generation to support multi-purpose platform activities, cost-benefit analyses and business scenarios.

This paper presents a novel methodological framework for the environmental, social and economic assessment of the reuse opportunities versus decommissioning of O&G platforms. The methodology is twofold: multi-criteria analysis for a qualitative assessment of the best reuse option and quantitative Key Performance Indicators (KPIs) for the assessment of the sustainable selection between decommissioning and reuse. The methodology requires the inputs of experts and stakeholders with different roles and backgrounds and considers the reuse for energy production, educational tourism and aquaculture.

The paper structure is as follows. The framework and its steps are described in Section 2, including the discussion about the framework limitations and exportability. The case study, including environmental conditions and promising offshore activities for the platform reuse, is presented and the selection of the optimal reuse configuration is carried out in Section 3. In Section 4, the performance of the optimal reuse configuration is evaluated by means of KPIs and its feasibility is assessed and compared to the decommissioning option. Some conclusions are finally drawn in Section 5.

2. Description of the framework

This Section aims at describing the original framework for supporting decision makers in the selection between reuse and decommissioning of O&G platforms. The overview of the steps of the framework are presented in Sub-section 2.1. The first two steps compose a multi-criteria evaluation of the benefits and impacts of potential offshore activities at the site in case of reuse. The possible activities at the selected location are assessed first (step 1, Sub-section 2.2). Then, the assessment of the optimal combination of activities is based on expert judgement and ranking of the alternatives (step 2, Sub-section 2.3). The third step is the preliminary assessment of the productivity of the offshore installation based on the alternative for the reuse selected in the first step (Sub-section 2.4). The fourth step is the evaluation of KPIs of the reuse optimal combination (Sub-section 2.5) and the fifth step is the comparison with the decommissioning alternative (Sub-section 2.6).

2.1. Overview of the framework

The development of a framework that allows the design and optimization of platforms to support different eco-sustainable activities is of fundamental importance in view of the cessation of extraction activities at existing O&G platforms. It is an iterative process, which must involve all stakeholders and investors from the earliest stages of development [24].

The first two steps are a multi-criteria evaluation of the possible combinations of reuse activities to be carried out at the platform. In step 1, called pre-screening, the preliminary feasibility of the various proposals for the use of the maritime space is assessed, excluding those that are not practicable on the basis of some identified limit values. The result of the pre-screening step is the identification of possible uses, which are separately analysed and evaluated in terms of their production potential. These uses are then combined in various ways by identifying some conceptual proposals of Multi-Use Platforms (MUPs).

The second step, called ranking, consists of assigning a score to the performance of the different MUP alternatives based on selected criteria, including.

- the state of advancement of the technology based on its reliability and performance;
- the environmental impact, considering the use of marine space, the effects on different species and the maintenance requirements;
- the risks, related to geotechnical failure, danger to maritime activities and pollution;
- the costs, depending on the depth of installation, the energy conversion system if applicable, the mechanical complexity of the system and the planned maintenance interventions.

The result of the ranking step is a ranking of the various proposals, which allows for the selection of the best combination of re-use activities for the given site.

In the third step, the selected MUP is then designed in advance, taking into account technological synergies, conflicts of use and space optimization.

The first three steps of this framework are based on the work carried out under the FP 7 European MERMAID Project (2011–2014); details can be found in Ref. [25]. he scoring methodology has been updated in time and a new Excel table to support the experts in the scoring exercise has been prepared. The assessment, scoring and ranking of the alternative can be generalised for any case study.

The fourth step is the assessment of the performance of the selected MUP in terms of KPIs and the comparison with the decommissioning option. The selection of these KPIs is totally novel and allows for a rapid and "objective" assessment, based on a few parameters, that represents both the technological benefits and the environmental benefits. The fifth and final step is the comparison between decommissioning and reuse based on the KPIs. If positive (i.e. if re-use is a suitable alternative to decommissioning) this assessment is preliminary to the detailed assessment based on GIS mapping of the existing uses and of the resource distribution in the same marine area.

These steps are synthesised in Fig. 1.

2.2. Pre-screening and identification of conceptual reuse configurations

Many different activities can be integrated into an offshore platform, such as aquaculture, renewable energy, transportation, tourism. The possibility of combining these activities in a given site is dependent on the technical feasibility of each activity individually and on the production potential in the case of their eventual combination in a multi-use scheme. The feasibility of the individual uses is determined for each activity by comparing the local data with some threshold values, for example: i) in the case of wind energy, the average values of wind speed are compared with minimum values known from previous studies, as the technology is now at an advanced stage of development; ii) in the case of wave energy, since threshold values are not yet available in the literature, an average wave power of 10 kW/m is assumed as the minimum value for single-use installations; this value comes from the combined consideration that the development of most wave energy devices at nearly prototype scale has been historically referred to 20 kW/m available wave power, but the devices nowadays are scaled with the available wave power and the maximum values of the available wave power in less energetic seas, such as the Mediterranean, can fairly reach 10 kW/m; iii) in the case of aquaculture, the feasibility can be assessed on the basis of the results of similar facilities in the area, considering the local species and their production, environmental impacts etc.

On the basis of the results of the pre-screening step, the uses of the marine space that can be taken into consideration for Single-Use Platforms (SUPs) or Multi-Purpose Platforms (MUPs) are identified and some conceptual hypotheses of combination are formulated.

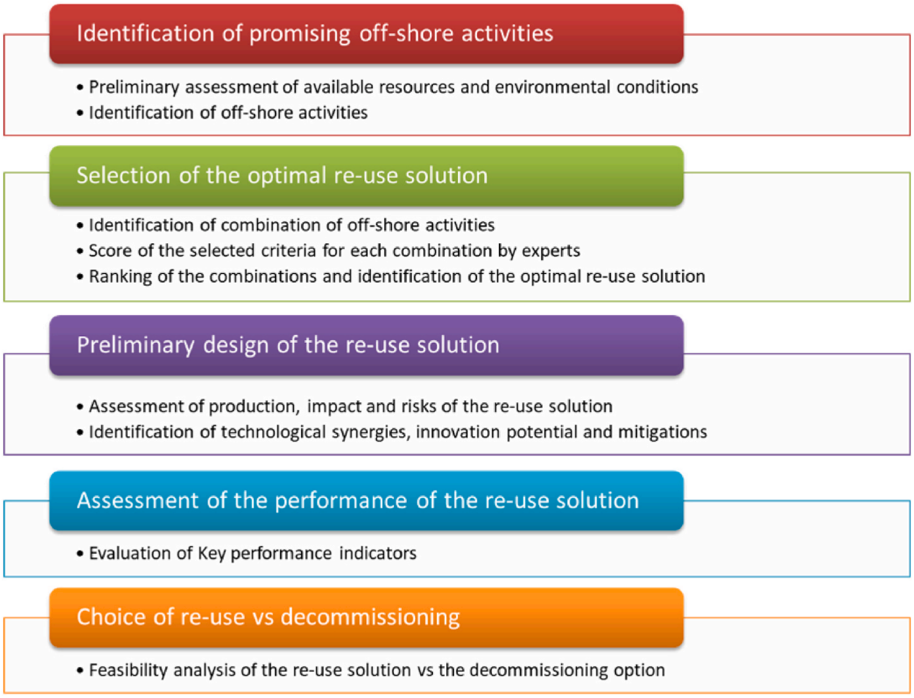
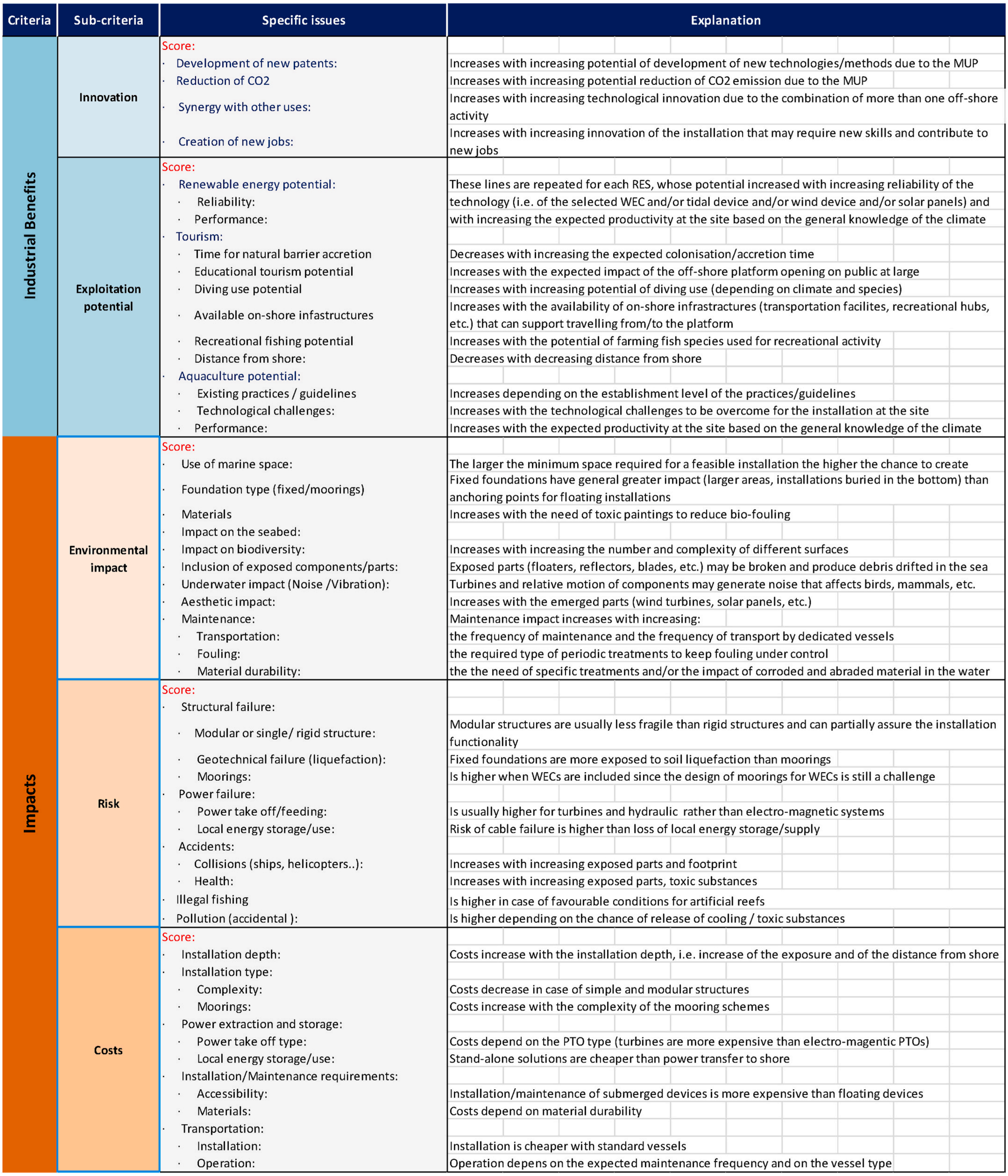


Fig. 1. The five steps of the framework for the choice between reuse and decommissioning.

2.3. *Ranking and selection of the reuse configuration*

In the ranking step, the SUPs and/or MUPs identified in the previous step are evaluated on the basis of selected criteria that take into account the performance of the platform and the impacts during the entire life cycle of the platform itself (from the design and installation phases to the operational and maintenance phases).

The criteria and sub-criteria that identify the industrial benefits, social, economic and environmental impacts of multi-use installations, and the related explanations, are shown in Fig. 2. More details about



Criteria	Sub-criteria	Specific issues	Explanation
Industrial Benefits	Innovation	Score:	
		· Development of new patents:	Increases with increasing potential of development of new technologies/methods due to the MUP
		· Reduction of CO2	Increases with increasing potential reduction of CO2 emission due to the MUP
		· Synergy with other uses:	Increases with increasing technological innovation due to the combination of more than one off-shore activity
		· Creation of new jobs:	Increases with increasing innovation of the installation that may require new skills and contribute to new jobs
	Exploitation potential	Score:	
		· Renewable energy potential:	These lines are repeated for each RES, whose potential increased with increasing reliability of the
		· Reliability:	technology (i.e. of the selected WEC and/or tidal device and/or wind device and/or solar panels) and
		· Performance:	with increasing the expected productivity at the site based on the general knowledge of the climate
		· Tourism:	
		· Time for natural barrier accretion	Decreases with increasing the expected colonisation/accretion time
		· Educational tourism potential	Increases with the expected impact of the off-shore platform opening on public at large
		· Diving use potential	Increases with increasing potential of diving use (depending on climate and species)
		· Available on-shore infastructures	Increases with the availability of on-shore infrastructures (transportation facilites, recreational hubs, etc.) that can support travelling from/to the platform
		· Recreational fishing potential	Increases with the potential of farming fish species used for recreational activity
		· Distance from shore:	Decreases with decreasing distance from shore
		· Aquaculture potential:	
		· Existing practices / guidelines	Increases depending on the establishment level of the practices/guidelines
		· Technological challenges:	Increases with the technological challenges to be overcome for the installation at the site
		· Performance:	Increases with the expected productivity at the site based on the general knowledge of the climate
Impacts	Environmental impact	Score:	
		· Use of marine space:	The larger the minimum space required for a feasible installation the higher the chance to create
		· Foundation type (fixed/moorings)	Fixed foundations have general greater impact (larger areas, installations buried in the bottom) than anchoring points for floating installations
		· Materials	Increases with the need of toxic paintings to reduce bio-fouling
		· Impact on the seabed:	
		· Impact on biodiversity:	Increases with increasing the number and complexity of different surfaces
		· Inclusion of exposed components/parts:	Exposed parts (floaters, reflectors, blades, etc.) may be broken and produce debris drifted in the sea
		· Underwater impact (Noise /Vibration):	Turbines and relative motion of components may generate noise that affects birds, mammals, etc.
		· Aesthetic impact:	Increases with the emerged parts (wind turbines, solar panels, etc.)
		· Maintenance:	Maintenance impact increases with increasing:
		· Transportation:	the frequency of maintenance and the frequency of transport by dedicated vessels
		· Fouling:	the required type of periodic treatments to keep fouling under control
		· Material durability:	the the need of specific treatments and/or the impact of corroded and abraded material in the water
	Risk	Score:	
		· Structural failure:	
		· Modular or single/ rigid structure:	Modular structures are usually less fragile than rigid structures and can partially assure the installation functionality
		· Geotechnical failure (liquefaction):	Fixed foundations are more exposed to soil liquefaction than moorings
		· Moorings:	Is higher when WECs are included since the design of moorings for WECs is still a challenge
		· Power failure:	
		· Power take off/feeding:	Is usually higher for turbines and hydraulic rather than electro-magnetic systems
		· Local energy storage/use:	Risk of cable failure is higher than loss of local energy storage/supply
		· Accidents:	
		· Collisions (ships, helicopters..):	Increases with increasing exposed parts and footprint
		· Health:	Increases with increasing exposed parts, toxic substances
		· Illegal fishing	Is higher in case of favourable conditions for artificial reefs
		· Pollution (accidental):	Is higher depending on the chance of release of cooling / toxic substances
	Costs	Score:	
		· Installation depth:	Costs increase with the installation depth, i.e. increase of the exposure and of the distance from shore
		· Installation type:	
		· Complexity:	Costs decrease in case of simple and modular structures
		· Moorings:	Costs increase with the complexity of the mooring schemes
		· Power extraction and storage:	
		· Power take off type:	Costs depend on the PTO type (turbines are more expensive than electro-magentic PTOs)
		· Local energy storage/use:	Stand-alone solutions are cheaper than power transfer to shore
		· Installation/Maintenance requirements:	
		· Accessibility:	Installation/maintenance of submerged devices is more expensive than floating devices
		· Materials:	Costs depend on material durability
		· Transportation:	
		· Installation:	Installation is cheaper with standard vessels
		· Operation:	Operation depens on the expected maintenance frequency and on the vessel type

Fig. 2. Criteria, with sub-criteria and related explanations, for the assessment of industrial benefit and impacts of the alternative MUPs.

these criteria can be found in Refs. [21,25]. The criteria have been revised, to account for the existing O&G infrastructure and to better reflect the social component of the reuse. Specifically, with respect to previous studies, the innovation criterion within the industrial benefit includes two additional sub-criteria, i.e. the contribution to the reduction of the carbon footprint and the creation of new job opportunities, while the technological innovation sub-criterion was changed into the easier-to-quantify development of new patents. The Exploitation potential criterion was expanded to represent the tourism activity with related sub-criteria, that consider the creation of an artificial reef close to the platform, the attractiveness of the submerged part of the platform for diving, the reuse of the platform and neighbour area for recreational fishing, the set-up of educational tourism activities. Besides the potential for different recreational activities, the distance from shore and the availability of on-shore infrastructure are key points for the feasibility of the suggested tourist activities. The Risks criteria now includes illegal fishing and accidents, to account respectively for illegal practices around the platform and possible accidents due to collisions (helicopters, ships, etc.) or health accidents (for instance due to materials and toxic paintings).

The assessment and scoring of the alternatives require the involvement of experts from different backgrounds: engineers, marine ecologist, sociologists, economists, biologists, etc. The experts have a first meeting to analyse together the case study and the potential economic activities, to prepare a table of alternative MUPs. The assessment of each alternative MUP is then done separately by each expert through the table with the entries (i.e. the criteria and sub-criteria) in Fig. 2 that is provided in the form of an excel sheet, integrated by menu windows. The menu windows, few of which are shown as an example in Fig. 3, facilitate the experts in their assessment and connect their opinion to the scoring scale. The score scale by default in the Excel sheet ranges from 1 to 5 being 1 the lowest impact or benefit, but it can be changed by the experts at the beginning of their evaluation. The correspondence between the selection in the menu window, i.e. the assessment by words, and the score is then automatically adjusted. For instance, a medium impact is automatically changed from 3 to 5 depending on the selection of the scoring scale from 1 to 5 and from 1 to 10 respectively.

Some of the sub-criteria require a separate assessment of the benefits and impacts due to each activity proposed in the MUP. For instance, the performance of a wind energy installation is assessed separately from the performance of a wave energy installation (see the Industrial Benefits criterion, sub-criterion Exploitation potential). Some of the sub-criteria instead require an assessment of the potential synergies among the different activities. For instance, the pollution risk is higher for one activity (i.e. depending on the need of cooling fluids) than for another one but the two activities may both produce a pollution risk and may be both included in the MUP. The expert should therefore decide a coherent scoring for the integration of these activities, i.e. if choosing the maximum score due to the activities, if taking the average value or if considering increments of the impact for the combination of different activities. The use of an Excel sheet allows a straightforward implementation of the selected rule by each of the expert and for each of the sub-criterion.

