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Assessing the sustainability of Blue Economy activities using an ecosystem and life cycle-based approach: Possibilities, challenges and implications for an informed policy making

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ABSTRACT

The global ocean faces increasing exploitation to meet the demand of a rapidly growing globalisation. Human marine activities are leading to local environmental pressures/benefits, for example on marine ecosystems and their services, but also through their value chains on terrestrial ecosystem services, and to global pressures such as global warming. Effective management of marine activities is essential for the conservation of the natural environment. There is a growing need for holistic sustainability assessment tools capable of quantifying environmental impacts at various geographical scales, alongside evidence-informed policies. This study examines the evolving marine policy landscape, identifies key legislation that supports the sustainable growth of the Blue Economy, traces its historical development, and explores the integration of ecosystem services assessment and life cycle assessment as methodologies for assessing environmental sustainability within this legislation. The review shows that current legislation falls short in providing instructions on how to measure sustainability impacts in a consistent way, i.e., which methods/indicators to use. Therefore, this study supports evidence-informed policy-making by proposing a quantitative and comprehensive environmental sustainability impact assessment methodology, integrating both ecosystem and life-cycle based methods, to a Belgian multi-use case study involving offshore wind energy and mussel farming. Considering the impacts that were possible to assess and the limits of the methodology used, the value of the positive impacts of the MUOF was +61.3 M€ y^{-}, while the negative ones were −4.0 M€ y^{-1}, resulting in a net handprint of +57.0 M€ y^{-1}, primarily attributed to the benefits of the local ecosystem service 'offshore renewable energy' However, such a solution is not necessarily scalable, due to cumulative impacts. An analysis was conducted to identify areas for enhancing the methodology to more effectively meet policy needs. The study highlights the importance of using scientifically grounded methods to inform policy decisions.

1. Introduction

Human dependence on marine resources has grown steadily throughout history in a multitude of sectors as the oceans provide a wide range of valuable goods and services (Erlandson and Fitzpatrick, 2006; Barbier, 2017). However, over the past century, human societies have reached demographic levels and socioeconomic scales that threaten the marine environment through overexploitation, pollution, climate change, and habitat destruction (Halpern et al., 2019). The rapid development of marine activities, similar to activities on land, has resulted in unprecedented pressures that have increased the risk of exceeding ecological tipping points, which may lead to irreversible changes in marine ecosystems (Heinze et al., 2021).

Various sustainability assessment frameworks and tools exist to

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quantify the environmental impacts of human activities on marine ecosystems, using different methods and indicators. This diversity, coupled with the lack of consensus on the definition of sustainability, often leads to confusion on how to measure these impacts (Smit et al., 2021; O'Mahony, 2022; Turschwell et al., 2022). In this study, the working definition of a sustainable Blue Economy by the European Commission is adopted: *"A sustainable Blue Economy promotes economic growth, social inclusion, and improved livelihoods while ensuring the environmental sustainability of the natural capital of the oceans and seas. The sustainable blue economy encompasses all sectoral and cross-sectoral economic activities related to the oceans, seas, and coasts. It comprises emerging sectors and economic value based on natural capital and non-market goods and services through the conservation of marine habitats and ecosystem services" (European Commission, 2021).*

Two promising tools, namely life cycle assessment (LCA) and ecosystem services assessment (ESA), have significant potential to inform policy-making on sustainable Blue Economy activities. On one hand, the internationally standardized LCA quantifies the potential environmental burdens of products (i.e., goods and services) from a lifecycle perspective at a global scale, i.e., covering the entire value chain of a product, including raw material extraction, manufacturing and processing, distribution, use, and end-of-life (ISO, 2006). The general procedures for conducting an LCA have been delineated in the ISO 14040/14044 standards (ISO, 2006), serving as a basis for the development of regional guidelines such as the Product Environmental Footprint (PEF) Guide (European Commission, 2018). Meanwhile, ESA is an ecosystem-based methodology that quantifies the benefits of ecosystems to human well-being through the supply of ecosystem services at a local/regional scale (Costanza et al., 1997). Compared to LCA, ESA requires further standardization for planning and decision-making (Rosenthal et al., 2015). The publication of the UN's Millennium Ecosystem Assessment report in 2005 encouraged the development of ESA frameworks, guidelines, and/or manuals by various international organizations such as the UN Statistical Commission, the International Union for Conservation of Nature (IUCN), the Secretariat of the Convention on Biological Diversity (CBD) and the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES) (CBD, 2012; IPBES, 2016; Neugarten et al., 2018; Edens et al., 2022). These guidelines have been adopted at a supranational level. For example, the European Commission (EC) has developed and applied an operational integrated analytical framework, based on the IPBES guidelines, to systematically map and evaluate changes in ecosystem condition and services across Europe (Maes et al., 2020).

While valuable individually, LCA and ESA alone cannot comprehensively assess both the positive and negative environmental impacts of human activities across multiple interactions and geographical scales. Moreover, the interpretation of results can be challenging for policy makers unless they are presented in a clear, understandable, and aggregated way. Consequently, efforts have been made to integrate both methodologies (De Luca Peña et al., 2022) and thus develop a quantitative and comprehensive environmental sustainability assessment (QCESA) methodology. Based on literature reviews (Othoniel et al., 2016; VanderWilde and Newell, 2021; De Luca Peña et al., 2022; Rugani et al., 2023), several generic conceptual LCA-ES integration methodologies have been developed, including the studies by Hardaker et al. (2022); Alshehri et al. (2023), Oginah et al. (2023) and Taelman et al. (2024). Most of these LCA-ESA integration methodologies have been applied to case studies within terrestrial ecosystems, with only few applications in aquatic ecosystems, e.g., Blanco et al. (2018) and Briones-Hidrovo et al. (2020), and often relying on semi-quantitative approaches (De Luca Peña et al., 2022). Nevertheless, the QCESA methodology proposed by Taelman et al. (2024), within the Sustainable Marine Ecosystem Services (SUMES) project (Grant number: HBC.2019.2903), allows the integration of LCA and ES through monetary valuation and the quantitative assessment of the positive and negative, local to global effects of human activities, covering both terrestrial and marine ES (De Luca Peña et al., 2024a). This positions SUMES as one of the most advanced, QCESA methodologies for analysing environmental impacts of marine human activities.

There is a growing need for QCESA tools, such as the SUMES methodology, which can be applied to various ongoing marine activities, and support informed policy-making. Applying such a methodology ensures that policies are based on sound science, minimizes bias and uncertainty, and strengthens the democratic process by providing factual evidence to support decision-making (European Commission, 2022). Sharing the findings of such a tool demands presenting them in an aggregated manner to guarantee comparability and reliability (Sala et al., 2018). Monetary valuation stands out as one of the viable aggregation methods to achieve this objective. Although monetary valuation has its drawbacks (e.g., concerns about treating ecosystems as commodities undermining their intrinsic value, the volatile nature of monetization, the differences in results depending on the monetary technique used), a clear advantage is that it allows results to be aggregated into a single unit, facilitating and simplifying the interpretation and communication of results, and thus helping decision makers to better understand trade-offs (ISO, 2019; Amadei et al., 2021). In the Belgian context, the SUMES methodology could be particularly useful. Due to the relatively small marine area of the Belgian Continental Shelf (BCS) and the variety of single and multi-use activities that take place there, each with their own temporal and spatial characteristics (i.e., energy production, shipping, dredging, fishing, aquaculture, sand extraction, coastal protection, military activities, tourism, preservation of cultural heritage, research, commercial, and industrial activities) (FDS, 2020), it is very important to understand the potential burdens and benefits of these human activities to provide valuable insights to policy makers.

