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Beyond LCOE: A multi-criteria evaluation framework for offshore renewable energy projects

María M. Vanegas-Cantarero [a,*], Shona Pennock [a], Tianna Bloise-Thomaz [a], Henry Jeffrey [a], Matthew J. Dickson [b]

[a] *School of Engineering, Institute for Energy Systems, The University of Edinburgh, Edinburgh EH9 3JG, UK*
[b] *CorPower Ocean AB, Västberga Allé 60, 126 30 Hägersten, Sweden*

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ABSTRACT

The transition to low-carbon energy systems is a complex process that implies radical technological changes, greenhouse gas emission reductions, and benefits to the local economies yet, also significant investment, a need for capacity building, strengthening supply chains and supporting legal frameworks. Consequently, the choice of renewable energy technologies should be based on a comprehensive assessment addressing the different dimensions that are affected. Clean energy technologies are traditionally evaluated on the basis of their techno-economic performance. Such an approach penalises emerging energy technologies that are generally more capital-intensive given their innovation requirement and the lack of support mechanisms facilitating their industrial roll-out. In this paper, a multi-criteria evaluation framework is proposed encompassing three important broad dimensions: techno-economics, environment and socio-economics. The applicability and flexibility of the proposed evaluation framework are demonstrated on different case studies. First, the hypothetical deployment of a floating offshore wind farm both in Scotland and Portugal is evaluated. Later, the proposed framework is used to evaluate the deployments of wave energy devices in the same two locations. The results show that this multi-criteria approach provides a more holistic overview of the performance and implications of renewable energy technologies, particularly emerging ones, and can better support decision- and policy-making in the medium- and long-term. Furthermore, the framework can be used by researchers, investors, developers and/or analysts to assess energy planning alternatives.

1. Introduction

The current state of climate emergency calls for the rapid deployment of renewable energy technologies. According to the Intergovernmental Panel on Climate Change (IPCC), renewable energy technologies should supply between 70% and 85% of the world's electricity in 2050 to limit global warming to 1.5 °C [1]. Furthermore, renewable energy has shown resilience in the midst of the COVID-19 pandemic and is now poised to be a key element of stimulus packages and recovery strategies around the globe [2].

Among the portfolio of clean energy alternatives for the energy transition, offshore renewable energy (ORE) is an emerging yet promising energy sector. Floating offshore wind and wave energy, in particular, are ORE sources with great yet under-exploited potential. On one hand, floating foundations enable power generation from the strongest winds given that the turbines are not subjected to the water depth constrains that limit bottom-fixed wind turbines [3]. On the other hand, wave energy devices are means to transform the kinetic and potential energy of waves into electricity with more predictability and less intermittency than solar and wind energy [4]. In Europe, offshore wind and ocean energy are expected to reach 300 GW and 40 GW of installed capacity respectively by 2050 [5], whilst ocean energy is expected to reach 55 GW by 2050 globally [6].

Despite the promising outlook, these nascent energy technologies are currently facing numerous and diverse challenges. The novel designs face issues of efficiency and reliability (which are inherent to emerging technologies). Furthermore, in the case of ocean energy technologies such as wave, the wide diversity of designs available and the lack of convergence toward one or, at least, a select few of these designs hinder industrial roll-out and the commercialisation of the technologies. Most of the designs available have been deployed for technology demonstration purposes. Thus, the industry has not been able to benefit from economies of scale and volume. Additionally, there is no well-established supply chain to support the development and commercialisation of these technologies. Finally, these challenges are

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* Corresponding author.
E-mail address: maria.vanegas@uni-flensburg.de (M.M. Vanegas-Cantarero).

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Nomenclature

AEP	Annual Energy Production
AHP	Analytical Hierarchy Process
CAPEX	Capital Expenses
CfD	Contract for Difference
CPO	CorPower Ocean AB
dCor	Distance Correlation
EROI	Energy Return on Investment
FiT	Feed-in-Tariff
FOW	Floating Offshore Wind
FOWCoE	Floating Offshore Wind Centre of Excellence
FTE	Full-time Employment
GHG	Greenhouse Gas
GVA	Gross Value Added
GWP	Global Warming Potential
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
IxI-IO	Industry-by-Industry Input Output
LCA	LifeCycle Assessment
LCOE	Levelised Cost of Energy
MAUT	Attribute Utility Theory
MAVT	Multiple Attribute Value Theory
NPV	Net Present Value
O&M	Operations and Maintenance
OPEX	Operational Expenses
ORE	Offshore Renewable Energy
OTEC	Ocean Thermal Energy Conversion
PROMETHEE	Preference Ranking Organisation Method for Enrichment Evaluation
PV	Photovoltaic
SAW	Simple Additive Weighting
SOWEC	Scottish Offshore Wind Energy Council
TOPSIS	Technique for Order Preference by Similarity to Ideal Solutions
TRL	Technology Readiness Level
UMACK	Universal Mooring, Anchor & Connectivity Kit
VIC	Variabilities and Interdependencies of Criteria
VIKOR	Compromise Ranking Method
WEC	Wave Energy Converter

exacerbated by the inherent risks, complexity, and scale of offshore projects. This situation hampers the cost-competitiveness of ORE technologies relative to more mature renewable energy technologies such as onshore wind, solar photovoltaic (PV), or geothermal and overshadow their potential contribution to the global energy mix.

Due to their emerging nature, these ORE technologies are not yet widely considered as viable alternatives in energy plans and strategies directing the global energy transition. The premise that renewable energy technologies should be compared based on their techno-economic performance imposes a partisan view and penalises emerging energy technologies. Nonetheless, emerging technologies are poised to contribute to low-carbon/net-zero future energy systems and this penalty hampers their competitiveness.

Table 1
Algorithm used in the Scopus web search.

1	*(("multi criteria" OR "multi-criteria") AND ("evaluation" OR "analysis" OR "decision making" OR "decision-making") AND "renewable energy") AND (LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "cp")) AND (LIMIT-TO(LANGUAGE, "English")) AND (EXCLUDE(PUBYEAR, 2021))*

The ORE sector is arduously working to address the challenges hindering industrial roll-out. However, the authors argue that nascent energy technologies should be assessed in a fair and transparent manner and considered as part of the portfolio of alternatives for future low-carbon energy systems. For this, this paper proposes a multi-dimensional evaluation framework to consider not only the techno-economic performance of these technologies but their impact on the environment, society and local economies. The proposed multi-dimensional framework builds upon previous experience of the use of multi-criteria analysis and comprises three dimensions, namely techno-economics, environment and socio-economics. Thereby, the proposed framework merges aspects of the energy trilemma and offers a thorough assessment of emerging ORE technology performance. Short-term economic objectives are balanced against the medium- and long-term benefits of emerging ORE technologies in this assessment.

The advantages and limitations of the framework are demonstrated with its adoption for the evaluation of hypothetical floating offshore wind farms in Scotland and Portugal and deployments of arrays of CorPower Ocean's wave energy converters (WEC) in the same two locations. It is worth noting that CorPower (CPO) follows a structured five-stage product verification process and has planned to deploy an array of WECs in 2022–2023 as part of the last stage of this process [7]. The case studies examined are based on preliminary data obtained from the full-scale demonstration and deployment in stage four.

The remainder of the paper is structured as follows: Section 2 provides an overview of previous approaches found in the scientific literature to evaluate renewable energy technologies and justifies the need for holistic evaluation approaches; Section 3 describes the dimensions, metrics and multi-criteria decision-making methods selected for the proposed evaluation framework and provides a detailed account of the selected case studies; Section 4 reports on the implementation of the proposed framework on the selected case studies and the insight derived and provides examples of the uses of the framework; Section 5 provides a summary of the advantages and limitations of the proposed framework and outlines further research opportunities; finally, Section 6 presents the conclusions of the work based on the implementation of the framework on the case studies.

2. Literature review

The transition to low-carbon energy systems is a comprehensive energy problem that calls for a transformative process encompassing changes in multiple dimensions [8]. This requires the consideration of factors and determinants beyond technology and economics. Multi-criteria analysis has been increasingly adopted to address the multi-dimensionality issue of the energy transition.

2.1. Multi-criteria analysis

Multi-criteria analysis has gained popularity among the scientific community in the last few decades. A search in SCOPUS for publications using the algorithm detailed in Table 1 returns a total of 764 articles or conference papers released between 1997 and 2020. The number of publications advocating for holistic assessments of renewable energy alternatives has been increasing exponentially as can be seen in Fig. 1.

A closer look at the most common keywords used in these publications provides insight into the energy technologies being studied,

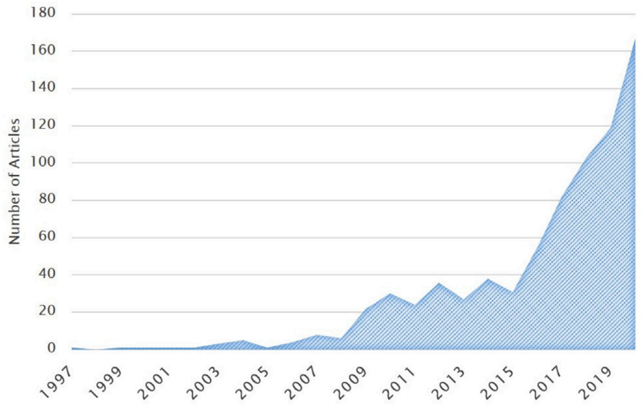


Fig. 1. Number of annual publications resulting from the SCOPUS search and released between 1997 and 2020.

the purpose or objectives of the multi-criteria analysis, the range of dimensions and indicators included and the most commonly adopted methods. Fig. 2 provides a summary of this information.