The scores awarded by each expert for each entry in the list (i.e. for each sub-criterion) are averaged. The experts then reconvene together with their tables filled-in and with the average values assigned to each criterion. They have to discuss about the relevance, i.e. the weight, to be assigned to each criterion. Previous work indeed showed the relevant sensitivity to different weights of the results of multi-criteria analyses. The experts are therefore advised to discuss the weights after the scoring, to limit as much as possible their capacity to guess the winning solution and affect to some extent the results based on their subjective assessment. The weights are assigned to each criterion, and the final score of each MUP is then obtained by the difference between Industrial Benefits and Impacts. The MUP characterised by the highest score is the selected configuration for the reuse of the O&G platform.

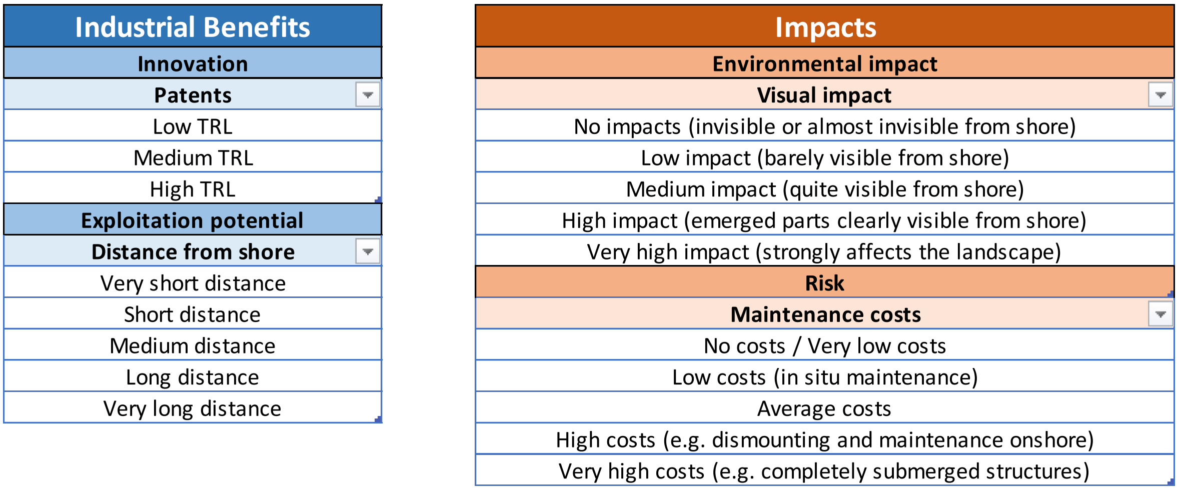
2.4. *Preliminary design of the selected reuse configuration*

The preliminary design of the selected MUP is then carried out considering the annual production (of energy, aquaculture, etc.), the marine space occupation and the technological synergies among the economic activities. Hypothetical case studies in the Mediterranean Sea were analysed by Refs. [21,25,26].

By way of illustration, as for the preliminary design of RE plants, it is necessary to: i) identify the available climate datasets; ii) select the most appropriate devices, based on production ranges, impacts, installation mode; iii) calculate the production and estimate the costs. As for the tourism, it is necessary to determine the most promising activities (guided tours at the platform, diving experiences etc.), the number of people potentially involved per year, the costs of the boats based on the length of the routes, the incomes, the possible impacts. Concerning aquaculture, after selecting the most promising species for the area, it is necessary to identify the kind of cages and their mutual position, the feeding system, the maintenance requirements and the general management.

2.5. *Identification of the Key Performance Indicators*

The starting point for the identification of the KPIs was the analysis



Industrial Benefits
Innovation
Patents
Low TRL
Medium TRL
High TRL
Exploitation potential
Distance from shore
Very short distance
Short distance
Medium distance
Long distance
Very long distance

Impacts
Environmental impact
Visual impact
No impacts (invisible or almost invisible from shore)
Low impact (barely visible from shore)
Medium impact (quite visible from shore)
High impact (emerged parts clearly visible from shore)
Very high impact (strongly affects the landscape)
Risk
Maintenance costs
No costs / Very low costs
Low costs (in situ maintenance)
Average costs
High costs (e.g. dismounting and maintenance onshore)
Very high costs (e.g. completely submerged structures)

Fig. 3. Examples of the Menu windows of the Assessment excel sheet facilitating the expert scoring of each sub-criterion.

of the OECD Indicators for “Sustainable Ocean Economy” [27]. These indicators are meant for calculation at national scale instead for decision making at local scale, however their content was used as inspiration to deliver a generally applicable and recognised method.

These indicators are divided into 6 main categories and are shortly reviewed in the following.

1. Natural capital of the oceans, represented by the indicators: threatened marine fish species, urbanisation in coastal areas, biological status of fish stocks. These indicators were not included in the selected KPIs since it is not expected that the reuse or the decommissioning will have any relevant impact on the fish status or on the coastal urbanisation.
2. Environmental dimension of well-being and resilience. These indicators are not yet defined and the EUROSTAT database [28] does not help since it does not include indicators for marine areas. One can refer to the Good Environmental Status descriptors delivered by Ref. [29], which however can be used in the Environmental Impact Assessment (EIA) for specific GIS (Geographic Information System) based analysis to prioritise data clusters [30].
3. Environmental and resource productivity, represented by the indicator: international marine bunker CO_2 emissions as share of total emissions. In this framework, the impact of the trips from/to the reused platform for Operation and Maintenance (O&M) is considered negligible and it is disregarded, while the benefit due to the (RE) production is taken into account.
4. Economic opportunities from pursuing ocean sustainability, represented by the indicators: ocean-related RE public Research and Development (R&D) budget, ocean-related RE share, innovation in selected ocean-related technologies and share. Given the uncertainty in the estimation of the changes of these indicators due to the selection of reuse instead of decommissioning, it is cautiously assumed that the reuse will not produce any significant variation of the investments in RE research or any relevant boosting of RE technologies with respect to the decommissioning case. The economic opportunities will be instead represented in terms of employment change – connected therefore to the below reported category 6.
5. Policy responses directed at ocean sustainability, represented by the indicators: Uptake of best policies and practices against illegal, unreported and unregulated fishing, share of marine area designated protected, extent of marine protected area coverage, number of ocean-sustainability related policies, ocean sustainability related tax revenue, ocean-related fossil-fuel support measures. Since both decommissioning and reuse are not fully covered by existing policies, assumption is that the two choices will impact in the same way this category n.5 and the related indicators are therefore disregarded.
6. Socio-economic context, represented by the indicators: marine landings volume, aquaculture production volume, employment in fishing and aquaculture, fishing fleet, trade in fisheries product, marine freight transport, trade-in-ocean tourism services, coastal population. The new KPIs will take into account the socio-economic context in terms of employment opportunities and environmental awareness of ocean sustainability issues. The impacts on trade, freight and population are considered negligible and disregarded.

In this context, the following issues are considered to be relevant for the selection of KPIs for choosing between decommissioning and reuse of O&G platforms.

1. The financial investment for the maintenance of the existing platform and for the construction of the new structures and devices [31];
2. The financial operating and maintenance cost for the various reuse activities;
3. The financial revenues from the economic reuse activities [32];
4. The social costs due to the impact on the seascape [33] and to interference with navigation;
5. The social benefits from employment growth, from ecological monitoring linked to energy infrastructures [34] and from the increase in environmental awareness related to tourism education [35];
6. The environmental costs due to the eventual air and water pollution caused by reuse activities, to the impacts on the seabed [36], to the potential spread of invasive species [37] and to the noise disturbance on avian and mammal species [38];
7. The environmental benefits due to the reduction of illegal fisheries, to the increased biodiversity [39] and to the reduction of CO_2 emissions thanks to renewables.

Many assessment methodologies have been applied in the economic literature, with a smaller or larger involvement of stakeholders according to the alternative adopted sustainability paradigms [40]. However, the pursued aim of this paper is to suggest a general decision-making framework that allows for an exploratory analysis of technical options and produces outputs that can be easily discussed with the stakeholders. This led to focus on the three indicators explained in the following, which can synthetize the problem in economic terms while considering a number of the cited technical issues.

The economic indicator “*eco*” represents the financial costs and revenues and it is evaluated in €/y, by applying the payback periods suggested in the literature to transform (stock) investments into (flow) costs; this indicator therefore involves the previous relevant issues from 1 to 3.

The social indicator “soc” is evaluated in terms of the potential increase of employment and is represented as additional income in €; this indicator refers to the previous issue n.5.

The environmental indicator “*env*” is represented by the following four components.

1. The avoided CO_2 emissions (issue n. 7) thanks to RE production, that are evaluated in € according to international prices for tons of carbon sequestration;
2. The impacts on the seascape and on the navigation (issue n. 4) and on seabed and pollution (issue n. 6), that are evaluated in terms of occupation of marine space (defined as Marine Footprint, *MaFo*). The occupation in km^2 can be translated into € by assigning a cost for the occupation of marine space C_{MS} (€/m^2);
3. The potential increase of social awareness related to environmental preservation (issue n.6), due to the impact of educational tourism (defined as Environmental Education, *EnEd*). It is supposed that every person, involved in the educational activities and warned about initiatives related to environmental conservation, will be willing to pay an annual standard sum named Willingness To Pay (WTP, in €) multiplied by *EnEd* (dimensionless) for the preservation of marine biodiversity due to the impact of educational tourism, resulting in an environmental benefit given by this per capita spending increase, expressed in €.
4. Finally, the impacts of reuse activities altogether on the potential conflict of uses, that are expressed again as a function of the occupation of the marine space, *MaFo*.

Based on the proposed methodology, the KPIs for each reuse activity can be evaluated as a function of economic parameters and of the two main variables *EnEd* and *MaFo* defined for that activity (in €), to allow for the comparison with decommissioning costs (Section 2.6).

2.6. *Evaluation of the reuse compared to decommissioning*

Based on the economic, social and environmental relevant issues, synthetized and evaluated through the KPIs, it is necessary to define the conditions to be met in order to verify the potential advantages of reuse compared to decommissioning.

These conditions were thus determined in terms of the previously described indicators (*eco*, *soc*, *env*), expressed in € and depending themselves on the decisional variables *EnEd* and *MaFo*. The decommissioning option was characterised by means of the parameter *dec* (representing the decommissioning costs per year), also evaluated in terms of euros. Specifically, the two conditions to be annually met are the following.

- The condition of financial (private) sustainability: capitals invested in reuse altogether must produce a positive rate of return (i.e., 1€ invested must produce profits larger than 1€); this condition means that the investors need to make a profit compared to the decommissioning option:

$$\sum_i eco_i \geq dec \qquad \text{Eq. 1}$$

- The condition of economic (social) sustainability: capitals invested in reuse altogether must increase social, economic and environmental welfare; this condition means that the sum of economic, social and environmental impacts in monetary terms must be positive and must produce a gain for the society as a whole compared to decommissioning:

$$\sum_i eco_i + \sum_i soc_i + \sum_i env_i \geq dec \qquad \text{Eq. 2}$$

In the previous equations, the subscript *i* indicates the different reuse activities considered. Each KPI *eco*, *soc* and *env* needs to be evaluated for each activity and summed up to obtain a cumulative value for the selected combination of reuse activities.

The general method presented in this Section 2 is applied in the following Sections 3 to 5 to the specific case study of Amelia platform to provide the reader with a practical example.

3. Hypothetical reuse options of an O&G platform in the Mediterranean Sea

This Section aims at presenting the case study and selecting the optimal combination of reuse activities (i.e., the first and the second steps of the presented framework are here applied to the selected case study). The overview of the hypothetical case study, i.e. the O&G platform "Amelia B" offshore the coastline of the Emilia-Romagna Region, in the North-East of Italy, Adriatic Sea, is given in Sub-section 3.1. The promising offshore activities are then preliminarily identified in Sub-section 3.2 and the optimal combination is assessed in Sub-section 3.3.

3.1. Overview of the case study

The "Amelia B″ platform (Fig. 4) is an 8-leg steel reticular structure located in the Adriatic Sea, 28 km away from the Emilia Romagna coast, in the province of Ravenna, on a depth of about 31 m (44,407508°N; 12,662225°E). With a height of 50 m above sea level and a horizontal surface of about 52 m^2, the platform was built in 1991.

The North Adriatic Sea is a shallow, semi-enclosed basin. It has an average slope of 0.35 m/km and an average depth of 40 m. It is characterized by sharp water column stratification and very high productivity [42]. The cyclonic circulation is highly variable with the seasons and it is mainly driven by the prevailing winds and river current from the North-East (Bora) and South-East (Sirocco). The most important influence is the Po River with an average annual flow of 1700 m3/s. Fine-grained sediments are predominantly mud. The average coarse-grained content (>63 μm) is less than 8 % by dry weight. Tidal fluctuations in the region are small. The average high tide range is ±0.4 m, with extreme year values around ±0.85 m. The most intense storms come from Bora with waves reaching up to 3.5 m per year and up to 6 m every 100 years. Wind speed is greater from the Bora sector, usually reaching 35 knots, but it rarely exceeds 30 knots from the longer Scirocco sector.

The most relevant environmental features of the region are.

- low tidal environment (tide amplitude less than 1 m);
- semi-enclosed basin (average slope 0.35 m/km, average depth 40 m);
- high seasonality of hydrological variability; rapid stratification; very high production rates;
- high population density, tourism;
- eutrophication, pollution, large-scale development of marine and coastal infrastructures, a.o. 100 offshore gas platforms in sedimentary environments (~10–120 m).

Fig. 4. Location of the "Amelia B″ platform within the many platforms offshore the Emilia Romagna region (data from Ref. [41]), Italy and view of the "Amelia B".

The province of Ravenna is particularly rich of O&G platforms and many experiments have been set to promote synergies in their use and to boost blue economy. Two wave energy converters (WECs) were deployed by ENI: ISWEC integrated with photovoltaic (PV) panels at the PC80 platform [43] and PB3 by OPT at the "Amelia B″ platform. From Ravenna to Rimini, the cleaning of the leg platforms, where mussels spontaneously grow, within the asset integrity, lead to the collection of about 10–12 thousand quintals of mussels per year, representing the 5 % of Emilia Romagna mussels production and the 25 % of the Ravenna coast ([44]). Educational tourism is proposed through periodic visits to the Garibaldi C platform, offshore Ravenna. The visits highlight the relevance of the activities carried out by the platform owner with respect to the circular economy [45]. It is worthy to remark that the wreckage of the Paguro platform offshore the coast of Ravenna [46] in 1965, leaving the platform foundation in the sea, without disturbing the colonisation and the attracted mammals, created an area of high tourist relevance due to diving.

3.2. *Promising offshore activities at the O&G platform*

The hypothetical reuse of the "Amelia B″ platform may include different economic activities, such as fish farming, creation of an offshore maritime hub, set-up and maintenance of a floating greenhouse, creation of an offshore tourist site, that may be powered by local energy production systems. For the purpose of this research, the activities are considered in the following and shortly discussed to set-up the MUP alternatives for the ranking step.

In the rather warm Mediterranean Sea, fish farming is the most promising offshore activity from an economic point of view, due to the use of mature and reliable technologies and to the mild water temperature [47]. However, the shift of fish-farming from near-shore to offshore may cause a relevant social opposition due to the many operating traditional factories. In the specific case of the "Amelia B″ platform, offshore aquaculture has been already successfully tested in the area thanks to the mussels collection involving local fisherman at the leg platforms (Sub-section 3.1), and therefore fish farming may be considered as one of the potential reuse activities.

As well as the wrecked Paguro platform or as well as the Garibaldi C platform (Sub-section 3.1), also "Amelia B″ platform could become respectively an area of high diving interest or a platform hosting educational tourism. Given the 28 km distance of the area from shore and the speed of typical diving boats of about 15 kn, the platform can be reached in about 1 h. The more complex business of creating an offshore recreational hub is not considered because of the potential conflicts with environmental associations.

The mild Adriatic Sea cannot lead to huge marine RE production but can lead to a production sufficient to support locally the economic activities selected for the reuse, so that the platform in the new configuration can be energetically independent. Given the maturity of the technology and the relatively small bottom depth, fixed medium-size wind turbines are considered to achieve the best compromise among the low-speed winds and the costs. As for the WECs, floating point absorber devices are considered, to harvest energy in a multi-directional climate and to limit the environmental footprint. Tidal energy has to be disregarded because of the negligible tidal range and of the low-speed currents. Solar energy can combine maturity of technology and safety of installation thanks to the platform deck, and it is characterised by the minimum environmental impact if compared with marine renewables.

3.3. *Selection of the reuse configuration of the O&G platform*

Based on the preliminary considerations drawn in Sub-section 3.2, the configurations for the hypothetical reuse are assumed to host the two main economic activities that appear to be promising in the area: either fish farming or tourism. The reuse configurations include only fish farming, only tourism or the combination of the two activities. These activities are assumed to be energetically supported by the local production from different RES: first only solar, as it is considered to produce the minimum impact on the environment thanks to the chance of installation of the panels on the O&G platform deck; then wave energy as it is floating and therefore is producing a lower impact than the fixed wind turbines; then the medium-size fixed wind turbines suited for intermediate depths as at the "Amelia B″ platform; finally, the three sources are combined in pairs and all together. The total number of reuse configurations to be scored by experts is 17, see Table 1.

Four experts were involved in this analysis with different background and specifically: 2 engineers (1 expert of off-shore structures and 1 expert of marine renewables), 1 economist, 1 marine ecologist. The experts were provided with the Excel sheet including the criteria and related sub-criteria reported in Fig. 2, integrated by the menu windows as in Fig. 3. The scoring scale from 1 to 5 was fixed by the experts prior to the secret scoring made separately by each expert. The way one expert assigned the scores is given in Appendix A1 as an example.

The weights assigned to each criterion were discussed among the experts and were defined instead after the scoring exercise. The same weight was given to each sub-criterion. The experts decided to assign 100 % to the total weight of both Benefits and Impacts. Specifically, it was decided to give a higher weight to Exploitation (60 %) rather than Innovation (40 %) because of the higher uncertainty in the assignment of the scores to the innovation criterion. An equal weight of 30 % was assigned to both risks and costs, while a greater weight of 40 % was assigned to the environmental impact, considering that the green transition is of outmost importance in the decision of re-use an existing platform.

