Life Cycle Assessment of Marine Renewable Energy Systems

A Literature Review for Environmental Sustainability Assessment of Floating Modular Energy Islands (FMEIs)

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Life Cycle Assessment of Marine Renewable Energy Systems: A Literature Review for Environmental Sustainability Assessment of Floating Modular Energy Islands (FMEIs)

Bas, B.[1*], Gervásio, H.[2], Borg, R. P. [3], Tesch, L.[2], Musarat, M. A. [3], Jiang, X. [4]

[1] Department of Civil Engineering, Istanbul Bilgi University, Istanbul, Türkiye
[2] ISISE, Department of Civil Engineering, University of Coimbra, Coimbra, Portugal
[3] Faculty for the Built Environment, University of Malta, Msida, Malta
[4] Department of Maritime and Transport Technology, Delft University of Technology, Netherlands

*E-mail: bilge.bas@bilgi.edu.tr

Abstract. Floating Modular Energy Islands (FMEIs) are modular floating structures which combine different types of renewable energy production systems. FMEIs are still at their conceptual phase; however, they promise good potential for using the limited ocean space in an efficient way to produce renewable energy. Since those systems would have different components and related materials, offshore construction/installation work and systems to transport generated energy to land, their environmental sustainability is an important aspect to evaluate, as for other existing marine renewable energy systems. Life cycle assessment (LCA) is a scientific, standardized and quantitative methodology for the evaluation of environmental sustainability and it is accepted to be compatible for the evaluation of marine renewable energy systems. This study focuses on previous applications of LCA on various marine renewable energy systems, which have the potential of being a component of a floating modular energy island. With this aim, a brief literature review on possible different components of energy islands is conducted. Offshore wind energy, tidal energy systems, wave energy converters, floating solar energy and hydrogen energy are selected to be reviewed in the study. For the literature review, a common literature screening methodology is developed with a similar keyword group except the marine renewable energy type considered. Selected papers in each energy type production technology are reviewed with reference to the main phases of a LCA study: Goal and Scope Definition; Life Cycle Inventory (LCI); Life Cycle Impact Assessment (LCIA) and Interpretation. Under each subtitle, the approaches followed are assessed covering the important aspects, methodology/criteria considered, and challenges encountered. By this way, it is aimed to generate knowledge on the LCA methodology as a guideline for the FMEIs.

1. Introduction

The global transition to renewable energy is underpinned by ambitious policies and targets aimed at reducing carbon emissions and fostering sustainable development. Governments worldwide are setting aggressive goals to increase the share of renewable energy in their power generation mix, focusing on harnessing wind, solar, and other clean energy sources. These policies are crucial for mitigating climate change and ensuring energy security for future generations (European Commission 2020).

Offshore energy plays a pivotal role in this transition, offering vast potential for generating renewable power. Offshore wind farms, in particular, have become a cornerstone of renewable energy strategies due to their ability to capture stronger and more consistent winds compared to onshore installations (European Commission, 2020). Additionally, offshore energy projects can integrate other marine-based renewable technologies, such as wave and tidal energy, creating a diversified and resilient energy portfolio (Ocean Energy Europe, 2025).

Efficient marine spatial planning is vital for the success of offshore energy initiatives. As the demand for marine resources grows, there is an increasing need for multi-use approaches that balance energy production, environmental conservation, and other maritime activities. Multi-use strategies can optimize the utilization of marine areas, reduce conflicts between different stakeholders, and enhance the overall sustainability of marine ecosystems (European Environment Agency, 2024).

Floating Modular Energy Islands (FMEIs) represent an innovative solution to address the challenges of marine space usage and renewable energy generation. These islands are modularized, interconnected floating structures that function together to produce, store, convert, and transport renewable energy (Marino, 2024; Kurniawati, 2023). Their modular nature allows for flexible deployment and scalability, making them suitable for different marine environments and energy needs.

At the moment, FMEIs are still at their conceptual phase, and it is essential to ensure that those innovative energy solutions will contribute positively to the global sustainability goals. By assessing their environmental impact through environmental LCA, we can identify and mitigate potential negative effects on marine ecosystems, resource consumption, and greenhouse gas emissions, optimize the design and operation of FMEIs to minimize their ecological footprint, and ultimately, develop more efficient and eco-friendly energy technologies.

Environmental Life Cycle Assessment (LCA) is a scientific, quantitative, and standardized methodology that evaluates the environmental impacts of products, processes, and services considering their whole life cycles (ISO, 2006). This paper explores the possible environmental impacts of FMEIs by examining previous LCA studies on different possible components of them and aims to present a comprehensive understanding of the applied LCA methodology. This is intended as the basic knowledge, in order to support the development of a specific methodology for the application of LCA for future FMEIs.