In addition to scientific advancements in the field of environmental sustainability, (inter)national agreements and conventions also urge governments around the world to incorporate sustainability and conservation goals into legal policy instruments, thereby mitigating and reducing our impacts on the marine environment (Verleye et al., 2018; Lescrauwaet et al., 2022). A major challenge in advancing the Blue economy is to balance socio-economic development with marine protection. The need for environmental protection is spread across a range of legal instruments, from the global to the regional level, which help to regulate the use of marine space by providing a set of objectives, guidelines, and incentives for stakeholders to adopt sustainable practices.

The overall goal of this study is to highlight the importance of using pragmatic, QCESA tools that are scientifically sound, to facilitate evidence-informed decision-making in policy-oriented recommendations. To achieve this, first, this study aims to navigate through the complexity of global, European, national (i.e., Belgium), and subnational (i.e., Flanders) regulations to identify the instruments currently relevant for sustainably advancing the Blue Economy, by providing an overview of such legislation and understanding the historical changes in environmental legislation with regard to the inclusion of ESA/LCA. Second, to demonstrate the applicability of QCESA tools, this study builds on the LCA study of De Luca et al. (2024b). To achieve this, the methodology of Taelman et al. (2024) is applied to incorporate ecosystem services into a sustainability assessment of a Belgian multi-use study (offshore wind energy and mussel farming). Third, this work analyses how the SUMES methodology aligns with marine policy instruments and positions it within the broader science-policy landscape. Additionally, it also provides recommendations and insights into areas needing more attention to enhance the integration of QCESA tools into marine policy and to improve their effectiveness in informing policy decisions. Ultimately, these efforts are essential to ensure the sustainable management of the Blue Economy in the North Sea and have the potential to serve as a informative tool for all European marine waters.

2. Methodology

Section 2.1 clarifies the approach taken to arrive at a list of policy instruments focusing on environmental sustainability, relevant to a broad set of Blue Economy activities. Section 2.2 describes a novel methodology to account for changes in marine and terrestrial ecosystem services and global impacts due to marine activities and Section 2.3 explains the marine case study to which this methodology is applied.

2.1. Marine policy instruments targeting sustainability and the blue economy

A non-exhaustive review was conducted to identify relevant global, European, and Belgian marine policy instruments and to assess their integration of an ecosystem services approach and/or life cycle thinking. As part of the SUMES project, a thorough legal-policy analysis was carried out by the Flemish Marine Institute (VLIZ) (Custodio et al., 2021) supplemented with legal information from the Compendium for Coast and Sea (Dauwe et al., 2022) and the comprehensive study of Rodriguez-Perez et al. (2023). These studies provide a solid basis for understanding the policy landscape relevant to the Blue Economy (applicable to most marine activities, therefore not specified by sector) and minimise bias in the selection of policy instruments. This review targeted policy instruments, such as agreements, treaties, directives, regulations, decisions, and communications. The selected list of relevant policy instruments was screened for 1) whether they are binding for the member states, 2) whether they take into account ecosystem or life cycle based approaches to address for sustainable development, and 3) whether monetary valuation of environmental impacts is proposed.

2.2. A quantitative ecosystem and life cycle-based approach to support the blue economy

A careful sustainability assessment of single and multi-use marine activities plays an essential role in supporting sustainable Blue Growth. In the context of a Flemish funded SUMES project, a new QCESA methodology has been developed as explained in Taelman et al. (2024). The methodology integrates global life-cycle impact categories such as human toxicity, accelerated climate change, and eutrophication with impacts on local marine and terrestrial ecosystem services (ESs) - including provisioning, regulating, and cultural services. The selection of relevant local ES is described in Custodio et al. (2022) and Van de Pol et al. (2023). Ecosystem services assessment is used to quantify the site-specific impacts on the marine environment, while life cycle assessment addresses the more global impacts. However, the value chain of marine activities also includes terrestrial processes (e.g., mining) that cause local terrestrial changes in their surroundings. Therefore, new site-generic characterization factors (CFs) have been developed to account for ES changes due to land use in the product value chain, but the methodology also allows for the inclusion of site-specific information on ES changes (e.g., in the marine environment). A total of 55 indicators are covered (See Table 20 in **SI**). Monetization of impacts (both local and global ones) is proposed as an aggregation technique at the level of endpoint or Areas of Protection (AoPs): human health and wellbeing (HH&WB), natural resources (NR) and ecosystem quality (EQ). The potential positive (benefits or handprint) and negative (burdens or footprint) environmental impacts can be visualized in a 2-dimensional graph.

2.3. Application of SUMES methodology to a multi-use case study

This paper tests the SUMES methodology (Section 2.2) on a Belgian case study of marine multi-use and demonstrates how the results of such an analysis can guide policy-making. The BCS is characterized for being a temperate, shallow shelf system (Van de Pol et al., 2023). Moreover, Belgium is the world's fourth largest producer of offshore wind energy, with a installed capacity of 2.3 GW by the end of 2021, expected to increase to around 6 GW with the Princess Elisabeth Zone (FPS Economy, 2024) projecting a total installed capacity between 3.1 and 3.5 GW by 2030 (Degraer et al., 2021; FPS Economy, 2024). In addition, the Belgian marine spatial plan actively promotes the multiple use of marine space, in particular with energy production areas designated as aquaculture zones (Belgium Government, 2020). Since 2016, a few pilot-scale aquaculture projects have taken place in the BCS, either nearshore or offshore, demonstrating the feasibility of offshore mariculture activities, focusing on the blue mussel (*Mytilus edulis*) and seaweed cultivation. As there are currently no commercial marine mussel farms within a wind farm concession zone, a designed offshore mussel farm (OMF) and value chain was used to model the potential environmental impact of such a multi-use wind/mussel farm (see Box S1 in **SI** and also De Luca et al. (2024b) for more details) (see Fig. 1). The functional unit consists of a basket of products (European Commission, 2012), namely the yearly average electricity and mussel production (Fig. S1 in **SI**). Table 1 provides a brief overview of how the local and global impacts were calculated for the multi-use case study. While marine ESs were quantified individually through different models/indicators for each marine ES, a more generic approach was taken to quantify terrestrial ES and global impacts through an improvement of the ReCiPe method (Taelman et al., 2024).[1]

To quantify the impacts of a multi-use offshore farm, a wide range of primary and secondary data were collected through 1) technological data for the Life Cycle Inventory (LCI) (provided by the concession holders of the offshore wind farm (OWF), or obtained from literature, expert meetings, and/or ecoinvent v3.8 database), 2) workshop data to select relevant local marine ESs, 3) ecological and/or biophysical data to assess the local changes on marine environment and its ESs, and 4) monetary values to aggregate these impacts into a single value. Further details on the data used in this study can be found in Custodio et al. (2022), Van de Pol et al. (2023), De Luca et al.(2024a), Taelman et al. (2024), De Luca et al. (2024b), and **Section 5** in **SI**. Moreover, impacts are measured against the 'before' situation (i.e., the reference situation or baseline before the MUOF).

