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Monetized (socio-)environmental handprint and footprint of an offshore windfarm in the Belgian Continental Shelf: An assessment of local, regional and global impacts

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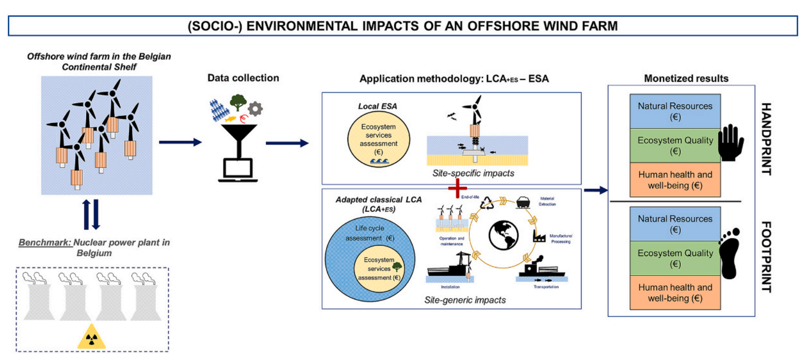
HIGHLIGHTS

- Merging two ways to integrate LCA and ESA.
- Application of integrated LCA and ESA frameworks to an offshore wind farm in Belgium.
- Site-specific and site-generic impacts on ecosystem services are considered.
- Quantification of the (socio-) environmental handprint and footprint.
- Results show the offshore wind farm has a large handprint compared to its footprint.

GRAPHICAL ABSTRACT



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ABSTRACT

Renewable offshore wind electricity is as one of the major renewable energy sources on our path towards carbon neutrality. As for all energy technologies, offshore wind farms (OWFs) will have both local and global negative and positive impacts. Understanding and quantifying these burdens and benefits requires a holistic sustainability assessment. This study tests and applies a novel (socio-) environmental impact assessment framework to quantify

Abbreviations: Area of Protection, AoP; Belgian Continental Shelf, BCS; characterization factors, CFs; Common International Classification of Ecosystem Services, CICES; end-of-life, EoL; Ecosystem service, ES; ecosystem service assessment, ESA; Ecosystem Services Valuation Database, ESVD; ecosystem quality, EQ; European Commission, EC; functional unit, FU; human health and well-being, HH&WB; The International Council for the Exploration of the Sea, ICES; International Energy Agency, IEA; life cycle assessment, LCA; life cycle inventory, LCI; life cycle impact assessment, LCIA; natural resources, NR; offshore high voltage station, OHVS; offshore wind farm, OWF; operation and maintenance, O&M; social-life cycle assessment, S-LCA; Vlaamse Regulator van de Elektriciteits-en Gasmarkt, VREG; willingness-to-pay, WTP.

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Ecosystem services
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the monetized (socio-) environmental footprint and handprint of an offshore wind farm located in the Belgian Continental Shelf. This framework consists of a combination of two ways of integrating Life Cycle Assessment (LCA) and Ecosystem Services Assessment (ESA) to quantify both the site-specific and site-generic impacts on ecosystem services (ESs) over the lifetime of a human intervention. For the operation and maintenance stage of the OWF, impacts on three local ESs were quantified, i.e. offshore wind energy provisioning, nursery and habitat maintenance and aesthetic value, while for the other life cycle stages site-generic impacts on multiple ESs were calculated. A comprehensive list of data was inventoried to conduct both the LCA and ESA studies. The monetized impact results were then aggregated and monetized at the level of three areas of protection, i.e. human health and well-being, natural resources and ecosystem quality. The results show that the OWF has a net handprint of +€85,196, mainly due to electricity production, while the absolute footprint (−€4039) consists largely of impacts associated to the supply chain of materials to manufacture the offshore windfarm. Furthermore, this study compares the (socio-) environmental performance of an OWF with nuclear energy, which is used as benchmark because of its high importance for electricity supply in Belgium. This study is a first step towards a valuable contribution to understanding the multi-scale burdens and benefits of offshore wind energy, which can support decision- and policy-making.

1. Introduction

Nowadays, the demand for energy and electricity is continuously increasing worldwide. The International Energy Agency (IEA) estimated a 6% increase in the global electricity demand only in 2021 and also foresees a 2.7% growth between 2022 and 2024 [1].

So far, fossil-fuel sources, such as coal, covered more than half of the global electricity demand, despite the growth in renewables [1]. According to the IEA [2], in 2020, over half of the electricity generation came from coal and gas (35% and 23% respectively), followed by renewables (29%) and nuclear energy (10%). Nevertheless, in Europe, renewables such as wind and solar energy (22%) overtook fossil gas (20%) and coal power (16%) for the first time in 2022 [3].

To meet this increasing electricity demand and also to align with the climate-neutrality targets set by the European Commission (EC), the renewable energy sector must considerably grow in the coming years to provide almost two thirds of the global energy supply by 2050 [4,5]. According to EMBER [3], Europe's energy transition has accelerated, which may lead to a faster scale up of the renewable energy sector than expected. Nevertheless, there are still concerns that climate-neutrality targets, such as a global Net Zero by 2050, will be difficult to achieve without the use of sources such as nuclear energy [6]. For example, the phase-out of all nuclear electricity generation is expected in European countries such as Germany, United Kingdom and Belgium, meaning that most of the transition to clean energy will have to rely on renewables [1].

One of the renewable energy sectors that is foreseen to be scaled up across the world is the offshore wind energy industry. Only in the EU, the total installed capacity of offshore wind farms (OWFs) is expected to increase to 300 GW by 2050, which will contribute in achieving climate neutrality by 2050 [7]. One of the countries contributing to this aim is Belgium, positioned as the fourth largest producer of offshore wind energy with a current installed capacity of 2.3 GW by the end of 2021, occupying an area of approximately 238 km^2 in the Belgian Continental Shelf (BCS) [8,9]. Today, Belgium has nine operational OWFs and the average annual production of offshore wind energy in Belgium is approximately 8TWh [10]. This production is foreseen to increase by the new Belgian marine spatial plan (2020–2026), with the development of a second area for offshore renewable energy of 285 km^2, close to the French marine waters. This new area, called "The Princess Elisabeth Zone" aims for a total installed capacity between 3.1 and 3.5 GW [8].

Apart from the obvious advantages of renewable energy, e.g. reduction of carbon emissions, one has to bear in mind that the expansion of OWFs can lead to effects of various scale and nature, i.e. local to global and positive to negative effects on the ecosystems and human activities [7,11,12] To have a better understanding and to capture these multiscale positive and negative effects, a comprehensive impact assessment is needed. Some of the assessment tools that could be used for determining the impacts of OWFs are life cycle assessment (LCA) and ecosystem services assessments (ESA). LCA is an anthropocentric methodology typically used to assess potential environmental impacts over the entire or partial life cycle of a product or service (i.e. from raw materials extraction to its production, transport, installation, use and end-of life) at a global scale [13–16]. These impacts are classified in specific categories (i.e. known in LCA as *impact categories*) and are quantified through different indicators, having different units. To transform the inventory flows (i.e. amount of emissions, resources extracted, waste generated, land occupied or transformed) from all life cycle stages into the units of the indicator, characterization factors (CFs) are used as unit conversion factors [14]. On the other hand, ESA is an ecocentric methodology, which assesses the provision of ecosystem services (ESs), i.e. the benefits that ecosystems provide to humans, assessed at a local and/or regional scale [13,14].

To quantify the local and regional effects of OWFs on marine ecosystems and its services, most of the existing studies in literature rely on site-specific impact assessment methods, monitoring data or experimental techniques. For example, some studies used models to investigate bird risk collision and displacement, effects of biofouling communities at local and regional scale (i.e. biodeposition, oxygen and phytoplankton depletion), spillover effects of fishery exclusion and changes in the trophic web functioning [17–26]. Meanwhile, other studies are a result of long-monitoring programmes and experimental work, which have studied the effects of OWFs on sediments, food web structure and composition, and different group of organisms, i.e. macrobenthic fauna, biofouling communities, demersal and pelagic fish and sea mammals [8,12,27–31].

Few studies have used qualitative ESAs to evaluate how OWFs can change marine ecosystem functioning leading to changes in ESs from marine ecosystems [11,32–36]. The ES can be divided in three categories, i.e. provisioning, regulating and maintenance, and cultural services. To properly conduct an ESA, relevant ESs for a particular case study must be selected. This can be done by finding evidence in literature, but stakeholder involvement is also extremely important [33,37]. For example, Custodio et al. [37] present an approach on how to systematically capture stakeholders' opinions on relevant ESs in the Belgian Continental Shelf (BCS). Baulaz et al. [32] and Van de Pol et al. [35] are the only studies that propose a conceptual ESA model of the effects of OWFs on ESs supply that can help transitioning from a qualitative to a quantitative approach.

The global effects on the other hand are mainly related to the value chain of an OWF (i.e. environmental burdens occurring throughout its life cycle processes) and they can be assessed with the LCA methodology. Most of the existing peer-reviewed articles that use LCA mainly focus on investigating: 1) how certain technical aspects of OWFs can affect their environmental performance (i.e. wind turbine design, foundation design, location, distance to shore, depth) [38–41], 2) how OWFs potentially contribute to a reduction of CO_{2-}eq. emissions [42–46], or 3) the environmental performance of OWFs vs. onshore wind farms

[46–49]. Few other studies have a different scope, for example Elginoz and Bas [50] conducted an LCA in the context of a multi-use platform to determine the impacts of offshore wind energy combined with wave energy, while Arvensen et al. [51] assessed the impacts of an entire offshore power grid in the North Sea. Angelakoglou et al. [52] made a benchmark study to evaluate not only the environmental performance of a land-base, coastal and offshore wind farm, but also their energy feasibility, economic viability and social impacts. However, the social impact assessment mainly relied on literature sources. The recent social life cycle assessment (S-LCA) study of Buchmayr et al. [53] implemented a framework to study both the local and global sustainability of wind energy power plants (onshore and offshore).

To simultaneously study the local and global effects of a human activity on the environment, a holistic methodology is required. This can be achieved by combining or integrating methodologies such as LCA and ESA, which has been done in several studies under the context of different human activities . In literature, most of the LCA-ESA integration methodologies focus on incorporating terrestrial ESs into LCA or are applied to case studies related to terrestrial ecosystems and to a lesser extent to aquatic ecosystems [14]. However, the new methodology of Taelman et al. [54] moves one step further by allowing the quantitative assessment and integration of LCA and ESA methods through monetary valuation techniques to cover local and global effects of human activities, targeting both terrestrial and marine ESs.

So far, there are no studies that comprehensively evaluate both positive and negative impacts of OWFs on terrestrial and aquatic ecosystems, particularly on marine ecosystems and its services, and at different geographical scales. Therefore, the main goal of this study is to measure these impacts by demonstrating and applying the (socio-) environmental impact assessment framework of Taelman et al. [54] to a real OWF case study in the BCS. To this end, data was collected in an exhaustive manner, from technological data for the life cycle inventory (LCI) to biophysical data for the ESA and monetary values to aggregate the results of both methods. Possible trade-offs between the (socio-) environmental burdens and benefits of an OWF are analyzed per area of protection (i.e. human health & well-being, ecosystem quality and natural resources). These burdens and benefits of the OWF are represented as a *footprint* and *handprint* respectively [55]. Given the high share of nuclear power generation in Belgium and the plans for its phasing out (which would increase reliance on renewable energy sources), this study also includes a benchmark to compare the (socio-) environmental impacts of the OWF with that of a nuclear power plant. The findings can support decision-making in a political context and it is a first step towards a comprehensive (socio-) environmental assessment of an existing marine activity.

2. Materials and methods

The methodology to conduct this study is presented in this chapter and subdivided in the following way: Section 2.1. describes the OWF used in the study, Section 2.2. provides an overview of the (socio-) environmental impact assessment framework developed by Taelman et al. [54], Section 2.3 explains in a nutshell how this framework was applied to the OWF case study, while Section 2.4 and Section 2.5 provide more details of this application, specifically when using LCA and ESA, respectively. Section 2.6 explains how the results were combined to obtain a handprint and footprint of the offshore wind farm. Finally, Section 2.7 describes the benchmark study, including a description of the nuclear power plant, data collection and methods used to quantify impacts.

2.1. Description of the offshore wind farm case study

Due to confidentiality, detailed information on the design of the OWF components cannot be provided, however ranges and aggregated values are indicated throughout this study. The OWF is located approximately 35–55 km from the Belgian coast, covers an area of 14–20 km^2 and it is estimated to be operational for 20 years. The OWF has between 20 and 75 wind turbines with a capacity between 3 and 10 MW and with monopile foundations. An offshore high voltage station (OHVS) is connected to the wind turbines via a local grid with a length between 30 and 50 km (i.e. infield cables). The electricity produced by the wind turbines is transmitted from the OHVS to shore via a submarine export cable with a length between 40 and 60 km. On shore, the submarine export cable is connected to a land cable in a connection pit located in the nearest Flemish coastal city to the OWF. The land cable continues the transmission of electricity to an onshore high voltage station for voltage control and from here the connection is made to ELIA's (the electricity system operator of Belgium) high voltage transmission grid (Fig. 1).

2.2. A general overview of the LCA$_{+ES}$-ESA framework

To study both the local and global (socio-)environmental effects of an OWF, a (socio-) environmental impact assessment framework (i.e. LCA$_{+ES}$-ESA) proposed by Taelman et al. [54] was applied. This methodology is built on the integration of two methodologies, i.e. LCA and ESA, to quantify both *site-specific* impacts (e.g. local impacts of a human activity on its surrounding location) and *site-generic* impacts (e.g. multiple local/regional impacts which are spread as they are linked to certain processes in the value chain of a human activity) on *ecosystem services*, as well as other global environmental impacts (e.g. global warming, ecotoxicity) along the value chain of a human activity (Fig. 2).