In terms of purpose or objectives, generally, multi-criteria analysis has been used as a tool to facilitate or support decision-making [9]. This type of analysis eases the selection of an alternative among a portfolio of solutions based on scores in a set of evaluation criteria or influencing factors. The most common applications in the publications retrieved from SCOPUS relate to the assessment of energy plans and policies with views to achieving sustainable development [10,11] and/or project selection and allocation, i.e. investment decisions [12–14]. However, multi-criteria analysis has also been adopted for site selection [15,16] and sustainability assessments [17,18].

In terms of dimensions examined in a multi-criteria analysis, Fig. 2 shows that economics [19,20], sustainability [21,22] and climate change [23,24] have been commonly considered. Studies including an economic dimension have adopted indicators such as investment costs, operation and maintenance costs, revenues, among others. Studies including sustainability or climate change-related dimensions generally adopted environmental impact indicators such as greenhouse gas emissions, carbon footprint, water consumption, among others. A more thorough review of the publications shows that, more recently, multi-criteria analyses are increasingly including social and/or political dimensions with indicators such as social acceptance [25], job creation [26], public policy and financial support [27], among others.

In terms of methods adopted for weighting and scoring in multi-criteria analysis, Fig. 2 shows that the studies published between 1997 and 2020 have most commonly adopted single synthesising criterion approaches such as the analytical hierarchy process (AHP) [28,29] and the technique for order preference by similarity to ideal solutions (TOPSIS) [30,31] as well as outranking methods such as the preference ranking organisation method for enrichment evaluation (PROMETHEE) [32,33] and the Compromise Ranking Method, also known as VIKOR [34,35]. In cases where the decision-making process is surrounded by uncertainty and either obtaining accurate values for the criteria is challenging or there may be bias issues in the weighting of the criteria, researchers have opted for fuzzy logic [36,37].

Finally, in terms of energy technologies being assessed, Fig. 2 shows that mature renewable energy options such as wind [38,39] and solar energy [40,41] have been extensively examined. Other technologies commonly included in the these studies are bioenergy [42] and nuclear energy [43].

2.2. Multi-criteria analysis for ORE technologies

Only a handful of studies have carried out a multi-criteria analysis and considered emerging ORE technologies. Among the publications retrieved from SCOPUS, only 15 include emerging ORE technologies such as floating wind, wave energy and/or ocean thermal energy conversion. Table 2 presents an overview of these studies. Two-thirds of these use multi-criteria analysis for energy planning purposes, namely site selection or RE portfolio design. The remainder use multi-criteria analysis either for energy policy or environmental assessments. As can be seen, most of the studies review cases where wave and/or tidal energy are considered. Floating offshore wind and other ORE technologies such as ocean thermal energy conversion (OTEC) or salinity gradient have been studied less frequently. It is important to highlight that these 15 studies include dimensions encompassing technology, environment, society and the economy. The indicators used under these dimensions vary from study to study, however, there are a few that are commonly considered, namely investment or capital costs, resource potential, CO_2 emissions and job creation.

2.3. Unidimensional analysis of ORE technologies

Unidimensional assessments of emerging ORE technologies are more common in the scientific literature. In the past, researchers have examined different ocean energy devices or projects with a strong emphasis on the techno-economic or environmental dimensions. For example, Myhr et al. [58] calculated and compared the levelised cost of energy (LCOE) of eight offshore wind farms with different foundation and mooring systems. The authors examined the cases of six floating and two bottom-fixed offshore wind turbines. Their results show that floating wind turbines present equal or lower LCOE in comparison to bottom-fixed concepts. However, LCOE estimates are site and technology dependent and, thus, direct comparisons are challenging. Furthermore, the authors pointed out that the nascent nature of the technologies as well as several factors and/or assumptions such as the project life span or the accuracy of the load factor contribute to uncertainties in the results. Similar conclusions were derived by Behrens et al. [59] but for a wave energy project. In this study, the authors calculated and compared the LCOE of three different types of wave energy converters assumed to be deployed in Australian coastal regions. Their findings suggest that LCOE analyses are limited in scope and cannot be used to estimate the myriad of impacts of the technologies in the local and global economy. However, they are insightful, particularly due to the early development stage at which these technologies stand, and can be used as foundation for further studies.

Other studies have focused on the environmental dimension and performed lifecycle and environmental impact assessments of different emerging ORE technologies. For instance, Weinzettel et al. [60] evaluated the environmental impacts of a floating offshore wind farm from a lifecycle perspective and reported results in terms of 8 different impact categories. The authors found two significant differences in the lifecycle of floating and bottom-fixed wind farms, namely the materials used and the capacity factor. These differences lead to higher environmental impacts in some categories for the floating devices. However, overall, the authors obtained comparable results for both technologies and concluded that this method provides a comprehensive analysis of the environmental burdens of the technologies. Elginoz and Bas [61] investigated the environmental sustainability of a multi-use offshore platform which combines wind and wave energy converters. The authors also adopted the lifecycle assessment (LCA) methodology and identified the manufacturing phase as the main source of pollution. Their results highlight the significant role of recycling at the end of life. Finally, the authors concluded that the LCA methodology can be useful to improve the design of a technology or to ease the comparison of technologies or functionalities. Uihlein [62] conducted a comprehensive study comprising LCAs of multiple wave and tidal devices. In this extensive assessment, the author also concluded that the manufacturing stage of structural components, moorings and foundations have the largest environmental impact. Moreover, the author highlighted that the large range in embodied carbon and energy outputs indicates that

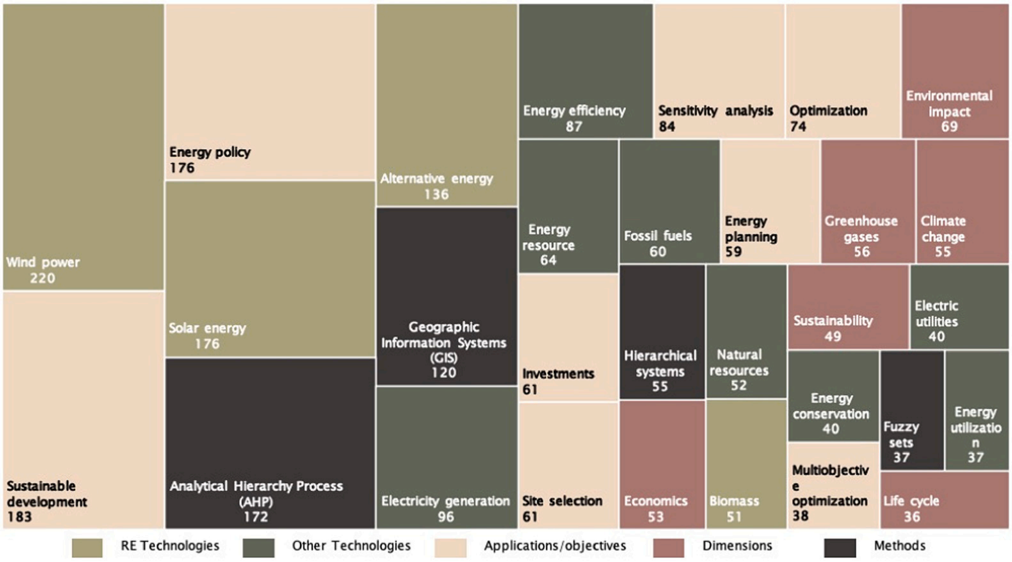


Fig. 2. Most common keywords in studies published between 1997 and 2020 retrieved from SCOPUS. The numbers in each branch of the treemap represent the number of papers in which the keyword is used.

the results are highly sensitive to the device design and, thus, this type of assessment can be valuable at early stages in a technology's development path.

Lastly, a few studies have focused on the socio-economic dimension and have performed macro-economic assessments of emerging ORE technologies. Draycott et al. [63] performed a macro-economic assessment of a wave energy project in Scotland and Portugal. The authors estimated the peak annual employment and gross value added (GVA) expected from the installation and manufacturing of the wave energy converters. The authors concluded that this type of analysis can be insightful and provide an overview of the wider economic benefits of wave energy. Also, the authors noted that this type of analysis can be complementary to techno-economic analysis. Allan et al. [64] used a similar input–output modelling approach to estimate the economic impacts of the technologies in the Scottish energy mix, including marine energy. The authors highlighted that emerging RE technologies, albeit at a nascent stage, have stronger linkages to the local economies than mature technologies.