3. Results and discussion

This chapter first presents the results of the non-exhaustive review study on global/EU/Belgian policy instruments relevant to supporting the sustainable Blue Economy transition (Section 3.1), exploring the challenges of assessing the Blue Economy's sustainability within marine policy and examining how the integration of QCESA methodologies can improve relevant policy instruments. This is followed by the results of applying the SUMES methodology to the multi-use case study in the North Sea (Section 3.2). Furthermore, the potential to integrate QCESA methodologies into the science-based policy making process is investigated, considering both the challenges and advantages (Section 3.3).

3.1. A non-exhaustive review of marine policy instruments and their role in sustainable management of blue economy activities

This review targeted policy instruments that focus on 1) the measurement of environmental sustainability of human activities in general, including those related to the Blue Economy, and 2) the environmental sustainable management of the Blue Economy in particular (although not sector-specific). The review also helps to identify policy instruments into which QCESA tools can potentially be integrated and add value to policy making. Fig. 2 shows a timeline of key global and European legal instruments that support the development of an environmentally

[1] The framework of Taelman et al. (2024) has been already applied to an OWF case study and results are shown in De Luca et al. (2024a), where benchmarking with nuclear power is also performed.

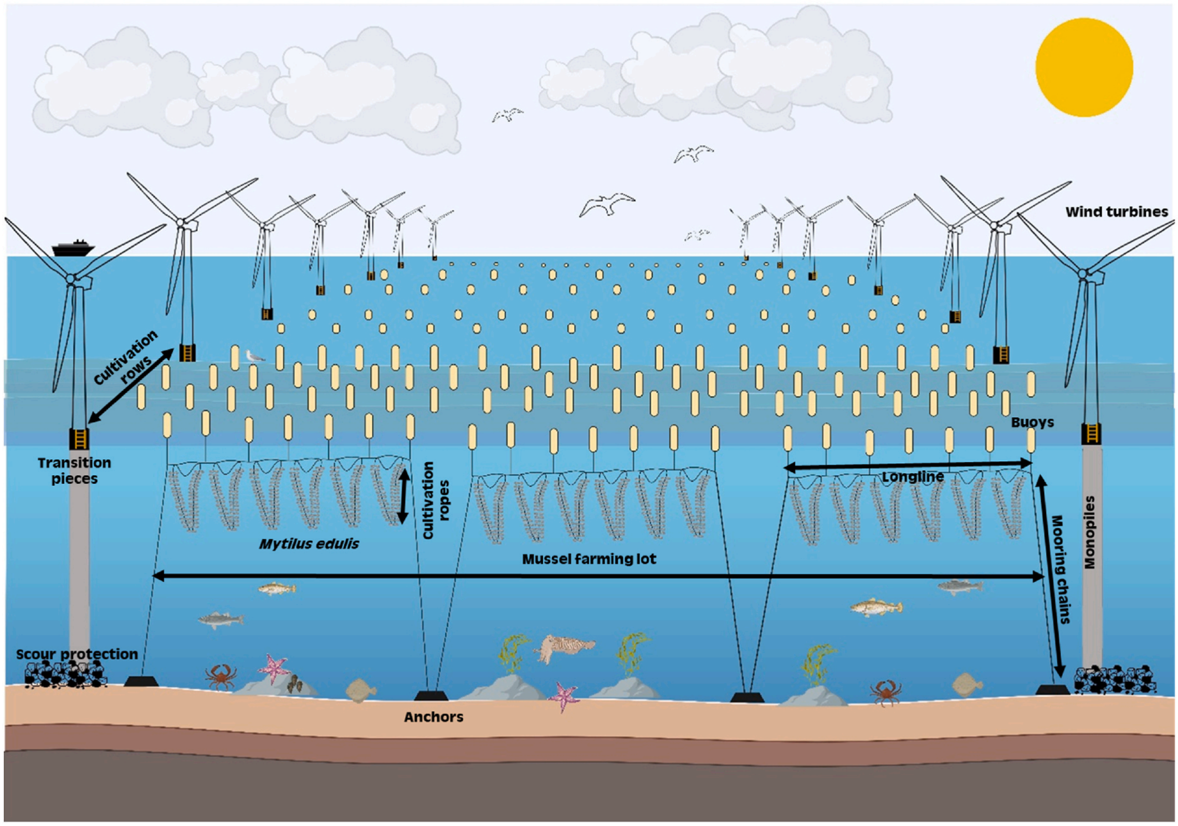

Fig. 1. Simplified visualisation (not scaled) of a multi-use offshore farm, combining wind energy and mussel (Mytilus edulis) aquaculture. The multi-use offshore farm (MUOF) is situated offshore, covering an area of approximately 14–20 km^2. It includes between 20 and 75 wind turbines, each with a capacity ranging from 3 to 10 MW. Exact details cannot be provided due to a confidentiality agreement with the concession holders. The MUOF features three longlines within a mussel lot, with each longline spaced 57 m apart. The mooring chains are 43 m long. Additionally, there are seven cultivation rows located within the vicinity of four wind turbines. For a detailed description of the design, please refer to De Luca et al. (2024b). (Figure created with BioRender).

sustainable Blue Economy and apply to most marine activities. More detailed information on global, European and Belgian policy instruments is discussed chronologically in **Section 2** in the **SI**.

3.1.1. The challenges for marine policy when assessing the sustainability of the blue economy

Both global and European marine policies are dynamic and evolving fields, with ongoing efforts to address local/regional impacts such as biodiversity loss, marine litter and ocean acidification through ecosystem-based approaches as well as value chain or life cycle analysis. A relevant and complex issue arises when considering the geopolitical context in which individual European countries have their own national policies and strategies in line with EU directives and regulations. As the latter often lack detailed instructions on how to measure impacts, their translation into national policies allows some flexibility, foremost in the choice of indicators and methods. As a result, national legislation and sustainable Blue Economy strategies are not necessarily comparable between countries. Moreover, an assessment of the aforementioned policy instruments (see Table S1a in the **SI**) shows that both ecosystem services and life cycle thinking approaches have only recently been documented. Legally binding instruments are less concrete than non-legally binding ones in answering the question of how to measure certain sustainability impacts. Additionally, there remains a lack of consensus within marine policy on 1) the indicators and methodologies to be used to measure the sustainability of marine activities (sectoral ones can differ from non-sectoral ones), 2) the terminology to be used to refer to positive and negative impacts, and 3) the way in which aggregation should be carried out to facilitate the interpretation of the environmental impact of Blue Economy activities. Some instruments, particularly the Corporate Sustainability Reporting Directive, suggest using monetary valuation to report sustainability. The European Commission's communication 'Transforming the EU's Blue Economy for a Sustainable Future' also recommends quantifying the economic value of ecosystem services. However, the specific indicators and monetary techniques to be used remain vague. Additionally, references to the inclusion of environmental costs are primarily framed as requirements for cost-benefit analyses (see Table S1b in **SI**). Although the European Commission launched a report in 2021 (European Commission, 2021), which recommends using a set of preliminary criteria and indicators (covering a value chain and/or ecosystem perspective) to assess the sustainability of Blue Economy activities in different sectors, it needs further refinement. Because it is not mandatory for use in sustainability reporting, there is a risk of inconsistency and incomparable sustainability results.