The quantification of site-specific impacts on ESs requires local ESA studies, ideally for the entire human activity value chain. However, when local ESs data is not available (or cannot be generated) for each of the processes in the value chain, it is still possible to account for impacts on ESs in a site-generic way. To do so, Taelman et al. [54] developed new characterization factors and midpoint impact categories, adapting this way a classical life cycle impact assessment method (ReCiPe 2016 (H) v1.05) to also account for the impact on provisioning, regulating and cultural ESs due to *land use* (i.e. transformation and occupation of land along the value chain), next to the more traditional impact categories such as global warming and eutrophication. These site-generic CFs are calculated based on the Ecosystem Services Valuation Database (ESVD) and expressed in monetary terms (more details in Section 1.1 of Supplementary Material B and [54]. As a consequence, it was not possible to develop CFs for seabed transformation and occupation. The adapted classical LCA is further referred to as LCA$_{+ES}$.

Before combining the results of the local ESAs with the ones of LCA$_{+ES}$, a revision of the conventional areas of protection (AoPs) in LCA was conducted. These conventional AoPs do not cover the impacts that human activities have on ESs categories (i.e. provisioning, regulating, and cultural), therefore the (socio-) environmental impact assessment framework of Taelman et al. [54] proposes a way to redefine these AoPs to integrate LCA$_{+ES}$ and ESA. To summarize, each AoP includes (1) the results on impacts on local ESs covering often only a few value chain processes, addressed by ESA studies (i.e. *site-specific ESs impacts*), (2) the results of the classical LCA impact pathways by applying the ReCiPe 2016 method covering the entire value chain (i.e. *ReCiPe results*) and 3) the modelling of the land use impact category was altered in a way to also account for ESs changes linked to the remaining value chain processes not capture by (1) (i.e. *site-generic ESs impacts*. More specifically, the AoP Natural Resources (NR) includes the impact pathways towards natural resources from LCA$_{+ES}$ and provisioning services from ESA, Ecosystem Quality (EQ) the impact pathways on ecosystem health from LCA$_{+ES}$ and regulating services from ESA, and Human Health and Well-being (HH&WB) the impact pathways on human health from LCA$_{+ES}$ and cultural services from ESA. After redefining these AoPs, aggregation is performed using monetary techniques and the results are expressed as handprint (benefits) and footprint (burdens) for each AoP per functional unit (FU). These aggregated results are further referred to as the LCA$_{+ES}$-ESA results.

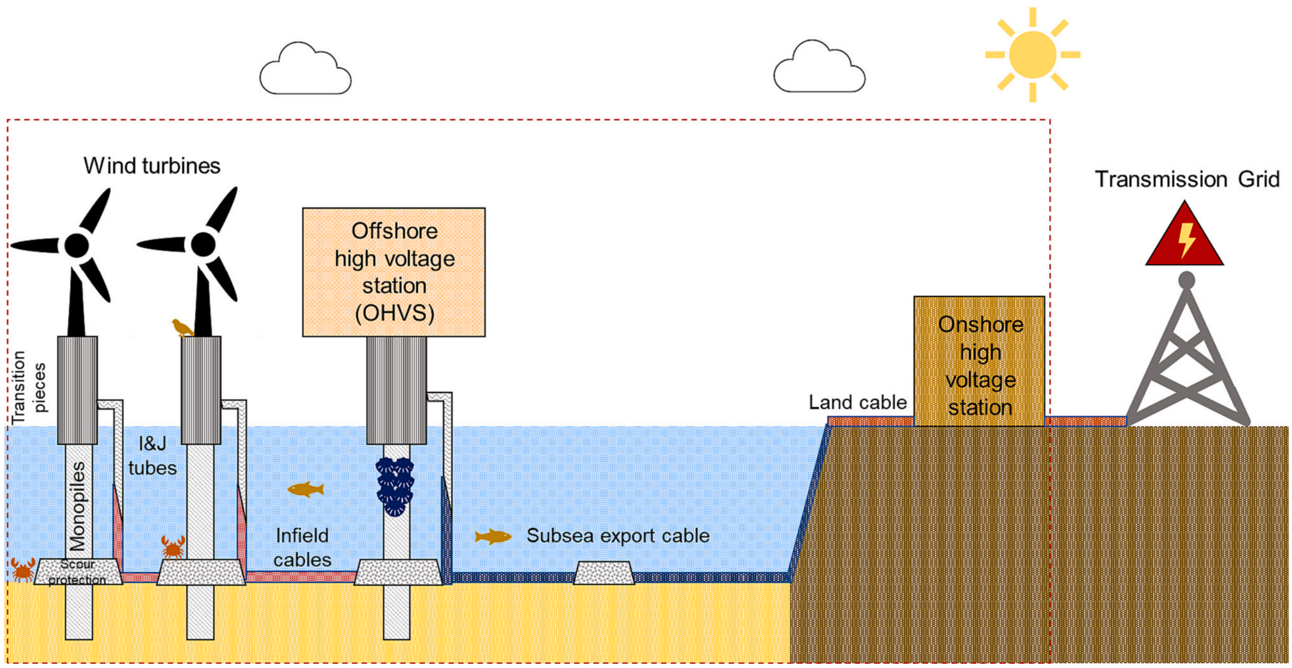

Fig. 1. Components of an offshore wind farm. The system boundaries of the case study are depicted with a red-dashed line. The I and J-tubes refer to the shape of the steel tubes that protect the cables between the top of the foundation and the sea bottom. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

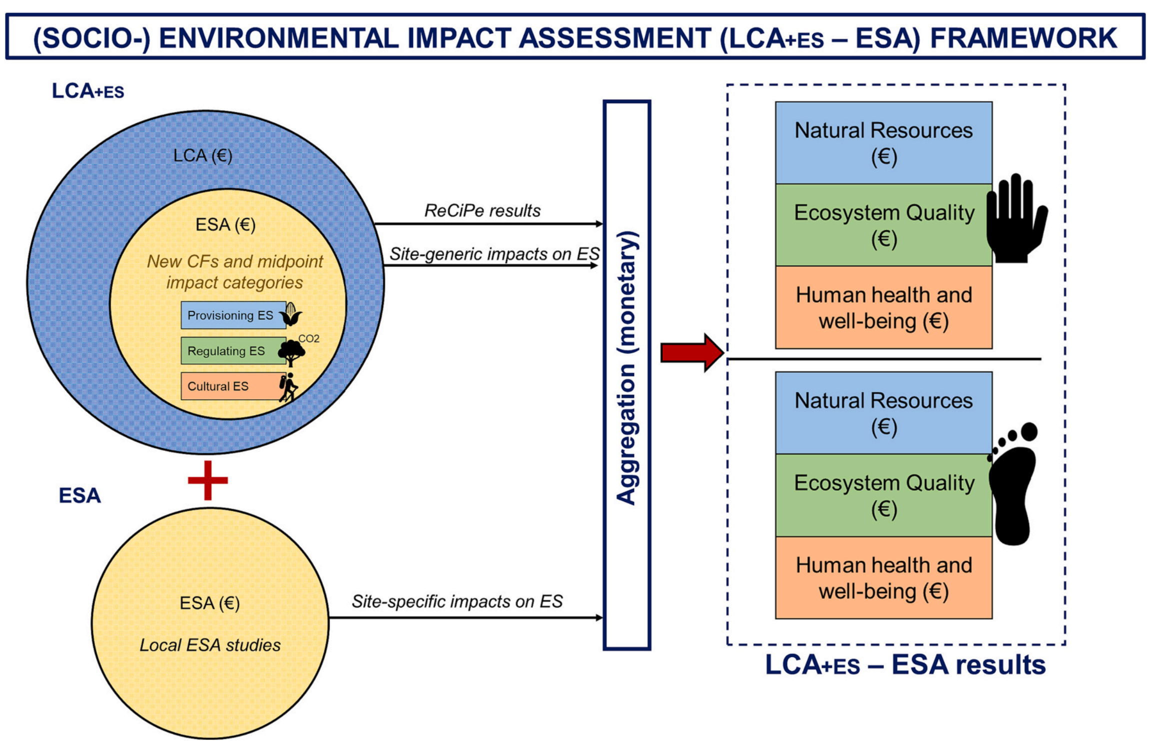

Fig. 2. (Socio-) Environmental impact assessment framework (LCA$_{+ES}$-ESA): This framework combines two ways of integrating LCA and ESA, where the monetized results from an adapted classical LCA (LCA$_{+ES}$) and local ESA studies are aggregated. By doing this, both site-specific and site-generic effects on ESs are included in the framework. A classical LCA is adapted by replacing a traditional land use impact category from the ReciPe method in LCA with new midpoint impact categories that consider the impact of land transformation and occupation on three groups of ESs, i.e. provisioning, regulating, and cultural. The impact is quantified by developing new characterization factors, which take into account the loss or gain of ESs in euro. This adapted classical LCA, namely LCA$_{+ES}$ has as outputs: i) the global environmental impacts quantified with ReCiPe and ii) the site-generic impacts of ESs. The monetized results from LCA$_{+ES}$ and ESA are aggregated in newly developed AoPs: natural resources, ecosystem quality and human-health and well-being and these combined results from the (socio-) environmental framework are expressed as handprints and footprints. Adapted from De Luca et al. [14] and Taelman et al. [54].

2.3. Application of the LCA$_{+ES}$-ESA framework to the OWF case study

The processes in the value chain of an OWF are manifold, i.e. manufacturing, installation, transportation, operation and maintenance and end-of-life processes [54]. As mentioned in Section 2.2., ideally local ESAs should be conducted for each of the processes in the value chain of an OWF to quantify the impacts on ESs and then aggregated with the impacts quantified with LCA. However, there are no local ESA studies available for each of these processes, therefore, this study conducted local ESAs to quantify the impacts on local *marine* ESs impacts due to the *operation and maintenance phase* of the OWF, which will be further explained in Section 2.5. The impacts on other ESs, which are all *terrestrial*, due to the remaining processes in the value chain were quantified in a site-generic way by applying the CFs developed by Taelman et al. [54]. Other global environmental impacts caused by these processes were also quantified with the ReCiPe 2016 method (e.g. climate change, ecotoxicity, etc) (see Section 2.4). The following sections (Section 2.4 and Section 2.5) show more details on how this methodology is applied and Fig. S7 in Supplementary Material B depicts the application of the LCA$_{+ES}$-ESA framework to this case study.

2.4. Adapted classical LCA (LCA$_{+ES}$)

An adapted classical LCA was conducted following the ISO 14040–14,044 standards [56]. The goal of this study, as mentioned beforehand, is to evaluate comprehensively the (socio-) environmental impacts of an OWF throughout its life cycle stages to determine its monetized footprints (burdens) and handprints (benefits) per AoP and this way inform decision-making processes in the context of OWFs.

For this study, the entire life cycle of the OWF is considered (i.e. from cradle to grave) comprising the following stages: manufacturing, installation, transportation, operation and maintenance and end-of life (Fig. 3). All components of the OWF are taken into account up to the onshore high voltage station (Fig. 1). In addition to this, a 20-year lifetime is assumed for the wind farm [57]. The impacts assessed through an adapted LCA are expressed per FU (1 GWh of electricity delivered to the grid) and then monetized to have a common unit of € per GWh.

The foreground system is visualized in Fig. 3. For most processes considered, primary data was collected including publicly-available data and confidential data from the OWF's concession holders [58]. Secondary sources, such as peer-reviewed articles [39,41], master theses [59,60] and processes from Ecoinvent v3.8 database were used and adjusted for this case study whenever primary data was lacking. A description of the foreground processes in this study can be found below and Table 1 shows an aggregated LCI for all these processes. More details on the description of the system and assumptions for each life cycle stage (Section 2.4.1, Section 2.4.2, Section 2.4.3, Section 2.4.4. and Section 2.4.5.) can be found in Table SA1 and Figures SA1, SA2, SA3, SA4, SA5, SA6, SA7 in Supplementary Material A.

2.4.1. Manufacturing

The foreground system considers the manufacture of an OWF with 20–75 turbines, whose main components are rotor blades, towers, hub, nacelle (i.e. generator, gearbox, switchgear system, motors), LV transformer and other electrical equipment.

The type of foundations are monopiles with a diameter of five meters. In total, the manufacturing of 20–75 steel monopiles was modelled, including the monopiles of both the turbines and OHVS. Besides monopiles, steel transition pieces are also part of the foundation