The discussion about the sensitivity analysis of the weights to different background expertise in the group scoring the criteria is already provided by [21]. It was however verified that the ranking of the MUPs did not change by varying the weight of ±10 %.

The final score of each MUP in each expert sheet is obtained by subtracting the weighted average scores of the impacts from the benefits. The sheets of all the expert are combined together, i.e. by sum. The selected configuration is the one characterised by the highest score, which in this case consists of the combination of fish farming and tourism activities, supported by local RE generation by solar panels and wind turbines (MUP 17 in Table 1). The final rank is reported in the last column of Table 1. MUP 16, including also wave energy devices, occupies the second ranking position with the highest score for industrial benefits due to the strong contribution to innovation. Whilst MUP 17 will be retained as the optimal selected configuration for this specific site, MUP 16 will be also considered as additional scenario to MUP 17 in the exploration of the solution that will be discussed in Sub-section 4.3.

Table 1
Reuse configurations of the O&G platform.

Name	Fish farming	Wind	Wave	Solar	Tourism	Rank
MU 1	x			x		9
MU 2	x		x			16
MU 3	x	x				15
MU 4	x		x	x		8
MU 5	x	x	x	x		7
MU 6				x	x	4
MU 7			x		x	17
MU 8	x	x		x		5
MU 9		x			x	12
MU 10			x	x	x	11
MU 11		x	x	x	x	6
MU 12	x			x	x	3
MU 13	x		x		x	14
MU 14	x	x			x	13
MU 15	x		x	x	x	10
MU16	x	x	x	x	x	2
MU17	x	x		x	x	1

3.4. Preliminary design of the reuse configuration of the O&G platform

The preliminary design considered both the optimal configuration, MUP 17 (fish farming, wind, solar panels and educational tourism) and MUP 16 (that differs from MUP 17 only for the addition of wave energy devices), the latter because of the interest showed by stakeholders and because of its highest industrial benefit. The design also of the wave component will lead to the use of the last two steps of the framework not only in the decision but also in the exploratory mode.

The detailed design, including costs, is reported in Appendix A.1, while the main results are here summarised.

On the deck of the "Amelia B″ platform, up to 150 solar panels can be installed. The high-performance SunPower Maxeon 3 panels [46] with a surface area of 1.77 m^2 were selected. The annual energy available is on average equal to $E_{pv} = 313.28$ kWh/m^2 and the annual energy production for each panel equals 553.80 kWh/y.

The AquaBuOY wave energy device of the point-absorber type was selected, because of three main reasons: the bi-modal wave climate in the Adriatic Sea; the similarity with the PB3 device [48] that was installed at the platform in the years 2018–2019; the availability of AquaBuOY power matrix in the literature [49]. The average annual wave energy E_{wave} at the "Amelia B″ platform is 37.07 MWh/y and the average annual value of the energy produced by the WEC equals 2.29 MWh/y. The AquaBuOY WEC with its anchoring system occupies an area of about 300 m × 300 m, as each anchor line is 150 m long in plan according to the mooring system adopted for the PB3.

At the "Amelia B″ platform, the average wind speed at a height of 31 m is equal to 4.23 m/s; the average energy produced per year by a Libellula 60i [50] is equal to 84.01 MWh/y and the hours of operation are on average 64 %. In case more than one turbine is installed in the area around the platform, the distance among the turbines is about 140 m (i.e. 7 times the rotor diameter).

Based on a recent similar study [26] in the North Adriatic Sea, the seabass was selected for fish farming in this region. It was also assumed that the basic module of the fish farm consists of 10 cages with a diameter of 30 m, which requires an area of 320 m · 500 m, considering the cage layout, the navigation channels and the feeding platform. The fish farm requires a (small) power supply, including batteries and a generator set to smooth peaks and assure power continuity.

The educational tourism consists of the visit the platform for educational and recreational purposes. It is assumed to take place on a seasonal basis.

Periodic maintenance of the structure is here supposed to be at least partially replaced by the mineral deposition technique, that requires a (small) power supply but can significantly reduce the costs. The technique is applied to all the submerged part of the platform to avoid corrosion.

4. Performance of the reuse configuration of the O&G platform

In this Section, the fourth and the fifth steps of the framework are applied to the case study and the conditions in which reuse may prove to be advantageous are discussed. Specifically, in Sub-section 4.1, the method presented in Sub-section 2.5 for defining the KPIs is applied to the design of the activities carried out in Section 3.4 and Appendix A.1. Sub-section 4.2 describes the main steps for the evaluation of the KPIs and their relation with the MUP design parameters, while the details about the calculations is given in Appendix A.3. The results for the optimal MUP, including wind and solar energy, fish farming and educational tourism (i.e. MUP 17) are presented and discussed versus the decommissioning option in Sub-section 4.3. The framework is then used also in exploratory mode in case wave energy is included in the RE mix (i.e. MUP 16).

4.1. Modelling activities at the O&G platform in terms of KPIs

The three selected reuse activities can be modelled, in terms of the defined KPIs (*eco*, *soc* and *env*, Section 2.5) based on the following considerations.

- RE production: the produced energy is supposed to be used only to power the fish farm (see Sub-Section 3.2), so there is no revenue but there is a financial cost for the installation and maintenance. The environmental impact has a negative component, that can be related to the extension of the energy plant, and a positive component, corresponding to the reduction of carbon footprint (i.e., the energy required by the fish farm is not produced by fossil fuels). As for the social benefits, it produces an increase in employment. Note that the KPIs referring to RE production are indicated with the subscript "*ene*" in the equations reported in the following and in Appendix A.3.
- Fish farming: it ensures a financial profit, which depends on the fish production and therefore on the extension of the fish farm. It produces a positive social impact, i.e. an increase in employment, but it has a negative environmental impact that can be expressed as a function of the occupied marine space, i.e. again in terms of the extension of the fish farm. Note that the KPIs referring to fish farming are indicated with the subscript "*fis*" in the equations reported in the following and in Appendix A.3.
- Tourism: it provides a financial profit, that does not depend on the plant extension, since tourism is based on visits to the existing O&G platform area. Tourism social impact consists of an increase in employment. Tourism environmental impact does not include a negative component, since the activity does not require additional occupation of the marine space or introduction of new materials or infrastructures. As observed in Sub-section 2.5, educational tourism can have a positive environmental impact related to social awareness of biodiversity conservation, which can be evaluated as an increase of the standard WTP of the people involved in educational tourism activities for biodiversity. Note that the KPIs referring to educational tourism are indicated with the subscript "*tou*" in the equations reported in the following and in Appendix A.3.

The two financial and economic conditions, Eq. (1) and Eq. (2), which have to be met for each year, can be expressed for this specific combination of reuse activities as:

$$\sum\nolimits_{i=tou,fis,ene} eco_i \geq dec \qquad \text{Eq. 3}$$

$$\sum\nolimits_{i=tou,fis,ene} eco_i + \sum\nolimits_{i=tou,fis,ene} soc_i + \sum\nolimits_{i=tou,fis,ene} env_i \geq dec \qquad \text{Eq. 4}$$

where: *dec* are the decommissioning costs divided by the years of duration of the reuse; eco_i, soc_i, env_i are respectively: the net profit, the social benefit and the environmental cost/benefit of the activity i.

The evaluation of Eq. (3) and of Eq. (4) will prove if a combination of reuse activities that meets both the financial and the economic conditions, ensuring a benefit of the reuse compared to decommissioning, exists or not. Eq. (3) and Eq. (4) will be solved considering also the scenario of $dec = 0$ to discuss the issue of the responsibility of the decommissioning operation and of the related costs in case of reuse.

4.2. Evaluation of the KPIs

Based on the design information reported in Appendix A.2, the assessment of production and costs for wind, wave and solar energy and for fish farming was carried out as a function of the number of turbines, devices, panels and cages respectively, and therefore as a function of the occupied marine space. The results are shown in Table 2, accounting for the assumptions in Appendix A.3 and considering that.

Table 2
Energy and Fish farming production and costs as a function of the occupied marine space.

	Design parameters for Energy Production and Costs																	
Solar	**N° panels**	**12**	**24**	**36**	**48**	**60**	**72**	**84**	**96**	**108**	**120**	**132**	**144**	**156**	**168**	**180**	**192**	**204**
	Production (MWh/y)	6.65	13.29	19.94	26.58	33.23	39.87	46.52	53.16	59.81	66.46	73.10	79.75	86.39	93.04	99.68	106.33	112.97
	Area (10^{-4} km^2)	0.21	0.42	0.63	0.85	1.06	1.27	1.48	1.70	1.91	2.12	2.33	2.55	2.76	2.97	3.18	3.39	3.61
	Investment (10^{-1} M€)	0.84	1.33	1.82	2.31	2.80	3.29	3.78	4.27	4.76	5.25	5.74	6.23	6.72	7.21	7.70	8.19	8.68
	Maintenance (10^{-2} M€)	0.67	1.06	1.46	1.85	2.24	2.63	3.02	3.42	3.81	4.20	4.59	4.98	5.38	5.77	6.16	6.55	6.94
Wave	**N° devices**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**12**	**14**	**16**	**18**	**20**	**25**	**30**
	Production (MWh/y)	2.29	4.58	6.87	9.16	11.45	13.74	16.03	18.32	20.61	22.90	27.48	32.06	36.64	41.22	45.80	57.25	68.70
	Area (km^2)	0.09	0.18	0.27	0.36	0.45	0.54	0.63	0.72	0.81	0.90	1.08	1.26	1.44	1.62	1.80	2.25	2.70
	Investment (M€)	1.45	2.90	4.35	5.80	7.25	8.70	10.15	11.60	13.05	14.50	17.40	20.30	23.20	26.10	29.00	36.25	43.50
	Maintenance (M€)	0.12	0.23	0.35	0.46	0.58	0.70	0.81	0.93	1.04	1.16	1.39	1.62	1.86	2.09	2.32	2.90	3.48
Wind	**N° panels**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**12**	**14**	**16**	**18**	**20**	**25**	**30**
	Production (MWh/y)	84.01	168.02	252.03	336.04	420.05	504.06	588.07	672.08	756.09	840.10	1008.12	1176.14	1344.16	1512.18	1680.20	2100.25	2520.30
	Area (km^2)	0.02	0.04	0.05	0.07	0.09	0.11	0.12	0.14	0.16	0.18	0.21	0.25	0.28	0.32	0.35	0.44	0.53
	Investment (M€)	0.24	0.49	0.73	0.98	1.22	1.47	1.71	1.96	2.20	2.45	2.94	3.43	3.92	4.41	4.90	6.12	7.34
	Maintenance (M€)	0.02	0.04	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20	0.24	0.27	0.31	0.35	0.39	0.49	0.59

	Design parameters for Fish farming production, costs and required energy						
Fish farming	**N° cages**	10	20	30	40	50	60
	Size, m x m (cages aligned longshore)	320x500	740x500	1160x500	1580x500	2000x500	2420x500
	Area (km^2)	0.16	0.21	0.42	0.63	0.84	1.05
	Capital costs (M€)	1.77	2.66	5.32	7.10	8.87	10.6
	Operating costs (M€)	3.38	5.08	10.16	10.16	16.93	20.32
	Fish production (ton/y)	700	1’400	2'100	2'800	3'200	3'600
	Net Profit per year (M€)	5.892	11.785	17.677	23.5700	29.462	35.355
	Required energy (MWh/y)	201.04	396.24	591.44	786.64	981.84	1'177.04

- annual O&M costs were assumed to be the 8 % of the initial investment cost for all the RE plants, following the cautious value assigned to the wave energy sector [51];
- economic and spatial synergies among the activities and the devices are disregarded.

The following assumptions are considered for the KPIs calculation.

i) Capitals invested in fishery, solar, wave and wind energy are covered within the Payback Period (PBP) suggested in the literature (i.e., 15, 15, 30 and 50 years, respectively).
ii) The social benefit related to the increased employment in the different sectors is evaluated in monetary terms by using yearly incomes per people employed, by considering flow impacts (e.g., workers in management and maintenance) but disregarding stock impacts (e.g., workers in design and R&D);
iii) The possible negative environmental impacts related to the boats, used for tourist activities and for fish farming, are assumed to be negligible.
iv) The occupation of marine space is supposed to be a cost, that can be estimated by assigning a cost per unit surface for the occupation of marine space C_{MS} (€/m^2). This cost is here assumed to be equal to 1 €/m^2, but the case of $C_{MS} = 0.5$ €/m^2 will be also examined. This value is fixed as a reference cost to be changed for specific site conditions, given the wide range of values typically assigned to the marine space, from O(0,01) to O(100) €/m^2 depending on the use and related costs and benfits (marine protected area, fishing), on the location (population, gross domestic product, etc.) and on the climate (and related seasonality), see a.o [50,52].

4.2.1. *How to estimate economic KPIs*

The economic KPIs *eco* are calculated as the difference between the economic benefit due to the energy production, the fish production or the benefits from the tourism and the costs for the plant construction and maintenance or for setting-up the tourist activities.

In this case, since the RES production is targeted only to supply the MUP activities and the exceeding energy is not sold, the net profits for wave, wind and solar panels, eco_{wave}, eco_{wind} and eco_{PV}, correspond only to the costs of the plants, i.e. have a negative sign. These costs depend on the extension of the plants themselves and on the energy production by each plant, and therefore on the occupation of the marine space.

In order to evaluate the contribution of the different RES to the mix, it should be satisfied the following condition that the RES produce the amount of energy required by the fish farm and by the mineral deposition plant:

$$E_y = E_{fis} + E_{carb} = E_{y,wave} + E_{y,wind} + E_{y,PV} \qquad \text{Eq. 5}$$

where E_y is the yearly energy production that is a combination of wind ($E_{y,wind}$), wave ($E_{y,wave}$) and solar ($E_{y,PV}$) energy; E_{fis} is the energy required by the fish farming that depends on the fish production and therefore on the plant extension and related marine space $MaFo_{fis}$; E_{carb} is the annual energy required by the mineral deposition system, equal to 74.28 MWh/y (Table A.4).

The economic KPI for RES, eco_{ene}, depends on $E_{y,wind}$, $E_{y,wave}$ and $E_{y,PV}$, that can be expressed as functions of the number of the devices and, thus, of the corresponding extension of wind, wave and solar plants, i.e. as functions of $MaFo_{wind}$, $MaFo_{wave}$ and $MaFo_{PV}$ respectively, by interpolating the data in Table 2. These variables $MaFo_{wind}$, $MaFo_{wave}$ and $MaFo_{PV}$ can be expressed in turns as functions of the occupation of the marine space due to the fish farm $MaFo_{fis}$, by interpolating again the data in Table 2 for different scenarios of RES combination in Eq. (5).

Since the solar plant is the less expensive of the RE plants and it is installed on the platform deck, without further occupation of the marine space, the maximum number of PV panels (144, in the case of the "Amelia B" platform) is supposed to be installed. A fixed cost of 0.001 M€/y, a fixed extension 0 km^2 and $E_{y,PV} = 79.75$ MWh/y are therefore assumed in the calculations.

The net profit of fish farming, eco_{fis}, is the difference between the sold fish production and the investments and maintenance costs of the plant; both the benefit and the total cost can be expressed as functions of $MaFo_{fis}$, by interpolating the data in Table 2.

The net profit due to the installation of the mineral deposition system, eco_{carb}, is constant, since it is sized for the existing platform, and it is estimated to reduce the maintenance costs of 0.3 M€/y.

As for the tourism, eco_{tou} is given by the profits only, assuming the costs related to onshore structures and boats to be negligible. The profits depend on the number of people involved in the activity, on the costs per person and on the number of days of favourable weather when the tourist activity can be carried out.

4.2.2. How to estimate environmental KPIs

Considering the energy production, the environmental indicators env_{wave}, env_{wind}, env_{PV} consist of two components.

- a positive component, due to the reduction of carbon footprint obtained by supporting the MUP activities (i.e. the fish farm and the mineral deposition system) with RES rather than with fossil fuels; this component depends on E_y and thus on the marine space occupied by wind, wave and solar panels ($MaFo_{wind}$, $MaFo_{wave}$ and $MaFo_{PV}$);
- a negative component, that is modelled as function of the occupation of the marine space $MaFo_{wind}$, $MaFo_{wave}$ and $MaFo_{PV}$.

These components can be thus expressed as functions of $MaFo_{fis}$, by interpolating again the data in Table 3 for different scenarios of RES combination in Eq. (5).

The fish farming environmental KPI env_{fis} is expressed as function of $MaFo_{fis}$ only and thus it has a negative sign; it is obtained by interpolating the data in Table 2 for different fish production and corresponding E_{fis}.

The environmental KPI for tourism, env_{tou}, represents the (positive) increase of environmental awareness $EnEd$ depending on the number of tourist and on their WTP for environmental conservation, see Sub-Section 5.1. $EnEd$ is one of the two independent variables in Eq. (3) and Eq. (4) together with $MaFo_{fis}$. The value of $EnEd$ is made varying with continuity.

4.2.3. How to estimate social KPIs

Finally, for all the activities, social indicators soc_{ene}, soc_{fish} and soc_{tou} are defined based on the number of people employed, on the duration of employment and on the salaries, taking into account the PBP of fish farming and RE installations. These indicators therefore are not derived by interpolation or best fitting and their detailed calculations are reported in Appendix A.3.

4.3. Reuse vs decommissioning: the decision

The conditions that could make reuse advantageous compared to the decommissioning option are identified by solving Eq. (3) and Eq. (4). The value of dec is assumed to be 0.69 M€, i.e. the total decommissioning costs of 19 M€ divided by 27.5 years as the average break-even period [53,54].

Figs. 5 and 6 show Eq. (3) and Eq. (4) as a function of the variables $MaFo_{fis}$ (i.e. the occupation of marine space by the only activity producing profits) and $EnEd$ for $dec = 0.69$ M€ and $dec = 0$ respectively.

In each graph, the financial condition is represented by a vertical grey line, since it is independent from $EnEd$. The points satisfying the inequality in Eq. (3) are all the ones to the right of that line. This suggests to select a combination of activities ensuring the satisfaction of the financial condition with the lowest value of $MaFo_{fis}$, that is represented by the intersection of the vertical line with the horizontal axis.