This review has shown that multi-criteria analysis has become a popular approach to explore renewable energy alternatives, evaluating both the techno-economic and environmental performance of these technologies. Only recently, socio-economic indicators have been included in multi-criteria analyses [65,66] and their use, albeit not yet widespread, can be valuable in terms of the post-COVID green economic recovery. The review also showed that only a handful of studies involve emerging ORE technologies and these use the multi-criteria approach primarily for site selection or RE portfolio design. However, in this paper, the authors argue that the multi-criteria approach could be used to evaluate emerging RE technologies in a more comprehensive manner combining the usual techno-economic or environmental dimensions and considering additional dimensions such as socio-economics.

3. Methodology

This paper proposes an evaluation framework for ORE projects that encompasses metrics in the techno-economic, environmental and socio-economic dimensions as shown in Fig. 3. The framework merges two well-established approaches: the "Political, Economic, Social, Technological, Legal" or PESTLE analysis [67] and multi-criteria decision making. In this sense, the framework examines not only the technical parameters of the ORE project but the surrounding policy and legal conditions as well as the environmental, economic and societal conditions at the intended location. Thereby, it enables a comprehensive evaluation of emerging technologies beyond widely used yet unidimensional assessments such as LCOE and LCA. It is important to highlight that the proposed framework can be modified or expanded to include additional indicators based on the interests and/or requirements of a project's stakeholders as well as to emphasise or prioritise specific dimensions based on the judgement or perspective of a project's stakeholders by adjusting the weights used for scoring and ranking the alternatives.

3.1. Multi-criteria evaluation

The evaluation of the emerging energy alternatives is based on key mechanisms of multi-criteria decision making, namely normalisation, weighting and scoring. The outcomes of a multi-criteria evaluation may vary depending on the methods chosen for these three mechanisms. Wątróbski et al. [68] highlight the importance of selecting adequate methods since different methods can lead to different results for the same problem. After a comprehensive review of state-of-the-art multi-criteria decision analysis methods, Wątróbski et al. [68] provided a generalised method selection framework accompanied by an online tool based on properties of the multi-criteria problem such as objective of the process, types of indicators selected, characteristics of weights and presence of uncertainties. The methods selected for the multi-criteria evaluation framework for ORE projects are primarily based on the findings from Wątróbski et al. [68].

For a multi-criteria problem with quantitative weights, no considerations of uncertainty and with the objective of ranking and selecting an alternative, Wątróbski et al.'s [68] framework suggests methods such as Multiple Attribute Utility Theory (MAUT), Multiple Attribute Value Theory (MAVT), Simple Additive Weighting (SAW), VIKOR, TOPSIS, among others. TOPSIS or its modified version is deemed suitable for the multi-criteria evaluation framework for ORE projects proposed in this paper given the combination of cost and benefit metrics selected. On one hand, metrics that reflect a positive performance, i.e. when growth in an indicator is seen as beneficial, are referred to as benefit criteria. On the other hand, metrics that showcase a negative performance, i.e. when a decline in an indicator is preferred, are referred to as cost criteria. Given the different measurement units of the selected evaluation criteria, normalisation becomes a critical step. In this paper,

Table 2
Studies performing multi-criteria analysis and considering emerging ORE technologies between 1997 and 2020.

Authors	Year	Scope	Technology	Objective	Dimensions	Indicators
[17]	2002	Energy planning	OTEC	Sustainability assessment of new RE	– Energy resources, – Environment capacity, – Social indicators, – Economic indicators	– Efficiency, – Installation, – Electricity cost, – CO_2 emissions, – Land requirement
[44]	2016	Other	Wave	Preliminary design of multi-use offshore platforms	– Technical, – Environmental, – Social, – Economic	– Resource potential, – Innovation, – Exploitation potential, – Environmental impact, – Risks, – Costs
[45]	2009	Energy planning	Wave	Site selection		– Ocean depth, – Sea bottom type, – Existing underwater cables, – Marine protected areas, – Port location, – Shoreline, – Power grid location, – Military exercise areas, – Climatology of wave significant height, – Period, – Power
[46]	2016	Energy planning	Wave, tidal	Site selection	– Technical (resource potential), – Infrastructure and Logistics, – Environment	– Min. wind speed, – Min. wave power density, – Depth range, – Min. distance to shore, – Electricity network, – Max. distance to suitable ports, – Shipping traffic classification, – Environmental protection designation
[47]	2017	Energy planning	Wave	Site selection		– Energy flux, – Bathymetry slope, – Wave breaking, – Shipping traffic, – Distance to shore
[48]	2018	Energy planning	Tidal	RE portfolio design	– Technical, – Environmental, – Societal, – Economic	– Investment costs, – O&M costs, – Primary energy saving, – Realisation time, – Climate change, – Job creation
[49]	2018	Energy planning	Wave	Identification of opportunities for the co-location of marine aquaculture and renewable energy production		– Resource potential, – Structural requirements, – Limits for O&M activities, – Grid transmission, – Biological requirements for fish species
[50]	2017	Energy planning	Tidal	Prioritisation of dam sites	– Business drive, – Potential opportunity, – Overall costs, – Uncertainty and conflict	– Site data, – Tidal energy conversion, – Investment return, – Supply diversification, – Technological improvement, – Supporting regulations, – LCOE; – Cultural conflict among local stakeholders; – Uncertainties
[51]	2020	Energy planning	Wave	Site selection	Technical	– Exploitable storage of energy, – Accessibility, – Availability, – Energy production, – Monthly Variation Index, – Design wave height
[52]	2020	Energy planning	Tidal	RE portfolio design		– Investment costs, – Operating and maintenance costs, – Primary energy saving, – Sustainability of climate change, – Job creation

(*continued on next page*)

a widely used method referred to as vector normalisation has been adopted, following Chen's [69] findings which suggest the use of this technique in combination with TOPSIS and for a mixture of cost and benefit criteria. In this method, the non-normalised values $x_{i,j}$ for

Table 2 (*continued*).

Authors	Year	Scope	Technology	Objective	Dimensions	Indicators
[53]	2019	Energy policy	ORE	Stakeholder accept. Identifying best strategies for different groups of stakeholders.	– Economic impacts, – Environmental impacts, – Stakeholder engagement, – Other social impacts	– Project co-benefits, – Cost vs beneficiaries, – Scalability, – Marine environment, – Emissions, – Stakeholder engagement, – Stakeholder incentives, – Equality
[54]	2020	Environ. assessment	FOW	Lifecycle assessment		– Climate change, – Resource depletion, – Water use, – Marine ecotoxicity, – Air quality, – Cumulative energy demand
[55]	2009	Energy planning	OTEC	RE portfolio design	– Technology, – Environment, – Economy, – Society	– Efficiency, – Installation, – Electricity cost, – CO_2 emissions, – Land requirement
[56]	2018	Other	Tidal	Selection of solutions for environmental impacts		– Cost, – Stage of development, – Relevance to tidal lagoons, – Expected success, – Number of direct and indirect impacts addressed, – Level of uncertainty
[57]	2018	Energy policy	Tidal	Stakeholder acceptance		– Costs and benefits, – Environmental impacts, – Stakeholder engagement opportunities

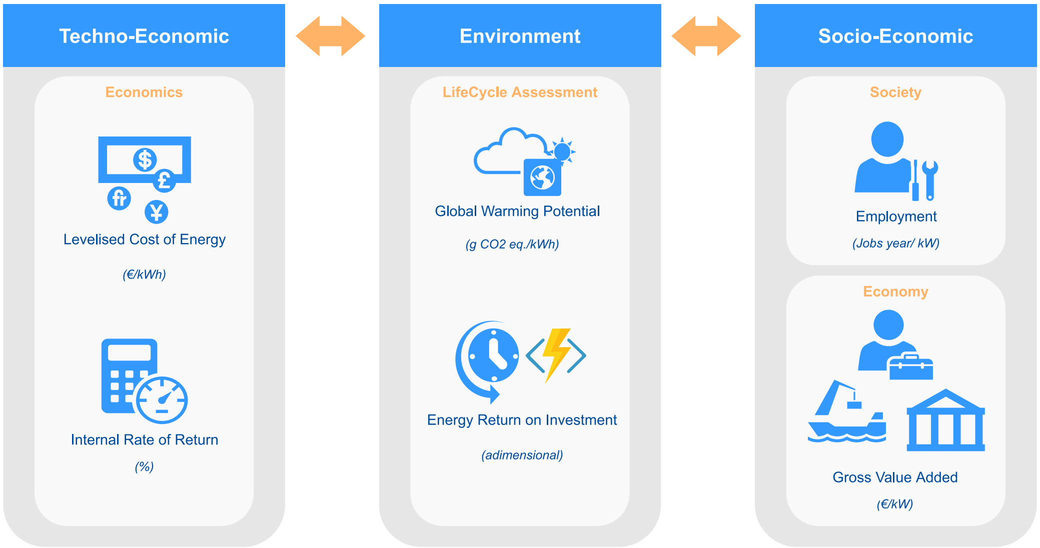


Fig. 3. Proposed framework for a multi-criteria evaluation of offshore renewable energy projects.