Moreover, at a Belgian level, the Marine Environmental Law (**Section 2.3** in **SI**) does not indicate that a future revision of the Belgian MSP should integrate the ecosystem services approach and value chain thinking, as put forward by the EU, to ensure a more holistic approach (UNESCO-IOC & European Commission, 2021). In addition, although the Belgian MSP allows for multi-use, it fails to provide guidelines on how to quantify the potential environmental impact of shared activities. Clear regulations for the siting, development, and operation of multi-use solutions that have the potential to minimise environmental impacts and ensure compatibility with other ocean uses. At present, there are only licences for single activities and no licences for multiple combined activities. The lack of a clear regulation for multi-use projects can lead to unforeseen transaction costs, alongside other issues such as long periods for obtaining licenses, expensive insurance, high interest rates

Table 1
List of methodologies to quantify the local marines ESs, local terrestrial ESs and global impacts.

Type of impact	Details on type of impact	Details on background modelling[a]	Link to AoP
Local marine ES	Provisioning ES: wild aquatic animals	Adapted ECOPATH model (see SI)	Natural resources
	Provisioning ES: farmed aquatic animals	Average annual production of mussels	
	Provisioning ES: sand and other materials	NA	
	Provisioning ES: surface navigation	Cost of detour for installing the OWF and ship collisions	
	Provisioning ES: renewable offshore energy	Average annual production of electricity	
	Regulating ES: nursery and habitat maintenance	Adapted model of Blandon and Zu Ermgassen (2014).	Ecosystem Quality
	Regulating ES: climate regulation	Adapted model of Heinatz and Scheffold (2023); Filgueira et al. (2019).	
	Regulating ES: mediation of waste	Toussaint et al. (2021); Personal communication with aquaculture expert (2023).	
	Cultural ES: wildlife watching	Adapted ECOPATH model, adapted model of Brabant and Vanermen (2020) and Soudijn et al. (2022).	Human health and Well-being
	Cultural ES: recreational fishing	Adapted ECOPATH model	
	Cultural ES: aesthetic value	Assumption	
Local terrestrial ES	Provisioning ES	Based on the ESVD, CFs developed in Taelman et al. (2024)	Natural Resources
	Regulating ES		Ecosystem Quality
	Cultural ES		Human health and Well-being
Global impacts	Mineral resource scarcity	Based on modified ReCiPe in Taleman et al. (2024)	Natural resources
	Fossil resource scarcity		
	Global warming, terrestrial ecosystems		Ecosystem Quality
	Global warming, aquatic ecosystems		
	Ozone formation, terrestrial ecosystems		
	Terrestrial acidification		
	Freshwater eutrophication		
	Marine eutrophication		
	Terrestrial ecotoxicity		
	Freshwaster ecotoxicity		
	Marine ecotoxicity		
	Water consumption, terrestrial ecosystems		
	Water consumption, aquatic, ecosystems		
	Global warming, human health		Human health and Well-being
	Stratospheric ozone depletion		
	Ionizing radiation		
	Ozone formation, human health		
	Fine particulate matter formation		
	Human carcinogenic toxicity		
	Human non-carcinogenic toxicity		
	Water consumption, human health		

[a] More information on the background modelling can be found in Section 5 of the SI. NA: not as data limitations prevented quantification.

(Ciravegna et al., 2024). The latter can discourage governments and private companies from investing in these projects (Ciravegna et al., 2024). To minimise this, a clear legal basis for multi-use projects is needed, outlining specifically how to measure sustainability. This not only will reduce the uncertainty but will also better inform decision-makers to develop potential mitigation measures to reduce the risks. Likewise, regulation needs to be adapted to recognise products from a multi-sectoral sources, such as offshore mussel cultivation within wind energy farms, categorized and approved for human consumption. Meanwhile, there should be more incentives as part of energy transition policies to promote social acceptance of offshore wind projects embedded in a multi-use context.

3.1.2. Which policy instruments relevant for the blue economy can benefit of incorporating QCESA methodologies?

Overall, the review identified a significant challenge within marine policy instruments: the lack of specific guidance on how to measure sustainability and which aspects to measure. This ambiguity, particularly evident at the European level, has resulted in Member States making individual choices regarding the set of indicators and methodologies to be used to conduct sustainability assessments. Consequently, this divergence can lead to incomparable results. QCESA methodologies could greatly assist marine policy instruments, particularly the Corporate Sustainability Reporting Directive, Marine Spatial Planning Directive, and Environmental Impact Assessment (EIA) Directive, by steering the development of clear and harmonized guidelines for measuring sustainability in the Blue Economy sector.

3.2. Quantification of the handprint and footprint by applying the QCESA methodology on the multi-use offshore farm

The environmental sustainability results of the case study presented in this section comprise the following: 1) local marine ESs, 2) local terrestrial ESs, and 3) global impacts. According to Taelman et al. (2024), positive impacts (benefits) are *handprints* and negative impacts (burdens) are *footprints.* The *net impact* is calculated by subtracting the negative impacts from the positive impacts.

3.2.1. Local marine ESs impacts

To quantify and value the local marine ESs, various methods and indicators were used for each ES (Table 1**)**. More details on these methodologies can be found in **Section 5** of the **SI**. The final results for the local marine ESs are presented in Table 2, Table S17, and Fig. S3 in the **SI**. Overall, the provisioning ES, renewable offshore energy made the largest contribution to the handprint of the MUOF, particularly on the AoP NR (+44.9 M€ y^{-1}), followed by the regulating ES, mediation of waste, mainly affecting the AoP EQ (+14.5 M€ y^{-1}). The ES farmed aquatic animals (i.e., the harvested mussels) also had a significant positive impact, with +0.2 M€ y^{-1}, although not in the same order as the ESs mentioned above. The largest contribution to the footprint comes from the provisioning ES, surface for navigation (AoP NR: −0.8 M€ y^{-1}) followed by the cultural ES, recreational fishing (AoP HH&WB: −0.2 M€