The economic condition is instead represented by curves, since it depends on both $MaFo_{fis}$ and $EnEd$. The violet and the blue curves represent Eq. (4) in case C_{MS} equals respectively 1€/m^2 and 0.5 €/m^2. The economic condition is satisfied by all the points above the blue or the violet curve.

The solution of the system of inequalities is given thus by the intersection between the curve representing the economic condition and the vertical line representing the financial condition.

In Fig. 5, the solution which satisfies both the conditions is identified by: $MaFo_{fis} = 2.21$ km^2 and $EnEd = 11.87$. In case of the lower value of C_{MS}, the value of $EnEd$ equal to 10.53 would be sufficient. In more details, considering the required energy by fishery E_{fis} corresponding to $MaFo_{fis}$, the configuration of MUP 17 would consist of.

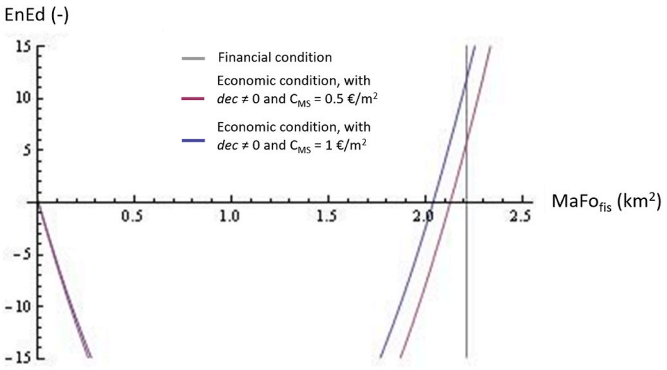


Fig. 5. Graphical representation of Eq. (3), i.e. the financial condition, and of Eq. (4), i.e. the economic condition (shown for different values of C_{MS}), for MUP 17 with $dec = 0.69$ M€.

Table 3
Synthesis of the most relevant features of the existing frameworks.

			Decommissioning		Re-use scenario		Re-use activities					assessment		
	Scope of the framework	Method	partial	full	fixed	variable	single RE	multiple RES	aquaculture	fish farming	tourism	env	soc	eco
Lumina (2010)	decision between decommissioning scenarios	MCA	🟩	🟩								🟩		🟩
Martins et al. (2020)	evaluation of decommissioning scenarios	MCA	🟩	🟩								🟩		
Leporini et al. (2019)	evaluation of re-use scenarios against decommissioning scenarios	DCA+LCA	🟩	🟩		🟩		🟩				🟩		🟩
Zagonari (2021)	evaluation of re-use scenario against decommissioning	MCA+CBA		🟩	🟩		🟩		🟩		🟩	🟩	🟩	🟩
This paper	decision between re-use scenarios and decommissioning	MCA+LCSA		🟩		🟩		🟩		🟩	🟩	🟩	🟩	🟩

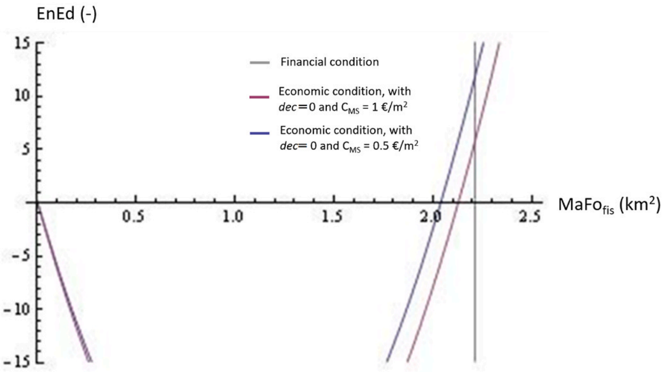


Fig. 6. Graphical representation of Eq. (3), i.e. the financial condition, and of Eq. (4), i.e. the economic condition (shown for different values of C_{MS}), for MUP 17 with $dec = 0$ M€.

- 110 fish cages, with an extension of 2.21 km^2 and an energy requirement of 1′204 MWh/y,
- 12 wind turbines, with an extension of 0.20 km^2 and an energy production of 976 MWh/y.

This MUP would result in financial and economic benefits of the reuse compared to decommissioning, in case the educational tourism is sufficiently effective, i.e. in case it produces an increase of at least 11.87 or 5.81 times the WTP for marine biodiversity preservation if C_{MS} equals 1 or 0.5 €/m^2 respectively.

In Fig. 6, the solution is: $MaFo_{fis} = 2.24$ km^2 and $EnEd = 11.99$ or $EnEd = 5.86$ for C_{MS} equal to 1 or 0.5 €/m^2 respectively. As for fish farming and energy production, the MUP will consist essentially of the same components as derived from Fig. 5, i.e. the value assumed by dec is almost irrelevant in this range $dec = [0, 0.69$ M€].

The comparison between Figs. 5 and 6 shows thus that the impact of political decisions about who will bear the costs of decommissioning is basically irrelevant in this case, being the investment costs of the reuse extremely high. Moreover, the value of *EnEnd* is greater for greater value assigned to C_{MS}, that means: "if I value more the marine space, then my WTP for biodiversity conservation is also higher".

The analysis of the reuse option through the proposed procedure therefore leads to the following insights.

- A combination of activities exists, which ensures the satisfaction of both the financial and economic conditions, Eq. (3) and Eq. (4). The total spatial extension of the reuse activities in this case is $MaFo = 2.43$ km^2.
- The impact of the political decision on the allocation of *dec* has no relevance in the choice between the reuse and the decommissioning, due to the large investment costs of reuse activities (i.e. the investment costs for fish farming in this case, since this is the only activity producing direct benefits by selling its production).

Before taking the final decision, the solution should then be combined with a GIS map of the area showing the potential conflict of uses and it should be discussed with local and national managers and authorities for permitting issues and for defining responsibilities. As for this specific application, the extension of the required marine space would be unsustainable because of maritime routes and other existing O&G platforms at short distance, leading back to the choice of decommissioning.

4.4. Use of the framework for the exploratory analysis of the results

Fig. 7 explores the case of MUP 16, including in the analysis the contribution of wave energy to the RE mix.

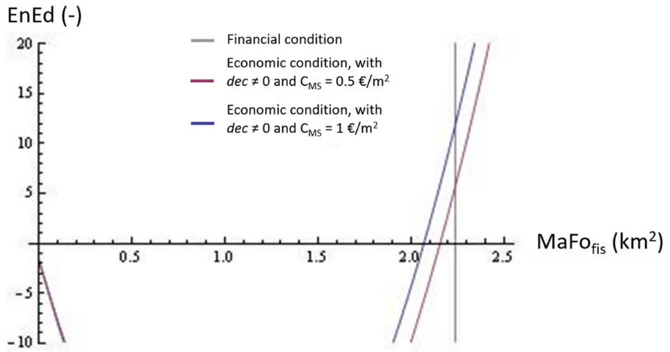


Fig. 7. Graphical representation of Eq. (3), i.e. the financial condition, and of Eq. (4), i.e. the economic condition (shown for different values of C_{MS}), for MUP 16, in case wave energy devices produce the 10 % of the required energy by the fish farm.

Both the minimum necessary extension of the fishery plant $MaFo_{fis}$ and the minimum necessary impact of the environmental education *EnEd* proportionally decrease with increasing the percentage of wave energy in the RE mix. However, the total occupation of the marine space *MaFo* and the costs increase.

In case the 10 % of the required energy is provided by a wave energy plant, the reuse activities should include for $dec = 0.69$ M€.

- 100 cages, with $MaFo_{fis} = 1.98$ km^2;
- 10 wind turbines, with $MaFo_{wind} = 0.17$ km^2, $E_{y,wind} = 867$ MWh/y;
- 42 WECs, with $MaFo_{wave} = 3.79$ km^2, $E_{y,wave} = 96$ MWh/y

for a total $MaFo = 5.94$ km^2. The corresponding value of *EnEd* increases with increasing C_{MS}, being 5.12 and 10.54 in case C_{MS} equals respectively 0.5 and 1 €/m^2.

Therefore, as already derived from the application of the ranking to the MUP alternatives (Sub-Section 3.3), the inclusion of wave energy production within the reuse activities, i.e. MUP 16, wouldn't be a viable solution, although leading to a significant industrial innovation.

5. Comparison of the new framework with existing ones

The aim of this Section is to compare the new framework with existing ones related to the decision making between decommissioning and reuse of O&G platforms. As stated in the Introduction, there are a very few studies centred on this issue. Sub-section 5.1 discusses the gaps of existing conceptual frameworks, i.e. the Life Cycle Assessment (LCA) [20] and the multi-criteria frameworks [19,55]. Sub-section 5.2 discusses the applicability of the decision support tool [17]. Sub-section 5.3 summarises critically the outcomes.

5.1. Conceptual frameworks

Leporini et al. [20] considered the reuse of O&G platforms for the production of RE (wind and solar) against standard decommissioning scenarios, including total removal or partial removal with the possibility to use the sub-structure as an artificial reef. They also combined different scenarios for the use of the produced energy: hydrogen production, electricity production, desalinisation, onshore methanation process. They performed a Discount Cash Flow Analysis (DCFA) and a LCA in the case of 4 real platforms, specifically: 2 very similar 4-legged platforms with 3 production wells and two very similar 4-legged platforms with 3 production wells, located in the Adriatic Sea and in the North Sea. While they used quantities, materials, costs, etc. for these 4 specific platforms, the procedure can be in principle applied to other platforms. The environmental impact was assessed following the IMPACT 2002+ method [56] and implementing these specific categories within the Ecosystem quality “damage category”: Aquatic eco-toxicity, aquatic eutrophication, aquatic acidification. Other categories within the Ecosystem quality referred to terrestrial features, while other “damage categories” involve Human health, Climate change and Resources, including global warning and non-renewable energy within the categories that could be of interest also in this case study.

The main similarities and differences of the framework [20] with the new framework are here summarised.

- The new framework includes a wider variety of environmental impacts that are specifically related to the design, the durability and the components of marine RE devices; it does not assess instead direct impacts on human health but it includes indirect impacts through the risk of collision or of pollution.
- The new framework includes not only environmental but also social and economic impacts.
- In the new framework the value of the discount rate can be different from zero; the value of zero is however assumed since it is the only acceptable value when assessing environmental impacts. Under the assumption of zero discount rate, the new framework collapses in [20].

Martins et al. [19] proposed a set of technical, societal, safety, economic and environmental criteria (with related sub-criteria) to standardise the selection of the most suitable decommissioning scenario of O&G platform. It should be mentioned that they do not propose a comprehensive method, including the way to select the stakeholders or to perform the ranking or to assign the weights. They also did not perform any kind of example application of their set of criteria. They discussed instead the relevance i) of weights assignment to the different criteria and sub-criteria; ii) of detecting the overlap and correlation among criteria; iii) of selecting and evaluating the sub-criteria on a case-by-case basis. Their set of criteria is similar to the set of criteria proposed by the new framework for the selection of the most suited reuse opportunity at a given site. The new framework and the previous work however have a different scope and it is therefore not meaningful to perform any kind of comparison or try to apply the framework [1] to the case study proposed here.

Zagonari [55] combined a multi-period Cost-Benefit Analysis (CBA) with a multi-period Multi Criteria Analysis (MCA) to analyse the reuse versus the total removal of an O&G platform. This framework was applied to the same platform considered in this paper. The main differences between the previous work and the new framework can be summarised as follows.

- The reuse scenario was fixed, including only one Resource and it could not be straightforward applied to multiple energy sources. The new framework instead is generally applicable to a number of different energy sources, by selecting the marine space occupation as the common variable for their comparison.
- The work was not focused on including tourism and specifically educational tourism; in the new framework the social impact of educational tourism is considered by adopting the WTP for biodiversity conservation.

The previous work was therefore meant to discuss the reuse against decommissioning in case of a specific reuse scenario. The new framework differs from the existing framework i) in terms of the scope, i.e. decision instead of evaluation; ii) in terms of exportability, i.e. inclusion of a number of different activities; iii) in terms of criteria, i.e. inclusion of the social impact due to tourism. Given the differences between the previous and the new frameworks, and furthermore the application to the same case study, the interested reader is referred to the literature for more details about the assumptions, hypotheses and results derived from the previous work.

5.2. Decision support tools

The only available multi-attribute framework to decide about decommissioning or reuse of an O&G platform is the PLATFORM tool, which was developed in Analytica, a general-purpose visual environment for building quantitative decision models [17].

The PLATFORM tool allows the users to.

- select among the following decision options: complete removal with or without explosive severing and removal of shell mounds, or partial removal with the option of adding quarry rock enhancement for the reefing option;
- analyse these different scenarios for a range of platforms in the US, whose characteristics are given as input to the tool;
- include impact analysis of the decommissioning options on economics, society and environment.

The model incorporates user interfaces, a hierarchy of influence diagrams to build and organize the model, range sensitivity analysis to identify key sources of uncertainty or disagreement, and Monte Carlo simulation to analyse uncertainties.

The PLATFORM tool.

- is not exportable directly to areas different from US; it can be scoped for other areas by interacting with the developers;
- based on the US experience and eventually on the delivery date of the tool, it considers the rig-to-reef conversion as the only option for reusing an O&G platform; the user cannot therefore include and select different activities;
- takes into account somewhat similar to our KPIs, but in terms of impact due to partial or total removal, instead of assessment of the performance of the reuse configuration in terms of impacts and benefits; the KPIs (named “attributes” in PLATFORM) are mainly related to the environment (air quality, water quality, marine mammals and birds, marine resources fish biomass, benthos), a few include also the society (ocean access, compliance) in terms of acceptance of the partial or total removal decision (i.e. social benefits like new jobs, new skills, etc. are not included as the innovative component of the reuse is basically missing) and the economic costs, which depend again on the selected features for the partial or total decommissioning;
- gives as output the sensitivity analysis of the difference in value between complete removal and partial removal for the selected platform, by changing the swing weight for each attribute and the cost uncertainty from 10th to 90th percentile while keeping the other variables at their base values.

Besides the impossibility to scope the PLATFORM tool in our case study, it is clear that the kind of answer we can obtain from this framework and from the PLATFORM tool is different as the starting point is different.

- The PLATFORM tool is meant to support decision between partial and full removal of the structure, with partial removing including an activity that is not assumed to be an economic activity (i.e. the rig-to-reef). The new framework proposed here is meant to support decision between full removal and reuse of the assigned platform, where reuse consists of the optimal combination of economic activities (i.e. fish farming, tourism, energy) at the site.
- The PLATFORM tool assesses the economic, social and environmental impact of the full removal and of the partial removal of the platform itself, while this new framework assesses the social, economic and environmental impacts and benefits of the optimal configuration of reuse and finds its layout (i.e. the “size” of the different economic activities) that can make the reuse more sustainable than the decommissioning.

It is thus impossible to perform a direct comparison of the results of the framework here presented with the only tool dealing with O&G platform decommissioning.

5.3. Synthesis of the new framework against existing frameworks

The previous frameworks differ among each other and from this new framework first of all because of the scopes and because of the method/s adopted to construct the framework itself. Depending on the method/s adopted, some frameworks include the assessment of social, economic and environmental impacts while other are limited to one or two of them. All the frameworks represent both full and partial decommissioning scenarios.

Each framework considers then a different combination of decommissioning and reuse scenarios. Decommissioning may be full, with the total platform removal, or partial, with the sub-structure in place for artificial reef purposes. Reuse scenarios may be fixed or variable, integrating reuse activities in multiple ways. Reuse activities may be limited to energy production or may consider also aquaculture, tourism, fish farming.

Table 3 summarises and compares the most relevant features of the new framework against existing ones.

6. Conclusions

The paper presented an original 5-steps framework for the assessment of the sustainable solution between reuse and decommissioning of an O&G platform at a given site.

The framework allows first to scope the best option for the platform reuse, based on multi-criteria analysis of different alternatives. The framework can be used as the basis for the discussion among experts providing a robust set of criteria and a well-defined scoring methodology that can be generalised and applied to any case study. The scoring table provided to the experts has been generalised into an excel tool that can be used by any expert at any site. The assessment is facilitated by menu windows, allowing for a coherent scaling of the score, and through the selection of appropriate score combination in case of expected synergies among the different economic activities. The weights to be applied in the evaluation should be agreed among the experts based on preliminary discussion with the entities interested in the re-use/decommissioning: financers, O&G owners, green associations, local population, managers.

The framework supports then the decision making by solving an economic and a financial inequality based on quantitative social, environmental and economic KPIs of the reuse performance. The decision can be therefore taken based on “objective” data from the preliminary design of the re-use, essentially the marine space and the costs.

The application of the framework to a typical 8-legs platform in the Adriatic Sea considered 3 different reuse activities (renewable energy, aquaculture and educational tourism) while contributing to platform maintenance with mineral deposition technology. The optimal configuration for the reuse consisted of fish farming, solar panels and wind turbines. It is worthy to remark that given the distance from shore and the absence of power connection to shore, the energy is produced to support fish farming and therefore fish farming is the only activity producing monetary benefits. The sustainable size of the MUP what would be more advantageous than the decommissioning is however too large to make the reuse a viable solution in view of the potential conflict of uses. Therefore, technological advances are still required in this area (and financial incentives) to make room to Blue Growth activities in the Med Sea.

CRediT authorship contribution statement

B. Zanuttigh: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. **E. Dallavalle:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Writing – original draft, Writing – review & editing. **F. Zagonari:** Conceptualization, Data curation, Formal analysis, Methodology, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Barbara Zanuttigh reports financial support was provided by Government of Italy Ministry of Education University and Research.

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A. Appendix.

A.1 Example of a coherent scoring with related motivations

This section of the appendix reports as an example the motivations and the related way to assign the scores by one of the four experts involved in the case study. The expert has an ocean engineering background. The resulting scoring Table is reported in Figure A1.

Innovation criterion

- The lower the Technology Readiness Level (TRL) of the technologies to be tested and the more original the combination of activities the higher the chance of development of new patents. The development of new patents is driven by wave energy (score 3), while solar, wind and fish farming are considered already well established (score 1). The presence of an additional RE source increases the score (of 1), given the greater probability that the combination can lead to unexpected technological advances but the lower probability of an increased number of new patents if another type of activity is mixed in (i.e tourism, fishing).
- The higher the production of RE, the wider the use of ecologically friendly materials, the greater the recycling of existing structures, the higher the reduction of CO_2. In this case, the reduction of CO2 is considered directly proportional to the number of RES exploited by the different configurations (for instance: 1, 2, 3 in case of only solar, or wind and solar, or wind wave and solar).