alternatives (or rows) $i = 1, \dots, n$ and indicators (or columns) $j = 1, \dots, m$ are transformed as follows:

$$d_{i,j} = \frac{x_{i,j}}{\sqrt{\sum_{k=1}^{n} x_{k,j}^2}}. \tag{1}$$

After normalisation, the resulting values $d_{i,j}$ are summarised in a decision matrix **D**:

$$\mathbf{D} = \begin{pmatrix} d_{1,1} & d_{1,2} & \cdots & d_{1,m} \\ d_{2,1} & d_{2,2} & \cdots & d_{2,m} \\ \vdots & \cdots & \ddots & \vdots \\ d_{n,1} & d_{n,2} & \cdots & d_{n,m} \end{pmatrix} \tag{2}$$

For the weighting, a novel correlation-aware model developed by Akestoridis and Papapetrou [70] was adopted to determine the relative importance of the evaluation criteria. This weighting method, known as *variabilities and interdependencies of criteria* (VIC), relies on the variability and (linear and non-linear) dependency between the evaluation criteria to estimate objective weights. However, it is worth noting that the proposed framework is compatible with the use of user-defined weights as will be demonstrated in the case studies. VIC estimates the relative importance of each criterion as follows:

$$g_j = \frac{\sigma_j}{\sum_{k=1}^{m} \tau_{j,k}}, j = 1, \dots, m, \tag{3}$$

where σ_j represents the standard deviation of criterion c_j and $\tau_{j,k}$ represents the distance correlation (dCor) (see [71]) between criteria c_j and c_k. The objective weight for every criterion is calculated as per

Eq. (4):

$$w_j = \frac{g_j}{\sum_{k=1}^{m} g_k}, j = 1, \dots, m. \tag{4}$$

The VIC method results in a weight vector $\mathbf{w} = (w_1, w_2, \dots, w_m)$, where $w_j \geq 0$ and the sum of all weights equals to 1. The resulting weights reflect the relative importance of a criterion depending on the amount of variation and independence that the criterion has relative to the others. In this way, the VIC method addresses the risk of double counting or introducing bias in highly dependent criteria. This issue is of great relevance for energy decision-making, where the criteria can be closely interlinked.

From **D** and **w**, a weighted normalised decision matrix **S** was calculated such that $s_{i,j} = w_j d_{i,j}$ for $i = 1, \dots, n$ and $j = 1, \dots, m$.

For the scoring, the modified version of TOPSIS (mTOPSIS) [72] was adopted, which uses the weighted Euclidean distances between each of the alternatives and the positive and negative ideal solutions in **D**. For both benefit and cost criteria, the weighted Euclidean distances are calculated as per Eqs. (5) and (6) respectively:

$$e_i^{max} = \sqrt{\sum_{j=1}^{m} w_j \left(d_j^{max} - d_{i,j}\right)^2}, i = 1, \dots, n, \tag{5}$$

$$e_i^{min} = \sqrt{\sum_{j=1}^{m} w_j \left(d_{i,j} - d_j^{min}\right)^2}, i = 1, \dots, n, \tag{6}$$

where $d_j^{max} = max\left\{d_{i,j} \mid i = 1, \dots, n\right\}$ and $d_j^{min} = min\left\{d_{i,j} \mid i = 1, \dots, n\right\}$. The resulting score for every alternative t_i is estimated as follows:

$$t_i = \frac{e_i^{min}}{e_i^{min} + e_i^{max}}, i = 1, \dots, n. \tag{7}$$

3.2. Indicators

The proposed framework seeks to facilitate the evaluation of a set of emerging energy alternatives using a set of criteria or metrics which will be described in this section.

In the techno-economic dimension, the framework suggests the use of the LCOE and the Internal Rate of Return (IRR). The former represents the discounted lifetime costs of a project over the energy produced throughout the lifetime of the project. This metric eases the comparison of costs between energy projects as it accounts for disparities in terms of capacities, efficiencies, locations, etc. The LCOE in this study is calculated as per Eq. (8) below.

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + A_t + D_{n+1}}{(1+i)^t}}{\sum_{n}^{t=1} \frac{AEP_t}{(1+i)^t}}, \tag{8}$$

where I_t refers to the investment or capital expenses (CAPEX) in year t, A_t represents the operational expenses (OPEX) in year t, D represents the decommissioning costs at the end of the lifetime of the project (assumed to take place one year after the end of the lifetime), i is the discount rate, AEP_t refers to the electricity generated by the project in year t and, finally, n represents the total economic lifetime of the project.

The Internal Rate of Return (IRR) relies on the net cash flows of the project, i.e., the investment, revenue and costs. As can be seen in Eq. (9), the IRR is the rate of return when the net present value of the sum of all cash flows equal to zero.

$$NPV(0) = -I + \sum_{t=1}^{n} \frac{Revenue - Cost}{(1 + IRR)^t}, \tag{9}$$

where $NPV(0)$ is a net present value of zero, I is the initial investment, $Revenue$ is the annual income derived from the sale of electricity at an average annual wholesale market price WMP_t added to other sources of revenue such as incentives or subsidies, $Cost$ represents the annual operational costs and n is the lifetime of the project.

In the environmental dimension, the framework utilises the global warming potential (GWP) and the energy return on investment (EROI). These two metrics can be estimated as a result of an environmental life cycle assessment, which entails a systematic analysis of resource use and pollutant emissions at every life cycle stage. This type of analysis is governed by the ISO 14040 standards [73,74] and are sometimes used to certify environmental credentials.

The GWP is a representation of the total contribution to global warming resulting from the total emissions of greenhouse gases throughout the different life cycle stages of an energy project, from material extraction through manufacturing and operation to decommissioning and disposal, per unit of energy generated. This metric is calculated as per Eq. (10) and facilitates the comparison of the environmental impacts resulting from different energy projects and can inform developers, investors and policymakers of emissions reduction opportunities across a project.

$$GWP = \frac{\sum_{t=1}^{n} ECsys_t}{\sum_{t=1}^{n} AEP_t}, \tag{10}$$

where $ECsys_t$ is the embodied carbon of the entire system throughout the lifetime of the project.

The EROI is a representation of the economical efficiency of an energy alternative and is defined as the ratio of total energy generated during the lifetime of a project ($\sum_{t=1}^{n} AEP_t$) to the cumulative energy demand or the total energy invested throughout the lifetime of the project ($\sum_{t=1}^{n} CED_t$) for, e.g., construction, maintenance, and decommissioning. It is calculated as per Eq. (11) below.

$$EROI = \frac{\sum_{t=1}^{n} AEP_t}{\sum_{t=1}^{n} CED_t} \tag{11}$$

Finally, in the socio-economic dimension, the framework suggests the quantification of benefits to the local economies in terms of employment and gross value added (GVA) generated. Both metrics can be derived from an input–output analysis and the Leontief inverse matrix following the methodology adopted by Allan et al. [64] and Crooks et al. [75]. The initial step is to calculate the net spend (NS_{cc}) of the project's cost centres in the region under consideration as per Eq. (12).

$$NS_{cc} = GS_{cc} * \left[\left(1 - L_j\right)\left(1 - Dw_j\right)\left(1 - Dp_j\right)(1 - S)\right], \tag{12}$$

where GS_{cc} represents the gross spend in cost centre cc, and the remaining factors represent ready reckoners including leakage (L), deadweight (Dw), displacement (Dp_j) and substitution (S) for industry j. The leakage reflects the share of the spend that is invested in the region under consideration. The deadweight accounts for delays or obstacles for additional economic activities occurring in the region of interest due to the project's activities. Displacement accounts for the shift of existing work for an industry activity in the region of interest due to work required for the project. Finally, substitution accounts for the shift in focus from existing operations to those needed for the project in the region in question. The only ready reckoner that is assumed to be non-zero in our case studies is leakage. The leakage rate for industry j is estimated from the region of interest's Industry by Industry (IxI) Input–Output (IO) tables as follows:

$$L_j = \frac{Imp_j}{TDU_j + Imp_j}, \tag{13}$$

where Imp_j refers to the imports in industry j and TDU_j refers to the total domestic use in industry j.

This approach uses the features of the Leontief inverse to investigate the interactions between the industrial sectors in a local economy to determine the impact of the economic sectors involved in an energy project on the local economy in terms of GVA- and employment-output. GVA and employment effects are calculated from the IxI IO table through Eqs. (14) and (15).

$$GVA_{eff,j} = \sum_i g_i L_{i,j} \tag{14}$$

Table 3
Summary of key assumptions in case studies.