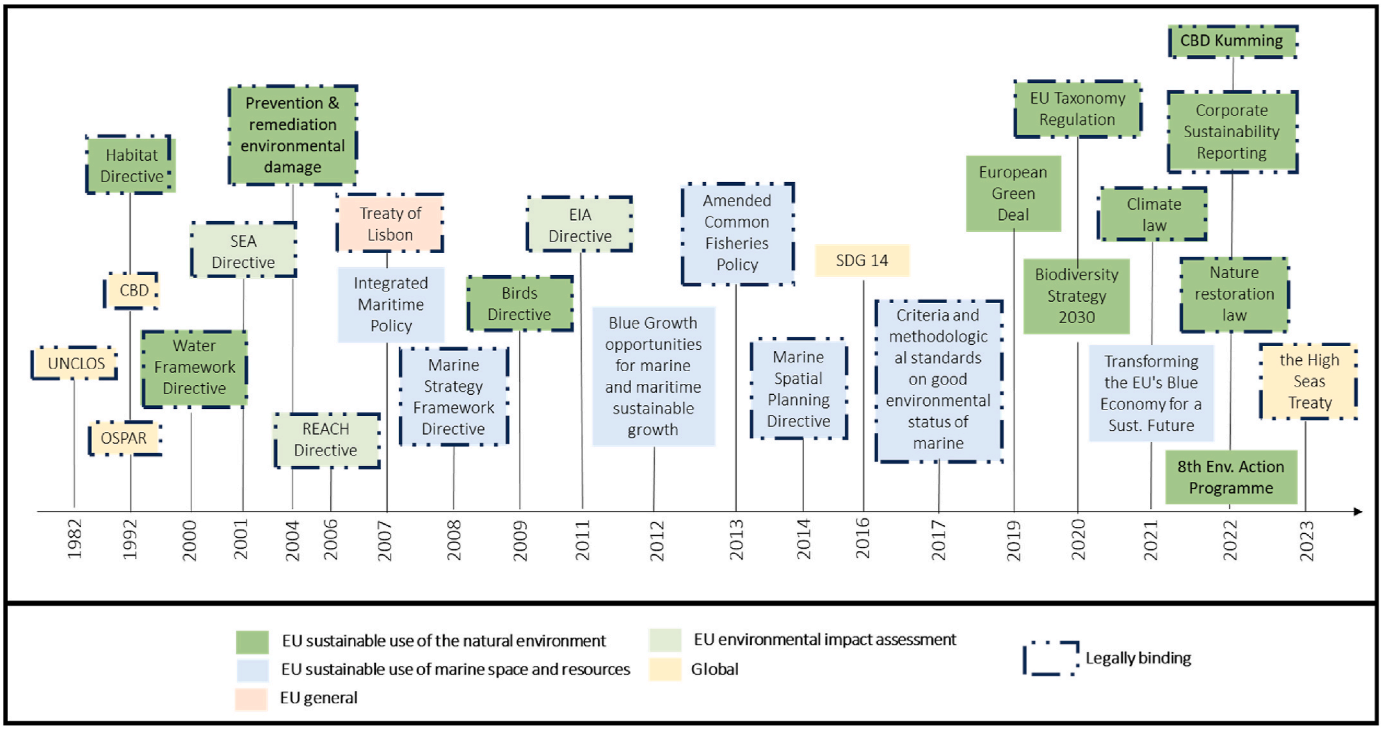

Fig. 2. Historic overview of the key legislative instruments to the pursuit of an environmentally sustainable Blue Economy, which applicable to most marine activities.

y^{-1}). The latter ES are negatively affected by the installation of a MUOF as it reduces the recreational fish landings and imposes transport detours. In summary, the provisioning ESs contribute most to the handprint and footprint, followed by the regulating ESs and the cultural ESs. The net impact of the local marine ESs changed by the MUOF is positive, namely +58.6 M€ y^{-1}.

3.2.2. Local terrestrial ESs impacts

The results for the local terrestrial ESs are presented in Table 2, Table S18, and Fig. S3 in the **SI**. Overall, the results show that the terrestrial part of the value chain of the MUOF generates a footprint on all categories of ESs (provisioning, regulating, and cultural), with the AoP EQ (regulating ESs) having a higher impact (−0.042 M€ y^{-1}) compared to the AoP NR (−0.038 M€ y^{-1}) and AoP HH&WB (−0.027 M€ y^{-1}). Most of the impacts on all categories are mainly attributed to the intensive occupation of forests and mineral extraction sites, where wood products, minerals and metals are used for the manufacturing of (intermediates of) the MUOF. Occupation of these grounds leads to impacts on ESs such as air quality regulation, climate regulation and water flows regulation (De Luca Peña et al., 2024a). Summing up the results for all local terrestrial ESs a net footprint of −0.1 M€ y^{-1} is obtained.

3.2.3. Global impacts

The global impacts are endpoint results from an LCA analysis (cradle-to-grave) obtained with the ReCiPe 2016 method (De Luca Peña et al., 2024a,b; Huijbregts et al., 2017). All impact categories were included in the assessment except for land use, which was replaced with the results from the local terrestrial ESs impacts (see **Section 3.2.2** and Table S19 in the **SI**) (De Luca Peña et al., 2024a; Taelman et al., 2024). The handprint in this case is derived from the avoided products (i.e., through energy recovery and material recycling, virgin production can be avoided) and the footprint is derived from all global impact categories.

The AoP HH&WB had the largest benefits coming from the avoided products (+1.2 M€ y^{-1}), followed by the AoP NR (+273,587 € y^{-1}) and the AoP EQ (+125,815 € y^{-1}) (Table 2 and Fig. S3 in the **SI**). These benefits are mainly attributed to the OWF from the recycling of steel, especially for the wind turbines and foundations [43]. Similarly, most of the footprint is on the AoP HH&WB (−2.1 M€ y^{-1}), followed by the AoP NR (−0.8 M€ y^{-1}) and AoP EQ (−0.2 M€ y^{-1}). Again, a slightly higher proportion of these burdens come from the OWF (52%) than from the OMF (48%). These burdens are mainly related to the supply of primary and secondary materials for the production of the components of the MUOF (approx. 66%), e.g., steel to manufacture the OWF's wind turbines and foundations. The combustion of diesel oil, especially during the MUOF's operation, also contributes to the overall burdens (14%) (De Luca et al., 2024b). More details on the impacts of an MUOF can be found De Luca et al. (2024b) and Table S19 in the **SI**. The net global impacts of the OWF are −0.5 M€ y^{-1} and those of the OMF are −1.0 M€ y^{-1}, i.e., the mussel farm contributes more to the net global impacts of the MUOF at −1.5 M€ y^{-1}.

3.2.4. Aggregated impacts

The results of the sustainability assessment correspond to the sum of the handprint and footprint of the local marine ESs (**Section 3.2.1**), the local terrestrial ESs (**Section 3.2.2**) and the global impacts (**Section 3.2.3**). As shown in Table 2 and Fig. S3 in the **SI**, the handprint (+61.3 M€ y^{-1}) of the MUOF is much larger than its footprint (−4.0 M€ y^{-1}), resulting in a net handprint of +57.0 M€ y^{-1}. The handprint is mainly attributed to the AoP NR due to the provisioning ES, renewable offshore energy. This is followed by the AoP EQ with the mediation of waste ES and the AoP HH&WB with the avoided burdens from the global impacts. On the other hand, the footprint is mainly attributed to AoP HH&WB due to the burdens stemming from the global impacts and from the local marine recreational fishing ES. In addition, the AoP NR also has a significant contribution to the footprint due to the negative impacts on provisioning services 'surface for navigation' and 'wild aquatic animals', and the burdens from the global impacts. The footprint on the AoP EQ stems mainly from the burdens of the global impacts. Looking at the contribution per human activity (Fig. 3), i.e., the OWF and OMF, most of the handprint of the MUOF is attributed to the OWF, especially due to the impacts stemming from the local marine ESs (89.7%), followed by the OMF's impacts on the local marine ESs (7.6%), and to a lesser extent,

Table 2
Total net handprint and footprint of the multi-use offshore farm (MUOF) using the SUMES methodology. AoP: area of protection; NR: natural resources; EQ: ecosystem quality; HH&WB: human health and well-being.