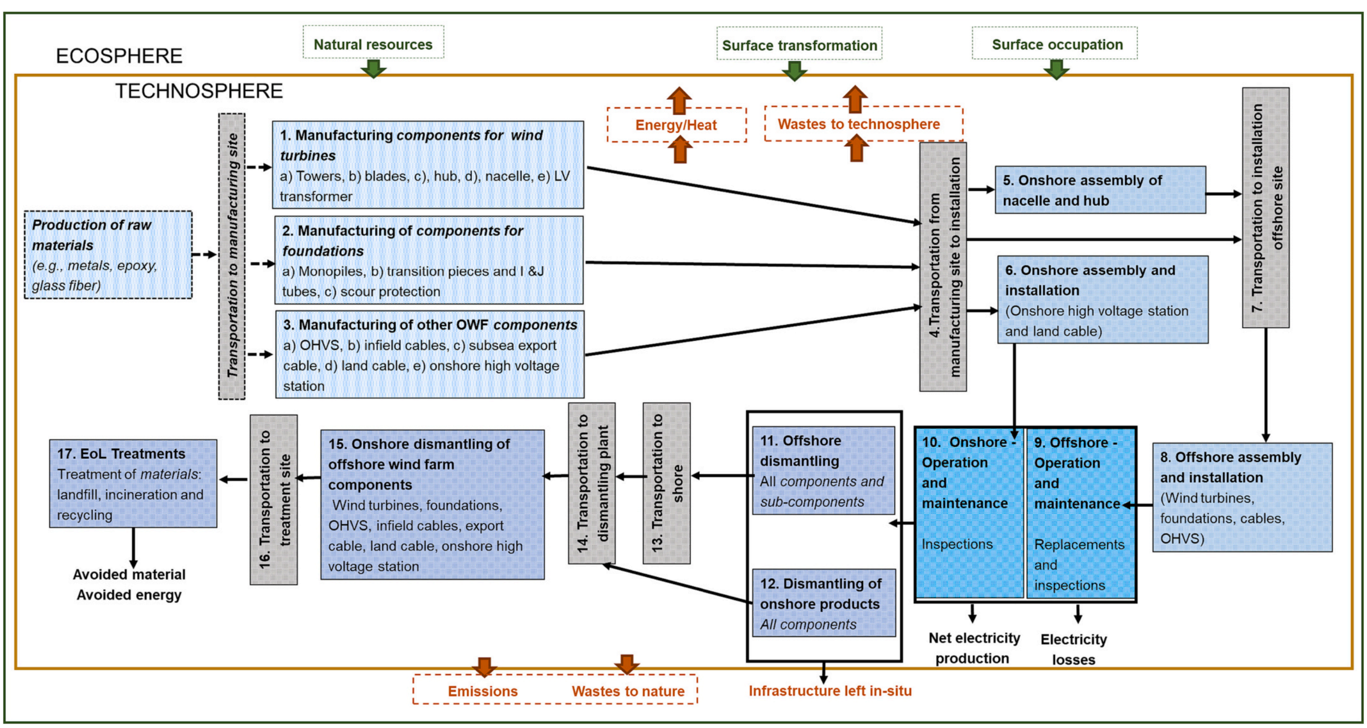

Fig. 3. Process scheme depicting the life cycle stages considered in the OWF case study and its stressors. *Blue boxes:* depict all the life cycle stages (i.e. supply chain of raw materials, manufacturing, assembly, installation, operation and maintenance, dismantling, dismantling at plant and EoL treatments). *Grey boxes:* Transportation processes. Green boxes: The extraction of natural resources and surface occupation and transformation (land and/or seabed) by each life cycle stage. *Orange boxes:* Energy and heat consumption, heat released, wastes generated and emissions released by each life cycle stage. The OWF's electricity production and its losses are taken into account in the operation and maintenance stage. Part of the monopiles and scour protection will not be dismantled and instead remain in-situ (i.e. water column and seabed). The benefits of recycling and energy recovery technologies are considered as avoided burdens in EoL treatments. Boxes with *full lines* depict the foreground system (i.e. processes for which we collected data), while the boxes with *dashed lines* show examples of the background system (i.e. data from the value chain obtained from the database Ecoinvent). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Aggregated inventory for all the life cycle stages (manufacturing, installation, transportation, operation and maintenance, primary dismantling, secondary dismantling, EoL) of an OWF. The inventory includes the materials and energy inputs, as well as the inputs from nature (i.e. land or seabed transformation and occupation), and also outputs such as the net electricity production in the OWF and the avoided products/energy.

Process input/outputs	Component							Unit
	Wind turbines	*Foundations*	*Infield cables*	*OHVS*	*Subsea export cable*	*Land cable*	*Onshore high voltage station*	
Manufacturing								
Metals (steel, cast iron, copper, aluminium, lead, precious metals, non-ferrous metals)	1.0E+04	3.1E+04	7.6E+02	5.7E+02	2.2E+03	2.2E+01	9.8E+01	tonnes
Composites	1.3E+03	–	–	–	–	–	3.4E-01	tonnes
Wood and paper	5.6E+01	–	–	1.2E+01	–	–	3.9E+00	tonnes
Plastics, rubber, insulation material	3.4E+02	–	2.2E+02	3.3E+02	1.3E+03	8.2E+00	1.5E+00	tonnes
Fluids and oils	8.9E+01	–	–	8.4E+01	–	–	4.0E+01	tonnes
Gases	2.5E-01	–	–	3.2E-01	–	–	1.1E-01	tonnes
Silica	2.8E+01	1.3E+05	–	–	5.6E-03	9.6E-05	–	tonnes
Rock (for scour protection)	–	1.3E+05	–	–	2.4E+03	–	–	tonnes
Water	1.7E+03	–	–	–	–	–	–	tonnes
Electricity	3.3E+06	–	1.5E+06	2.6E+04	3.2E+06	–	2.4E+04	kWh
Natural gas	1.4E+07		–	4.0E+05	–	–	3.7E+05	MJ
Heat	1.2E+06	–	1.0E+07	–	2.2E+07	–	–	MJ
Installation and assembly (onshore and offshore)								
Fluids and oils	2.8E+02	1.1E+03	1.2E+03	4.1E+00	5.2E+02	–	–	tonnes
Metals	–	–	–	–	–	–	1.3E+00	tonnes
Concrete, dolomite	–	1.1E+03	–	–	–	3.9E+02	–	tonnes
Plastics	–	–	–	–	–	5.9E+03	–	m
Water	6.8E+02	–	–	–	–	–	–	tonnes
Electricity	3.1E+05	–	–	–	–	–	–	kWh
Natural gas	8.5E+05	–	–	–	–	–	–	MJ
Heat	8.3E+04	–	–	–	–	–	–	MJ
Land and seabed transformation	–	4.3E+04	–	–	1.1E+03	–	7.8E+02	m^2
Operation and maintenance								
Metals (steel, cast iron, copper)	1.9E+02	–	–	–	–	–	–	tonnes
Composites	6.0E+00	–	–	–	–	–	–	tonnes
Wood and paper	3.3E-01	–	–	–	–	–	–	tonnes
Fluids and oils	6.6E+02	6.1E+02	1.6E+00	1.2E+03	8.9E+00	–	–	tonnes
Silica	7.7E-01	–	–	–	–	–	–	tonnes
Natural gas	8.3E+03	–	–	–	–	–	–	MJ
Electricity	4.6E+03	–	–	–	–	–	9.0E+02	kWh
Heat	4.8E+03	–	–	–	–	–	–	MJ
Land and seabed occupation	–	8.5E+05	–	–	–	–	1.6E+04	m^2a
Electricity production in the OWF (20 years)*	1.07 + 04	–	1.05 + 04	1.05 + 04	1.04 + 04	1.05 + 04	1.05 + 04	GWh
Dismantling (primary and at dismantling plant)								
Materials left in-situ	–	1.45E+05	–	–	2.4E+03	1.9E+01	–	tonnes
Fluids and oils	3.4E+02	1.4E+03	1.8E+03	2.7E+04	4.9E+02	–	–	tonnes
Natural gas	8.5E+05	–	–	4.0E+05	–	–	3.7E+05	MJ
Electricity	2.3E+04	–	1.5E+06	2.6E+04	3.2E+06	–	2.4E+04	kWh
Heat	1.1E+06	–	1.0E+07	–	2.2E+07	–	–	MJ
EoL								
Avoided products	1.02E+04	2.16E+04	8.74E+02	5.52E+02	3.17E+03	2.43E+01	9.42E+01	tonnes
Avoided energy (electricity & heat)	1.91E+06	–	3.2E+04	2.53E+06	1.89E+05	1.20E+03	1.13E+06	MJ
Materials to landfill**	1.69E+03	1.1E+03	–	3.07E+02	–	3.88E+02	7.84E+00	tonnes
Materials to incineration**	2.04E+02	–	2.7E+01	1.23E+02	1.04E+02	8.52E-01	4.04E+01	tonnes
Materials to recycling**	1.03E+04	2.2E+04	9.5E+02	5.68E+02	3.43E+03	2.93E+01	9.58E+01	tonnes
Transportation								
from manufacturing site to West-Flanders port and from West-Flanders port to installation site	1.3E+07	1.1E+08	5.1E+06	8.9E+04	4.3E+06	1.7E+04	1.7E+04	tkm
during operation and maintenance (from West-Flanders port to operation site OWF)	2.1E+05	–	–	–	–	–	4.4E+06	tkm
post-primary dismantling and to dismantling plant (from operation site OWF to West-Flanders port and from West-Flanders port to dismantling plant)	9.6E+05	3.1E+06	3.1E+05	1.2E+05	3.1E+05	2.8E+04	9.7E+03	tkm
to EoL treatment (landfill, incineration, recycling)	5.5E+05	9.7E+03	6.6E+03	1.2E+04	6.6E+03	5.9E+03	2.7E+03	tkm

* .The production takes place in the wind turbines but losses occur during the transportation of the electricity through the infield cables, OHVS, subsea export cable, land cable and onshore high voltage station. It was assumed that 90% of the losses occur in the infield cables and subsea export cable and 10% in the OHVS. No losses are considered in the land cable and onshore high voltage station. The electricity received at the onshore high voltage station is the *net electricity produced in the OWF* over its lifetime and expressed in GWh.

** The burdens associated with the EoL treatment (i.e. materials, energy requirements, emissions) are incorporated in the processes selected from the Ecoinvent database to model the recycling, landfilling and incineration of materials.

assuming that all of them have the same dimensions, as well as the I- and J- tubes (see Fig. 1). Finally, to protect the monopiles installed in the seabed against erosion, a scour protection system is required.

The offshore transmission system is comprised by an OHVS, infield cables and a subsea export cable. The OHVS collects the electricity produced by the wind turbines via 33 kV infield cables, and converts it for transport to shore through a 170 kV subsea export cable. The onshore transmission system consists mainly of a 150 kV land cable connected to the subsea export cable in a connection pit at the shore, which transports the electricity to an onshore high voltage station [41,58,59].

2.4.2. Installation

The installation stage was divided in two main processes: offshore installation and onshore installation. The offshore installation comprises the installed wind turbines, foundations, scour protection and offshore transmission system (i.e. cables and OHVS), whereas the onshore installation comprises the installed land cable and onshore voltage station. For the modelling of the installation of these components, information on the materials and equipment needed and the fuel consumption of this equipment was mainly compiled from primary data [58] and from Tsai et al. [41], Birkeland [59] and Arvesen et al. [61].

2.4.3. Operation and maintenance

The operation and maintenance (O&M) phase includes all activities (offshore & onshore) carried out to ensure the continuity of an OWF's efficient operation during its lifetime. For each component of the OWF, O&M activities were determined by personal communication with the concession holders and making some assumptions based on literature data to fill data gaps [41,59]. During the estimated time of operation of the OWF, there is on average a yearly electricity production of 532.761 GWh. This value was used to estimate the total electricity produced during the lifetime of the OWF (i.e. 20 years), which is approximately 10,655 GWh [58]. Losses were also included, amounting to about 2.5% [58], with a net electricity production for a 20-year period of 10,389 GWh, or 519.44 GWh per year. We have assumed that 90% of the losses occur during the transport of electricity through the infield cables and subsea export cable and 10% in the OHVS [62]. The amount of energy loss through the land cable and onshore high voltage station is assumed to be minimal and therefore omitted. Fig. S5 in Supplementary Material B shows the flow of electricity through the different OWF components is presented.

For the maintenance stage, two categories of activities were defined in this study including regular inspections and replacement of components. The regular inspections are considered for all the components except the land cable [58], while the replacement of components was only taken into account for the wind turbines.

2.4.4. End-of-life

The end-of-life (EoL) of the OWF was divided in three main stages: primary dismantling, dismantling at plant and final EoL following the work of Vanderveken [60].

Primary decommissioning offshore and onshore includes the activities and equipment needed for the initial de-installation (or removal) of the OWF components from the installation site (e.g. the removal of wind turbines using a jack-up rig vessel). To determine the equipment required and its fuel consumption for the primary dismantling, the inverse of the installation steps and auxiliaries used, was assumed [41,60]. This stage also takes into account the components or part of the components that are left in-situ both offshore and onshore. This study models a baseline scenario where the scour protection and part of the monopiles (2 m below the seabed) remain in-situ, while the remaining offshore components (i.e. wind turbines, remaining part of monopiles, transition pieces, infield cables and submarine export cable) are taken to shore.

For the dismantling stage, all the components are further dismantled into specific materials that are transported to their respective end-of-life treatments, i.e. recycling, incineration and landfill. To determine the treatment of each material from a particular component, the work of Vanderveken [60] was used as baseline. Avoided products, both materials and energy, were also considered in the model. The avoided materials correspond to recycled metals and plastics and the avoided energy to recovered heat and electricity from incineration. Processes from Ecoinvent database were used and adjusted to model the quantities of these avoided products.

2.4.5. Transportation

The transportation of the OWF components were disaggregated into five main processes: transportation to the manufacturing site, transportation to installation (offshore & onshore), transportation to shore (after primary dismantling offshore), transportation to dismantling plant and transportation to the EoL treatment.

2.4.6. Background system

The background system includes all the upstream and downstream processes that were not directly considered in the foreground system, such as the extraction and production of raw materials and their transportation, manufacturing of transportation modes (vessels or lorries), electricity and heat production, etc. Data for these processes is mainly generic and was obtained from the Ecoinvent v3.8 (cut-off allocation – unit) database. More information can be found in Supplementary Material A.

2.4.7. Quantification of the impacts with LCA_{+ES}

To model the LCA_{+ES} impacts of the production of 1 GWh of electricity delivered to the grid, the SimaPro V9.2.0.2 software was used. To quantify the endpoint results, the life cycle assessment impact assessment method (LCIA) used was ReCiPe 2016 method [63], however slightly adjusted as proposed by Taelman et al. [54]. All the midpoint categories were quantified except for land use, which was replaced by three new midpoint impact categories, i.e. "provisioning services, terrestrial", "regulating services, terrestrial" and "cultural services, terrestrial", resulting in 19 midpoint impact categories (more details in Section 1.1. in Supplementary Material B). This replacement was done to avoid any double-counting as the impacts on ESs quantified through the developed CFs were linked to land transformation and occupation as pressure. Only terrestrial ESs are considered because of a lack of CFs for seabed occupation and transformation [54].

To obtain the site-generic impacts on ESs, the CFs developed by Taelman et al. [54] are multiplied to the LCI of land transformation and occupation flows used along the value chain, extracted from SimaPro (more details in Taelman et al. [54]). These results are expressed in € per GWh for the newly developed impact categories, and categorized within the respective AoP. The results of the remaining ReCiPe 2016 method midpoint impact categories (all except for land use) are expressed in different units (see Box S1 in Supplementary Material B) . However, through the midpoint-endpoint effect pathway modelling (CFs available from ReCiPe 2016 method found in Huijbregts et al. [63]), they can be normalized and categorized in their respective AoP with specific units (i. e. AoP NR: $\$_{2013}$ per GWh; AoP EQ: species loss.year per GWh; AoP HH&WB: DALY per GWh) (more details in Section 1.1.2. and Section 1.1.3. in Supplementary Material B). To aggregate the results from the site-generic impacts on ESs with those of the ReCiPe 2016 method, the latter ones needed to be converted into $€_{2022}$ per GWh. To achieve this, economic conversion factors were used to monetize these results at the endpoint level [54] (see Box S2 in Supplementary Material B).