- The greater the synergy with other ocean uses such as wind and aquaculture, the greater the benefits due to shared Power Take-Off (PTO), power connections, infrastructures and foundations. The basic score of 1 is assigned for only 2 activities and it is increased by 1 with increasing of 1 activity.
- Finally, the higher the innovation, the higher the need of new and interdisciplinary skills and the higher the potential creation of new jobs. Specifically, the score of 2 is assigned to fish farming and to tourism, because the required skills are already available but the potential new market is significant. The score of 1 is assigned to the well-established sola panel technology while the score of 3 is assigned in case of the less known wave energy technology and of the wind technology, that has a great potential market. In all configurations, the addition of one use gives an increase of 0.5, since the integration requires more interdisciplinary skills than all others and more people dedicated to the installation.

Exploitation potential

- Wind energy has high reliability (score 4) but low-medium performance at the “Amelia B” platform (score 2), wave energy has low-medium reliability (score 2) and low performance (score 1), solar energy has high reliability and medium-high performance (scores equal to 4 and 3). In absence of one of the energy sources, the score 1 is assigned both to performance and reliability.
- Tourism activities assume to be only of the educational type and given the experience with other platform in the same area the impact can be classified as medium (score 3). The presence of available infrastructure at coasts to support offshore activities is indeed high in the whole Emilia-Romagna region (score 4) and the distance from shore is relatively close (score 3). The other tourism activities (reef, fishing, etc.) are not here considered and therefore they automatically score 1.
- The aquaculture potential is quantified based on three sub-criteria: i) the existing practice in the area is considered as a positive indicator of economic viability; ii) the technical challenges are identified in advance, taking into account the characteristics of the area (bottom depth and characteristics, flow rates) and the species to be farmed (based on the site-specific values of selected parameters such as nutrients, oxygen, water temperature and nitrate); iii) the performance is estimated taking into account the data on stocks and growth rate available from similar farms. Fish farming is based on high expertise (score 4, taken into consideration that there are many fish farms in the area but not offshore floating ones), low-medium challenges (score 2) and medium-high performance (score 3), given the lower sea temperature than in the Southern Italy and in the adjacent Greece.

Environmental impact

- -The more space required for installation, the greater the potential for conflicts (with shipping, fishing, protected areas, etc.) and the larger the footprint, which can affect the illumination and therefore the oxygenation of the water column. Given the sizes of the devices/equipment to be installed, the impact decreases from wave energy devices (score 4), to fish cages (score 3), wind turbines (score 2) and solar panels (score 1). The score for each configuration is given based on the use generating the highest impact, for instance: if wave energy devices are included in the reuse together with tourism and solar energy, then the score is driven by wave energy devices and equals 4. However, when more activities producing impact because of foundations are included (for instance, wave energy, wind energy and fish farming) then 0.5 additional point is added for each use to the main score (in this case, wave energy is the driver with a score equal to 4, but the final score is 5 to account for wind turbines and fish cages that both affect the size of the area occupied by the devices and equipment). Since solar panels are installed on the platform deck and tourism does not impact on the space required, these activities do not produce any additional point.
- The size of the energy farm and of the fish farm depend on the site local conditions and the judgement should take into account the comparison with target values for feasible installations. Given the extremely mild climate in the Northern Adriatic Sea, and the lower efficiency of wave energy devices with respect to wind turbines and solar panels, the scores 1, 2 and 3 are assigned to solar, wind and wave energy farms to take into account that the required area leading to a reasonable production will be greater for wave energy than for the other resources. Specifically, solar panels do not require additional space as they are installed on the deck of the existing platform. The total score for the size of the energy farm is therefore driven by the highest one in the combination, and an additional point of 0.5 is given when other sources are present with the exception of solar panels that do not require additional space. As for fish farming, the score of 3 (given to all MUPs with aquaculture) accounts for the lower sea temperature than in the Southern Adriatic Sea or in Greece that requires wider available areas for the same production. Tourism requires only the platform without additional marine space, and therefore scores the minimum value of 1.
- Fixed foundations usually have a greater impact than anchor points for floating installations (larger area, equipment buried in the seabed). Therefore, configurations with wind energy have higher scores (score 4) than the ones with wave energy (score 3) and fish farming (score 2), while solar energy and tourism activities do not require any additional foundation (score 1). As above, the score is driven by the activity characterised by the highest and combination of more activities leads to an increased score (i.e. the addition of 0.5 for each added activity with the exception of solar panels and tourism).
- New materials in the water are a source of biodiversity, however bio-fouling may compromise the regular operation of hinges, may increase the friction and the draft of floating devices. Therefore, toxic paintings may be required to avoid these consequences. Wave energy has the highest score (score 4) due to the use mainly of steel for the construction of these devices, while fixed wind turbines are mainly constructed by concrete (score 3) and fish cages by synthetic materials (score 2); solar panels are emerged (score 1) and tourism activities may include the creation of an artificial reef to increase the site attractiveness (score 1). As above, the score is driven by the activity characterised by the highest impact.
- Complex design may include exposed components/parts that may be broken due to wave action and produce debris drifted in the sea. In this case wind turbines have the minimum score because of compactness (score 1). Solar panels may be subjected to breakage and tourism may generate waste (score 2). Fish cages and especially wave energy devices may include specific components that can produce debris (and therefore scores equal to 2 and 3 are assigned). As above, the score is driven by the activity characterised by the highest and combination of more activities leads to an increased score (i.e. the addition of 0.5 for each added activity).
- Wind energy turbines, some WECs and some power-take off technologies may affect birds, mammals, etc. because of noise and vibration. Scores equal to 2 and 3 are assumed for wind turbines and WECs respectively, while other activities do not have impact under this aspect (score 1). The score is based on the maximum among the activities without adding points.
- The visual impact of submerged or floating devices is negligible even if they are installed near-shore, conversely wind turbines and wave energy devices with emerged parts may be visible also from offshore. In this case, due to the mild sea bottom, the presence of the turbines leads to the

highest visual impact (score 4), followed by the standing platform that is necessary to hold the solar panels with its deck (score 2), while floating wave energy devices will be almost invisible from shore (score 1). All other activities will have no impact. The score is based on the maximum among the activities.

- -The impact of maintenance should take into account: i) the expected frequency of maintenance and hence the impact from transportation; ii) the type of regular treatment required for fouling control; iii) the need for special treatment and/or exposure to corrosive and abrasive substances in water. It is assumed that the low frequency maintenance required by some activities can be performed in conjunction with the high frequency maintenance of other activities. Wind turbines with concrete piles require less maintenance than wave energy devices, as their functionality is not compromised by fouling and concrete is more durable than steel. Fish farming requires regular maintenance (every 2/3 days) due to feeding transportation over all the year. Tourism requires daily trips depending on seasonality. Transportation scores: 1 for wind turbines and solar panels; 2 for wave energy devices; 4 for tourism; 5 for fish farming. Fouling scores: 1 for wind and solar panels; 2 for tourism and fish farming; 3 for waves. Durability scores: 1 for wind; 2 for fish farming, for tourism and solar panels (associated to the platform materials); 3 for wave. The score is based on the maximum among the activities.

Risk

- Modular structures offer the advantage of ensuring partial operation when installed in farms thanks to the presence of many modules. The higher the structural modularity, the lower the expected structural failure. Fish cages, solar panels and wind turbines lead therefore to the lower score of 2, while wave energy devices that often include peculiar components have a score of 3. For tourism this sub-criterion is not applicable and a score of 1 is assigned.
- Geotechnical failure risk is expected to be higher for fixed foundations than for floating foundations due to soil liquefaction; anchors even if exposed at this same risk, lead to a lower risk of the whole installation since they are multiple. Wave energy and fish farming lead to a score of 2 while wind energy to a score of 4. Also, for tourism and solar panels a score equal to 4 is considered, due to the use of the fixed platform.
- The mooring design is still one of the major technical issues for floating wind turbines and WECs. Therefore, the risk related to moorings of these devices is expected to be high. Given the choice of fixed wind energy turbines, the score for wind is 1 as well as for solar and tourism for which this sub-criterion is not applicable. In case of fish cages and wave energy devices the score equals 2 and 3 respectively.
- Hydraulic PTOs are usually characterised by higher failure risk than electro-magnetic PTOs. The score of 2 is assigned to wind and/or wave energy devices, while 1 is assigned to solar panels.
- The risk of cable failure and therefore the risk of failure of the energy transmission to shore is higher than the risk to lose the produced energy when locally stored or used to power other activities. In this case, the energy is supposed to be locally used for the economic activities and therefore a score of 1 is given to all alternatives.
- The presence of structures in the sea, and in particular of O&G platforms, may lead to accidents related to collisions with transportation vessels and to unsafe working conditions with impact on human health. In this case, the presence of the platform is common to all alternatives. The score for collisions basically increases with increasing the size of the devices and of the reuse area and with increasing the transportation in the area (e.g. due to tourism). and it is therefore estimated as the average between the two scores assigned to the two sub-criteria included in the environmental impact criterion. As for health, all the activities with the exception of tourism are assumed to produce the same potential impact on health accidents, leading to a common score of 2 and an exceptional score of 3.
- The reuse of O&G platforms may induce and/or intensify illegal fishing activities (score 2 for all alternatives as the reuse is a common feature). These activities may be further boosted in presence of wind turbines whose foundations usually attract crustaceans and other valuable species (score 3). Other activities do not produce any significant attractiveness of valued species.
- The higher pollution risk is assigned in presence of tourism (score 3). Also, the pollution risk is high when the installation of RE systems requires the use of lubricants and cooling fluids or in case aquaculture is included, because it can lead to wastewater containing nutrients, chemicals, and pharmaceuticals. Therefore, a score 2 is assigned to all the installations with fish farming and wave energy devices. Other activities lead to a score of 1 as they do not impact on pollution.

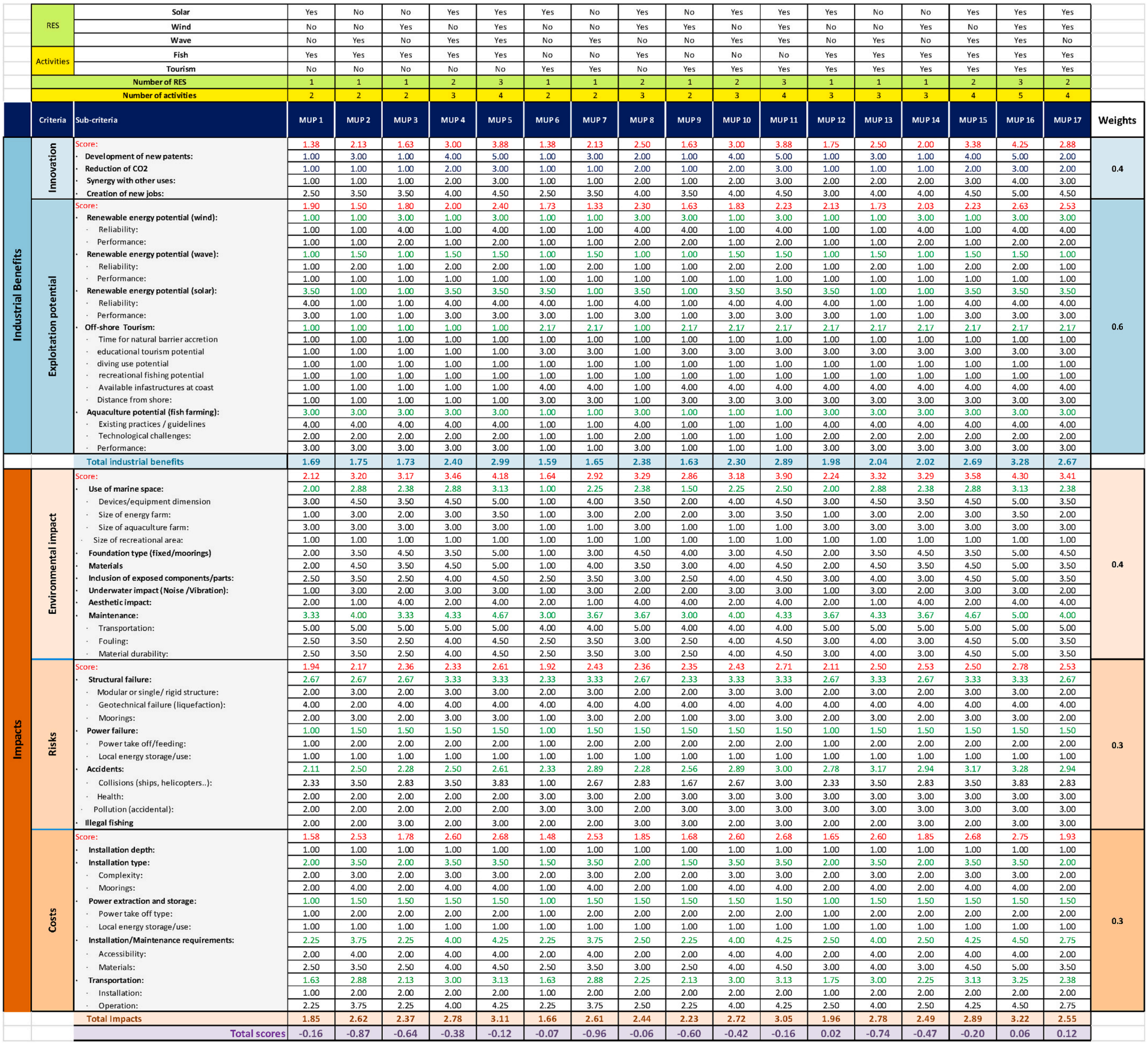
In all the sub-criteria, the score is based on the maximum among the activities.

Costs

- Installation depth. Both the wind/wave loads and the distance from the shore increase with increasing the installation depth, therefore both the installation and the maintenance costs increase. In this case, the installation depth is the same because it coincides with the seabed depth at the “Amelia B″ platform and the score of 1 is assigned to all the alternatives.
- Installation type. Costs can be reduced by installing simple and modular structures that do not require to be specifically designed and manufactured; the scores for the complex designs are directly related to the scores assigned to the structural failure and specifically the structure modularity.
- The mooring cost depends on the mooring scheme, on the material of the mooring lines, on the installation depth and thus to the mooring line length. Moorings that have to let the wave energy devices as much free as possible to maximise wave energy production and at the same time have to assure station keeping (score 4) are much more expensive than moorings for fish farming (score 2).
- Power extraction and storage. The cost of the Power Take-Off (PTO) includes both the cost of the system (turbines are generally more expensive than electro-magnetic PTOs) and the cost required for its development in case innovative concepts are considered. Alternatives including wind or wave are scored 2, without any specific hypothesis about the selected PTOs. The same score equal to 1 is assigned to alternatives that do not include neither wave nor wind energy.
- The local use of the generated power is cheaper than the transfer to shore; in this case, all alternatives foresee the local use leading to the same score of 1.
- Installation/maintenance requirements. Installation and maintenance of devices installed on the seafloor and fully completely submerged have higher costs than for floating devices; parts that need to be removed and maintained on land are also costlier than those that can be maintained in-situ. In this case, wind, fish farming and solar energy do not require to be maintained on shore (score 2) while wave energy devices may require to

be dismounted and thus lead to a higher score (score 4). Maintenance of the existing platform for tourist activities also lead to a score of 2.

- Durable materials require less frequent treatments or substitution; the related score is directly dependent on the material durability of the maintenance sub-criterion under the environmental impact. The maximum score among the combined activities is retained.
- Transportation includes the costs for installation, which is cheaper if it can be performed with standard vessels, and for the costs for operation, which depend on the type of vessels and on the maintenance frequency. In this case, standard vessels are assumed for all the alternatives (score 1) with the exception of wind and waves where some special features may be considered (score 2). As for the operation costs, they are assumed to depend on the installation/maintenance requirements scored above.