AoP	Type of impact	Details type of impact	MUOF (€ y-1)		
			OWF	OMF	Total
NR	Local marine ESs	***Provisioning ESs***			
		Wild aquatic animals	−47,969	5257	−42,712
		Farmed aquatic animals	NR	235,727	235,727
		Sand and other materials	ND	ND	ND
		Surface navigation	−774,428	NR	−774,428
		Renewable offshore energy	44,931,560	NR	44,931,560
		Total net	***44,109,163***	***240,984***	***44,350,147***
		%	***99.5%***	***0.5%***	***100.0%***
	Local terrestrial ESs	***Provisioning ESs***			
		Occupation	−15,818	−21,571	−37,389
		Transformation	287	−1806	−1519
		Total net	***−15,531***	***−23,377***	***−38,908***
		%	***39.9%***	***60.1%***	***100.0%***
	Global impacts	Avoided burdens	189,125	84,461	273,587
		Burdens	−368,400	−337,254	−705,654
		Total net	***−179,274***	***−252793***	***−432067***
		%	***41.5%***	***58.5%***	***100.0%***
	TOTAL IMPACT	***Total net AoP NR***	***43,914,358***	***−35,186***	***43,879,172***
EQ	Local marine ESs	***Regulating ESs***			
		Nursery and habitat maintenance	1633	ND	1633
		Climate regulation	−2085	1052	−1033
		Mediation of waste	10,065,801	4,422,850	14,488,651
		Total	***10,065,348***	***4,423,902***	***14,489,251***
		%	***69.5%***	***30.5%***	***100.0%***
	Local terrestrial ESs	***Regulating ESs***			
		Occupation	−13,350	−11,086	−24,436
		Transformation	−4517	−13,963	−18,480
		Total net	***−17,867***	***−25,049***	***−42,917***
		%	***41.6%***	***58.4%***	***100.0%***
	Global impacts	Avoided burdens	86,189	39,626	125,815
		Burdens	−123,900	−126,946	−250,846
		Total net	***−37,711***	***−87,321***	***−125,032***
		%	***30.2%***	***69.8%***	***100.0%***
	TOTAL IMPACT	***Total net AoP EQ***	***10,009,770***	***4,311,532***	***14,321,303***
HH&WW	Local marine ESs	***Cultural ES***			
		Recreational wildlife watching	−0.1	ND	−0.1
		Recreational fishing	−238,183	−67	−238,249
		Total net	***−238,183***	***−67***	***−238,249***
		%	***99.97%***	***0.03%***	***100.0%***
	Local terrestrial ESs	***Cultural ESs***			
		Occupation	−3561	−5146	−8707
		Transformation	−5538	−13,100	−18,637
		Total net	***−9098***	***−18,246***	***−27,344***
		%	***33.3%***	***66.7%***	***100.0%***
	Global impacts	Avoided burdens	856,166	384,556	1,240,722
		Burdens	−1,121,363	−1,037,628	−2,158,991
		Total net	***−265,196***	***−653,072***	***−918,269***
		%	***28.9%***	***71,1%***	***100.0%***
	TOTAL IMPACT	***Total net AoP HH&WB***	***−512,478***	***−671,385***	***−1,183,862***
All AoPs	***TOTAL AGGREGATED IMPACT***	***Total net all AoPs***	***53,411,650***	***3,604,962***	***57,016,612***

ND= No data available for the quantification; NR: not relevant for a particular activity.

the avoided burdens from the OWF and OMF (2.6%). In the case of the footprint, the global impacts from the OWF (37.7%) had a slightly higher impact than the global impacts of the OMF (35%) (Fig. 3). The local marine ESs impacts due to OWF (see Table 2 and Fig. S3 in the **SI**) also had a significant contribution (24.8%), while the impacts of the OWF and OMF on the local terrestrial ESs were small at 2.6%. The footprint of the OMF on the local marine ESs is almost negligible (<0.005%) affecting only the recreational fishing ES (see Table 2 and Fig. S3 in the **SI**).

3.3. *Integrating QCESA methodologies into the science-based policy making process*

QCESA tools, such as the SUMES methodology, and the results obtained from its application to a multi-use case study, generate new knowledge and evidence. They provide policymakers with insight into emerging problems and providing potential solutions, aiding them in making informed policy choices. This relationship is further illustrated in Fig. 4, which depicts the possible interactions between science and policy.

3.3.1. *The advantages of using QCESA methodologies*

QCESA tools, such as the SUMES methodology, have the ability to identify the most significant environmental burdens and benefits, categorizing them as a footprint and handprint, respectively. This simplifies communication to policymakers and improves informed decision-making about trade-offs between various sectoral activities, i.e., it allows investments to be steered towards more sustainable practices and guarantees a balance between public and private benefits (Fig. 4). The uptake of QCESA methodologies by companies will depend heavily on

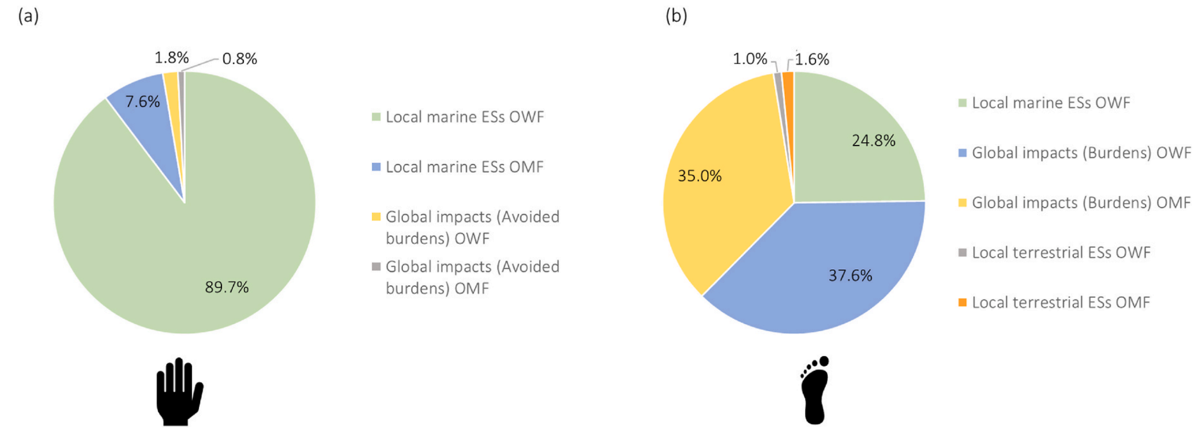

Fig. 3. The proportions of positive impacts contributing to the handprint (a), and the proportion of negative impacts contributing to the footprint (b), are visualized. The footprint of the OMF on the local marine ESs is negligible (<0.005%) and thus not visualized. OWF: offshore wind farm; OMF: offshore mussel farm; ESs: ecosystem services.