2.5. Local ecosystem services assessment (ESA)

As mentioned beforehand, local marine ESA studies were included in this study for the operation activities of the OWF. This section describes 1) how marine ESs were selected and 2) the methodologies used for their quantification and monetary valuation. To aggregate the results at the level of the three AoPs mentioned above, the monetized results from the ESAs have to be expressed per FU (i.e. GWh delivered to the grid). This section explains how this was achieved for each ES assessed.

2.5.1. Identifying, selecting and quantifying marine ESs affected by OWFs in the BCS

Building further on the work of Van der Biest et al. [64], Van de Pol et al. [35] provide a list of 15 ESs relevant for the BCS, regardless of human activities. The list includes six provisioning services, five regulating services and four cultural services based on the Common International Classification of Ecosystem Services (CICES) (Fig. 4). These ESs were

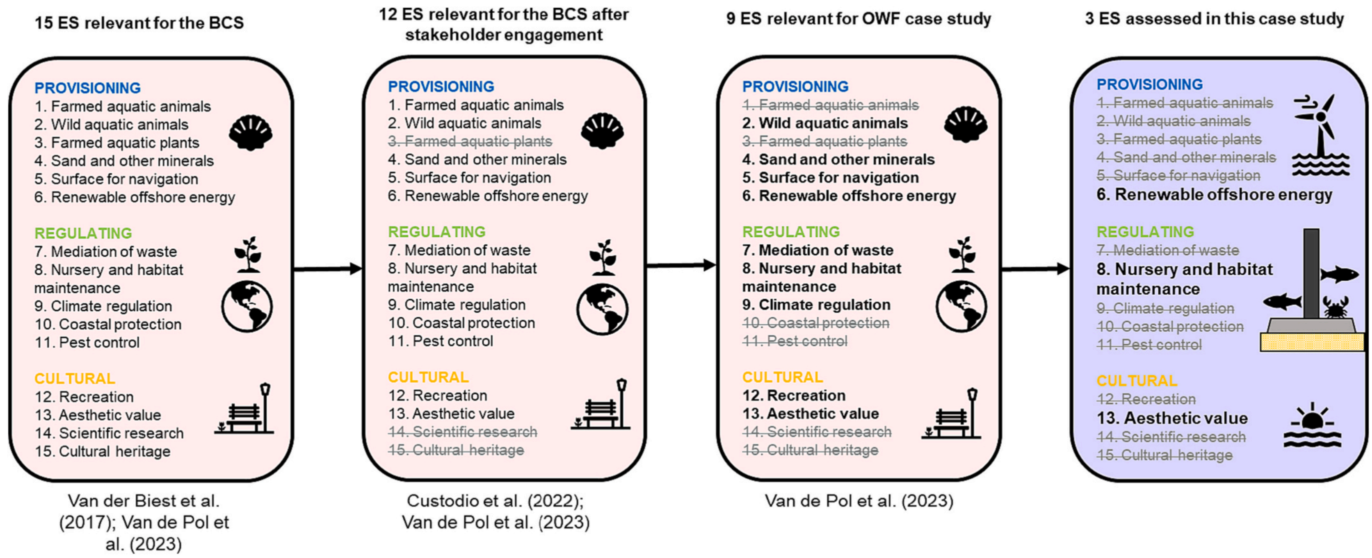

Fig. 4. Scheme showing the process in selecting relevant marine ESs services in the BCS and for this case study. The ESs were selected based on a ranking exercise with stakeholders in Belgium. The relevance of this ESs might differ depending on the location of study.

presented to a selected group of stakeholders, who prioritized the ESs based on their relevance to the BCS and OWF as an activity through a ranking exercise that led to a final list of 12 ESs (for more information, see [35]and [37]) (Fig. 4). However, not all these ESs are affected by the activity of producing electricity offshore, and for this reason, Van de Pol et al. [35] conducted a literature review and consulted experts to narrow down the list to nine marine ESs that could potentially be affected by OWFs during its operation (Fig. 4). Of this shortlist, four are provisioning ESs (wild aquatic animals, sand and other minerals, surface for navigation, renewable offshore energy), three are regulating ESs (mediation of waste, nursery and habitat maintenance, climate regulation) and two cultural ESs (recreation and aesthetic value). The recreation activities considered were wildlife watching (i.e. birds and sea mammals) and recreational fisheries. More details on the selection criteria for these ESs are found in Custodio et al. [37] and Van de Pol et al. [35].

The purpose of this study is to demonstrate the applicability of the LCA$_{+ES}$-ESA framework to a marine case study, and therefore we selected one ES per category (i.e. provisioning, regulating, cultural) for valuation. The marine ESs considered are renewable offshore energy, nursery and habitat maintenance, and aesthetic value (Fig. 4). Caution is needed in interpreting the final results, as the remaining relevant local ESs for OWFs (cfr Fig. 4; wild aquatic animals, sand and mineral extraction, surface navigation, mediation of wastes, climate regulation, recreation) are not included in this study.

2.5.2. Renewable offshore energy ES

Offshore renewable energy is an ES, but at the same time the impacts of the LCA$_{+ES}$ study are expressed per FU, i.e. 1 GWh of electricity delivered to the grid. However, the handprint of a FU is not often explicitly quantified in a classical LCA study, unlike the impacts along the value chain (i.e. focus on the negative impacts). Therefore, the LCA$_{+ES}$-ESA framework is innovative because it allows the handprint of the FU to be quantified by considering the provisioning ES of energy production.

The provisioning of renewable offshore energy was quantified by calculating the average annual electricity production of the OWF (GWh per year), see O&M in Section 2.4.3, which can also be expressed in € per GWh using the market price of electricity as a proxy indicator of how much people are willing to pay for energy produced by an OWF. To align with the system boundaries of the LCA$_{+ES}$, it is important to value this ES correctly, i.e. we need to determine how much society is willing to pay for grid-supplied electricity, which is a basic need. Therefore, distribution costs, taxes and transmissions costs of offshore wind energy should be deducted from the Flemish market price. This data (i.e. the energy cost) was obtained from the Vlaamse Regulator van de Elektriciteits-en Gasmarkt (VREG) for a Flemish household with an average electricity consumption of 1600 kWh during the day and 1900 kWh at night time between 2019 and 2022 (Table S7 in Supplementary Material B). This dataset was used to calculate an annual average market price of electricity delivered at the grid. The year 2022 was not included in the calculations because of exceptionally high energy prices due to the on-going war in Ukraine. Also, market prices up to the lifetime of the OWF are not easy to obtain given their unpredictability as it depend on e.g. the occurrence of international wars or the degree of increase of future electricity demand because of the electrification of transportation vehicles [65]. These high energy prices in Flanders are mainly due to the way the EU energy market operates. The EU electricity market is based on a system of marginal prices, in which electricity producers receive the same price for the energy they sell. In this system, the electricity produced by the plants with the lowest marginal costs (i.e. the cheapest power producers) is bought first, and the most expensive offers are at the end of the queue. At the end, when demand is meet, the price is determined by the most expensive energy source, in this case natural gas produced in Russia [66] (see Box S5 in Supplementary Material B for more details on the calculations).

2.5.3. Nursery and habitat maintenance ES

To quantify the nursery and habitat maintenance, indicators such as nursery areas or spawning areas (km^2 nursery area), habitat diversity (No. habitats per km^2), change in recruitment in adults (%), among others have been proposed [67]. Nevertheless, data availability to assess these indicators was limited, e.g. GIS layers for mapping nursery grounds were not found. Therefore, *juvenile fish density* (individuals km^{-2}) was used as a proxy indicator for the creation of a new nursery ground or habitat [68].

To study and quantify the changes in the ES nursery and habitat maintenance due to the presence of an OWF, the methodology of Blandon and Ermgassen [69] was adapted. This approach first quantifies the change in *juvenile density* (i.e. density of individuals younger than one year) due to OWF for different fish species. The next step is to determine the potential recruitment enhancement of fish biomass (i.e. transitioning of these six-month old fish to become an adult population and thus potential catch) given the initial effect of OWFs on the juvenile individuals [68].

One of the first steps is to identify relevant fish species whose nursery grounds overlap with or are close to the OWF. These valuable nursery locations in the North Sea and BCS were identified using the graphs of Judd et al. [70] and Maes et al. [71]. Other selection criteria included are the economic importance of the fish and how accessible and/or available the data is for certain species. Finally, the fish species selected, based on the criteria mentioned beforehand, were Common sole (*Solea solea*), European plaice (*Pleuronectes platessa*), Atlantic cod (*Gadus morhua*), Whiting (*Merlangius merlangus*), European sprat (*Sprattus sprattus*) and Lemon sole (*Microstomus kitt*). Despite *whiting* not having a nursery ground but a spawning ground in the norther edge of the BCS, it was included in the analysis due to the potential edge effects of OWFs [72].

A next step is to estimate the changes in juvenile fish density (ind/km^2/year) (i.e. for individuals less than one year old) in the area around the OWF both before and after its presence. A dataset of bottom trawl samples from Vandendriessche et al. [72] was used for the years 2005 to 2013 and sampled in the Bligh Bank and Thornton Bank to study the effects of OWFs. For this analysis, samples taken in the surroundings of the Bligh Bank area were considered. From this data, the juveniles were filtered based on their length. The mean length of one-year-old individuals for each fish species was found in published graphs from the International Council for the Exploration of the Sea (ICES) fact sheets [73]. This information was used to exclude data points relating to fish from one year onwards. We assumed that the retained data points represent six-month old fish following the reasoning of Blandon and Ermgassen [69] [68].

The change (Δ) in the density of six-month (or half-year) old fish ($N_{0.5}$) was used to calculate the proportion of individuals that survived their first year of life or became adults to age class $\boldsymbol{i}$, obtaining the density enhancement for each age class $\boldsymbol{i}$ and fish species $\boldsymbol{j}$ using the following equation: $N_{ij} = N_{0.5j}{*}e^{\left(-M_j{*}(i-0.5)\right)}$, where N_{ij} is the density enhancement for age class I and species j (ind age I km^{-2} $year^{-1}$), $N_{0.5}$ the change in abundance of six-month year old juveniles after the OWF installation (individuals age 0.5 km^{-2}) for species j, I is the age class and M_j the natural mortality of species j [68].

To obtain the total annual production and express the enhancement in kg m^{-2} $year^{-1}$, the von Bertalanffy growth equation is used to estimate the average length of a fish for each age class up to the maximum age that a fish can reach. After obtaining the average length, this value is used to calculate the average weight of a fish for each age class using a length-weight relationship equation. All life history parameters required for these equations were obtained from FishBase [74] and the ICES fact sheets for each species [73]. We chose life history parameters of studies conducted in the Southern North Sea, or if these were not available, we considered data from the North Sea in general. Finally, the total annual enhancement of a species (kg km^{-2} $year^{-1}$) was calculated by summing the incremental increase in weight and then multiplying by the density (N_i) for each age class [68]. More details on the parameters and equations used can be found in Table S8 and Box S3 in Supplementary Material B.

To evaluate the economic value (€ km^{-2} $year^{-1}$), the annual increase or decrease in fish weight (for each weight class) was multiplied by the annual average market price of each fish species (€ kg^{-2}), which indicates the value of the additional or reduced fish biomass available to the fishery as a result of the installation and operation of an OWF. Market prices were obtained by calculating the annual average of prices published by the Vlaams Centrum voor Agro- en Visserijmarketing and the Department Landbouw & Visserij of the Flemish government between the years (2007–2020) [75–77]. A list of market prices for each species is shown in Table S9 in Supplementary Material B.

To connect this ES to the FU, the entire area occupied by the OWF in the BCS was assumed to have potential for nursery and habitat maintenance enhancement or diminution. Furthermore, the OWF has an annual average net electricity production of 519 GWh. From this, a conversion factor of 30 GWh km^{-2} $year^{-1}$ was obtained and applied to express the value of this ES in € per GWh delivered to the grid.

2.5.4. Aesthetic value ES

The impact on aesthetic value due to the presence of an OWF is difficult to quantify because the literature does not address the impact of existing OWFs, but is rather prospective in the sense that it focuses on characteristics of OWFs such as size or distances to shore, which can be optimized when installing an OWF to minimize the impact on this ES.

The study by Wen et al. [78] is a recent paper that examines the visual impacts of wind farms (onshore and offshore) by quantifying the willingness-to-pay (WTP) for seascape/landscape maintenance (€ per household per year) through the development of meta-analytic functions based on several individual studies. Similarly, Mirasgedis et al. [79] also conducted a meta-analysis to compare their WTP results with other studies. The studies considered in Wen et al. [78] assessed, for instance, how WTP changes against different attributes such as the distance of wind farms to residential areas, height of wind turbines and number of wind turbines. We examined this paper to determine if the integral function developed to quantify the WTP linked to the attribute 'distance to shore' could be used as an indicator of the OWFs visual impacts (more details on how this was done is found in Box S4 in Supplementary Material B).

The function of Wen et al. [78] provides numbers on the WTP to move an OWF further offshore, and results show that people are willing to pay less to move OWFs near the shore further away and willing to pay more for OWFs that are already located offshore (see Fig. S6 in Supplementary Material B). These results are perceived illogic because OWFs located close to shore should be linked to a higher WTP. For this reason, we decided to look deeper into the cited sources used by Wen et al. [78] to determine exactly what attributes these studies assess. It turned out that the studies did not consider distance as a single attribute, i.e. the scenarios for the choice experiments were based on multiple attributes (e.g. distance, height of wind turbine, size of wind farms, changes on electricity bills, type of energy sources), and they focused mainly on prospective scenarios (i.e. to optimize wind farms that *are planned to* be constructed). Therefore, it seems neither Wen et al. [78], not the original cited sources contained the correct information to be used in the context of this study. More detailed information on this sources is found in Table S10 in Supplementary Material B.