Case study	Floating offshore wind 1	Floating offshore wind 2	Wave energy 1	Wave energy 2
Technology	SWAY	SWAY	CorPower	CorPower
Device rating	5 MW	5 MW	350 kW	350 kW
Farm size	500 MW	500 MW	10 MW	10 MW
Lifetime	20 years	20 years	20 years	20 years
Discount rate	8.2%	8.2%	7.0%	7.0%
Capacity factor	46.6%[a]	39%[a]	38.8%	40.1%
Location	Peterhead, Scotland	Aguçadoura, Portugal	Orkney Islands, Scotland	Aguçadoura, Portugal
Distance from shore	200 km	200 km	10 km	10 km
Subsidy/incentive (€/MWh)	CfD Strike Price: 209	FiT: 191	CfD Strike Price: 209	FiT: 191
Length of program	15 years	15 years	15 years	15 years
Electricity price (€/MWh)	54.32	41.00	54.32	41.00
Annual inspections per device	3	3	6	6
Main structural material	Alloyed steel	Alloyed steel	Steel and fibreglass	Steel and fibreglass
LCOE assumptions based on	[58,76]	[58,76]	UMACK Project [77]	UMACK Project [77]
LCA assumptions based on	[60]	[60]	[78]	[78]

[a] Load factor.

$$E_{eff,j} = \sum_{i} w_i L_{i,j}, \tag{15}$$

where $GVA_{eff,j}$ and $E_{eff,j}$ are the GVA and employment effects for industry j respectively, g_i is the ratio between the GVA of industry i and the total output at basic prices, w_i is the ratio between full-time equivalent (FTE) employment for industry i and the total output at basic prices (also for industry i), and $L_{i,j}$ is the corresponding value in the inverse Leontief matrix for industries i and j.

The last step is to estimate the GVA benefit GVA_{cc} and the job-years supported Emp_{cc} by the different economic activities in the project's cost centres. This is done by multiplying the net spend on cost centre cc in a given year by the respective GVA and employment effects as shown in Eqs. (16) and (17).

$$GVA_{cc} = NS_{cc} * GVA_{eff,j} \tag{16}$$

$$Emp_{cc} = NS_{cc} * E_{eff,j} \tag{17}$$

As can be seen, some of the selected indicators depend on common information, assumptions and input variables such as discount rates, capital costs, annual energy production, among others. Given the interlinkages between the indicators and the mixture of cost and benefit criteria selected for the multi-criteria analysis, the use of the modified TOPSIS method in combination with the vector normalisation and the VIC weighting method is found to be a suitable methodology. The implementation is be demonstrated in the case studies described below.

3.3. Case studies

The case studies that will be assessed using the comprehensive multi-criteria evaluation framework proposed in this paper include a floating offshore wind farm and a wave energy farm in Scotland and Portugal respectively. The key assumptions adopted in the case studies are summarised in Tables 3 and 4.

3.3.1. SWAY floating offshore wind concept

The first case study is that of a hypothetical 500 MW floating offshore wind farm that uses a floating concept known as Tension-Leg-Spar or SWAY developed in Norway by SWAY AS [79]. The floating concept can be seen in Fig. 4a. The SWAY system is a floating spar wind turbine for offshore locations in the range of 60–300m+ water depths [80]. The design consists of a floating tower anchored through a single tension-torsion leg to the seabed and able to tilt 5–8 degrees along with the turbine with changing wind directions. A 1:6 prototype was deployed in 2012 in Hjeltefjorden, east of Øygarden in Hordaland, Norway. To demonstrate the use of the proposed multi-criteria evaluation framework, the LCOE and LCA assumptions and results from Myhr et al. [58] and Weinzettel et al. [60] respectively have been adopted. For the metrics in the socio-economic dimension, the cost assumptions from Myhr et al. [58] have been adopted along with the industrial sectors and leakage rates detailed in Table 4. Two scenarios will be explored, namely a deployment in the North Sea and another one in the Atlantic Ocean. For the techno-economic assessment, two market-pull mechanisms are assumed to be in place for the first 15 years of the project supporting income generation. For the deployment in Scotland, a contract for difference (CfD) with a strike price of €209/MWh has been used assuming a similar support than the one received by EA 1 (developed by ScottishPower Renewables Ltd) in Allocation Round 1 in Scotland [81]. In the case of the deployment in Portugal, a Feed-in-Tariff (FiT) of €191/MWh has been assumed based on the existing FiT for pre-commercial hydropower plants up to 20 MW [82]. Complementarily, average annual electricity prices of €54.32/MWh and €41/MWh are assumed in Scotland and Portugal respectively based on 2019 average wholesale prices witnessed in these countries [83].

3.3.2. CorPower Ocean's wave energy converter

Other two case studies assuming a 10 MW wave energy farm using CorPower Ocean's point absorber WEC are considered. CorPower Ocean is a Swedish wave energy technology developer planning to introduce its device into the market by 2024. The company has designed a 350 kW WEC, as can be seen in Fig. 4b, with a heaving buoy on the surface absorbing energy from the movement of the ocean waves. The device is currently in stage 4 of a structured five-stage product verification process. To date, a small scale prototype, critical subsystems and a fully integrated 1:2 scale WEC have been tested.

Corpower is preparing the first full-scale WEC for dry testing and ocean deployment by the end of 2021. This is expected to aid the technology achieve a Technology Readiness Level (TRL) of 7. The deployment will take place off the coast of Aguçadoura in northern Portugal. For this case study, the techno-economic, environmental and socio-economic assessments were developed by the Policy and Innovation Group at the University of Edinburgh [84] as part of the project "Universal mooring, anchor & connectivity kit demonstration" (UMACK) [77].

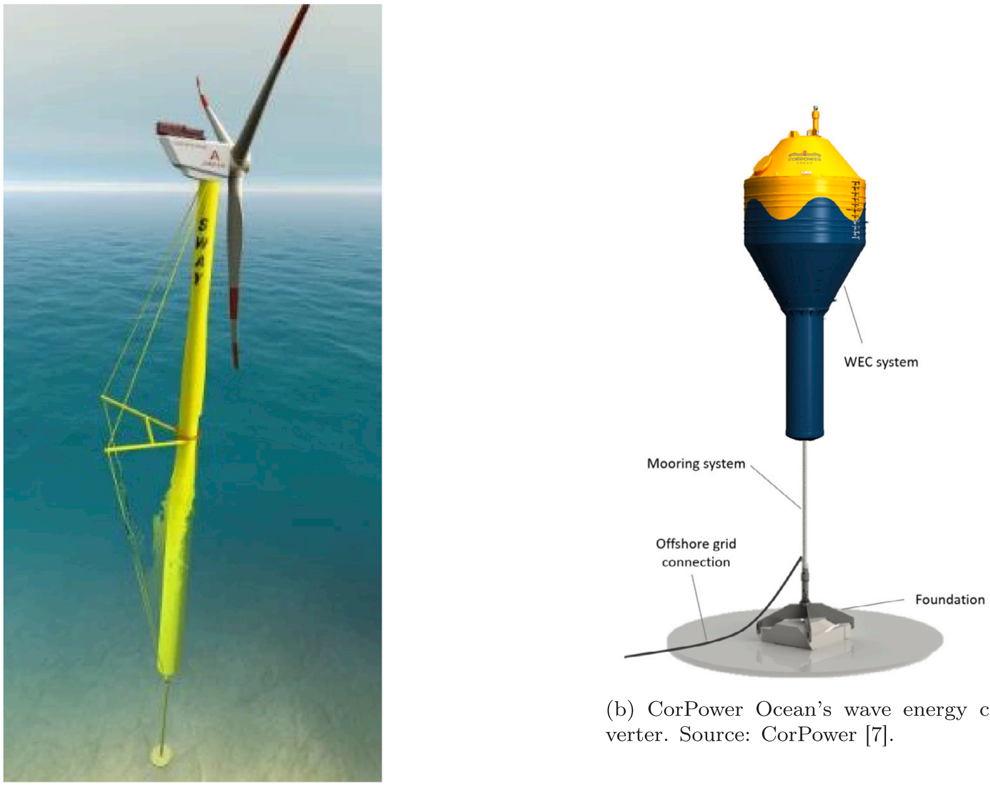
As in the case of floating offshore wind, two deployments are assumed: one in Scotland and another in Portugal. The assumptions regarding market-pull mechanisms and electricity prices remain the same as can be seen in Table 3. Some assumptions have not been disclosed due to confidentiality reasons.

4. Results

This section presents the results from the implementation of the proposed multi-criterial evaluation framework on the different case studies outlined in Section 3.3. These results are illustrated in Fig. 5,

Table 4
Summary of industries assumed to be involved in case studies.

SIC code	SIC code description	Leakage rate (%)	
		Scotland	Portugal
Floating offshore wind farms			
27	Manufacture of electrical equipment	61	48
28	Manufacture of machinery and equipment	58	49
50	Water transport	55	11
65	Insurance, reinsurance and pension funding	46	11
71	Architectural and engineering activities, technical testing and analysis	40	12
Wave energy farms			
20	Manufacture of basic chemicals	65	37
25	Manufacture of fabricated metal products, except machinery and equipment	50	39
27	Manufacture of electrical equipment	61	48
28	Manufacture of machinery and equipment	58	49
31	Manufacture of furniture	0	0
43	Other specialised construction activities	0	0
49	Other passenger land transport	51	11
50	Water transport	55	11
61	Telecommunications	50	15
64	Financial service activities, except insurance	46	11
65	Insurance, reinsurance and pension funding	46	11
68	Real estate activities on a fee or contract basis	0	0
69	Legal activities	46	12
71	Architectural and engineering activities, technical testing and analysis	40	12
74	Environmental consulting activities	46	12
77	Rental and leasing activities	0	0



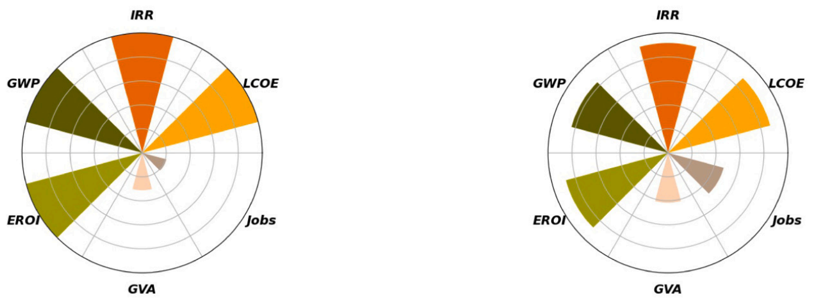
(a) Floating wind turbine design. Source: SWAY AS and NREL [79].