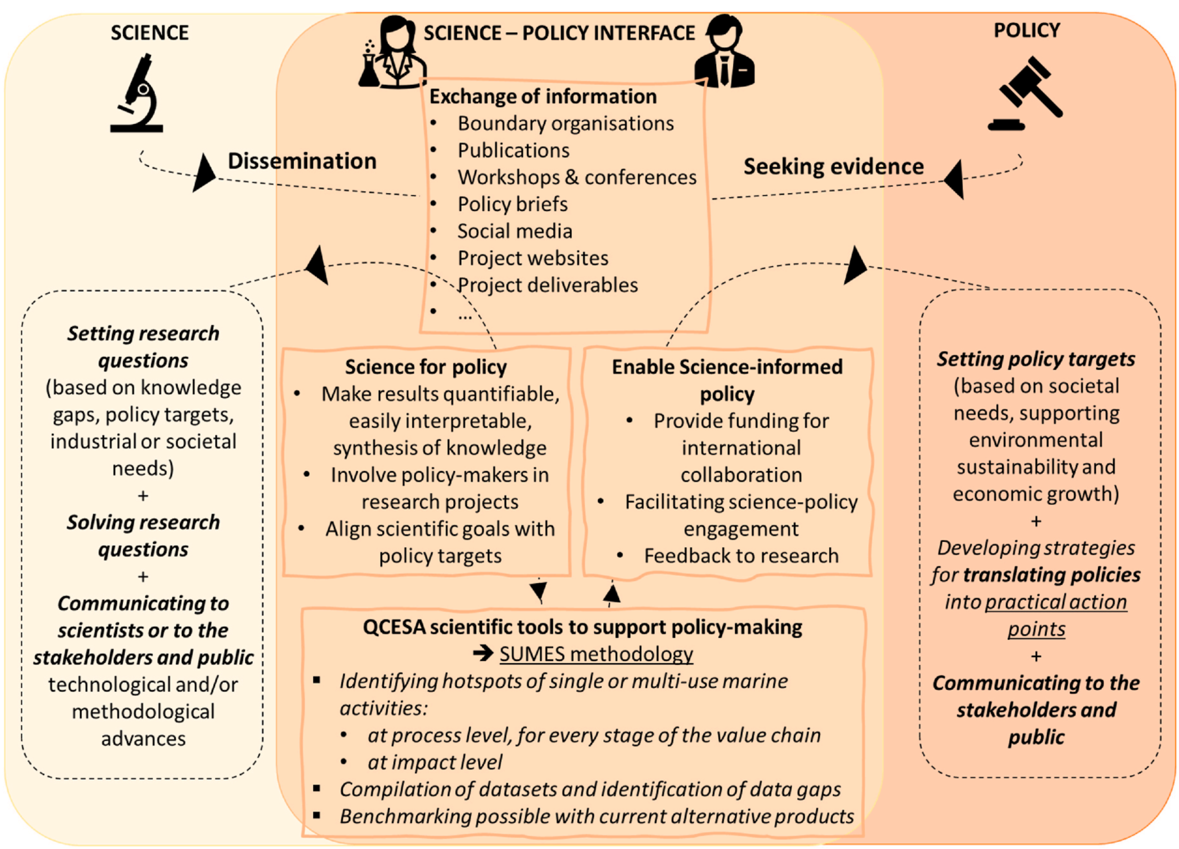

Fig. 4. Focusing on the science-policy interface and the interrelation with QCESA tools, e.g., the SUMES methodology.

the influence of policy instruments. It is essential that policymakers use scientific data and research to make better informed decisions. Scientific innovation contributes to evidence-informed policymaking (rather than evidence-based, acknowledging the fact that science also has its limitations), ensuring that policies are based on reliable and up-to-date information (European Commission, 2022). Currently, there is a mix of sectoral legislation, especially at a national (i.e., Belgium) and sub-national (i.e., Flanders) levels, alongside broader legislation (i.e., non-sectorial) focused on promoting sustainability. While the latter often falls short in providing concrete guidance on how to take sustainable actions or how to carry out measurements, sector-based legislation forces commercial companies to individually and fully comply with sector-specific operational standards and regulatory requirements. However, legislation that addresses integration across sectors is lacking (Garcia et al., 2014). This suggests that the current suite of sector-specific legislation may not achieve the broader ecosystem and environmental policy outcomes required (Boyes et al., 2016; Cormier et al., 2018; Piet et al., 2023).

There is a need to establish a common understanding – at the national, EU and global level – of how Blue Economy activities can have (un)sustainable outcomes, and on the assessment procedure to be followed (i.e., which sustainability indicators, and how and when should these indicators be measured), to enable transparent and consistent reporting. Recently, the EC reviewed existing sustainability frameworks for the Blue Economy and based on this, published a Blue Economy Sustainability Framework that provides a set of sustainability indicators per marine sector (targeting the most common sectors) (European Commission, 2021). These indicators can be environmental, economic, social and/or governmental. However, the list of indicators is still under discussion, and the way of aggregating the proposed indicators has not been elaborated. This lack of clarity makes interpretating results comparing between Member States difficult. As this work is still in progress, a QCESA methodology, such as that developed in the SUMES project, which includes economic valuation, could be beneficial to ensure a quantitative and holistic approach to measuring the environmental sustainability of ongoing marine activities. The application of such quantitative tools reveals, however, data gaps. Further advancements rely on agreements regarding which data to collect, and how to collect it efficiently. Nevertheless, existing European initiatives, such as the ICES working groups and EMODNET, serve as platforms where scientists collaborate to enhance the harmonization of marine data across Europe. Therefore, the SUMES methodology can provide a framework for the development of monitoring systems for Blue Economy activities.

Integrating scientific advancements into legislation requires a strategic approach. For instance, building strong collaborations to foster dialogue and investing in communication to translate scientific research into layman's terms are essential to ensure that policymakers can understand the implications and benefits. Furthermore, (part of) science needs to directly address policy needs, e.g., where the QCESA methodology fits perfectly into a policy (e.g., the Corporate Sustainability Reporting Directive (2022/2464/EU)), or can steer changes in future legislation requiring the establishment or adaptation of regulatory frameworks such as the Marine Spatial Planning Directive and the EIA Directive, where an ecosystem-based approach is very relevant, but the actual implementation is often limited (Willsteed et al., 2017; Stelzenmüller et al., 2018; EC-CINEA, 2021; Piet et al., 2023).

The development of policy instruments that encourage sustainable Blue Economy practices and penalize actions harming ecosystems involves regulations. Equally important are market-based mechanisms or incentives promoting responsible resource use and conservation. Although outside the scope of this study, these latter alternative instruments are also effective in shaping sustainable practices.