Among the sources used by Wen et al. [78], we found the study of Ladenburg and Dubgaard [80](2007) where they determined that, many days throughout the year, turbines are indistinguishable at distances even lower than 50 km due to weather conditions, and thus the visual impact would be negligible. Since the OWF in our case study is located approximately 35–55 km offshore, we assume that the impact on the aesthetic value is negligible. Even though this study considers this ES as negligible, it proposes a method for a proper quantification. To achieve this, additional research is needed, i.e. choice experiments should be conducted focusing on only offshore wind farms and individual attributes, time should be invested to collect valuable data for the attributes considered in the assessment. Moreover, when conducting these studies, attention should be given to the sociological aspects linked to the perception of the individuals answering the questionnaires in these choice experiments.

2.6. Aggregation of results to handprint and footprint

The results in Section 2.4 and Section 2.5 are aggregated to obtain the total monetized handprint (benefits) and footprint (burdens) of an OWF per AoP (i.e. all units are expressed in $€_{2022}$ per GWh) (see Fig. 2 and Section 3.1 in Supplementary Material B). As explained by Taelman et al. [54], in ESA, a positive and negative value correspond to a handprint and a footprint respectively, while in LCA_{+ES}, the opposite happens (i.e. positive values are burdens and negative values are benefits). For visualization purposes, the handprint is displayed as a positive effect (positive Y-axis) and the footprint as a negative effect (negative y-axis). Therefore, for the results of the LCA_{+ES}, the sign of the values has been changed to avoid misinterpretation.

2.7. Benchmark

To have a comprehensive understanding of the (socio-) environmental performance of an OWF, it can be compared to a relevant reference, i.e. an alternative energy source. Because of its historical and current importance for electricity supply in Belgium in recent years, nuclear energy is depicted as a benchmark to provide some insights into the difference in performance with OWFs from the perspective of (socio-) environmental impacts. Today, according to IEA [81], almost half of Belgium's electricity generated is provided by nuclear energy plants. The federal government in Belgium has plans to largely phase-out nuclear power plants by 2025, raising concerns about the country's energy security, as nuclear energy still accounts for the largest share of the Belgian electricity mix (i.e. 39% in 2020) [81,82]. Phasing out nuclear power could lead to a return to fossil fuels, reducing the possibility of achieving climate neutrality goals. In addition, nuclear energy is also considered a key source in the clean energy transitioning at the global level [6]. For these reasons, nuclear energy is considered a relevant benchmark, and the nuclear plant Doel in East Flanders (Belgium) was selected to conduct the analysis (more details on selection criteria in Section 4.1.1. in Supplementary Material B). This plant has four reactors installed between 1975 and 1985 with a total installed capacity of 2935 MW and covers an area of 80 ha. Since September 2022, one of the reactors has been shut down permanently to comply with the Belgian federal government's phase-out plans [83,84]. More details in Table S14 in Supplementary Material B.

2.7.1. Benchmark: LCA_{+ES}

Secondary data was used from a process in Ecoinvent v3.8 (cut-off allocation – unit) (i.e. electricity production, nuclear, pressure water reactor BE) as a proxy for the Doel plant. This process represents the production of electricity by a 1000 MW nuclear power reactor and includes the materials and auxiliaries, energy requirements, emissions and wastes generated (e.g. this process includes the transport, treatment and storage of spent nuclear fuel) during the construction of a power plant up to the production of 1 GWh of electricity delivered to the grid. We have assumed that the impacts per GWh of a 1000 MW plant are similar to those of a 2935 MW plant, as Doel has two 1000 MW reactors, but also two 450 MW reactors, which can be considered as one. Since data on the EoL of the nuclear power plant is limited, we have studied the value chain of nuclear energy from cradle-to-gate. Similar boundaries are used for the OWF case study when comparing (socio-) environmental impact results (see Fig. 5).

To quantify impacts we followed the steps outlined in Section 2.4.6. As with the OWF case, we do not have sufficient local ESA studies along the value chain, and therefore we follow the same steps in applying the CFs to quantify site-generic effects on ESs due to land use. The remaining impacts due to the nuclear plant were calculated using ReCiPe 2016 method [63].

2.7.2. Benchmark: local ecosystem service assessment (ESA)

A local ESA study was conducted to quantify site-specific effects on terrestrial ES during operation and maintenance activities of the plant. The effects were quantified using the spatially-explicit ECOPLAN toolbox (QGIS 2.18) [85], which analyses the impact on 18 ESs, relevant in Flanders (Belgium), due to changes in land use [86]. On top of these 18 ESs, the provisioning of electricity by the nuclear power plant was also calculated by estimating the average annual electricity production, which is 18,618.6 GWh per year for four reactors (Table S15 in Supplementary Material B) and expressed in € per GWh using the market price of electricity in Flanders (Belgium). There is no difference in the market price of electricity produced by an offshore wind farm or a nuclear power plant in Flanders because the price is determined by the most expensive type of energy, as explained in Section 2.5.2 [66].

The ECOPLAN tool has a geodataset that contains all the data needed for the quantification, e.g. land covers, land use, ESs specific maps, population densities [86]. To quantify the changes on the ESs, we first had to determine land cover before and after the installation of the nuclear plant. Before the installation, i.e. 1975, the area was agricultural (i.e. polders) and in the current situation, using the year 2015 as reference, the area consists of paved surfaces, buildings and low vegetation (mostly grass). More details on the application of the tool can be found in Section 4.1.3 in Supplementary Material B.

A similar approach as the OWF case was taken by selecting one ES per category (i.e. provisioning, regulating and cultural) for calculating the handprint and footprint in the benchmark assessment. The ESs

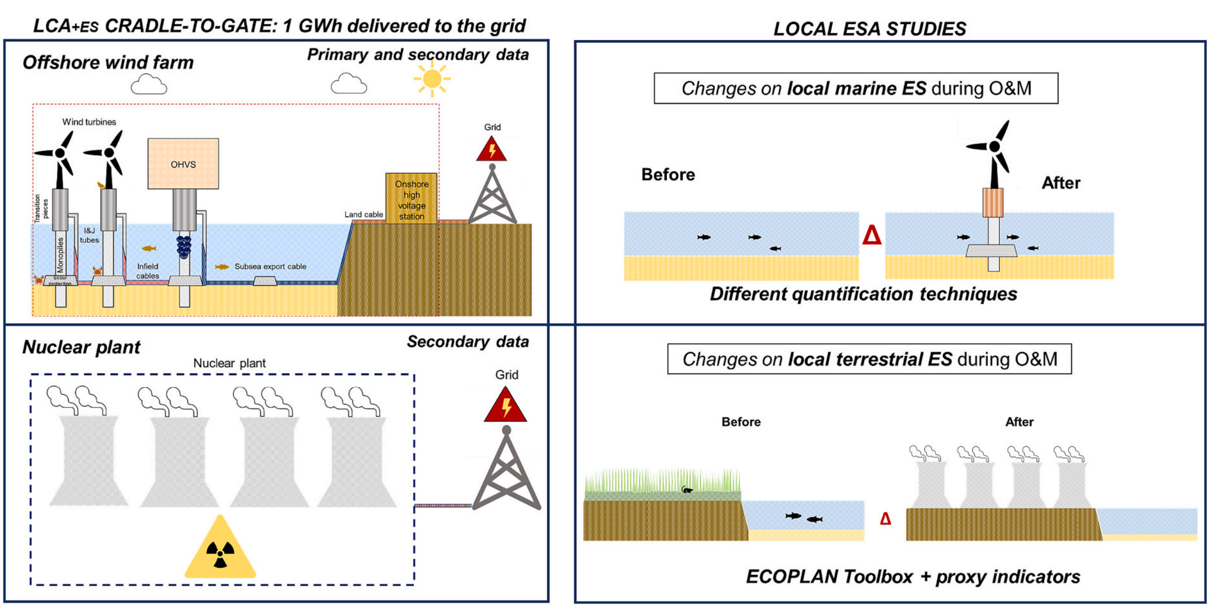

Fig. 5. This figure shows the system boundaries (cradle-to-gate) for the OWF in the BCS and the nuclear power plant in Belgium (LCA_{+ES}). The FU is 1 GWh delivered to the grid. The local ESA studies evaluate changes on local marine ESs and terrestrial ESAs during the O&M stages of the OWF and nuclear power plant, respectively.

selected should be quantifiable, monetizable and relevant, and if possible have a similar functionality as the local marine ESs. Based on these criteria, the ESs selected were: abiotic (i.e. nuclear) supply of energy (provisioning ES), soil carbon sequestration (regulating ES) and recreation and tourism (cultural ES). As explained earlier, the provisioning ES was calculated in the same way as the OWF (Table S15 in Supplementary Material B), while soil carbon sequestration was quantified using the ECOPLAN toolbox. For technical reasons, the recreation ES could not be quantified with ECOPLAN, so a proxy was used to quantify it in in a site-generic way. To this end, the ESVD was used to obtain the value of this ES for inland wetlands, under the assumption that this biome have similar characteristics to polder areas. The value of this ES had been converted to €/ha/year by Taelman et al. [54] and we assumed that this is the potential value for the recreation ES if left undisturbed. Following the methodology of Taelman et al. [54], a characterization factor for occupation was developed by calculating the difference between its reference (i.e. undisturbed ES) and occupied area with new land use (i.e. urban/industrial area). It was assumed that urban/industrial areas have no ES value. The CF was then multiplied by the LCI flow (i.e. the area occupied by the plant times the plant's years of operation) to obtain the total impact in €/GWh. More details can be found in Box S6 in Supplementary Material B.

3. Results

Two main groups of results are presented in this section, i.e. the (socio-) environmental impact assessment conducted only for the OWF (Section 3.1, Section 3.2. and Section 3.3) and for the benchmark analysis (Section 3.4). These main groups of results comprise: 1) the results of $LCA_{+ES,}$ (Section 3.1,1, Section 3.1.2, and Section 3.4.1), 2) the results of the local ESA studies (Section 3.2 and Section 3.4.2) and 3) the integrated results of the LCA_{+ES} and ESA (LCA_{+ES}-ESA) (Section 3.3. and Section 3.4.3). Positive impacts (benefits) are *handprints* while negative impacts (burdens) are *footprints*. The net impact, on the other hand, are the benefits from which the burdens are subtracted, which can result in an overall *net handprint* or *net footprint*.

3.1. LCA_{+ES}: *impacts of adapted classical LCA for OWF case study*

The results from LCA_{+ES} include the hotspot analysis from the classical LCA, using the ReCiPe 2016 method to quantify the impacts and the site-generic impacts on ESs due to land use obtained by applying the newly developed CFs by Taelman et al. [54].

3.1.1. *Hotspot analysis (ReCiPe results)*

The endpoint classical LCA impact results (cradle-to-grave) obtained with ReCiPe 2016 method are shown in Supplementary Material B, except for the land use impact category, which was replaced with the new ESs midpoint categories [54]. The impacts are the handprint derived from the avoided products and the footprint derived from the impact category results.

The handprint per FU (GWh) of avoided products (materials and energy) can be found in Table S1 in Supplementary Material B. The AoP HH&WB had the largest benefits from avoided products (+€2060.3), followed by the AoP NR (+€455.1) and the AoP EQ (+€207.4). The processes that contributed most to the benefits of avoided products are attributed to the production of steel (steel low-alloyed, chromium steel and galvanized steel). On the other hand, the footprint per FU (GWh) for each AoP is -€2707.9, −€299.4 and -€931.9 for the AoPs HH&WB, EQ an NR respectively (see Tables S2, S3, S4 and S5 in Supplementary Material B). As a final net result, we arrive to a *footprint* of -€1216.4, of which 50% is attributed to the AoP HH&WB (−€647.5), 40% to the AoP NR (−€476.8) and 10% to the AoP EQ (−€92).

At an impact category level, the categories that contributed the most to the impacts along the value chain were fine particulate matter and global warming (human health) for the AoP HH&WB, global warming (terrestrial ecosystems), terrestrial acidification and ozone formation (terrestrial ecosystems) for the AoP EQ and fossil resource scarcity for the AoP NR (Tables S2, S3 and S4 in Supplementary Material B).

At a process level, the processes that contributed the most to all three AoPs were related to the primary and secondary materials required to manufacture the OWF components, indicating that most of the burdens came from the supply chain (Table S6 in Supplementary Material B). The AoP HH&WB had the largest burden coming from the materials (−€3313) followed by the AoP NR (−€805) and the AoP EQ (−€355). The processes with the highest contribution to the burdens for the AoP HH&WB are attributed to the production of steel (e.g. treatment of electric arc furnace slag, pig iron and coke production), mining activities for the extraction of palladium, production of nylon 6–6 (needed in glass fiber reinforced composites, a material used in the manufacturing of blades), production of copper anodes and the production of electricity in South Africa, which is needed for the extraction of gold. For the AoP EQ, these processes were the production of pig iron, blasting for the extraction of raw materials and the production of nylon 6–6, while the for the AoP NR, these processes were the production of nylon 6–6, propylene and petroleum. Also, the process used from Ecoinvent as a proxy for transportation at sea (i.e. transportation by ferry) had a significant contribution to the net impacts along the value chain.

At the OWF component level, the impacts (i.e. without the avoided burdens) show that all components have a footprint along their value chain, with wind turbines being the highest contributor, followed by the subsea export cable, foundations, infield cables and OHVS (Fig. 6). On the other hand, most of the handprint (i.e. from the avoided burdens) is attributed to the EoL of the foundations and wind turbines, and this is mainly due to recycling. Overall, the net impacts show that along the value chain, the foundations are the only component with a handprint, while the other components have a net footprint of which the wind turbines are the largest negative contributor. The net handprint of the foundations is attributed to the way its EoL processes were modelled, i.e. part of the of the monopiles remain in-situ during its decommissioning and the part taken for treatment is recycled 100%.