2. Materials and Methods

The study is based on a detailed and structured literature search procedure, applied to compile relevant data on the state-of-the-art of LCA of marine renewable energy systems. As the first step of the mentioned procedure, Web of Science (WoS) (https://www.webofscience.com/wos/woscc/basic-search) database was searched for publications. Based on the objectives of this study, the type of renewable energy for each renewable energy type considered as a possible component of a modular energy island is combined with Life Cycle Analysis' OR 'LCA' as the common search term format of the study (i.e. 'offshore wind*' AND 'floating' AND 'LCA or Life Cycle Analysis') (Fig. 1). Determined keywords were searched in the titles, abstracts and keywords of the scientific journal papers, which were published in the period of 1st January 2010 – 31st March 2025. At the second step, the papers obtained with this search were analysed in terms of relevance of content and non-relevant papers were excluded from further use in this study. This step is executed in three rounds by focusing on the titles, abstracts and full texts, respectively. During the selection process, review papers are also excluded. After all these rounds, the final number of papers for each renewable energy type were determined and compiled (Fig. 1).

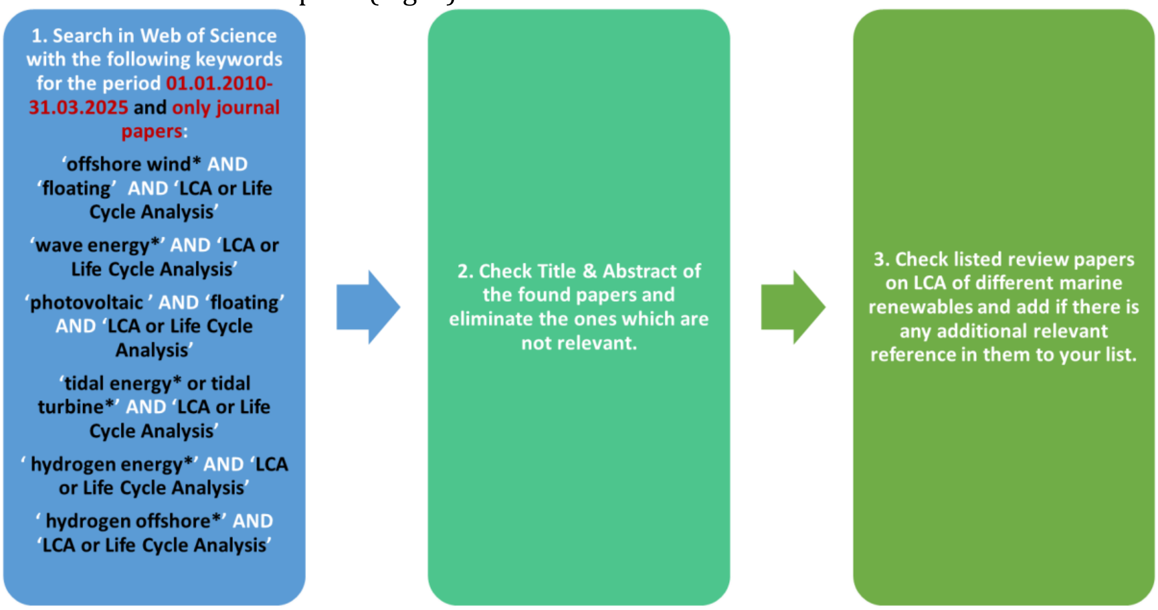

Figure 1. Applied literature review workflow in this study

3. Results and Discussion

In this section, firstly results of the conducted review for each marine renewable energy system is presented including the information related to the type of systems, main characteristics of the LCA studies, environmental hotspots and limitations & challenges. Later, a brief general evaluation of produced information is given for a more holistic look.

3.1 LCA of Floating Offshore Wind Turbines

In the energy sector, practical and robust measures are required to mitigate climate change impacts, which is why in recent times, wind power, which is a renewable energy technology, has become increasingly popular. It is also considered as a cost-efficient technology. It is essential to evaluate the environmental impact of these developed technologies even in the Operation and Maintenance (O&M) phase (Garcia-Teruel et al., 2022).

Selected papers for this review cover LCA studies executed for a floating offshore wind farm (Brussa et al., 2023; Ferreira et al., 2023; Garcia-Teruel et al., 2022; Poujol et al., 2020; Pulselli et al., 2022; Struthers et al., 2023), a deep water floating offshore wind turbine (de Paula & Carmo, 2022), a semi-submersible floating platform which combines offshore wind turbines and oscillating water column (OWC) type wave energy converters (Elginoz & Bas, 2017), onshore and offshore wind turbines (Wang et al., 2019), and a barge-type floating wind turbine (Yildiz et al., 2021; Yildiz et al., 2022).