3.3.2. The challenges of using QCESA methodologies

Despite the advantages QCESA methodologies, such as the SUMES one, Taelman et al. (2024) and De Luca et al. (2024a) highlighted some inherent limitations and/or the lack of accurate data. Some of the challenges include the high data requirements, which are not always available or accessible. This limitation can influence the modelling in LCA and ESA, such as the selection of models and indicators, which might need to rely on proxies and assumptions. Additionally, there is a risk of double-counting impacts. The impacts of an activity can vary spatially and temporally on larger scales, which must be considered. Valuing ESs and monetizing them also present challenges. Monetization can be volatile and time-dependent, and there are controversies regarding the commodification of nature, as nature has intrinsic value beyond monetary considerations. Furthermore, the valuation methods are not always consistent, leading to potential over- or underestimation of the impacts. These aspects must be carefully considered when applying the methodology and interpreting the results of a case study, such as the one presented in this work. Beyond these constraints, further advancements are needed to align the methodology with current legislative requirements and contribute to the development of evidence-based policies. For example, the Corporate Sustainability Reporting Directive focuses on both environmental and social impact reporting, whereas the methodology of Taelman et al. (2024) addresses only a few social aspects, such as human health and well-being (altered by changes in e.g., climate change, human toxicity, recreational ES). Future research could broaden this scope to include a more holistic set of social impact categories, such as fair wages, child labour, etc. Additionally, achieving a sustainable Blue Economy requires an equitable access to resources and distribution of its benefits (UNESCO, 2024). To achieve this, OCESA methodologies need to incorporate a clearer differentiation between private and public benefits. Moreover, there is an increasing number of policy instruments highlighting the importance of biodiversity (e.g., A/CONF.232/2023/4 and CBD/COP/15/L25). However, while biodiversity is complex concept encompassing the variety of life on Earth at all biological, including the diversity of species, ecosystems, and genetic diversity within species (McVittie and Faccioli, 2020), it is crucial to note that specific components like species richness and assemblages can be assessed directly. Local changes in these components can be evaluated, and ecological diversity indices can be calculated to compare different locations or track changes over time. Nevertheless, despite these assessment tools, marine biodiversity is complex and measuring its status or impact remains challenging (Teixeira et al., 2016; Costello et al., 2017; Smit et al., 2021). Integrating those efforts in the SUMES methodology would represent a significant step forward.

Transparently communicating uncertainty is a cornerstone for making well-informed decisions and supporting policy-making processes. Acknowledging the inherent variability and uncertainties within ecosystems is essential, recognizing that complete understanding may never be achieved. The reduction of uncertainty in scientific findings often occurs through rigorous peer review processes, typically confined to specific fields. Broadening the research scope to encompass diverse disciplines and fostering improved communication among stakeholders can further diminish uncertainties and enrich knowledge. To mitigate and address uncertainties effectively, integrating insights from social sciences on resource user behaviour is imperative. The structured frameworks and collaborative workflows within ICES play a pivotal role in fostering trans- and multidisciplinary research efforts.

In the context of the QCESA methodologies, there is a need for enhanced consideration of uncertainty, particularly during aggregation stages. Various methodologies, such as the widely utilized Monte Carlo method, offer valuable insights into quantifying data/model uncertainty, as demonstrated in studies like De Luca et al. (2024b) and Michiels and Geeraerd (2020). Additionally, Environmental Risk Assessment (ERA) offers a critical tool for guiding informed decision-making among policymakers, regulators, and industries, providing a structured approach to evaluate environmental impacts, integrating various aspects of human activities at sea, and reducing uncertainties through transparent risk characterization and management (National Research Council, 1994). The ERA methodology is valuable for addressing uncertainty by accounting for the probability of accurate ecosystem services results.

Additionally, while there is a step-by-step guide on how to use the SUMES methodology (Taelman et al., 2024), both industry and policy would benefit from an effective and user-friendly tool. This tool should allow different types of input data to be easily plugged in and results to be generated instantly, ideally with the ability to map them – a feature under development.

In the context of environmental permitting and tendering processes, where prospective analysis is essential, the QCESA, particularly the SUMES methodology, would benefit from the inclusion of future scenarios and scale and learning effects. For example, this could better account for technological uncertainties (Arvidsson et al., 2018). Such an approach allows decision-makers to anticipate and compare the environmental consequences of different options pre-emptively, providing a significant advantage in the pursuit of a sustainable Blue Economy.

When considering the environmental sustainability of marine activities, it is clear that the impacts of a single activity are significantly different from the combined effects of multiple installations of the same and/or different activities (Borja et al., 2024). The results obtained from the SUMES methodology cannot always add up linearly, but cumulative impacts (where the effect can be synergistic or antagonistic) at different spatial and temporal scales should be carefully considered. Currently, the results of the MUOF case study and QCESA methodology face limitations in adequately assessing the cumulative impacts, primarily attributed to the complex nature of marine ecosystems (Smit et al., 2021). Furthermore, challenges arise in distinguishing between the impact of external factors (e.g., seasonal variability, climate change) and direct impact of the activity (or activities). Moreover, quantification of potential feedback loops within ESs adds another layer of complexity to the assessment process. A critical advancement for the methodology is to achieve a comprehensive quantification of these cumulative impacts, a direction steered by recent legislation such as the agreement under the UN's Convention on the Law of the Sea on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction (A/CONF.232/2023/4). With these proposed improvements, the SUMES methodology could provide a more comprehensive and integrated perspective, which is needed to make (further) progress towards what is required by the European marine policy frameworks.

4. Conclusions and perspectives

The review of policy instruments revealed a mix of sectoral and sustainability-oriented legislation, with sectoral legislation, particularly at a national (e.g., Belgium) and sub-national (e.g., Flanders) levels, focusing on individual compliance but lacking cross-sectoral integration. National legislation is often aligned with EU frameworks, but consensus is lacking and better guidance on indicators, methodologies and aggregation methods is needed to assess the environmental impact of Blue Economy activities. The integration of LCA and ESA in legislation is also lacking support. However, adoption of QCESA methodologies could facilitate a holistic interpretation of results, crucial to support decision making at business and government level, i.e. to improve technologies/processes to become more sustainable, setting necessary and realistic sustainability targets or to provide clear guidance on sustainability reporting, respectively. For example, the QCESA methodology could support directives such as the Corporate Sustainability Reporting Directive, Marine Spatial Planning Directive and EIA Directive, harmonizing sustainability measurements for the Blue Economy.

To demonstrate the benefits of using quantitative tools to policymakers, this study applied a QCESA methodology developed by Taelman et al. (2024), presenting tangible indicators and aggregated monetary results distinguishing between benefits (handprint) and burdens (footprint). Considering the impacts that were possible to assess and the limitations of the methodology used, the findings indicate that the MUOF has an overall larger handprint compared to its footprint. However, the results need to be interpreted cautiously as they are not scalable and do not account for cumulative impacts. QCESA methodologies facilitate clear and concise communication of results to policymakers, by identifying hotspots at the level of processes and impact categories, aggregating the results into a single value, distinguishing between benefits and burdens at different geographical scales, and using straightforward terms such as "handprint" and "footprint" (Fig. 4). This methodology can contribute to a better understanding of the total environmental impact of activities, and which actions should be prioritized to reduce the footprint and/or increase the handprint. The comprehensive collection of data increases the robustness and accuracy of the SUMES methodology, and the methodology allows comparisons with other similar projects/design ideas, i.e. benchmarking with alternative sources is possible. While further advancements in the SUMES methodology are certainly needed, as outlined in the discussion section, to fully capture the complexity of marine ecosystems, biodiversity, and sustainability, QCESA methodologies provide a roadmap for future progress in sustainability assessments. Despite the challenges, this study advances impact-oriented research by highlighting the potential of the QCESA tools, such as the SUMES methodology, as tools for developing evidence-informed policy and strengthening the science-policy interface.

Declaration of generative AI in scientific writing

During the preparation of this work the author(s) used ChatGTP in order to erase spelling mistakes and improve the English writing. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CRediT authorship contribution statement

Laura Vittoria De Luca Peña: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jo Dewulf:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Jan Staes:** Writing – review & editing, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ine Moulaert:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sara Vandamme:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Johanna J. Heymans:** Writing – review & editing. **Sue Ellen Taelman:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

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