(b) CorPower Ocean's wave energy converter. Source: CorPower [7].

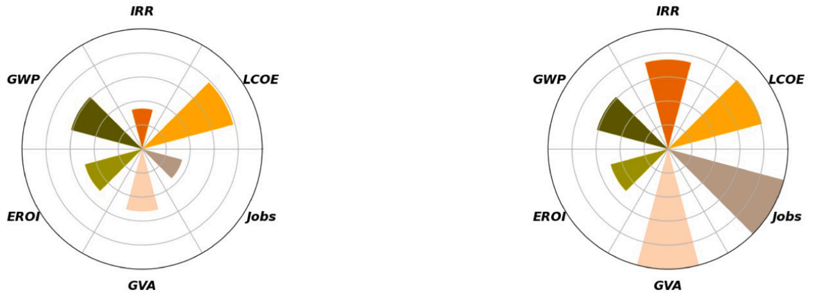
Fig. 4. Technology concepts considered in the selected case studies.

where the values have been normalised. In Fig. 5, the bars in the polar charts are representations of the performance of each case study in the evaluation criteria. In the case of benefit criteria such as GVA, jobs created, EROI or IRR, higher bars indicate higher values and, thus, better performance. Conversely, in the case of cost criteria such as LCOE or GWP, higher bars represent lower values and, thus, better performance. The detailed results will be described later in this section.

This section also demonstrates the use of the proposed multi-criteria evaluation framework for different applications, namely site selection, technology selection or both, using the previously described case studies. Furthermore, a sensitivity to weighting is presented, where user-defined weights are adopted instead of the objective weights calculated through the VIC approach.



(a) SWAY in Peterhead, Scotland (b) SWAY in Aguçadoura, Portugal



(c) CorPower in Orkney Islands, Scotland (d) CorPower in Aguçadoura, Portugal

Fig. 5. Multi-criteria evaluation of the case studies in Table 3. Values are normalised using the min/max approach for benefit and cost criteria. The bars in the polar charts are representations of the performance of each case study in the evaluation criteria and do not reflect the actual results of the evaluations. Where permitted, we have discussed the actual results in the text.

4.1. SWAY floating offshore wind concept

The following sections describe the results from the two case studies referring to the SWAY FOW concept and for the indicators included in the multi-criteria evaluation framework.

4.1.1. Peterhead, Scotland

The North Sea is an ideal location for offshore wind with wind speeds around the 10 m/s throughout the year [85]. The selected location for this case study, off the shores of Peterhead, Scotland, offers a wind potential of 1060 W/m^2 at 100 m hub heights [85]. In 2017, the first full-scale FOW farm – Hywind Scotland – began operations in this location [86]. These conditions, coupled with fairly attractive incentives such as the €209/MWh CfD strike price assumed in this case study, lead to an LCOE of €132.22/MWh and an IRR of 8.04%. Among the four case studies evaluated, this presents the lowest LCOE and the highest IRR. Scotland is currently striving to create a positive policy landscape for both the wind and marine energy industries, with the UK planning to introduce a separate technology pot for emerging technologies such as floating offshore wind in the next CfD round [87]. This could foster capacity additions that will continue to secure competitive rates in a CfD scheme, while providing a potential route to market for higher cost floating technologies.

In terms of the environmental dimension and assuming a load factor of 46.6%, the GWP of the 500 MW FOW wind farm in Scotland is 20.9 gCO$_2$eq/kWh. This leads to an EROI of 10.63%. The main contributor to the overall greenhouse gas (GHG) emissions is the manufacturing of the platform, followed by the turbine. This is due to the material requirements, particularly steel. Nonetheless, the consumption of fuel during the installation and decommissioning phases have a considerable impact as well.

In terms of the socio-economic dimension, the Scottish Offshore Wind Energy Council (SOWEC) [88] was formed in 2019 to maximise the economic benefits to Scotland from offshore wind deployments in Scottish waters. This initiative engages with key stakeholders such as developers to develop local skills, strengthen the supply chain and clusters, provide support for innovation, deliver jobs, investment and export opportunities and, ultimately, enable a pathway towards commercialisation. Similarly, the UK has established the Floating Offshore Wind Centre of Excellence (FOW CoE) [89] to accelerate the deployment of FOW farms, create opportunities for the local supply chain, and foster innovations in manufacturing, installation and operations and maintenance (O&M). It is estimated that the 500 MW FOW farm could generate €0.87 million per MW and support 11.32 job-years per MW. As can be seen from the leakage rates estimated from the IxI IO tables and detailed in Table 4, Scotland retains significantly less economic benefits than Portugal in the industrial sectors assumed to be involved.

4.1.2. Aguçadoura, Portugal

The waters off the port of Viana do Castelo offer considerable wind resource potential with a mean wind speed of 8.42 m/s and an approx. potential of 700 W/m^2 at 100 m hub heights [85]. The 500 MW floating offshore wind farm using the SWAY design assumed to be deployed in this location performs well in the techno-economic dimension with an LCOE of €150.02/MWh and IRR of 7.36%. This is assuming a FiT of €191/MWh. This is a good performance relative to the other case studies as can be seen in Fig. 5.

In the environmental dimension, the lower load factor in Aguçadoura (38.8%) relative to Peterhead increases the GHG emissions per unit of electricity and the performance of this case study in terms of GWP worsens as can be seen in Fig. 5b. The GWP in this case is 25.10 gCO$_2$eq/kWh and the EROI is 9.37%. The contributions from the materials and lifecycle stages to the environmental impact remain the same as no structural changes are assumed relative to the FOW farm in Scotland. Moreover, although marine operations are expected to vary dependent on the conditions at the deployment site, the lack of long-term track records for FOW deployments hampered the validation of site-specific assumptions for the environmental impact of marine operations and a generic installation and O&M strategies have been assumed for both sites considered. It is important to highlight that direct comparisons between LCA results across different energy alternatives are challenging due to the different assumptions and considerations involved in every analysis. A key consideration is the representation of marine operations as discussed by Pennock et al. [78], particularly the O&M lifecycle stage, due to the lack of track records to validate the models and/or assumptions. The use of differing methodologies and set of assumptions to represent the environmental impacts of the fuel consumption during the O&M phase result in a considerable range of impact of this phase within the overall LCA results. In this case study, due to data availability, the key factor influencing the results in the environmental dimension relative to the previous case study in Peterhead is assumed to be the resource potential and, thus, the annual energy production. Emission levels and embodied energy are assumed to be the same.

In the socio-economic dimension, it is estimated that the 500 MW FOW farm could generate €1.16 million per MW and support 26.06 job-years per MW for Portugal. From Table 4, it can be seen that the Portuguese economy retains more economic benefits in the industrial sectors assumed to be engaged in the supply chain relative to the Scottish case. Although more conservative results than in the wave energy case studies as can be seen in Fig. 5, these socio-economic benefits are considerable. For reference, the GVA of the activities related to the uses and resources of the sea, including emerging activities such as marine biotechnology, ocean renewable energy and land observation services, reached €8 million in 2018 and maintained 351 jobs in Portugal [90]. Portugal is focusing on FOW rather than bottom-fixed OW due to the bathymetry of the Portuguese sea and the higher wind potential in deeper waters. Portugal is following Scotland's steps allowing pre-commercial FOW projects to be deployed in Portuguese waters with support from key players in the finance and insurance services in Europe [91]. In its recently published National Strategy for the Sea 2021–2030 [90], the country establishes a commitment to reach 370 MW of offshore wind and wave energy by 2030.

4.2. CorPower's wave energy converter

The following sections describe the results from the wave energy case studies for the indicators included in the proposed multi-criteria evaluation framework.

4.2.1. Orkney Islands, Scotland

Scotland has laid out strategic objectives for offshore wind and marine renewable energy in its National Marine Plan [92] including (i) the sustainable development of offshore wind, wave and tidal energy in the most suitable locations, (ii) maximisation of economic benefits from these technologies by securing a competitive local supply chain in Scotland, and (iii) continuous policy support such as streamlining marine planning, consenting and licensing processes and transmission grid planning and development. Future rounds of the CfD scheme are expected to expand the number of technologies supported with emerging ORE projects being eligible to bid.