Looking only at the results of the manufacturing stage per component, the foundations have the highest negative contribution to all three AoPs (−€1992), particularly to the AoP HH&WB (−€1525). Most of the impacts come from the manufacture of monopiles (70%, −€1369) and the remaining contributions are from the transition pieces (30%, −€623) (Fig. S1 in Supplementary Material B). The impacts of both monopiles and transition pieces are related to steel manufacturing processes, which is to be expected as steel is the main material used in the manufacturing of these components (Fig. S3 in Supplementary Material B). Besides the foundations, the wind turbines also have a high negative contribution to all AoPs (€-1965), linked to the manufacturing of the nacelles (60%, −€1232), followed by the towers (20%, −€360) and the blades (10%, −€265). Looking more closely at the impacts of nacelles, the results show these impacts are mainly attributed to a supply chain for gold (i.e. global average of gold production) (40%, −€489), followed by the production of chromium steel in Europe (20%, −€259) and a supply chain for palladium (i.e. global average of palladium production) (10%, −€168) (Fig. S2 in Supplementary Material B). Gold and palladium are needed to manufacture electrical equipment for the nacelle, as mentioned in Supplementary Material A.

3.1.2. *Site-generic impacts on ecosystem services*

The results, expressed in $€_{2022}$ per FU show that all the categories of ESs (provisioning, regulating and cultural) undergo burdens, with the AoP EQ (regulating ESs) having a slightly higher net impact (−€41.4) compared to the AoP NR (provisioning ESs, −€36.6) and AoP HH&WB (cultural ESs, −€21.6) (Fig. S4 in Supplementary Material B). Most of the impacts of the regulating ESs come from intensive occupation on forest and also from occupation in mineral extraction sites, which mainly impact ESs such air quality regulation, climate regulation and regulation of water flows.

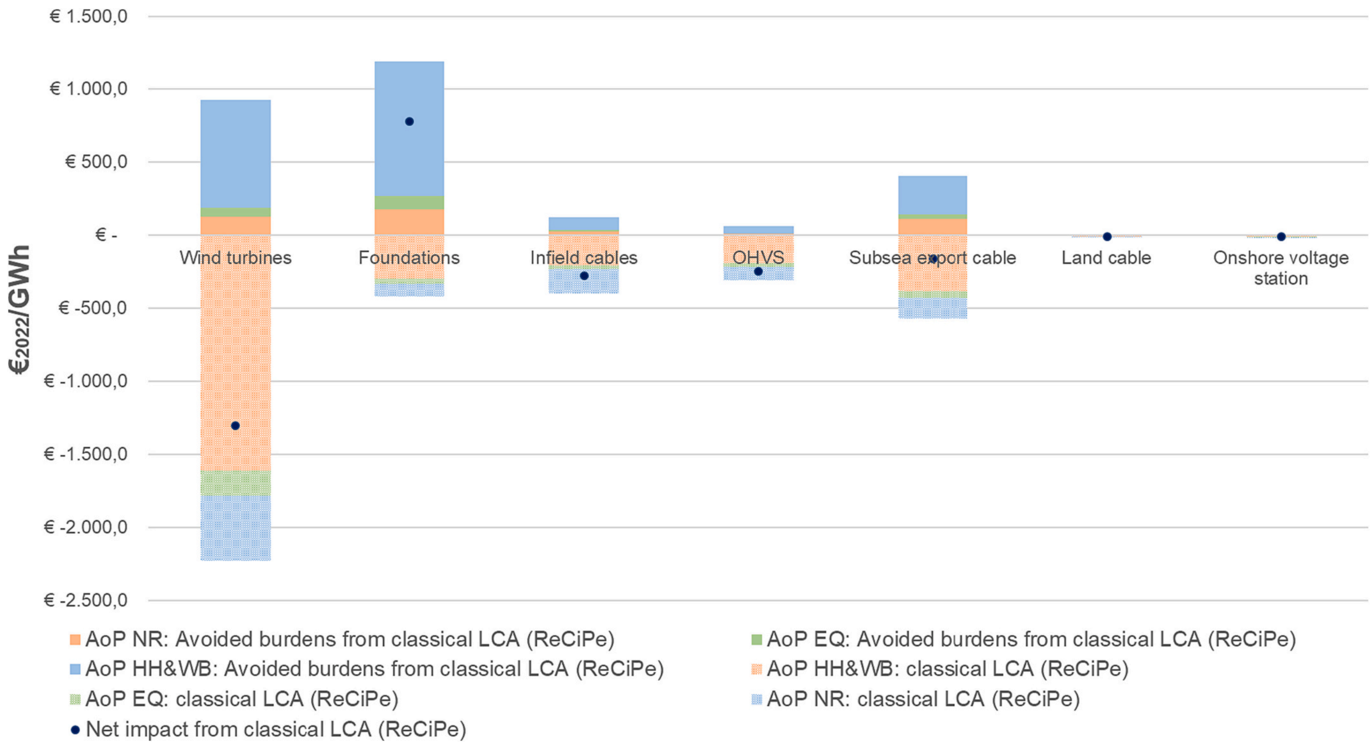

Fig. 6. Monetized handprint and footprint of the components of an OWF along its value chain. The handprint is associated to the avoided burdens (ReCiPe 2016 method) and the footprint to the burdens quantified with a classical LCA (ReCiPe 2016 method). The net impact from the classical LCA are depicted for each OWF component as blue dots. The results are expressed in € per GWh. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Local marine ESAs (site-specific impacts) for OWF case study

The results for the three ESs renewable offshore energy, nursery and habitat maintenance and aesthetic value are presented in Supplementary Material B (Box S15 Table S11 and Table S12), as well as the background calculations. The provisioning ES, renewable offshore energy, provided a significant positive value to human well-being (+86,500 € per GWh), followed by the nursery and habitat maintenance ES (+12.01 € per GWh). As explained in Section 2.5 given the distance of the OWF from the coast (i.e. 35–55 km), we considered the impact on the aesthetic value ES negligible.

3.3. Integrated LCA$_{+ES}$-ESA results for OWF case study

The results from the LCA$_{+ES}$-ESA correspond to the sum of the handprint and footprint from LCA$_{+ES}$ (i.e. ReCiPe results in Section

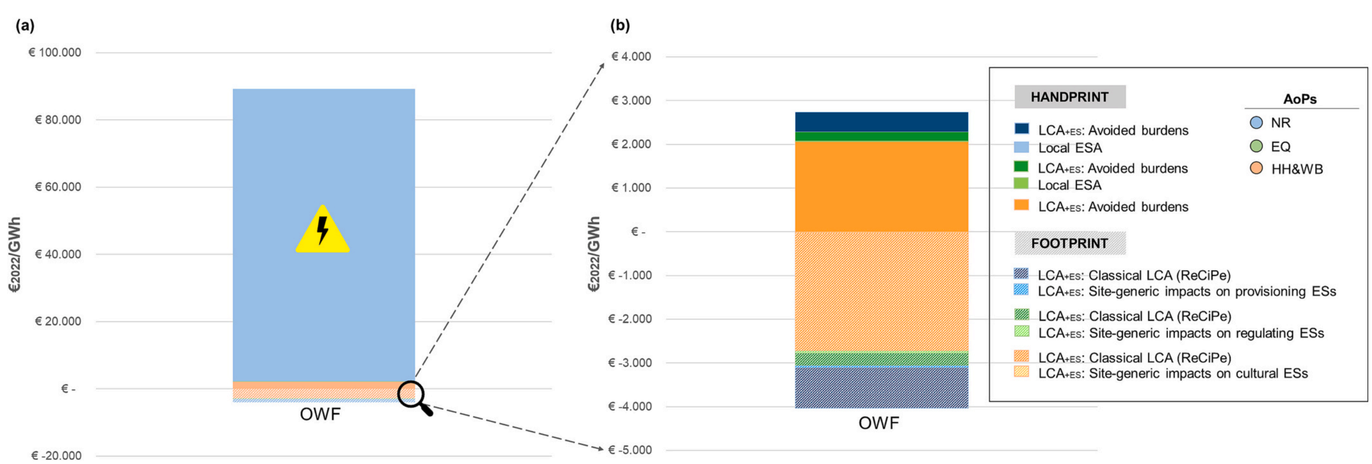

Fig. 7. Quantification of the handprint and footprint of an OWF. The handprint is depicted with colours that have a solid fill, while the footprint have a dashed fill. (a) LCA$_{+ES}$-ESA results of the OWF (cradle-to-grave), the largest handprint comes from the FU (i.e. local ES wind energy provisioning). Due to the large handprint of the AoP NR, the handprint and footprint of the AoP EQ is not very visible. (b) Handprint and footprint results of the OWF excluding the handprint of the FU. These results comprise the handprint and footprint of LCA$_{ES}$ (i.e. ReCiPe results and site-generic impacts on ESs) and the local marine ESs on each AoP. The impacts on the AoP NR, AoP EQ and AoP HH&WB are depicted in blue, green and orange colours respectively. Most of the handprint of LCA$_{+ES}$ is attributed to the avoided burdens, while the footprint to the ReCiPe results affecting particularly the AoP HH&WB. All the site-generic impacts on ESs are footprints. In Fig. 7b, the handprint value for the local ESA in the AoP EQ (i.e. nursery and habitat maintenance) is below 15 € per GWh, hence cannot be properly visualized. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.1.1. and site-generic impacts on ESs in Section 3.1.2) and ESA (local marine ESAs in Section 3.2). As shown in Fig. 7a,b and Table S13 in Supplementary Material B, the e handprint (+€89,235) of an OWF is much larger than its footprint (−€4039) to deliver 1 GWh of electricity to the grid. This results in a net handprint of +€85,196 for the OWF. This large handprint is mainly attributed to the AoP NR because of its FU, which is also the local ES renewable offshore energy.

If we remove the handprint from the FU, we can better see which results are attributed to the footprint and also to the handprint next to the FU. Within the AoP NR, the handprint partly consists of the beneficial impact of the avoided burdens, while the footprint is mainly attributed to the adverse impacts coming from the value chain (i.e. classical LCA results without land use impact category) and a small part to site-generic impacts on ES due to land use (i.e. new midpoint impact categories). The handprint in the AoP EQ is again mainly attributed to the avoided burdens and a minor part to the local ES nursery and habitat maintenance. As in the AoP NR, the footprint is mainly derived from the classical LCA results. Finally, the AoP HH&WB has the largest handprint related to avoided burdens compared to the other AoPs. There is no contribution from the local ES aesthetic value. In terms of footprint, the AoP HH&WB also has the largest footprint, which also mainly consists of the classical LCA results.

3.4. Comparison OWF and nuclear power plant: benchmark results

3.4.1. Results of LCA_{+ES} for the benchmark

3.4.1.1. Hotspot analysis. As mentioned in Section 2.7, the system boundaries for the benchmark study are cradle-to-gate, as the EoL data for the nuclear power plant is limited. The cradle-to-gate results for the OWF are not much changed from the cradle-to-grave results, as the largest contribution to the impacts is made by the manufacturing stage (83%) and to a lesser extent by the transport impacts (11%), installation stage (3%) and O&M stage (3%). Overall, the results from ReCiPe 2016 method (without land use impact category) show that the OWF adverse impacts are larger than the ones for the nuclear plant (see Table S17 in Supplementary Material B), especially for the AoP HH&WB (2 times larger), followed by the AoP NR (2.2 times larger) and AoP EQ. (1.1 times larger). The processes that made the largest contribution to the adverse impacts of the nuclear plant are the decarbonization of water, combustion of diesel and production of uranium for the AoPs HH&WB and EQ, and the use of natural gas and production of petroleum for the AoP NR. The contribution of spent nuclear fuel to the AoP HH&WB was smaller compared to the decarbonization of water, but it did contribute a lot to the ionizing radiation impact category, which is a subcategory of HH&WB. Overall, the most affected impact categories were fine particulate matter followed by water consumption (human health) for the AoP HH&WB, global warming (terrestrial ecosystems) and water consumption (terrestrial ecosystems) for the AoP EQ, and fossil resource scarcity for the AoP NR. The impacts of the nuclear power plant expressed per FU (GWh) for each AoP are $2.8E^{-02}$ DALY, $7.1E^{-05}$ species.year and $7.2E^{+02}$ $\$_{2013}$.

3.4.1.2. Site-generic impacts. The results show that neither the OWF nor nuclear power plant have beneficial impacts on ESs due to land use. The OWF has a larger adverse impact on the three ESs categories (i.e. provisioning, regulating and cultural) than the nuclear plant (Fig. S9 in Supplementary Material B), particularly on the regulating ESs (−€177.85), followed by the provisioning ESs (−€151.3) and cultural ESs (−€104.21). For the nuclear plant, the most affected ESs are the provisioning ESs (−€74.8), followed by the regulating ESs (−€56.6) and the cultural ESs (−€45.9). The impact of both the OWF and nuclear power plant is mainly due to intensive occupation of forests, with air quality, climate regulation and water provisioning being the most vulnerable ESs.

3.4.2. Results of local terrestrial ESAs for the benchmark (site-specific impacts)

The benchmark study considers the impact of the OWF on local marine ESs and the impacts of the nuclear plant on local terrestrial ESs. The results for the OWF are described in Section 3.2. For the nuclear power plant, . table S18 in Supplementary Material B contains the results for the three ESs selected for this study. Like the OWF, the provisioning of electricity ES has a large handprint (+86,500 € per GWh), while there is a footprint due to the remaining ESs with recreation having a slightly larger footprint (−1.38 € per GWh) than soil carbon sequestration (−1.18 € per GWh).

3.4.3. Integrated results LCA_{+ES}-ESA for benchmark

The results from the LCA_{+ES}-ESA applied to the benchmark study are visualized in Fig. 8a,b and Table S19 in Supplementary Material B. The handprint of the OWF is +€86,512 when not considering its EoL. This handprint is attributed to the AoP NR due to the FU. The nuclear power plant has the same handprint derived from the FU (+€86,500). If the FU-related handprint is removed from the overall results, it becomes clear that the OWF has the largest footprint on all AoPs compared to the nuclear power plant. Again, the footprint for both the OWF and nuclear power plant comes mainly from the classical LCIA results. The impacts on local ES due the nuclear power plant have a slight bigger contribution to the footprint compared to the OWF, which only has a handprint on the nursery and habitat maintenance ES (Table S19 in Supplementary Material B). The nuclear power plant-induced footprint on the local ES results from conversion into paved surfaces and buildings. Overall, the nuclear plant has a slightly higher net handprint (+€83,226) than the OWF (+€80,164) (note: the end-of-life phase not considered).