A brief summary of selected studies focusing on the main phases of the LCA study is presented as follows:

Goal and Scope Definition: The system boundary in the majority of the gathered studies was focused on cradle-to-grave, with a useful lifetime period from 20 to 30 years. The functional unit for all the studies was a unit of electricity output except Pulselli et al. (2022) by the functional unit defined for the LCA study was 'one year of operation of a 6 MW offshore floating wind turbine, assuming a lifetime of 20 years'.

Life Cycle Inventory (LCI): The LCI was built based on primary data and background data from several databases. The Ecoinvent database was the main background data source for most of the studies, except Yildiz, Hemida and Baniotopoulos (2021), who used Gemis 5, while Ferreira et al. (2023) used a combination of GaBi Professional and Ecoinvent databases and Yuan et al. (2023) used Chinese core life cycle database (CLCD) in combination with Ecoinvent database .

Life Cycle Impact Assessment (LCIA): LCIA were conducted by using calculation of carbon emissions using on Global Emission Model for Integrated Systems (GEMIS) & database (Yildiz, Hemida, & Baniotopoulos, 2022), CML 2001 (Elginoz & Bas, 2017; Ferreira et al., 2023), EPD (version 2018), Cumulative Energy Demand (CED) (Poujol et al., 2020; Brussa et al., 2023), IPCC 2013 (Pulselli et al., 2022), ReCiPe 2016 (Poujol et al., 2020; Garcia-Teruel et al., 2022; Struthers et al., 2023), AWARE (Poujol et al., 2020) and ILCD 2011 (Poujol et al., 2020).

Interpretation: The environmental hotspots of floating offshore wind turbines are mainly related to the raw material extraction, due to the metal alloy content in the devices both in platforms and wind turbines (Elginoz & Bas, 2017; Poujol et al., 2020; Yildiz et al., 2021; de Paula et al., 2022; Garcia-Teruel et al., 2022; Pulselli et al., 2022; Yildiz et al., 2022; Brussa et al., 2023; Ferreira et al., 2023; Yuan et al., 2023), except the transportation and installation of offshore wind turbines were the main responsible of the whole GHG emissions in one study by Wang et al. (2019). In addition, assumed recycling rates are effective on the overall results considering the high amount of avoided burdens at the End-of-Life (EoL) stage (Elginoz & Bas, 2017; de Paula et al., 2022; Yildiz et al., 2021; Pulselli et al., 2022, Yildiz et al., 2022; Ferreira et al., 2023; Yuan et al., 2023).

Limitations and challenges: Ambiguity stemming from the data requires further research with more reliable and reachable executive projects to make the results more reliable (Elginoz & Bas, 2017; Wang et al., 2019; de Paula et al., 2022; Brussa et al., 2023; Yuan et al., 2023). Especially, uncertainty of the Operation and Maintenance (O&M) activities is high due to lack of operational data inventory for offshore wind turbine operations (Garcia-Teruel et al., 2022; Yildiz et al., 2022). Besides, uncertainties in foreground & background data and geographical & temporal variability are another concern (Elginoz & Bas, 2017; Poujol et al., 2020; Garcia-Teruel et al., 2022; Struthers et al., 2023).

3.2 LCA of Wave Energy Converters

The North Sea, Atlantic Ocean, Mediterranean Sea and Black Sea promise a good potential for wave energy. WECs are still at their pre-commercial stage mainly developed in the EU region (holding 44% of global WEC patents). It is targeted that the current pilot scale projects would be reaching to commercial scale by the year 2030 (European Commission, 2020). Since 2010, about 160 devices have been installed in European seas with a total capacity of 13.5 MW including the decommissioned devices after test studies.

Selected papers for this review cover LCA studies executed for various type of WECs such as buoy-rope-drum (Zhai et al., 2018; Zhai et al., 2021), oscillating wave surge converter (Apolonia et al.,2021; Burgess et al., 2021; Uihlein 2016; Walker & Howell, 2011), point absorber (Pennock et al., 2022; Engelfried et al., 2025), attenuator (Thomson et al., 2019) and OWC (Elginoz & Bas, 2017).

A brief summary of selected studies focusing main phases of a LCA study is presented as follows:

<u>Goal and Scope Definition:</u> In all selected studies, the cradle-to-grave system boundary was applied. The selected functional unit was a unit of electricity output for most of the studies; except two of them were conducted for the WEC system operated for a defined useful lifetime (Zhai et al., 2018; Zhai et al. 2021).