Assuming a CfD strike price that enables wave energy to compete with other technologies in the Scottish energy market, the assumed 10 MW wave farm could form part of the portfolio of renewable energy producers in the country and contribute towards decarbonisation. The results cannot be made publicly available due to non-disclosure agreements with the developers, however, in Fig. 5c it can be seen that the LCOE is higher in comparison to floating offshore wind (refer to Figs. 5a and 5b). The IRR is 2.71%, thus, lower than in the other case studies. This reflects the more nascent, less developed nature of wave energy and suggests that, although there is large scope for cost reductions, stronger policy support is required to make wave energy projects more economically attractive.

In terms of the environmental dimension, the 10 MW array presents a GWP of 34.1 gCO_2eq/kWh and EROI of 6.6%. It is important to highlight that wave energy devices are still under development and design improvements can be expected. Carrying out comprehensive assessments such as LCA at early stages in the development of the technologies enables developers to improve the environmental and techno-economic performance of their devices thereby leading to important reductions in capital and operational expenses. For instance, CorPower is currently developing an alternative foundation and mooring solution, UMACK [77], which is expected to contribute to streamlining marine operations. Such improvements could decrease the environmental impact of the array and improve its cost effectiveness and performance relative to other wave energy technologies.

Wave energy capacity additions will be instrumental for Scotland's net zero and decarbonisation ambitions [93] and present significant supply chain development opportunities [94]. Building up on the experience from the oil & gas industry and its engagement in the offshore wind industry, Scotland could offer interesting supply chain development opportunities for the wave energy sector suggesting a symbiotic relationship between local economies and this energy sector. We estimate that the 10 MW array could generate €1.45 million per MW in GVA benefits and support 18.71 job-years. This suggests that wave energy could provide more socio-economic benefits (per unit of power) to the country than FOW (see Figs. 5a and 5c). This is mainly driven by the higher spend associated to this technology, however, the wave energy supply chain can benefit more from local suppliers than the FOW supply chain. Further research is required to thoroughly investigate the engagement of the different industrial sectors in the lifecycle stages of a wave energy project. The approach suggested in this paper and its outcomes are merely an indication based on the IxI IO tables of the countries and, thus, represent a snapshot of the national economies in 2015. Furthermore, the list of industrial sectors engaged and the share of retention (or leakage rates) assumed for the spending associated to the deployment requires a more detailed analysis.

4.2.2. Aguçadoura, Portugal

Portugal has long been interested in wave energy given its long coastline in the Atlantic Ocean. In 2008, Portugal saw the world's first commercial wave energy project start operation. Pelamis Wave Power's Aguçadoura Wave Farm began delivering 2.25 MW of electricity through an array consisting of three attenuator-type Pelamis devices. Based on the successful experience with projects such as Pelamis, Portugal seeks to establish about 370 MW of offshore wind and waves by 2030 [90]. By 2020, four Titles of Private Use of National Maritime Space have been awarded in Portugal for the production and testing of ocean renewable energy with an installed capacity of 25.42 MW. CorPower Ocean has secured a 10-year license that enables the demonstration phase of its technology in Portuguese waters. The company will deploy a full-scale prototype by the end of 2021 and, later, an array consisting of three devices.

Based on the current design and cost estimates from the developer (which cannot be disclosed due to confidentiality reasons), a 10 MW array of CorPower devices will perform well in both the techno-economic and environmental dimensions as can be seen in Fig. 5d. Nonetheless, this is dependent on the availability of market-pull mechanisms such as the assumed FiT of €191/MWh to support the bankability of the project. The estimated IRR is 5.98%. In terms of environmental impact, the project presents a GWP of 32.9 gCO_2eq/kWh and an EROI of 6.8%. The environmental impact results are site specific and have been described in detail by Pennock et al. [78]. Lastly, this case study presents the largest socio-economic benefits (per unit of power) as seen in Fig. 5d with an estimated €2.79/MW in GVA benefits and 54.27 job-years supported.

4.3. Multi-criteria evaluation

This section demonstrates the use of the proposed multi-criteria evaluation framework for different applications as well as how the approach can be adjusted to account for the priorities and interests of different stakeholders through a sensitivity analysis for the weights adopted.

Table 5
Results of multi-criteria evaluation for site selection.

Case study/criterion	LCOE	IRR	GWP	EROI	GVA	Jobs	Score
Wave 1 - Scotland	0.72	0.41	0.72	0.70	0.46	0.33	0.0
Wave 2 - Portugal	0.70	0.91	0.69	0.72	0.89	0.94	1.0
VIC weights	0.015	0.309	0.015	0.013	0.264	0.384	

Table 6
Results of multi-criteria evaluation for technology selection.

Case study/criterion	LCOE	IRR	GWP	EROI	GVA	Jobs	Score
FOW 1 - Scotland	0.62	0.95	0.52	0.85	0.51	0.52	0.67
Wave 1 - Scotland	0.79	0.32	0.85	0.53	0.86	0.85	0.33
VIC weights	0.079	0.295	0.155	0.151	0.161	0.159	

4.3.1. *Site selection*

The first application assumes that the proposed framework is used for the purpose of site selection. If a developer such as CorPower Ocean were to choose between the Orkney Islands and Aguçadoura for a potential deployment, the comprehensive evaluations shown in Figs. 5d and 5c could support an informed decision-making process. If the decision were to be based on the performance of the project in one dimension or criterion, e.g. GWP or LCOE, the outcome could be subjected to bias as the results are very similar. However, considering the three dimensions simultaneously allows for a more exhaustive comparison.

Table 5 shows the normalised results, objective weights calculated with the VIC method and the final score from the multi-criteria evaluation. Considering all dimensions, and based solely on the assumptions made for this study, the developer would choose Aguçadoura to deploy its technology. The most valuable results leading to this decision are the job-years supported, GVA benefit and IRR as can be seen from the weights calculated.

4.3.2. *Technology selection*

The second application assumes that the proposed framework is used for the purpose of designing a renewable energy portfolio, i.e., to choose between renewable technologies in a location. If a project developer in Scotland were to decide whether to deploy a FOW farm or a wave farm, the proposed framework could provide a comprehensive evaluation to assess the energy alternatives.

Table 6 summarises the results of the multi-criteria evaluation for technology selection in Scotland. In this case, FOW would be the alternative with the highest score. The decision is mainly driven by the outcomes in IRR, GVA benefit and jobs created. This suggests that the market-pull mechanisms available, the sustainability of the technological design, and the strength and structure of the supply chain are key factors influencing the final scores obtained in this multi-criteria evaluation.

4.3.3. *Site and technology selection*

The last application is a combination of the previous two, i.e., site and technology selection. If all alternatives were to be assessed with the multi-criteria evaluation framework, an analyst/ international project developer/ European grant funder would be able to account for a diversity of conditions that are either site- or technology-specific and that are not able to be considered when adopting a one-dimension approach.

In this complex situation, the multi-criteria evaluation framework proposed streamlines the decision-making process. Table 7 presents the comprehensive set of results. The most attractive alternative is the wave farm in Aguçadoura, Portugal. The objective weights estimated show that the decision is driven by the number of job-years supported, the GVA benefit and the IRR.

Table 7
Results of multi-criteria evaluation for both site and technology selection.

Case study/criterion	LCOE	IRR	GWP	EROI	GVA	Jobs	Score
FOW 1 - Scotland	0.43	0.63	0.36	0.62	0.25	0.18	0.31
FOW 2 - Portugal	0.49	0.58	0.44	0.55	0.34	0.41	0.39
Wave 1 - Scotland	0.55	0.21	0.59	0.33	0.42	0.29	0.20
Wave 2 - Portugal	0.53	0.47	0.57	0.34	0.81	0.85	0.80
VIC weights	0.048	0.186	0.101	0.107	0.242	0.316	

Table 8
Results of multi-criteria evaluation for both site and technology selection with equal weighting.

Case study/criterion	LCOE	IRR	GWP	EROI	GVA	Jobs	Score
FOW 1 - Scotland	0.43	0.63	0.36	0.62	0.25	0.18	0.38
FOW 2 - Portugal	0.49	0.58	0.44	0.55	0.34	0.41	0.43
Wave 1 - Scotland	0.55	0.21	0.59	0.33	0.42	0.29	0.19
Wave 2 - Portugal	0.53	0.47	0.57	0.34	0.81	0.85	0.72
Weights 1 - All equal	0.167	0.167	0.167	0.166	0.167	0.167	

Table 9
Results of multi-criteria evaluation for both site and technology selection with higher weighting in the techno-economic dimension.