4. Discussion

The structure of this section is organized in the following way: Section 4.1 and Section 4.2 describe the main challenges and provides recommendation for LCA_{+ES}, and local marine ESAs studies, respectively. Section 4.3 indicates the main advantages (Section 4.4.1.) and challenges (Section 4.4.2.) of the LCA_{+ES}-ESA framework. The discussion is finalized with challenges and recommendation for the benchmark analysis (Section 4.4).

4.1. LCA_{+ES}: challenges and recommendations

4.1.1. Data availability

Despite the fact that the exhaustive LCI (cfr Table 1) is based on primary data sources, there were still data gaps and these were filled by adapting data from peer-reviewed articles or databases (i.e. Ecoinvent), which may lead to a loss of accuracy in the results and over- or underestimation of the impacts. For example, both wind turbines and OHVS have electrical equipment whose composition was not specified in the primary sources used, so we used the study of [87] as a proxy to determine the composition of electrical equipment containing gold and palladium. Based on the results, both metals appear to contribute significantly to the footprint of wind turbines despite their low quantities. In future research, it would be better to have a clearer picture of these exact quantities to obtain more robust results. Another example of data limitations are the end-of-life stages of the OWF, which include different assumptions, leading to inaccuracies. There are still many uncertainties on the final EoL treatment for all the components, the equipment used for the dismantling and also, as mentioned in Supplementary Material A, it is not known whether the scour protection and part of the monopiles will be removed completely, partially or not at all (remaining in-situ). More data is needed to reduce the risk of underestimating the impacts and to increase the accuracy of the results.

4.1.2. Modelling of impacts with LCA_{+ES}

Conducting the LCA required several model choices that may affect

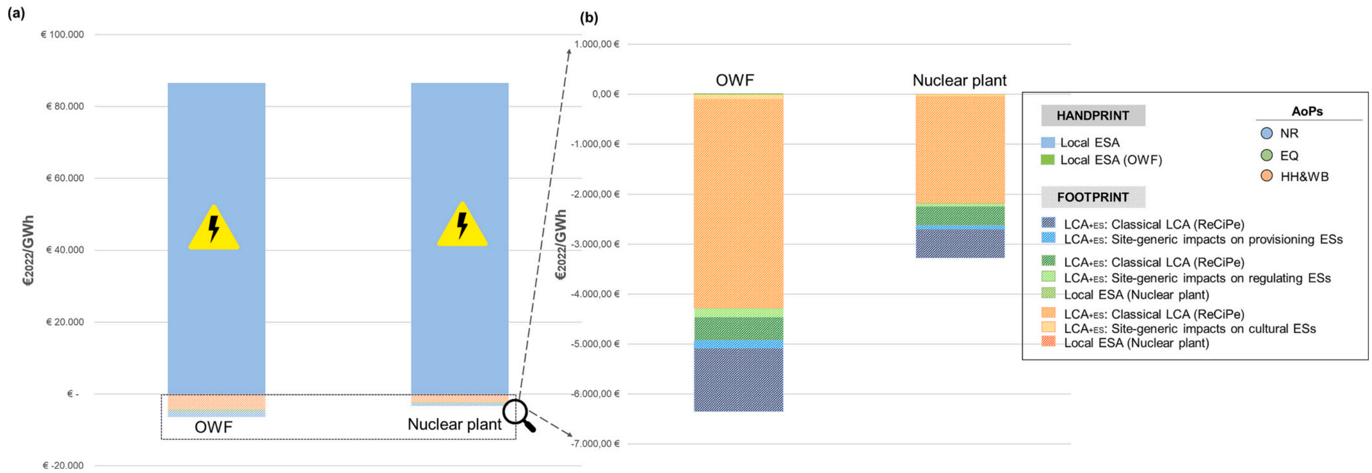

Fig. 8. Quantification of the handprint and footprint of an OWF and nuclear power plant. The handprint is depicted with colours that have a solid fill, while the footprint have a dashed fill. (a) LCA_{+ES}-ESA results of the benchmark study (cradle-to-gate), the largest handprint for both the OWF and nuclear plant comes from the FU (i.e. the local ES energy provisioning). Due to the large handprint of the AoP NR, the handprint and footprint of the AoP EQ is not very visible. (b) Handprint and footprint of the OWF and nuclear power plant excluding the handprint of the FU. These results comprise the handprint and footprint of LCA_{ES} (i.e. ReCiPe results and site-generic impacts on ESs) and the local ESs (i.e. marine for the OWF and terrestrial for the OWF). The impacts on the AoP NR, AoP EQ and AoP HH&WB are depicted in blue, green and orange colours respectively. Most of the footprint of LCA_{+ES} is attributed to the ReCiPe results affecting particularly the AoP HH&WB. Since the EoL of both the OWF and nuclear power plant is not included, the avoided burdens do not contribute to the handprint as in Fig. 7b. All the site-generic impacts on ESs are footprints. In Fig. 8b, the values for the local ESAs are below 15 € per GWh, hence cannot be properly visualized. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the accuracy of the results. For example, to model the avoided materials, a 1:1 substitution ratio was assumed for recycling In reality, however, this ratio is very likely to vary and ideally the substitution ratio should be calculated for secondary materials [88]. Future research on the EoL of OWFs should take this into account to obtain more robust results on the benefits of avoided materials. Moreover, the processes used from the Ecoinvent database to model the manufacturing of materials for the OWF may be based on newer technology than was available at the time the OWF was actually manufactured, leading to an underestimation of the impacts of the OWF. Similarly, to model marine transport at different stages of life cycle, a sea ferry was used as a substitute for different type of marine vessels, which may lead to an underestimation or overestimation of transport impacts. The footprint associated with the foundations is also expected to increase or decrease if the monopile is removed completely. In our model part of the monopile is left in-situ meaning that not the entire foundation is taken to its EoL treatment so these burdens (including transport) are not taken into account (see mass balance of foundations in Supplementary Material A), but at the same time the avoided products could be larger because there is more avoided material (i.e. more recycled steel). Impacts were physically allocated based on mass, but this could be improved in future research by performing, for example, an economic allocation.

Moreover, it should be noted that the site-specific effects on ESs presented in this study are the net results. When modelling the avoided materials and energy, there is also avoided *land use*. Ideally, land use and transformation for each avoided product (both materials and energy) should also be linked to the CFs developed by Taelman et al. [54] to calculate changes in ESs supply. However, as the site-generic impacts on ESs were not significant in the overall handprint and footprint of the OWF (see Fig. 6 and Section 2.3.4), the site-generic ESs changes due to land use of the avoided products were considered negligible in this study.

4.2. Local ESAs: challenges and recommendations

4.2.1. Data availability

For the renewable offshore energy ES, the Flemish market price of electricity (without taxes, distribution and transmission costs) was available but only for the years 2019–2022. Similarly, for the nursery and habitat maintenance ES, the dataset used to quantify the fish juveniles before and after the OWF installation had a short temporal coverage (i.e. 2005–2013) and the sampling was not continuous. To increase the accuracy of the results for both ESs, a continuous dataset covering a longer period is preferable. As mentioned in Section 2.5.4, visual impacts on aesthetic value are usually quantified in the literature at the time OWFs are planned (i.e. they investigate individuals' preference on the attributes of a potential OWF), without studying the impacts of already installed OWFs (i.e. during their operational stage), which are very likely to be different than the ones during the planning and construction phase. Moreover, these studies are designed to evaluate a combined effect of multiple attributes (e.g. distance, size wind farm, height turbines), some of which are no longer relevant in this case study because they cannot be changed (i.e. the OWF is already installed hence its distance to shore, size or height of turbines cannot be changed). Due to these limitations, this study does not have the appropriate data for the quantification of the impacts on this ES during the operation and maintenance of an offshore wind farm. It is therefore recommended that future research should focus on a single attribute and take into account the fact that an OWF is already installed far from the coast. Moreover, since the impacts of OWFs on the aesthetic value are site- and context-dependent, it would be interesting in a future work to apply this framework to an OWF case study whose location is nearer to shore and its seascape is more diverse.

4.2.2. Modelling of impacts with local marine ESAs

In particular, for the nursery and habitat maintenance ES, we first needed to understand what is really causing changes on this ES. OWFs can affect the nursery ES by becoming nursery ground areas (i.e. what we consider in this study) or by influencing nearby nursery grounds, e.g. becoming a spawning ground where larvae thrive and then migrate to nursery grounds. Whether the production of biomass (i.e. spawning grounds) or the attraction of fish to the OWF causes the changes in the nursery ES is not entirely clear [89]. For Belgium in particular, the results from the 3D hydrodynamic model of Barbut et al. (2020) show that the larvae thriving in OWFs is limited for sole but not for European plaice. This could be related to the fact that the nurseries of sole in the BCS are mainly coastal and thus these populations are not much affected compared to more offshore nurseries such as those of plaice [71,90].

This study only looked at juvenile fish species, but artificial structures, such as foundations and shipwrecks, can also become nurseries for other benthic fauna such as crabs, bristle worms and sea snails [91] in the BCS. More research on this is aspect needed to arrive at a more complete quantification of the impacts on the nursery and habitat maintenance ES due to an OWF in the BCS.

Moreover, since the main purpose of this study was to test the LCA_{+ES}-ESA framework on a real marine case, only three ES were incorporated in the assessment. However, future studies in the BCS should quantify and value (i.e. monetized) the supply of all nine marine ESs as mentioned in Section 2.5 allowing to cover impacts on biophysical structures and processes such as birds, sea mammals, benthic fauna, phytoplankton, zooplankton, biodeposition, organic processes, among others (see Fig. 4 in Van de Pol et al. [35]). An ongoing research will lead to a future publication on this matter, using different types of tools such as food web, biogeochemical and bird collision risk models. However, it is possible that also other ESs are relevant for this case study. The ESs presented at the stakeholders' workshop were generic for the BCS and not an ESs shortlist based on the potential effects of particular human activity (in this case offshore wind energy) [37]. In future research, a dedicated workshop could determine a full list of potential ESs affected by OWFs, e.g. how electromagnetic fields affect fish populations and hence ESs [8,92]. In addition, in this study, the impacts on local marine ESs are associated to the operation and maintenance stage but also during other stages impacts may occur. For example, short-term effects on marine populations, biodiversity, habitats and biogeochemistry have been identified during the OWF's installation [93], which could lead to changes on ESs [34]. Also, noise disturbance has been associated to changes in behaviour (i.e. avoidance) of harbour porpoises in the BCS. Even the decommissioning of an OWF could have potential ecological impacts on the marine ecosystem and its services, e.g. the removal of artificial reef habitat may affect local marine biodiversity [94]. By incorporating additional local marine ESs and by considering the potential local impact of their impacts during other life cycle stages, we can obtain a more comprehensive result of the impacts of an OWF by allowing the quantification of any changes to the currently measurable handprint and footprint. However, if the results of those other ESs are in line with the ones currently investigated, it is expected that the overall result will not change, i.e. offshore energy will be net positive due to its high FU-related handprint. It is nevertheless always interesting to analyse it to mitigate any local effects.

4.3. LCA_{+ES}-ESA

4.3.1. LCA_{+ES}-ESA: advantages of the framework

LCA_{+ES}-ESA is a ready-to-apply framework, as demonstrated in this case study, which allows to unveil handprints or footprint of different human activities on the environment, which are not easily seen when conducting a classical LCA. For example, the positive handprint of the FU was highlighted in this study, which also is an ES (i.e. offshore renewable energy). This framework also enables the quantification of site-specific effects on ES and if there is insufficient data to quantify them, it is flexible by providing a practitioner with an alternative to quantify effects on ES in a site-generic way. This was the case in this study, where it was not possible to collect data for all the ESs along the value chain of an OWF, but only for the operation and maintenance stage, hence impacts on ESs were calculated both in a site-specific and site-generic way. By allowing the integration of these site-specific and site-generic impacts on ESs with other impacts quantified in LCA, this study is a first step towards understanding the beneficial and adverse impacts of offshore wind energy. Despite these positive aspects, the framework faces some challenges, which are outlined in Section 4.3.2.

4.3.2. LCA_{+ES}-ESA: challenges of the framework

4.3.2.1. Data availability and accessibility. As demonstrated in Section 4.1.1. and Section 4.2.1., one of the biggest challenges in applying the LCA + ES-ESA framework to this OWF case study was data accessibility and availability. This is mainly due to the high data requirements and also data gaps. As discussed by De Luca et al. [14] and Taelman et al. [54], this is one of the main challenges in attempts to integrate LCA and ESA.

4.3.2.2. Risk of double-counting. A challenge of the LCA_{+ES}-ESA framework is its inability to fully capture the multiple interrelations among LCA and ES categories due to the complexity of the impact pathways [54]. Another challenge is the risk of double-counting, for instance, the quantified and monetized results from the local nursery ES must be carefully used since they can have an overlap with other ES that are in scope, such as the provisioning service, wild aquatic animals (cfr Fig. 4, [67]). Future publications on this matter should carefully consider this risk. Also, for instance, external factors such as environmental conditions, hydrodynamic regime and even climate change may contribute to changes in fish juvenile populations, increasing the risk of double-counting [90,95].

4.3.2.3. Accounting for long-term and regional impacts on marine ESs. The impacts of OWFs on marine ESs can have spatial and temporal variations at larger scales [32]. In addition, OWFs may also have unknow larger scale effects on the marine ecosystem, e.g. how changes in hydrodynamic conditions and primary production result on changes in the food chain which can lead to impacts on the provisioning of marine ESs [96,97]. Due to this spatial and temporal fluctuations, sometimes it is difficult to discern between natural- and anthropogenic-based stressors. To be able to quantify the positive and negative long-term and regional impacts of OWFs on these ESs, further research and monitoring is required.

4.3.2.4. Site-specific and site-generic impacts on ESs. There can also be impacts of *seabed transformation and occupation* on marine ESs, but these were not considered in the LCA_{+ES}-ESA framework. Taelman et al. [54] identified the lack of CFs for marine biomes as limitation of the ESVD database. This is particularly important because this study is set in marine context, so it would be relevant to understand the effects on ESs supply due to marine use.