<u>LCI:</u> Primary data of the studies were collected from the project design team, material experts and engineers (Apolonia et al., 2021; Elginoz & Bas, 2017; Pennock et al., 2022; Uihlein, 2016; Zhai et al., 2018; Zhai et al., 2021) and literature (Burgess et al., 2021; Engelfried et al., 2025; Thomson et al., 2009) including related device patent (Walker & Howell, 2011). Ecoinvent database was the main background data source for most of the studies, except Walker & Howell (2011) & Burgess et al. (2021), who used local databases. Besides, Uihlein (2016) accompanied the Ecoinvent database with the Thinkstep database and Zhai et al. (2018) & Zhai et al. (2021) also benefited from the literature data besides the Ecoinvent database.

<u>LCIA:</u> LCIA were conducted by using ReCiPe (Zhai et al., 2018; Apolonia et al., 2021; Pennock et al., 2022; Thomson et al., 2019; Burgess et al., 2021), CML 2001 (Elginoz & Bas, 2017), CML Baseline (Burgess et al., 2021), EF 3.1 (Engelfried et al., 2025), IMPACT 2002+, TRACI, CED (Thomson et al., 2009; Pennock et al., 2022), Australian Indicator Set v2.01 (Burgess et al., 2021) methodologies.

<u>Interpretation:</u> Environmental hotspots of WECs are mainly related to the raw material extraction, due to the steel content of the devices, which is the main material of the mentioned devices (Burgess et al., 2021). EoL stage is important due to reducing the environmental impacts significantly in all environmental impact categories due to the reason of mitigating the raw material consumption through recycling processes (Burgess et al., 2021), which shows that the results are sensitive according to the recycling rates applied (Elginoz & Bas., 2017).

Limitations and challenges: Immaturity of the WEC technology requires the usage of a high number of assumptions in LCA studies, which leads to lower data quality and uncertainties in the results and their interpretation. Since most of the WECs are at their development phase (lab-scale or pilot scale devices), operation and maintenance (O&M) data is mainly based on assumptions (Burgess et al., 2021; Pennock et al., 2022; Engelfried et al., 2025; Zhai et al., 2018; Zhai et al., 2021). Similar to O&M data, waste management methods at the EoL phase are mainly based on assumptions (Elginoz & Bas, 2017; Burgess et al., 2021; Pennock et al., 2022; Zhai et al., 2018; Zhai et al., 2021). Especially, assumed recycling rates of WEC components significantly influence the overall environmental impact considering that they contribute to the results in a positive way, which may differ for future EoL applications (Burgess et al., 2021). It is also important to consider that all of the possible environmental impacts of WECs are not covered through LCA methodology, which is open to be developed for taking account some new environmental impacts such as electromagnetic fields, changes in currents, noise and vibrations (Engelfried et al., 2025). Spatial and temporal homogeneity, representativeness and variations of the used primary & background data is another limitation (Zhai et al., 2018; Zhai et al., 2021). In addition, evaluating the environmental impacts through LCA for array of devices is a point to be developed (Uihlein, 2016; Apolonia et al., 2021; Engelfried et al., 2025), considering the most of the LCA studies are executed for single, prototype devices which will be used in arrays at the full scale.

3.3 LCA of Tidal Turbines

The North Sea, Atlantic Ocean, Mediterranean Sea have good potential for tidal energy. Similar to WECs, the EU is leading the tidal turbine technology development by holding 66% of global patents (European Commission, 2020).

Several LCA studies have been conducted on LCA of tidal turbines. In the following, a brief summary of selected studies focusing main phases of a LCA study is presented as follows:

Goal and Scope Definition: In the selected studies, both cradle-to-gate (Bianchi et al., 2024; Douziech et al., 2016) and cradle-to-grave system boundaries (Kaddoura et al., 2020; Rashedi et al., 2022; Uihlein, A., 2016; Walker et al., 2015; Walker & Thies, 2022) were applied. In some of the studies functional unit was a unit production of electricity (Bianchi et al., 2024; Douziech et al., 2016; Kaddoura et al., 2020); while considered devices had been selected as the functional unit of some other studies (Rashedi et al., 2022; Uihlein, A., 2016; Walker et al., 2015; Walker & Thies, 2022).

LCI: Primary data of the studies were collected from the project design teams and manufacturers (Douziech et al., 2016; Kaddoura et al., 2020; Uihlein, 2016; Walker et al., 2015; Walker et al., 2022) and the literature (Walker et al., 2015; Kaddoura et al., 2020; Rashedi et al., 2022). Ecoinvent database was the main background data source for most of the studies, except Walker et al. (2015), who used World Steel Association & University of Bath ICE databases. Besides, Walker et al. (2022) accompanied the Ecoinvent database with ELCD and USLCI databases.