Case study/criterion	LCOE	IRR	GWP	EROI	GVA	Jobs	Score
FOW 1 - Scotland	0.43	0.63	0.36	0.62	0.25	0.18	0.58
FOW 2 - Portugal	0.49	0.58	0.44	0.55	0.34	0.41	0.59
Wave 1 - Scotland	0.55	0.21	0.59	0.33	0.42	0.29	0.13
Wave 2 - Portugal	0.53	0.47	0.57	0.34	0.81	0.85	0.60
Weights 2 - Tech. Econ.	0.30	0.30	0.15	0.15	0.05	0.05	

4.3.4. *Sensitivity to weighting*

The proposed multi-criteria framework offers the flexibility to adjust the weights according to the interests and/or priorities of the project's stakeholders. Instead of the VIC weights, user-defined weights can be assigned to the criteria for the evaluation of the alternatives. For instance, an analyst could assign equal weights to all criteria, which is a common practice when evaluating sustainability issues. As can be seen in Table 8, the ranking is not affected. In both cases, with equal weighting and VIC-defined weights, wave energy in Portugal was the highest ranked alternative. However, the scores vary slightly relative to those in Table 7.

The results vary significantly if, for example, more emphasis (i.e., higher weights) is set on the techno-economic dimension as in the case described in Table 9. This could be the situation of an investor seeking to maximise the revenue resulting from the project. In this case, the wave farm in Aguçadoura, Portugal is the most attractive alternative but closely followed by the FOW farm in Peterhead, Scotland and the FOW farm in Aguçadoura, Portugal.

5. Discussion

The Intergovernmental Panel on Climate Change (IPCC) [1], the International Energy Agency (IEA) [6], and the International Renewable Energy Agency (IRENA) [95] coincide that renewable energy will be pivotal to limit global warming providing between 75% and 90% of total electricity supply. Although solar PV and onshore wind will be the most prominent renewable energy technologies deployed, other renewable energy technologies will be necessary to achieve these ambitious shares. With the underexploited energy potential from offshore wind and the oceans, emerging ORE technologies can be instrumental to achieve net zero emissions and low-carbon economies.

The outcomes from the different case studies show that, despite being more capital intensive than mature renewable technologies such as solar PV and wind, emerging ORE technologies are close to being competitive with fossil fuel-based generation. Nonetheless, it is worth highlighting that due to their nascent nature, emerging ORE technologies have significant cost reduction potential. As in the case of more mature technologies, where, e.g., the LCOE of solar PV has declined from \$ 0.381/kWh in 2010 to \$ 0.057/kWh in 2020 [96], less mature technologies such as FOW and wave energy can expect considerable cost reductions. In terms of environmental impact, these emerging ORE technologies show ranges of GWP between 20.90 and 34.08 gCO_2eq/kWh, which is drastically below the ranges of conventional fossil fuel-based generation ranging between 575 and approx. 1300 gCO_2eq/kWh [97]. Finally, in terms of the socio-economic benefits, emerging ORE technologies present significant opportunities to develop local supply chains and create local jobs, thus generating GVA benefits per MW installed ranging between €0.87M/MW and €2.79M/MW. These GVA benefits are higher than, e.g., the benefits generated from the installation and commissioning of onshore wind farms (approx. €0.73 M/MW) [98].

The results from the multi-criteria analyses presented in Section 4 show that adopting one-dimensional analyses to evaluate emerging ORE projects is an oversimplification of the many implications of the deployment of these technologies. More comprehensive assessments are required to incorporate the many complexities of the energy transition.

An interesting finding is that LCOE, a widely used metric for techno-economic evaluations, had low relevance in the decision-making process based on the multi-criteria and VIC weighting approach adopted, particularly due to the low variability among the resulting LCOEs of the evaluated alternatives. This finding reinforces the claim that unidimensional analyses are not sufficient to support informed decision making.

The multi-criteria framework includes metrics that have been previously adopted to assess ORE technologies, although not in a multidimensional setting. The framework can be adapted to include, e.g., additional LCA metrics such as eutrophication or resource depletion, financial indicators such as capital expenses per MW installed, and other macro-economic costs of energy such as transmission costs, variability costs (i.e., capacity payments for providing backup), and geopolitical impacts. Furthermore, the methodology proposed in this paper can be used to assess both mature technologies and emerging concepts such as co-located wave and wind farms [99].

Each of the metrics selected has limitations of its own which can be addressed with further research in future studies. For instance, due to the lack of long-term track records for ORE technologies, all metrics have inherent uncertainties including operation and maintenance costs, fuel consumption for marine operations, and the share of retention of socio-economic benefits in local economies. The case study of wave energy in Scotland presented comparatively lower GVA and employment benefits than the other case studies. However, this technology can provide significant benefits that include employment in rural/fragile communities, the development of skills and research expertise that are currently in shortage and system balancing to mitigate the intermittency of variable renewable energy such as wind. These benefits are not clearly reflected in the metrics we have adopted and, thus, could be included in future versions of this analysis. Moreover, further deployments are required to provide evidence and validate the assumptions adopted in evaluations of ORE technologies.

The normalisation, weighting and scoring methods selected are deemed appropriate to rank and select ORE alternatives considering the limited data available and the complexity of the energy transition. The vector normalisation method manages the combination of cost and benefit criteria and facilitates the identification of (positive or negative) ideal solutions through mTOPSIS. The VIC weighting method results in an objective quantification of the relative importance of every criterion accounting for the variation of the performance of the alternatives in the criteria and the interlinkages between the criteria. Moreover, the implementation of the proposed multi-criteria analysis provides a transparent manner of examining the many site- and technology-dependent particularities of ORE projects and enables a fairer approach to compare these alternatives. Furthermore, the framework can be extended to include additional criteria and/or adapted to adjust the weights according to the interests or priorities of different stakeholders. However, if the multi-criteria analysis were to include uncertainties, the proposed framework would require an update of the proposed methods. In this case, fuzzy methods (e.g. fuzzy TOPSIS or fuzzy VIKOR) or PROMETHEE II would be more suitable tools.

6. Conclusions

In the strive to select diversified energy portfolios for the energy transition, comprehensive and transparent assessments are required that reflect the complexity and multi-dimensionality of the transition to low-carbon energy systems. Clean energy technologies have been traditionally evaluated based on their techno-economic performance. This practice penalises capital-intensive energy technologies such as emerging offshore renewable technologies which could significantly contribute to diversified energy portfolios.

In this paper, a multi-criteria evaluation framework has been proposed to evaluate the performance of emerging offshore renewable energy technologies. The framework includes metrics that have been previously and individually used in PESTLE analyses to assess these technologies, e.g., the levelised cost of energy, the global warming potential resulting from an environmental lifecycle assessment and/or the gross value added and employment benefits, also referred to as social cost of energy. The combined used of these metrics in the proposed multi-criteria framework offers a comprehensive and transparent assessment that can support informed decision making.

The implementation of the proposed framework is demonstrated on a set of case studies that include deployments of floating offshore wind and wave energy technologies in Scotland and Portugal. The technology- and site-specific evaluations show that these emerging technologies are close to being competitive in terms of costs with fossil fuel-based generation, yet are substantially less environmentally harmful in terms of global warming potential. Finally, the assessments quantify the socio-economic benefits derived from the deployments based on the industries that have been assumed to be engaged in the supply chains and the state of the economies examined in 2015 according to the corresponding national input–output tables.

The proposed framework can be expanded or adapted to include additional metrics and to accommodate the priorities or interests of different project stakeholders through the adoption of user-defined weights for the evaluation criteria. The latter has been demonstrated with a sensitivity analysis. However, the framework could also accommodate uncertainties if fuzzy multi-criteria methods are adopted instead of the here suggested modified version of TOPSIS.

Due the nascent nature of the technologies examined and the lack of a long-term track record, further research is required to provide evidence and validate the assumptions adopted in the selected metrics. However, the proposed framework can contribute to enhancing the understanding and visibility of emerging technologies such as floating offshore wind and wave energy. This work has shown the value of accounting for aspects beyond techno-economics when evaluating emerging offshore renewable energy technologies. These technologies, albeit not commercially available yet, have significant potential and can be instrumental for low-carbon or net-zero energy systems.

CRediT authorship contribution statement

María M. Vanegas-Cantarero: Conceptualisation, Methodology, Software, Formal analysis, Writing – original draft. **Shona Pennock:** Conceptualisation, Methodology, Formal analysis, Writing – review & editing. **Tianna Bloise-Thomaz:** Conceptualisation, Methodology, Formal analysis, Writing – review & editing. **Henry Jeffrey:** Conceptualisation, Formal analysis, Resources, Writing – review & editing, Project administration, Funding acquisition. **Matthew J. Dickson:** Formal analysis, Resources, Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

One or more of the authors of this paper have disclosed potential or pertinent conflicts of interest, which may include receipt of payment, either direct or indirect, institutional support, or association with an entity in the biomedical field which may be perceived to have potential conflict of interest with this work. For full disclosure statements refer to https://doi.org/10.1016/j.rser.2022.112307. One author (Matthew J. Dickson) is currently employed by CorPower Ocean AB, an organisation that might benefit or be at a disadvantage from the published findings. It should be noted that this work received independent research funding and was neither commissioned nor funded directly by CorPower Ocean AB. Furthermore, whilst Matthew has contributed to this work in terms of investigation (data collection) and writing (reviewing) roles, the remaining authors have undertaken the roles of study conceptualisation, methodology, analysis and writing, as impartial third party researchers at the University of Edinburgh.

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