Moreover, there may be studies in other contexts where accounting few local ESAs for certain parts of the value chain may take a lot of time and effort, so it would be better to use the site-generic ESs calculations for the whole value chain. On the other hand, in studies, e.g. outside the European context, it would be better to rely on locals ESAs than site-generic impacts, since the CFs developed are based on the ESVD database, which is mainly built from European studies. The choice to prioritize local ESAs over site-generic impacts depends on the goal and scope of the study, as well as the tools and time available of the practitioner conducting the (socio-) environmental impact assessment.

4.3.2.5. Valuation of ES and monetization. Although monetization helps simplify the communication and interpretation of the results facilitating decision-making, it stills has several drawbacks. For instance, it is volatile and time-dependent measure, it can be subjective and there are still controversies about commodifying nature's assets. Also, the values obtained are highly dependent on the underlying valuation method, potentially over- or underestimating the impact on AoPs [54,98].

For example, a challenge for all local marine ESs, i.e. offshore renewable energy, nursery and habitat maintenance and aesthetic value was determining the (monetary) value for society. In the case of the offshore renewable energy, the market price of electricity without taxes, distribution and network cost was used for its valuation. In Belgium, the price people are paying is not defined per type of electricity but depends on the most expensive type of electricity in the energy mix [66], therefore it's difficult to differentiate what people are actually willing to pay for offshore wind energy. Other ways to value this ES could be by estimating how much people are willing to pay for electricity produced by OWFs or by using a proxy indicator based on how many people choose "green" suppliers of electricity (i.e. suppliers whose electricity mix is mainly comprised by renewable energy sources) but finding this data is difficult and time-consuming. Similarly, the market price of fish was also used to value the nursery ES, but this is an indirect way of valuing this ES and also has its limitations as it does not account for changes in price and exploitation intensity in response to fish abundance [67]. According to Liquete et al. [67], the appropriate valuation method for this ES is still under discussion and a range of methods exists, e.g. from production functions, contingent valuation to value transfer of WTP. In the case of the aesthetic value ES, though WTP seems a proper way to value for its valuation, the available studies cannot be used due to their scope and the way the choice experiments were designed (see Section 2.5.4.). If WTP is used, then choice experiments should focus only on a single relevant attribute (e.g. distance), or multiple attributes that are truly representative of the scope of the study. Other methods estimate the visual impacts of OWFs exist, for instance, the study of Gkeka-Serpetsidaki et al. [99] uses GIS tools and qualitative data (i.e. questionnaires from inhabitants) to estimate the visual impacts, but the drawback is that there is no monetary valuation.

4.3.2.6. Social and economic impacts of energy sources. Energy sources, such as offshore wind, can have social and economic impacts, for example, the potential to create tourism [100–102]. These aspects are beyond the scope of this framework, which assesses environmental and social impacts linked to ESs. The potential effects that changes in ES provision may have on society (e.g., changes in human activities, perceptions) are also outside the scope and these interactions need further research [103]. Future work should include these aspects to fully understand the sustainability of human activities, such as offshore wind and nuclear power generation.

4.4. Benchmark: challenges and recommendations

4.4.1. Data availability

As mentioned earlier in Section 2.7 no primary data was obtained for the nuclear power plant, but Ecoinvent data was used for modelling. As the Ecoinvent dataset does not contain information on the EoL of the nuclear power plant, the system boundaries of the assessment were changed to cradle-to-gate to have a fair comparison between the OWF and nuclear power plant. In September 2022, one of the four reactors in the Doel plant was permanently shut down. According to ENGIE [84], the dismantling phase, including the removal of infrastructure and radioactive materials, will begin in 2026, with an expected duration of about ten years. The footprint of dismantling a nuclear power plant is still very unclear; there are technological uncertainties and also the time-horizon of a nuclear plant's EoL is not precisely known. For example, a major challenge in the decommissioning of nuclear plants is the availability of space (i.e. geological repositories and storage facilities) to dispose radioactive waste [104]. By not including the EoL stage in the comparative assessment, the impacts of the nuclear power plant may be underestimated.

For the recreation cultural ES assessed in the benchmark, a proxy methodology was used due to a lack of available data. The conversion of landscapes to paved surfaces and buildings is expected to negatively affect the recreational experience, due to the loss of green areas. For future research, it is advised to review literature for key values, e.g. benefit transfer from other areas, to assess this ES.

4.4.2. Modelling with ecoinvent

As explained in Section 2.7, a process already established from the Ecoinvent database was chosen to quantify the impacts of a nuclear power plant. The results obtained are the aggregated results from cradle-to-gate of the nuclear power plant, but it would have been ideal to have disaggregated results to understand the contribution of the different life cycle stages (i.e. manufacturing, transport, installation, O&M) to the burdens and to have a fairer comparison with the OWF, for which results are presented per life cycle stage. According to other LCAs for nuclear power plants, uranium mining and milling processes are the main contributors to all the impact categories assessed in those studies [105–107]. Understanding whether these processes make a similar contribution to this nuclear plant would have been preferable.

Our results show that the AoP HH&WW is mainly affected by the decarbonization of water, which requires extracting water from the environment, increasing the potential for malnutrition [63]. Consequently, the impact category of water use has a larger contribution to the AoP HH&WB than, for example, the impact category of ionizing radiation, for which we might expect a larger impact. Neither Zhang and Bauer [107] nor EDF [105] presented results for the water use impact category, so we can make a comparison with our results. The study of NNB [106] included the water scarcity impact category and it appears to be one of the major contributors to the total impact, but their study does not quantify the effects of ionizing radiation. Similar to our results, Poinsott et al. [108] indicates that the impact on water use is mainly due to the reactors (i.e. water extracted for cooling). In this study, spent nuclear fuel (i.e. including treatment, storage, transport) is the largest contributor in the ionizing radiation impact category due to emissions of carbon-14. This goes in line with the results of EDF [105], but the results of Zhang and Bauer [107] show that uranium mining and milling had the largest contribution to this impact category for one of the plants assessed. In addition to this, the Ecoinvent process is for a nuclear power plant with a 1000 MW capacity, while the Doel plant has a 2935 MW capacity. While this is a good proxy because the reactors at Doel have a capacity of 1000 MW, it would be ideal to check whether there is an overestimation of impacts due to energy production efficiency and technological development. In future research, collecting primary data on the life cycle of nuclear power plants is crucial to improve the benchmark assessment.

Moreover, the process selected from Ecoinvent does not model the risk of a nuclear accident. Though the failure rate of reactor is low [109], if it ever happens, the consequences of an accident will be extremely severe on human health, and on ecosystems and its services [110]. In addition, the impacts of nuclear waste need to be properly addressed in future research. For example, the use of "space", i.e. the volume occupied in a geological repository for nuclear waste is not quantified due to a lack of CFs. Also, the risks of nuclear waste still have uncertainties as a result of epidemiological studies with limited quality or a lack of data [111]. This is something to consider when comparing the environmental performance of an OWF and a nuclear power plant, as the effects of nuclear power plants may be underestimated.

4.4.3. Selection of terrestrial and marine ecosystem services

In this study, changes on local marine and terrestrial ESs were assessed for the OWF and nuclear power plant respectively. For the OWF, three marine ESs (i.e. offshore wind energy provisioning, nursery and habitat maintenance, aesthetic value) were included in the assessment. For the nuclear power plant, three terrestrial ESs were also considered per category (electricity production, soil carbon sequestration and recreation).

The selection of ESs for a benchmark study is challenging. To determine relevant ESs for a specific study area, stakeholders' involvement and expert judgment is needed hence the relevance is case-by-case dependent [112]. These relevant ESs won't be necessarily the same for the two study areas, for example, in this benchmark study, local marine ESs are affected by the OWF, while the nuclear power plant affects terrestrial ESs. Ideally, the ESs chosen should have a similar functionality (e.g. nutrient cycling, erosion prevention, food provisioning), which was the case for the electricity production ES. However, due to lack of data and for technical reasons, this is not always possible and the ESs chosen were not the same. For example, the range of ESs that can be assessed with the ECOPLAN toolbox is large (i.e. 18), but not all ESs can be directly monetized, so other ways to do this need to be explored. For the cultural ES, the impact on aesthetic value was not quantifiable using this tool (see Section 4.4.4), so instead, the impact on the recreation ES was quantified in a site-generic way. Moreover, even if the marine and terrestrial ESs have a similar functionality (e.g. soil carbon sequestration and blue carbon sequestration), the biophysical structures (e.g. biological organisms, communities) and environmental conditions underpinning the delivery of ESs are different, which makes the comparison challenging.

In this benchmark study, the impact on the local marine and terrestrial ES had a minor contribution to the handprint and footprint of the OWF and nuclear power plant. (Fig. 6), but this could be different if more local ESs are included. For example, it would be interesting to compare the impacts on food provisioning, since both the OWF and nuclear power plant may potentially have a handprint or footprint on this ES [35]. It is therefore recommended to include more ESs in a future study, selecting them carefully, e.g. in stakeholders' or experts' workshop where both the impacts of an OWF and nuclear power plant are being discussed, to allow a fair comparison.

4.4.4. Modelling of impacts on ecosystem services

To model the impacts on terrestrial ESs due to the nuclear power plant, the ECOPLAN toolbox was used. This tool already includes relevant terrestrial ESs in Flanders, but it may be that depending on the case study, additional ESs should be quantified or that some of the ESs in the tool are not that relevant. For example, flood prevention is a river related benefit not included in ECOPLAN but it is relevant for Doel because the plant is located along the Scheldt river [113]. Due to lack of available data, it was not possible to quantify this ES. Also, thermal emissions due to cooling water releases may have potential impacts on freshwater and marine ecosystems and its services but the effect of this stressor was not quantified in this study [114–116]. Another example is the ES "house value due to green environment", which is incorporated in ECOPLAN and relates to aesthetic value. Particularly for Doel, housing and population density were already impacted in the 1960s due to plans to expand the port of Antwerp. This led to a large number of people leaving Doel and a decrease in property value [117]. Consequently, this ES is not relevant because we cannot properly discern the real impacts on this ES as a direct result of the nuclear power plant. Moreover, the nuclear power plant can also trigger potential changes on local ESs at other life cycle stages besides "operation and maintenance". For instance, the construction stage could have an impact on ESs due to stressors such as noise, dust, and increased transport of heavy vehicles.

5. Conclusions and perspectives

The comprehensive LCA_{+ES}-ESA framework developed by Taelman et al. [54] was applied to a marine human activity, specifically to a real case study of an OWF located in the BCS to study its monetized (socio-) environmental footprints (burdens) and handprints (benefits). The LCA_{+ES}-ESA framework is based on a two-layered integration of LCA and ESA to quantify both site-specific and site-generic effects on ESs. The application of this framework required extensive data collection, i.e. technological, biophysical and monetary data. This was the biggest challenge in applying the LCA_{+ES}-ESA framework, as data was not always available or accessible. It was also necessary to conduct an environmental LCA, with cradle-to-grave boundaries, to obtain the global adverse (burdens) and beneficial impacts (avoided burdens) associated with the lifetime of the OWF. For most life cycle stages, the impacts on terrestrial ESs were quantified in a site-generic way using the CFs developed by Taelman et al. [54], but for the O&M stage, the local impacts on three ESs, i.e. offshore renewable energy, nursery and habitat maintenance and aesthetic value, were quantified by conducting local ESAs. It was challenging to conduct these local studies because in some cases no clear indicator or data were available, and therefore they may be time-consuming or were not considered feasible. Monetary valuation techniques were used to aggregate the LCA_{+ES}-ESA results in three AoPs, i.e. HH&WB, NR and EQ. The results show that the OWF has a large handprint on the AoP NR, which is mainly attributed to the FU and local ES offshore renewable energy, whereas the main footprints of the OWF are associated to the classical LCA results generated by the ReCiPe 2016 method, especially on the AoP HH&WB. These burdens stem mainly from the manufacturing stage, specifically the supply chain, which are the materials needed for the manufacturing of the OWF's components indicating that this stage can be optimized in the future to reduce the burdens of OWFs .

This assessment also included a benchmark to compare the (socio-) environmental performance of OWFs with other energy sources. As nuclear power is the largest contributor to electricity generation in Belgium, this energy source was chosen as the benchmark. The results show that the OWF and nuclear power plant have almost the same handprint because the market price of electricity in the EU does not distinguish between energy sources. In terms of footprint, the OWF has almost twice the footprint of the nuclear power plant. However, these results must be interpreted with caution because the EoL of the nuclear power plant was not included in the assessment and this stage could potentially contribute significantly to the impacts. Moreover, secondary data for the nuclear power plant was used, which may deviate from the actual (socio-) environmental impacts of the Doel plant in particular. Future research should improve this to achieve a more complete (socio-) environmental impact assessment.

Despite the challenges when applying the LCA_{+ES}-ESA framework, such as data accessibility and availability, model choices, the risk of double-counting, the feasibility of local ESAs and the drawbacks of monetization techniques, this study made a valuable contribution in the application and demonstration of the LCA_{+ES}-ESA framework to a marine human activity. This framework has a very positive handprint from the OWF to be unveiled, which would not have been revealed by conducting a classical LCA that does not consider the handprint of the FU. Moreover, this study is a first step towards understanding and quantifying local to global adverse and beneficial impacts of offshore wind energy in a more holistic way to support decision-making processes and policy making. In future research, if feasible, more local marine and terrestrial ESAs should be included along the value chain to have a better integration of the site-specific effects on ESs, to achieve more comprehensive impact results of offshore wind energy. In addition to this, a sensitivity and uncertainty analysis should be conducted in a future work to have complete view of the robustness of results, which is critical in decision-making processes [118].

CRediT authorship contribution statement

Laura Vittoria De Luca Peña: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Sue Ellen Taelman:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Bilge Bas:** Writing – review & editing, Writing – original draft. **Jan Staes:** Writing – review & editing, Formal analysis. **Jan Mertens:** Writing – review & editing. **Julie Clavreul:** Writing – review & editing. **Nils Préat:** Methodology, Conceptualization. **Jo Dewulf:** Writing – review & editing, Supervision, Methodology, Funding acquisition, 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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2023.122123.

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