	RES	Solar	Yes	No	No	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes	No	No	Yes	Yes	Yes	
		Wind	No	No	Yes	No	Yes	No	No	Yes	Yes	No	Yes	No	No	Yes	No	Yes	Yes	
		Wave	No	Yes	No	Yes	Yes	No	Yes	No	No	Yes	Yes	No	Yes	No	Yes	Yes	No	
	Activities	Fish	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	
		Tourism	No	No	No	No	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
	Number of RES		1	1	1	2	3	1	1	2	1	2	3	1	1	1	2	3	2	
	Number of activities		2	2	2	3	4	2	2	3	2	3	4	3	3	3	4	5	4	
	Criteria	Sub-criteria	MUP 1	MUP 2	MUP 3	MUP 4	MUP 5	MUP 6	MUP 7	MUP 8	MUP 9	MUP 10	MUP 11	MUP 12	MUP 13	MUP 14	MUP 15	MUP 16	MUP 17	Weights
Industrial Benefits	Innovation	Score:	1.38	2.13	1.63	3.00	3.88	1.38	2.13	2.50	1.63	3.00	3.88	1.75	2.50	2.00	3.38	4.25	2.88	
		· Development of new patents:	1.00	3.00	1.00	4.00	5.00	1.00	3.00	2.00	1.00	4.00	5.00	1.00	3.00	1.00	4.00	5.00	2.00	
		· Reduction of CO2	1.00	1.00	1.00	2.00	3.00	1.00	1.00	2.00	1.00	2.00	3.00	1.00	1.00	1.00	2.00	3.00	2.00	0.4
		· Synergy with other uses:	1.00	1.00	1.00	2.00	3.00	1.00	1.00	2.00	1.00	2.00	3.00	2.00	2.00	2.00	3.00	4.00	3.00	
		· Creation of new jobs:	2.50	3.50	3.50	4.00	4.50	2.50	3.50	4.00	3.50	4.00	4.50	3.00	4.00	4.00	4.50	5.00	4.50	
	Exploitation potential	Score:	1.90	1.50	1.80	2.00	2.40	1.73	1.33	2.30	1.63	1.83	2.23	2.13	1.73	2.03	2.23	2.63	2.53	
		· Renewable energy potential (wind):	1.00	1.00	3.00	1.00	3.00	1.00	1.00	3.00	3.00	1.00	3.00	1.00	1.00	3.00	1.00	3.00	3.00	
		· Reliability:	1.00	1.00	4.00	1.00	4.00	1.00	1.00	4.00	4.00	1.00	4.00	1.00	1.00	4.00	1.00	4.00	4.00	
		· Performance:	1.00	1.00	2.00	1.00	2.00	1.00	1.00	2.00	2.00	1.00	2.00	1.00	1.00	2.00	1.00	2.00	2.00	
		· Renewable energy potential (wave):	1.00	1.50	1.00	1.50	1.50	1.00	1.50	1.00	1.00	1.50	1.50	1.00	1.50	1.00	1.50	1.50	1.00	
		· Reliability:	1.00	2.00	1.00	2.00	2.00	1.00	2.00	1.00	1.00	2.00	2.00	1.00	2.00	1.00	2.00	2.00	1.00	
		· Performance:	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
		· Renewable energy potential (solar):	3.50	1.00	1.00	3.50	3.50	3.50	1.00	3.50	1.00	3.50	3.50	3.50	1.00	1.00	3.50	3.50	3.50	
		· Reliability:	4.00	1.00	1.00	4.00	4.00	4.00	1.00	4.00	1.00	4.00	4.00	4.00	1.00	1.00	4.00	4.00	4.00	
		· Performance:	3.00	1.00	1.00	3.00	3.00	3.00	1.00	3.00	1.00	3.00	3.00	3.00	1.00	1.00	3.00	3.00	3.00	
		· Off-shore Tourism:	1.00	1.00	1.00	1.00	1.00	2.17	2.17	1.00	2.17	2.17	2.17	2.17	2.17	2.17	2.17	2.17	2.17	0.6
		· Time for natural barrier accretion	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
		· educational tourism potential	1.00	1.00	1.00	1.00	1.00	3.00	3.00	1.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
		· diving use potential	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
		· recreational fishing potential	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
		· Available infastructures at coast	1.00	1.00	1.00	1.00	1.00	4.00	4.00	1.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	
		· Distance from shore:	1.00	1.00	1.00	1.00	1.00	3.00	3.00	1.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
		· Aquaculture potential (fish farming):	3.00	3.00	3.00	3.00	3.00	1.00	1.00	3.00	1.00	1.00	1.00	3.00	3.00	3.00	3.00	3.00	3.00	
		· Existing practices / guidelines	4.00	4.00	4.00	4.00	4.00	1.00	1.00	4.00	1.00	1.00	1.00	4.00	4.00	4.00	4.00	4.00	4.00	
		· Technological challenges:	2.00	2.00	2.00	2.00	2.00	1.00	1.00	2.00	1.00	1.00	1.00	2.00	2.00	2.00	2.00	2.00	2.00	
		· Performance:	3.00	3.00	3.00	3.00	3.00	1.00	1.00	3.00	1.00	1.00	1.00	3.00	3.00	3.00	3.00	3.00	3.00	
		Total industrial benefits	1.69	1.75	1.73	2.40	2.99	1.59	1.65	2.38	1.63	2.30	2.89	1.98	2.04	2.02	2.69	3.28	2.67	
Impacts	Environmental impact	Score:	2.12	3.20	3.17	3.46	4.18	1.64	2.92	3.29	2.86	3.18	3.90	2.24	3.32	3.29	3.58	4.30	3.41	
		· Use of marine space:	2.00	2.88	2.38	2.88	3.13	1.00	2.25	2.38	1.50	2.25	2.50	2.00	2.88	2.38	2.88	3.13	2.38	
		· Devices/equipment dimension	3.00	4.50	3.50	4.50	5.00	1.00	4.00	3.50	2.00	4.00	4.50	3.00	4.50	3.50	4.50	5.00	3.50	
		· Size of energy farm:	1.00	3.00	2.00	3.00	3.50	1.00	3.00	2.00	2.00	3.00	3.50	1.00	3.00	2.00	3.00	3.50	2.00	
		· Size of aquaculture farm:	3.00	3.00	3.00	3.00	3.00	1.00	1.00	3.00	1.00	1.00	1.00	3.00	3.00	3.00	3.00	3.00	3.00	
		· Size of recreational area:	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
		· Foundation type (fixed/moorings)	2.00	3.50	4.50	3.50	5.00	1.00	3.00	4.50	4.00	3.00	4.50	2.00	3.50	4.50	3.50	5.00	4.50	
		· Materials	2.00	4.50	3.50	4.50	5.00	1.00	4.00	3.50	3.00	4.00	4.50	2.00	4.50	3.50	4.50	5.00	3.50	0.4
		· Inclusion of exposed components/parts:	2.50	3.50	2.50	4.00	4.50	2.50	3.50	3.00	2.50	4.00	4.50	3.00	4.00	3.00	4.50	5.00	3.50	
		· Underwater impact (Noise /Vibration):	1.00	3.00	2.00	3.00	3.00	1.00	3.00	2.00	2.00	3.00	3.00	1.00	3.00	2.00	3.00	3.00	2.00	
		· Aesthetic impact:	2.00	1.00	4.00	2.00	4.00	2.00	1.00	4.00	4.00	2.00	4.00	2.00	1.00	4.00	2.00	4.00	4.00	
		· Maintenance:	3.33	4.00	3.33	4.33	4.67	3.00	3.67	3.67	3.00	4.00	4.33	3.67	4.33	3.67	4.67	5.00	4.00	
		· Transportation:	5.00	5.00	5.00	5.00	5.00	4.00	4.00	5.00	4.00	4.00	4.00	5.00	5.00	5.00	5.00	5.00	5.00	
		· Fouling:	2.50	3.50	2.50	4.00	4.50	2.50	3.50	3.00	2.50	4.00	4.50	3.00	4.00	3.00	4.50	5.00	3.50	
		· Material durability:	2.50	3.50	2.50	4.00	4.50	2.50	3.50	3.00	2.50	4.00	4.50	3.00	4.00	3.00	4.50	5.00	3.50	
	Risks	Score:	1.94	2.17	2.36	2.33	2.61	1.92	2.43	2.36	2.35	2.43	2.71	2.11	2.50	2.53	2.50	2.78	2.53	
		· Structural failure:	2.67	2.67	2.67	3.33	3.33	2.33	3.33	2.67	2.33	3.33	3.33	2.67	3.33	2.67	3.33	3.33	2.67	
		· Modular or single/ rigid structure:	2.00	3.00	2.00	3.00	3.00	2.00	3.00	2.00	2.00	3.00	3.00	2.00	3.00	2.00	3.00	3.00	2.00	
		· Geotechnical failure (liquefaction):	4.00	2.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	
		· Moorings:	2.00	3.00	2.00	3.00	3.00	1.00	3.00	2.00	1.00	3.00	3.00	2.00	3.00	2.00	3.00	3.00	2.00	
		· Power failure:	1.00	1.50	1.50	1.50	1.50	1.00	1.50	1.50	1.50	1.50	1.50	1.00	1.50	1.50	1.50	1.50	1.50	
		· Power take off/feeding:	1.00	2.00	2.00	2.00	2.00	1.00	2.00	2.00	2.00	2.00	2.00	1.00	2.00	2.00	2.00	2.00	2.00	0.3
		· Local energy storage/use:	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
		· Accidents:	2.11	2.50	2.28	2.50	2.61	2.33	2.89	2.28	2.56	2.89	3.00	2.78	3.17	2.94	3.17	3.28	2.94	
		· Collisions (ships, helicopters..):	2.33	3.50	2.83	3.50	3.83	1.00	2.67	2.83	1.67	2.67	3.00	2.33	3.50	2.83	3.50	3.83	2.83	
		· Health:	2.00	2.00	2.00	2.00	2.00	3.00	3.00	2.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
		· Pollution (accidental):	2.00	2.00	2.00	2.00	2.00	3.00	3.00	2.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
		· Illegal fishing	2.00	2.00	3.00	2.00	3.00	2.00	2.00	3.00	3.00	2.00	3.00	2.00	2.00	3.00	2.00	3.00	3.00	
	Costs	Score:	1.58	2.53	1.78	2.60	2.68	1.48	2.53	1.85	1.68	2.60	2.68	1.65	2.60	1.85	2.68	2.75	1.93	
		· Installation depth:	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
		· Installation type:	2.00	3.50	2.00	3.50	3.50	1.50	3.50	2.00	1.50	3.50	3.50	2.00	3.50	2.00	3.50	3.50	2.00	
		· Complexity:	2.00	3.00	2.00	3.00	3.00	2.00	3.00	2.00	2.00	3.00	3.00	2.00	3.00	2.00	3.00	3.00	2.00	
		· Moorings:	2.00	4.00	2.00	4.00	4.00	1.00	4.00	2.00	1.00	4.00	4.00	2.00	4.00	2.00	4.00	4.00	2.00	
		· Power extraction and storage:	1.00	1.50	1.50	1.50	1.50	1.00	1.50	1.50	1.50	1.50	1.50	1.00	1.50	1.50	1.50	1.50	1.50	
		· Power take off type:	1.00	2.00	2.00	2.00	2.00	1.00	2.00	2.00	2.00	2.00	2.00	1.00	2.00	2.00	2.00	2.00	2.00	
		· Local energy storage/use:	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.3
		· Installation/Maintenance requirements:	2.25	3.75	2.25	4.00	4.25	2.25	3.75	2.50	2.25	4.00	4.25	2.50	4.00	2.50	4.25	4.50	2.75	
		· Accessibility:	2.00	4.00	2.00	4.00	4.00	2.00	4.00	2.00	2.00	4.00	4.00	2.00	4.00	2.00	4.00	4.00	2.00	
		· Materials:	2.50	3.50	2.50	4.00	4.50	2.50	3.50	3.00	2.50	4.00	4.50	3.00	4.00	3.00	4.50	5.00	3.50	
		· Transportation:	1.63	2.88	2.13	3.00	3.13	1.63	2.88	2.25	2.13	3.00	3.13	1.75	3.00	2.25	3.13	3.25	2.38	
		· Installation:	1.00	2.00	2.00	2.00	2.00	1.00	2.00	2.00	2.00	2.00	2.00	1.00	2.00	2.00	2.00	2.00	2.00	
		· Operation:	2.25	3.75	2.25	4.00	4.25	2.25	3.75	2.50	2.25	4.00	4.25	2.50	4.00	2.50	4.25	4.50	2.75	
		Total Impacts	1.85	2.62	2.37	2.78	3.11	1.66	2.61	2.44	2.23	2.72	3.05	1.96	2.78	2.49	2.89	3.22	2.55	
		Total scores	-0.16	-0.87	-0.64	-0.38	-0.12	-0.07	-0.96	-0.06	-0.60	-0.42	-0.16	0.02	-0.74	-0.47	-0.20	0.06	0.12	

Fig. A.1. Assessment Excel sheet completed by one of the four experts involved in the analysis of the case study. Scores are given according to the explanation in Appendix A.1. The weights of the criteria assigned by the expert team were added after the scoring performed by each expert but are shown here to give a full example of how each expert table looks like before being combined with the other expert tables and making the sum.

A.2 Preliminary design of the MUP

A2.1 Solar energy

The photovoltaic plant to be installed on the deck of the platform is designed starting from the irradiation data included in the PVGIS, developed by the European Commission [57]. The database provides data only on land, therefore the point considered for the analysis is the one that has the same latitude as the “Amelia B″ platform but different longitude since it is located on the coast (44.41; 12.31). The database provides, on an hourly level: G_i (W/m^2), the available (irradiated) power per unit of surface; P (W), the power produced by a standard photovoltaic system characterized by a given peak power. The years considered for the analysis range from 2005 to 2016.

For the selected point, an hourly (instantaneous) average annual power produced equal to $P_{pv} = 157.90$ W and an annual energy equal to $E_{pv} = 1384.71$ kWh/y, with an average efficiency of 17.72 %, were found for a 1 kW plant.

Considering the high-performance SunPower Maxeon 3 panels [58] with a surface area of 1.77 m^2, installed already by ENI within the PlaCE project, at another O&G platform in the Adriatic Sea (i.e. the Viviana platform), the annual production values per unit of surface were obtained in Figure A2. The results are consistent with the expected values for these areas: the average power over all years is equal to $P_{pv} = 35.72$ W/m^2, while the annual energy is on average equal to $E_{pv} = 313.28$ kWh/m^2. The annual energy production for each panel is instead equal to 553.80 kWh/y.

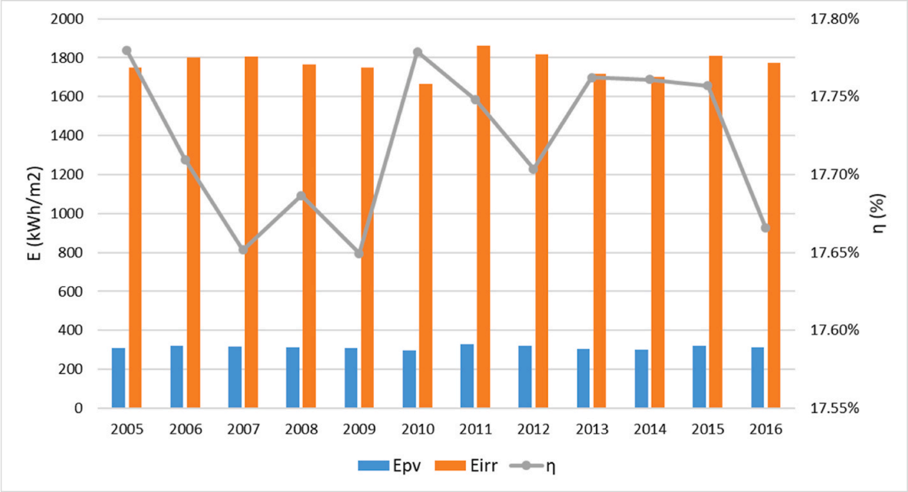


Fig. A.2. Available irradiated solar energy (E_{irr}) and energy produced by the PV panels (E_{PV}) per unit surface and PV panels efficiency (η) at the “Amelia B″ platform.

On the deck of the “Amelia B″ platform, up to 150 solar panels can be installed, in groups of 12 panels each. The costs for a group of 12 panels include: the cost of the 12 panels, 20 k€; the cost of 24 batteries, 29 k€; the cost of the control board, 35 k€ [59]. The cost of the panels is higher than on land as it includes anti-wind and anti-seagull structures. The cost of the control panel was kept constant as the number of panels increased. In favour of safety, the cost of the batteries has been multiplied by considering 24 batteries for every 12 panels. The annual O&M costs were assumed to be 8 % of the initial investment, following the literature on wave energy costs [51] that is more cautious than other estimates of O&M for other RE plants [60].

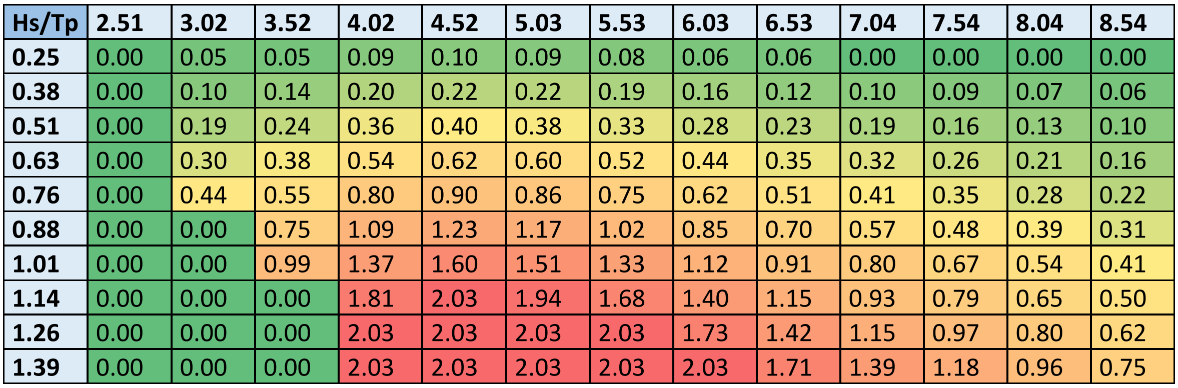
A2.2 Wave energy

The database used for the wave data is ERA5 [61], implemented and made available free of charge by the European Centre for Medium-term Meteorological Forecasts (ECMWF). The closest point to the “Amelia B″ platform selected for the analysis is that of coordinates: 44.5° N; 12.5° E. The data necessary for the evaluation of the available wave energy are the significant height H_s, the peak wave period T_p and the wave direction. These data were elaborated for all years from 2005 to 2020, on an hourly scale.

The average annual wave power P_{wave} and wave energy E_{wave} at the “Amelia B″ platform are respectively 0.93 kW/m and 37.07 MWh/y. To assess the potential production, a WEC of the point absorber type was examined and specifically the AquaBuOY, because of three main reasons: the bi-modal wave climate in the Adriatic Sea, with waves coming from two main directions, NE and SE (i.e. Bora and Scirocco), requiring a device capable to absorb energy from all wave directions; the similarity with the PB3 device [48] that was installed at the platform in the years 2018–2019; the availability of AquaBuOY power matrix in the literature [49].

The AquaBuOY device has much larger dimensions than the PB3 and it is designed for depths of 50–60 m [49], therefore it has been appropriately scaled according to the method suggested by Ref. [21]. The power matrix of the AquaBuOY scaled for the “Amelia B″ platform is shown in Table A1. The results of the producibility analysis are shown in Figure A3. The average annual value of the energy produced by the WEC is equal to 2.29 MWh/y. This is consistent with the actual energy production of the PB3 installed at the “Amelia B″ platform between the end of 2018 and the end of 2019 [62], thus verifying the effectiveness of the scaling procedure.

Table A.1
Power matrix of the AquaBuOY device scaled for the “Amelia B″ platform wave climate. The power values are reported in kW.



Hs/Tp	**2.51**	**3.02**	**3.52**	**4.02**	**4.52**	**5.03**	**5.53**	**6.03**	**6.53**	**7.04**	**7.54**	**8.04**	**8.54**
0.25	0.00	0.05	0.05	0.09	0.10	0.09	0.08	0.06	0.06	0.00	0.00	0.00	0.00
0.38	0.00	0.10	0.14	0.20	0.22	0.22	0.19	0.16	0.12	0.10	0.09	0.07	0.06
0.51	0.00	0.19	0.24	0.36	0.40	0.38	0.33	0.28	0.23	0.19	0.16	0.13	0.10
0.63	0.00	0.30	0.38	0.54	0.62	0.60	0.52	0.44	0.35	0.32	0.26	0.21	0.16
0.76	0.00	0.44	0.55	0.80	0.90	0.86	0.75	0.62	0.51	0.41	0.35	0.28	0.22
0.88	0.00	0.00	0.75	1.09	1.23	1.17	1.02	0.85	0.70	0.57	0.48	0.39	0.31
1.01	0.00	0.00	0.99	1.37	1.60	1.51	1.33	1.12	0.91	0.80	0.67	0.54	0.41
1.14	0.00	0.00	0.00	1.81	2.03	1.94	1.68	1.40	1.15	0.93	0.79	0.65	0.50
1.26	0.00	0.00	0.00	2.03	2.03	2.03	2.03	1.73	1.42	1.15	0.97	0.80	0.62
1.39	0.00	0.00	0.00	2.03	2.03	2.03	2.03	2.03	1.71	1.39	1.18	0.96	0.75

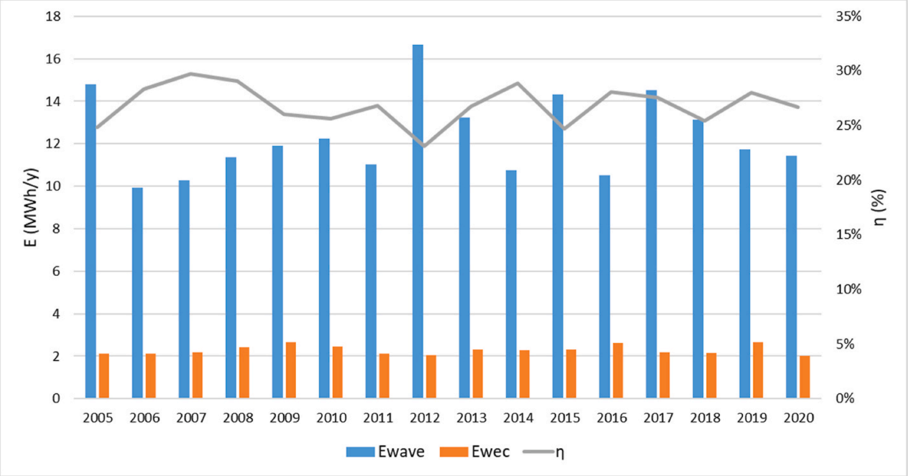


Fig. A.3. Available (E_{wave}) and produced (E_{WEC}) wave energy per unit surface and WEC efficiency (η) at "Amelia B″ platform.

The AquaBuOY WEC with its anchoring system occupies an area of about 300 m · 300 m, as each anchor line is 150 m long in plan according to the mooring system adopted for the PB3.

The costs related to the WEC can be roughly estimated as follows: lease and final purchase 900 k€; installation 500 k€; umbilical 50 k€ [59]. In the case of a WEC array, in favour of safety, no cost reductions were considered for joint anchors. The annual O&M costs were assumed to be the 8 % of the initial investment [51].

A2.3 Wind energy

Also in the case of wind data, the database used is ERA5. Despite the greater resolution with respect to the wave data, the point selected for analysis was the same for consistency (44.5° N; 12.5° E). The data necessary for evaluating the available wind energy are the u and v components of the wind speed at 10 m high asl. Also in this case, the data were elaborated on an hourly basis for the years from 2005 to 2016.

The wind turbine model selected for the producibility analysis is the Libellula 60i [50]. This turbine has a maximum power of 60 kW and guarantees good performance even at low winds and consequently an excellent ratio between cost and performance. It is assumed that the wind turbine can be installed over a fixed foundation in the area of respect of the platform, to avoid the structural issues in case of installation on the deck.

To evaluate the wind speed at the height of the rotor, the procedure reported by [47] was followed. In particular, given the wind speed v_0 at the height z_0 (10 m) the wind speed v_{hub} at the hub height z_{hub} (31 m in the case of Libellula 60i) is calculated by means of the formula:

$$v_{hub} = v_0 \frac{ln\left(\frac{z_{hub}}{m}\right)}{ln\left(\frac{z_0}{m}\right)} \tag{Eq. A.1}$$

where $m = 2 \cdot 10^{-4}$ is the surface roughness parameter.

At the "Amelia B″ platform, the average wind speed at a height of 31 m is equal to 4.23 m/s; the average energy produced per year by a Libellula 60i is equal to 84.01 MWh/y and the hours of operation are on average 64 %. The results are shown in Figure A4.

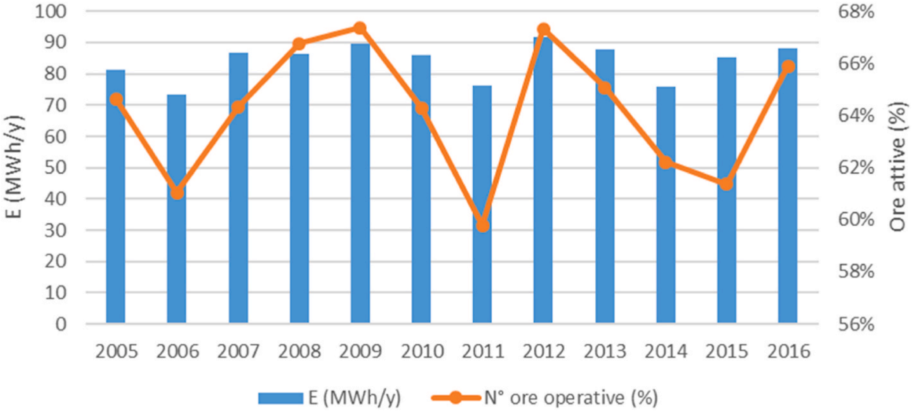


Fig. A.4. Operational time and annual wind energy produced by a Libellula 60i wind turbine at the "Amelia B″ platform.

In case of installation of an offshore wind farm, comprising a number of turbines, in the area of respect of the platform, the distance among the Libellula 60i turbines (with a diameter of 19 m each) is assumed to be equal to 7 diameters by 7 diameters.

Based on [52], the capital investment was assumed to be 4800 €/kW (more than twice and a half the cost of onshore installations). The initial investment cost was reduced by 15 % due to the absence of connection to the grid. The annual O&M costs were assumed to be the 8 % of the initial investment.

A2.4 Fish farming

Based on a recent similar study [26] in the North Adriatic Sea, seabass was selected for fish farming in this region. The know-how on seabass farming in the Mediterranean aquaculture industry has been built-up over the last 30 years and the demand for this fish species as a fresh product on the world market is increasing.

The following requirements should be considered when establishing and operating sea bass farms.

- To ensure good effluent dilution for fish stock, the local water depth should be not less than 30 m, with a large water flow. The minimum depth fixed by Italian legislation is 20 m.
- The distance among the cages should be as far as possible to ensure a good circulation of clean water between and within the cages.
- Sedimentary bottoms are preferred as they have less impact on benthic organisms and the moorings are easier to install and stretch.

In this case study, these additional requirements have been set to achieve sites specifications and ensure profitable utilization.

- the cage and associated equipment must stand the 50 years return period wave height, according to the NS9145 standard;
- high degree of automation for offshore services (especially feed distribution);
- gross annual revenue should be in the range of 20–30 % of total revenue;
- distance to port should be within 15 nautical miles;
- 31 m water depth.

It is assumed that the seafood market in the region and the surrounding area of Northern Italy can absorb the estimated production.

It is also assumed that the basic module of the fish farm consists of 10 cages with a diameter of 30 m, arranged in 2 columns and 5 rows. Considering the space required for the mooring system [26], the gap between the modules for free navigation by aquaculture service vessels and other maintenance vessels [26] and the space for the feeding platform for each module [26], the module requires an area of 320 m · 500 m.

The average production size of seabass is selected to be 400 g, requiring a growth period of 18 months. Assuming a coefficient of variation (CV) of 25 % for the whole production, each cage will produce the quantities and sizes shown in Table A3. If the production of each cage is estimated at 150 tons/cycle and a harvest period of several months is included, the total revenue for each cage is 1′178′500€/2 years.

Table A.3

Fish production per cage and size, considering the prices between 6 and 11 €/kg.

Commercial category	% of category, at 400 g average and CV 25 %	Price (€/kg) per category	Yield (ton) per cage	Gross revenue (€)
Sea Bass 200–300 g	16.5 %	6,00	24.7	148′200
Sea Bass 300–400 g	33 %	7,00	49.5	346′500
Sea Bass 400–500 g	33 %	9,00	49.5	455′500
Sea Bass 500–600 g	14.5 %	9,00	21.7	195′300
Sea Bass 600–700 g	2 %	11,00	3.0	33′000
Total production and revenue per cage (2 years)			148.4	1′178′500
Total production and revenue per module (1 year)			742	5′892′500

Fish farming requires [26].

- a continuous base load due to controls, monitoring and communication systems, on average equal to 0.66 kW, i.e. 16 kWh/day, independent from the number of cages;
- a variable electrical load for feeding fish equal to 50 kW for 10 cages (1 blowing and feeding system). Given the maximum feeding consumption of 40 ton/day, the machinery working time will be not less than 6 h/day from Autumn to Spring and 12 h/day during Summer;
- an electrical load of 16.67 kW for 10 cages, for the machines for freezing, storage at 0–4 °C, a desalination unit and a breathing air compressor for divers, also distributed over 6 h from Autumn to Spring and over 12 h during Summer.

A2.5 Tourism

The educational tourism is assumed to be implemented 6 months per year, with 40 people involved per day. The term “educational tourism” refers to the possibility to visit the platform for educational and recreational purposes, by dedicated boats departing at fixed times from the nearest port (from Pesaro, the platform can be reached in an hour and half of navigation).

In particular, based on the information about the actual diving activities at the nearby Paguro platform, it is assumed that 50 euros per person enables to cover costs for renting boats and other operating costs and to achieve a financial profit.

A2.6 Installation and maintenance issues

Periodic maintenance of the structure has to be carried out to assure its safe reuse. The costs for the verification of structural integrity (such as structural checks and asset integrity) and the costs for the verification of the effectiveness of the safety devices (such as navigation aid systems, fire & gas, fire prevention, etc.) are respectively 350k€/y and 150 k€/y in the case of the typical 8-legs O&G platform [53]. These costs refer to historical data relating to platforms no longer operational until their removal, and not to platforms converted for alternative uses to O&G production. These costs are to be considered with an accuracy range of ± 25 %.

The mineral deposition technique can significantly contribute to structural integrity by protecting the submerged part of the platform from corrosion [23]. An experiment was carried out at the Viviana platform, offshore the Abruzzo coast, in the Adriatic Sea. Two identical steel structures were placed on the sea bottom close to the platform. One of the structures was electrified while the other one was used to verify the physical-chemical effects on the structure integrity. The mineral deposition was found to be effective and the experiment started in Autumn 2020 is still ongoing to derive more quantitative results.

This experiment can be transferred to the protection of surfaces of any extension by means of a wire mesh equipped with.

- spacer elements (in high density polyethylene or similar), in order to keep the mesh from the structure to be protected (which constitutes the cathode) a few centimetres away. The spacers are arranged at a mutual distance of a few tens of centimetres, compatibly with the morphological complexity of the structure;
- a further network of electric cables (with mesh sizes also different from that of the support wire mesh) to which titanium alloy “sinkers” (or similar) are fixed and electrically connected, placed at a suitable distance (depending on the electrical components) from each other, and which constitute the anode of the electrolytic system.

Such network can create a sort of homogeneously distributed electrolytic cell along the entire structure. The possibility of defining the dimensions of the meshes of the net and the diameter of the cables allows to adapt the net to the dimensions of the structure or to the structural elements.

The characteristics of the system and the estimated consumption, assuming to extend the experiment to the total submerged area of the “Amelia B″ structure, are reported in Table A4.

Table A.4
Electrical load required for the mineral deposition activity extended to the entire submerged surface of the “Amelia B″ platform.

Total submerged area (m^2) =	3′200
Current density (A/m^2) =	1.06
Voltage (V) =	2.50
Required power (kW) =	8.48
Daily energy request (kWh/day) =	203.52
Annual energy request (MWh/y) =	74.28

A.3 Detailed calculation of KPIs

A3.1 Economic KPIs

A3.1.1 Renewable energy. As for the solar energy, since the photovoltaic plant is the less expensive of the RES plants and it has no occupation of sea space, being installed on the platform deck, the maximum number of PV panels (144, in the case of the “Amelia B″ platform) is supposed to be installed. A fixed cost of 0.001 M€/y, a fixed extension 0 km^2 and an energy production of 79.75 MWh/y are therefore assumed.

The relationship between produced energy and space requirements, by varying the number of wave or wind devices, can be interpolated from Table 2 and it is given by:

$$E_{y,wave} = MaFo_{wave} / 0.0393 \qquad \text{Eq. A.2}$$

$$E_{y,wind} = (MaFo_{wind} - 0.0019) / 0.0002 \qquad \text{Eq. A.3}$$

where $E_{y,wave}$ and $E_{y,wind}$ are the annual energy production by WECs and wind farm respectively, while $MaFo_{wave}$ e $MaFo_{wind}$ are the respective marine footprints.

For the same annual energy production E_y, the space requirement of the wind farm is therefore lower than the one of the WECs farm which means, when $E_y > 61$ kWh, the following equation always applies:

$$MaFo_{wind} = 0.0002{*}E_y + 0.0019 < 0.0393{*}E_y = MaFo_{wave} \qquad \text{Eq. A.4}$$

As for the costs of the two plants, the relationship between the produced energy and the initial investment, by varying the number of devices, can be also interpolated from Table 2 and is given by:

$$E_{y,wave} = (C_{wave} - 0.0007) / 0.633 \qquad \text{Eq. A.5}$$

$$E_{y,wind} = (C_{wind} - 0.0029) / 0.003 \qquad \text{Eq. A.6}$$

where C_{wave} e C_{wind} are the initial investment costs for the WECs and for the wind farm respectively.

Thus, wave energy is also more expensive than wind energy, for the same annual energy production E_y, which means, when $E_y > 0.7$ kWh, the following equation always applies:

$$C_{wave} = 0.6330{*}E_y + 0.0007 > 0.0030{*}E_y + 0.0029 = C_{wind} \qquad \text{Eq. A.7}$$

Financial and spatial planning considerations therefore suggest to provide the remaining energy by wind turbines only, as well as the optimal MUP 17 that was ranked first in the application of the steps of the framework from 1 to 3, see Sub-Section 3.3. The method was thus applied to support the decision between decommissioning and reuse (Sub-section 4.3) in the case of 0 % wave energy, i.e. MUP 17.

However, since MUP 16, including also wave energy, was ranked as the top MUP for industrial benefit, the analysis was carried out considering different percentages of wave energy production to support the exploratory use of this framework, see Sub-section 4.4.

The costs were thus calculated as a function of the marine footprint $MaFo_{ene}$ for different percentages of wave energy production (specifically from 0 % to 30 %), by combining the space requirements and the costs of wave and wind energy. The economic indicator for the energy production activity,

eco_{ene}, is therefore given by:

$$eco_{ene,o} = -0.0522 * MaFo_{ene,0}^2 + 0.2343 * MaFo_{ene,0} + 0.0063 \quad \text{Eq. A.8}$$

$$eco_{ene,10} = -1.1483 * MaFo_{ene,10}^2 + 5.1551 * MaFo_{ene,10} + 0.1555 \quad \text{Eq. A.9}$$

$$eco_{ene,30} = -3.3406 * MaFo_{ene,30}^2 + 14.997 * MaFo_{ene,30} + 0.4547 \quad \text{Eq. A.10}$$

where $MaFo_{ene}$ is the total marine footprint of the WECs and of the wind turbines, which doesn't comprise the space requirements of the PV plant installed on the deck.

Note that, since they represent costs, these indicators must be considered with the negative sign for the calculation of the economic and financial conditions.

A3.1.2 Fish farming. Beside requiring energy, fish farming also ensures a profit. Specifically, by approximating the profit per extension in quadratic terms, and considering that mineral accretion reduces maintenance costs by 0.3 M€/y [59], it is obtained by interpolation:

$$eco_{fis} = -11.3750 * MaFo_{fis}^2 + 25.3620 * MaFo_{fis} - 0.1322 + 0.3000 \quad \text{Eq. A.11}$$

where $MaFo_{fis}$ (km^2) is the space required by fish farming and C_{MS} (€/m^2) is the cost for the occupation of marine space.

A3.1.3 Tourism. As for the tourism, considering that costs related to onshore structures and boats are negligible, the economic parameter is given by the profits only:

$$eco_{tou} = N_p * C_p * N_d \quad \text{Eq. A.12}$$

where N_p is the number of people involved in the activity per day, C_p is the cost per person and N_d is the number of days of favourable weather when the tourist activity can be carried out. Specifically, considering that the activity can be carried out for 6 months per year, with the participation of 40 people per day at the price of 50€/person, the net income would be 365′000 €/y.

A.3.2 Environmental KPIs

A.3.2.1 Renewable energy. The environmental impact of RE has a positive component, due to the avoided CO_2 emissions, and a negative component, which can be directly related to the occupation of the marine space.

The negative component can be obtained by interpolating the total annual energy production E_y (MWh) as a function of $MaFo_{ene}$ for the considered fixed percentages of wave energy:

$$E_{y,0} = 0.2801 + 3.9054 * MaFo_{ene,0} - 0.8699 * MaFo_{ene,0}^2 \quad \text{Eq. A.13}$$

$$E_{y,10} = 0.224335 + 3.12829 * MaFo_{ene,10} - 0.6968 * MaFo_{ene,10}^2 \quad \text{Eq. A.14}$$

$$E_{y,30} = 0.1965 + 2.7397 * MaFo_{ene,30} - 0.6103 * MaFo_{ene,30}^2 \quad \text{Eq. A.15}$$

As for the positive component, based on the energy production expressed in kWh, the environmental benefit of RE production, given by the tons of avoided CO_2 emissions, can be calculated in euros, considering that the avoided CO_2 per unit of RE produced is equal to 820 gCO_2eq/kWh (see the IPCC report by [63]) and that the economic profit is equal to 60 €/ton.

The environmental indicator for the RE production activity is thus given by:

$$env_{ene,i} = E_{y,i} * \frac{820}{10^6} * 60 - C_{MS} * MaFo_{fis,i} \quad \text{Eq. A.16}$$

where $E_{y,i}$ is measured in kWh and it is defined for the different percentages of wave energy considered, with $i = 0, 10, 30$ %.

A.3.2.2 Fish farming. As in the case of RE production, the negative environmental impact of fish farming is directly related to the occupation of marine space:

$$env_{fis} = -C_{MS} * MaFo_{fis} \quad \text{Eq. A.17}$$

A3.2.3 Tourism. The environmental indicator for tourism activity is evaluated as:

$$env_{tou} = EnEd * WTP * N \quad \text{Eq. A.18}$$

where WTP is equal to 50€/y and $N = N_p * N_d$ is again the number of tourists per year.

A.3.3 Social KPIs

Finally, for all the activities, social indicators are defined based on the number of people employed, on the duration of employment and on the salaries. Specifically, as for the tourist activities, two workers employed for 6 months per year with a salary of 2′000 €/month are considered:

$$soc_{tou} = 2*6*2'000 = 24'000€ \qquad \text{Eq. A.19}$$

As regards the fish farming, two workers employed for 2 days per week with a salary of 2′000 €/month and 1 worker employed for 12 months with a salary of 2′000 €/month are considered, taking into account the PBP of the activity (15 years):

$$soc_{fis} = \left(2*\frac{2*52}{365} + \frac{1}{15}\right)*12*2'000 = 15'277€ \qquad \text{Eq. A.20}$$

Lastly, concerning the energy production activities, 1 worker employed for 12 months with a salary of 2′000 €/month is considered, taking into account the PBP of each RES installation (15, 30, 50 years):

$$soc_{ene} = \left(\frac{1}{15}*\frac{1}{30} + \frac{1}{50}\right)*12*2'000 = 2'880€ \qquad \text{Eq. A.21}$$

A.3.4 Summary of the KPIs calculation

The social indicators *soc* for each activity and the economic indicator for the tourist activities eco_{tou} are the only KPIs independent from the variables $MaFo_{fis}$ and *EnEd*, while all the other indicators can be interpolated from Table 2 as a function of $MaFo_{fis}$ or can be defined based on *EnEd* in the case of env_{tou}. The calculations of the KPIs for each activity are reported in Table A.5.

Table A.5
Evaluation of the KPIs.

Activity	KPI	Formula for the KPIs depending on the relevant variables
Tourism	eco_{tou}	$N_p \cdot C_p \cdot N_d = 365*10^{-3}$ M€
	soc_{tou}	$24 \cdot 10^{-3}$ M€
	env_{tou}	$EnEd \cdot WTP \cdot N$
Aquaculture	eco_{fis}	$-11.375 \cdot MaFo_{fis}^2 + 25.362 \cdot MaFo_{fis} - 0.1322 + 0.3$ (considering the profits from fish farming and the avoided maintenance costs thanks to the mineral accretion technique)
	soc_{fis}	$15.28 \cdot 10^{-3}$ M€
	env_{fis}	$-C_{MS} \cdot MaFo_{fis}$
RES production (0% wave)	$eco_{ene,0}$	$0.0522 \cdot MaFo_{ene,0}^2 - 0.2343 \cdot MaFo_{ene,0} - 0.0063$
	$soc_{ene,0}$	$2.88 \cdot 10^{-3}$ M€
	$env_{ene,0}$	$60 \cdot (820/10^6) \cdot E_{y,0} - C_{MS} \cdot MaFo_{fis,0}$
RES production (10% wave)	$eco_{ene,10}$	$1.1483 \cdot MaFo_{ene,10}^2 - 5.1551\, MaFo_{ene,10} + 0.1555$
	$soc_{ene,10}$	$2.88 \cdot 10^{-3}$ M€
	$env_{ene,10}$	$60 \cdot (820/10^6) \cdot E_{y,10} - C_{MS} \cdot MaFo_{fis,10}$
RES production (30% wave)	$eco_{ene,30}$	$3.3406 \cdot MaFo_{ene,30}^2 - 14.997 \cdot MaFo_{ene,30} + 0.4547$
	$soc_{ene,30}$	$2.88 \cdot 10^{-3}$ M€
	$env_{ene,30}$	$60 \cdot (820/10^6) \cdot E_{y,30} - C_{MS} \cdot MaFo_{fis,30}$

Data availability

Data will be made available on request.

References

[1] Perez-Collazo C, Greaves D, Iglesias G. A review of combined wave and offshore wind energy. Renew Sustain Energy Rev 2015;42:141–53.

[2] Buck BH, Nevejan N, Wille M, Chambers M, Chopin T. Offshore and multi-use aquaculture with extractive species: seaweeds and bivalves, aquaculture Perspective of multi-use sites in the open ocean. The Untapped potential for marine resources in the Anthropocene. Cham: Springer Nature; 2018. p. 20–3. https://doi.org/10.1007/978-3-319-51159-7_3.

[3] Lester SE, Stevens JM, Gentry RR, et al. Marine spatial planning makes room for offshore aquaculture in crowded coastal waters. Nat Commun 2018;9:945. https://doi.org/10.1038/s41467-018-03249-1.

[4] Westerberg V, Jacobsen JB, Lifran R. The case for offshore wind farms, artificial reefs and sustainable tourism in the French Mediterranean. Tourism Manag 2013;34:172–83.

[5] Karlõševa A, Nõmmann S, Nõmmann T, Urbel-Piirsalu E, Budziński W, Czajkowski M, Hanley N. Marine trade-offs: comparing the benefits of off-shore wind farms and marine protected areas. Energy Econ 2016;55:127–34. https://doi.org/10.1016/j.eneco.2015.12.022. ISSN 0140-9883.

[6] Jansen HM, Burg S, Bolman B, Jak RG, Kamermans P, Poelman M, Stuiver M. The feasibility of offshore aquaculture and its potential for multi-use in the North Sea. Aquacult Int 2016;24(3):735–56.

[7] Röckmann C, Lagerveld C, Stavenuiter J. Operation and maintenance costs of offshore wind farms and potential multiuse platforms in the Dutch North Sea. In: Buck BH, Langa R, editors. Aquaculture Perspective of multi-use sites in the open ocean; the Untapped potential for marine resources in the Anthropocene. Cham: Springer Nature; 2018. p. 97–113.

[8] Depellegrin DC, Venier Z Kyriazi, Vassilopoulou V, Castellani C, Ramieri E, Bocci M, Fernandez J, Barbanti A. Exploring Multi-Use potentials in the Euro-Mediterranean sea space. Sci Total Environ 2018;653:612–29.

[9] HIS Markit. Petrodata rigs. https://login.ods-petrodata.com/; 2022. October 2024.

[10] European Commission. Annual report on the safety of offshore oil and gas operations in the European union for the Year 2016, COM/2018/595 final. 2018.

[11] Claisse JT, Pondella DJ, Love M, Zahn LA, Williams CM, Williams JP, Bull AS. Oil platforms among most productive fish habitats. Proc Natl Acad Sci USA 2014;111(43):15462–7.

[12] Krause PR. Ecological value of Leave-in-place and reefing options in temperate environments: case studies from decommissioning projects in. California, USA: Society of Petroleum Engineers; 2014. https://doi.org/10.2118/168521-MS.

[13] Scarborough Bull A, Love MS. Worldwide oil and gas platform decommissioning: a review of practices and reefing options. 2019. Ocean Coast Manag 2019;168: 274–306.

[14] Kaiser MJ, Yu Y, Snyder B. Economic feasibility of using offshore oil and gas structures in the Gulf of Mexico for platform-based aquaculture. Mar Pol 2010;34: 699–707.

[15] Kaiser MJ, Snyder B, Yu Yunke. A review of the feasibility, costs, and benefits of platform-based open ocean aquaculture in the Gulf of Mexico. Ocean Coast Manag 2011;54(721e730).

[16] Nugraha RBA, Basuki R, Oh JS, Cho Il H, Naibaho N, Secasari Y, Mbay L. Rigs-To-Reef (R2R): a new initiative on re-utilization of abandoned offshore oil and gas platforms in Indonesia for marine and fisheries sectors. IOP Conf Ser Earth Environ Sci 2019;241:012014. https://iopscience.iop.org/article/10.1088/1755-1315/241/1/012014.

[17] Lumina Decision systems. Platform – the OST oil & gas platform decommissioning decision support tool: user guide. prepared for California Ocean Science Trust; 2010. May 16, 2010, https://www.oceansciencetrust.org/wp-content/uploads/2015/05/OilandGas_PlatformModelUserGuide.pdf. [Accessed 11 February 2023].

[18] Henrion M, Bernstein B, Swamyy S. A multi-attribute decision analysis for decommissioning offshore oil and gas platforms. Integrated Environ Assess Manag 2015;11(4):594–609.

[19] Martins ID, Moraes FF, Tàvora G, Soares HLF, Infante CE, Arruda EF, Bahiense L, Caprace J, Lourenço MI. A review of the multicriteria decision analysis applied to oil and gas decommissioning problems. Ocean Coast Manag 2020;184(2020): 105000.

[20] Leporini M, Marchetti B, Corvaro F, Polonara F. Reconversion of offshore oil and gas platforms into renewable energy sites production: assessment of different scenarios. Renew Energy 2019;135(2019):1121e1132.

[21] Zanuttigh B, Angelelli E, Kortenhaus A, Koca K, Krontira Y, Koundouri P. Methodology for multi-criteria design of multi-use offshore platforms for marine RENEWABLE energy harvesting. Renew Energy 2016;85:1271–89.

[22] PlaCE. PlaCE project website. https://bluegrowth-place.eu/; 2022.

[23] Margheritini L, Colaleo G, Contestabile P, Bjørgård TL, Simonsen ME, Lanfredi C, Dell'Anno A, Vicinanza D. Development of an eco-sustainable solution for the second life of decommissioned oil and gas platforms: the mineral accretion technology. Sustainability 2020;12(9):3742. https://doi.org/10.3390/su12093742.

[24] Stuiver M, Soma K, Koundouri P, Van den Burg S, Gerritsen A, Harkamp T, Dalsgaard N, Zagonari F, Guanche R, Schouten JJ, Hommes S, Giannouli A, Söderqvist T, Rosen L, Garção R, Norrman J, Röckmann C, de Bel M, Zanuttigh B, Petersen O, Møhlenberg F. The governance of multi-use platforms at sea for energy production and aquaculture: challenges for policy makers in European seas. Sustainability 2016;8(4):333.

[25] Zanuttigh B, Angelelli E, Bellotti G, Romano A, Krontira Y, Troianos D, Suffredini R, Franceschi G, Cantù M, Airoldi L, Zagonari F, Taramelli A, Filipponi F, Jimenez C, Evriviadou M, Broszeit S. Boosting blue growth in a mild sea: analysis of the synergies produced by a multi-purpose offshore installation in the northern Adriatic, Italy. Sustainability 2015;7:6804–53.

[26] Zanuttigh B, Palma G, Brizzi G, Bellotti G, Romano A, Suffredini R. Design of a multi-use marine area offshore the Mediterranean Sea. Ocean Eng 2021;221: 108515.

[27] OECD. OECD sustainable Ocean Economy database. https://stats.oecd.org/index.aspx?datasetcode=OCEAN; 2023.

[28] Eurostat. https://ec.europa.eu/eurostat/data/metadata/metadata-structure; 2022.

[29] European Commission. Directive 2008/28/EC of the European Parliament and of the Council of 11 March 2008 amending Directive 2005/32/EC establishing a framework for the setting of ecodesign requirements for energy-using products, as well as Council Directive 92/42/EEC and Directives 96/57/EC and 2000/55/EC, as regards the implementing powers conferred on the Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0028&from=DE; 2008.

[30] Abramic, et al. Environmental impact assessment framework for offshore wind energy developments based on the marine Good Environmental Status. Environ Impact Assess Rev 2022;97:106862. https://doi.org/10.1016/j.eiar.2022.106862. ISSN 0195-9255.

[31] Bull AS, Love MS. Worldwide oil and gas platform decommissioning: a review of practices and reefing options. Ocean Coast Manag 2019;168:274–306.

[32] Kruse SA, et al. Considerations in evaluating potential socioeconomic impacts of offshore platform decommissioning in California. Integrated Environ Assess Manag 2015;11:572–83.

[33] Cantle P, Bernstein B. Air emissions with decommissioning California's offshore oil and gas platforms. Integrated Environ Assess Manag 2015;11:564–71.

[34] Wang P, et al. A review of the state-of-the-art developments in the field monitoring of offshore structures. Ocean Eng 2018;147:148–64.

[35] Hsu CHC. Tourism education on and beyond the horizon. Tourism Manag Perspect 2018;25:181–3.

[36] Spagnolo A, et al. Offshore platforms: comparisons of five benthic indicators for assessing the macrozoobenthic stress levels. Mar Pollut Bull 2014;82:55–65.

[37] Vodopivec M, et al. Offshore marine constructions as propagators of moon jellyfish dispersal. Environ Res Lett 2017:084003.

[38] Mangano MC, Sarà G. Collating science-based evidence to inform public opinion on the environmental effects of marine drilling platforms in the Mediterranean Sea. J Environ Manag 2017;188:195–202.

[39] Sommer B, et al. Decommissioning of offshore oil and gas structures—environmental opportunities and challenges. Sci Total Environ 2019; 658:973–81.

[40] Zagonari F. Environmental ethics, sustainability and decisions: literature problems and suggested solutions. Springer; 2023.

[41] Ministry of ecological transition. Piattaforme marine. https://unmig.mite.gov.it/ricerca-e-coltivazione-di-idrocarburi/piattaforme-marine/; 2023. October 2024.

[42] Artioli Y, Bendoricchio G, Palmeri L. Defining and modelling the coastal zone affected by the Po river (Italy). Ecol Model 2005;184:55–68.

[43] Eni. ISWEC: energy from the sea. The data on the page will be updated with the presentation of the Strategic Plan 2023-2026. 2023. https://www.eni.com/en-IT/operations/iswec-eni.html. [Accessed 28 February 2023].

[44] AGI. ni: visita alla piattaforma Amelia D. https://www.agi.it/economia/news/2015-06-27/eni_visita_alla_piattaforma_amelia_d-278351/; 2015. October 2024, in italian.

[45] Eni. Energie aperte. https://www.eni.com/it-IT/media/eventi/percorsi-energia.html. [Accessed 28 February 2023].

[46] Associazione Paguro. Relitto piattaforma Paguro. Accessed october 2022. https://www.associazionepaguro.org/; 2022. July 2022.

[47] Zanuttigh B, Palma G, Brizzi G, Bellotti G, Romano A, Suffredini R. Design of a multi-use marine area offshore the Mediterranean Sea. Ocean Eng 2021;221: 108515.

[48] OPT, Ocean Power Technologies. PB3 PowerBuoy, ocean power technologies. https://oceanpowertechnologies.com/platform/opt-pb3-powerbuoy/. [Accessed 9 February 2023].

[49] Weinstein A, Fredrikson G, Parks M, Nielsen K. AquaBuOY-the offshore wave energy converter numerical modeling and optimization. Proceed IEEE MTTS 2004: 1854–9.

[50] Jin D, Hoagland P, Wikgren B. An empirical analysis of the economic value of ocean space associated with commercial fishing. Mar Pol 2013;42:74–84. https://doi.org/10.1016/j.marpol.2013.01.014.

[51] Fernandez-Chozas J, Kofoed JP, Jensen NEH. User guide – the COE calculation tool for wave energy converters: version 1.6, April 2014, DCE technical report N. 161. Aalborg University, Ocean and Coastal Engineering Research Group, Division of Civil and Environmental Engineering; 2014. ISSN1901-726X.

[52] Czermański E, Zaucha J, Oniszczuk-Jastrząbek A, Pardus A, Kiersztyn A, Czerwiński D. Valuation of marine areas for merchant shipping: an attempt at shipping spatial rent valuation based on Polish Marine Areas. Front Mar Sci 2024: 11. https://doi.org/10.3389/fmars.2024.1352598.

[53] Oil&Gas Authority. UKCS decommissioning – cost estimate 2021. https://www.nstauthority.co.uk/media/7680/ukcs_decomm_cost_estimate_2021_single_master.pdf; 2021.

[54] European Commission. Study on Decommissioning of offshore oil and gas installations: a technical. Legal and political analysis. 2022. ISBN 978-92-76-47526-2. Accessed July 2023, https://www.cde.ual.es/wp-content/uploads/2022/03/MJ0622084ENN.en_.pdf.

[55] Zagonari F. Decommissioning vs. reusing offshore gas platforms within ethical decision-making for sustainable development: theoretical framework with application to the Adriatic Sea. Ocean Coast Manag 2021;199:105409.

[56] Jolliet O, Margni M, Charles R, Humbert S, Payet J, Rebitzer G, Rosenbaum R. Impact 2002+: a new life cycle impact assessment methodology. Int J Life Cycle Assess 2003;8(6):324–30.

[57] European Commission. PVGIS (photovoltaic geographical information system) online tool, EU (European union) science hub. Last update 01/03/2022 2022. https://re.jrc.ec.europa.eu/pvg_tools/en/. [Accessed 28 February 2023].

[58] SunPower. SunPower Maxeon. https://sunpower.maxeon.com/it/; 2022.

[59] ENI private communication. Email by A. Giuggioli, May 4th, Verification of the costs for the tool under development in the framework of the PLACE project. 2022.

[60] IRENA. Renewable power generation costs in 2022. ISBN: 978-92-9260-544-5, downloadable at, https://www.irena.org/Publications/2023/Aug/Renewable-Power-Generation-Costs-in-2022; 2022.

[61] Hersbach H, Bell B, Berrisford P, Biavati G, Horányi A, Muñoz Sabater J, Nicolas J, Peubey C, Radu R, Rozum I, Schepers D, Simmons A, Soci C, Dee D, Thépaut J-N. ERA5 hourly data on single levels from 1959 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS), https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form. [Accessed 8 February 2023].

[62] OPT, Ocean Power Technologies. PB3 PowerBuoy® celebrates one year of maintenance-free continuous operation in the Adriatic Sea. https://oceanpowertechnologies.com/news/pb3-powerbuoy-celebrates-one-year-of-maintenance-free-continuous-operation-in-the-adriatic-sea/; 2020.

[63] Schlömer S, Bruckner T, Fulton L, Hertwich E, McKinnon A, Perczyk D, Roy J, Schaeffer R, Sims R, Smith P, Wiser R. Annex III: technology-specific cost and performance parameters. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, Adler A, Baum I, Brunner S, Eickemeier P, Kriemann B, Savolainen J, Schlömer S, von Stechow C, Zwickel T, Minx JC, editors. Climate change 2014: Mitigation of climate change. Contribution of working group III to the fifth assessment report of the Intergovernmental panel on climate change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2014.