LCIA: The main LCIA methodology used was ReCiPe for most of the studies included (Bianchi et al., 2024; Douziech et al., 2016; Kaddoura et al., 2020; Rashedi et al., 2022; Walker & Thies, 2022), except Uihlein (2016), who used multiple models for different impact categories (IPCC baseline model, accumulated exceedance, WMO model, RiskPoll model, Human health effect model, UseTox model, LOTOS-EUROS model, EUTREND model, CML 2002 reserve based). Here, Walker et al. (2015) couldn't be evaluated for this aspect since the LCIA methodology used was not mentioned.

Interpretation: Environmental hotspots of tidal turbines are mainly related to the raw material extraction and manufacturing the equipment (Bianchi et al., 2024; Kaddoura et al., 2020; Douziech et al., 2016; Walker et al., 2015;) and EoL stages (Douziech et al. 2016). The main contributor to the raw material extraction and manufacturing phases is the usage of steel in production of the turbines. Besides, copper and glass fibre reinforced plastic (GFRP) were important contributors to some environmental impact categories considered (Rashedi et al., 2022). Environmental impacts of the EOL stage are especially prominent for the toxicity related environmental impact categories due to waste disposal practices (Douziech et al. 2016). Besides, it is important to state that avoided primary production of metals due to recycling practices at the EoL stage is effective for various environmental impact categories (Douziech et al. 2016; Kaddoura et al., 2020). In another study which presents average value of evaluated devices (49 horizontal axis turbines), it was stated that the mooring & foundations were the components of the turbines, which contributed most to all considered environmental categories, which is followed by PTO components of them (Uihlein, 2016).

Limitations and challenges: Required data availability and its quality is crucial for the sake of conducting LCA studies. Lack of data and transparency of the industry is one of the main challenges for LCA studies of tidal turbines (Bianchi et al., 2024), and also this is one of the reasons of the lack of inventory data for those devices accompanied by the fact that the tidal turbines are still novel technologies (Douziech et al., 2016). The uncertainty of the future EoL practices is another limitation increasing the uncertainty of the results (Kaddoura et al., 2020). Besides, spatial variability of required data is an important point considering that the location and related environmental conditions will be the determining factors of the tidal turbine designs due to affecting the electricity mix and tidal potential (Douziech et al., 2016; Bianchi et al., 2024). In addition, some of the possible environmental impacts are open to being developed for a more comprehensive evaluation such as inclusion degradation of antifouling coatings in the marine environment, effect of marine life, etc (Walker et al., 2015; Douziech et al., 2016). Lastly, temporal variation of turbine designs, the energy sources, manufacturing technology, transportation vehicles & their power sources and installation methods in the future are not involved in the studies (Walker et al., 2015).

3.4 LCA of Floating Solar Energy

The upsurge in energy consumption per capita is draining the primary source of energy, hence the need to shift the thrust towards renewable energy sources (Goswami et al., 2019). Due to the advancement in the sustainable energy sector, photovoltaic (PV) systems have been developed and became significant for generating energy at a large scale. The demand for floating photovoltaics (FPV) has also increased; which are mostly adopted in the Asian region due to the suitable climate conditions (Ching-Feng, 2023; Clemons et al., 2021); however, looking at its potential, recently the work has been extended to the European region as well (Parascanu et al., 2025).

In the literature, there are some previous studies on LCA of FPV systems, which are various designs of floating platforms offshore (Parascanu et al., 2025) and on dam reservoirs and lakes (Clemons et al., 2021; Hayibo et al., 2022). Here, the studies which only focus on the amount of energy demand or GHG emissions, are not included due to the fact that the results are limited only to LCI; but not the assessment of environmental impacts. Thus, the number of studies included is limited.

In the following, a brief summary of selected studies focusing on the main phases of the LCA study is presented as follows:

Goal and Scope Definition: The selected system boundary in the considered studies was cradle-to-gate (Hayibo et al., 2022) and cradle-to-grave (Clemons et al, 2021; Parascanu et al., 2025), with a useful lifetime of the systems varying between from 25 to 30 years. The functional unit for all the studies was a unit electricity output.

LCI: The LCI was built, based on several databases to gather the primary and background data. The primary data of the studies were collected from the meteorological data, design documents of the analysed systems, literature and other data sources (Clemons et al., 2021; Hayibo et al., 2022; Parascanu et al., 2025). As background data, a combination of Ecoinvent and U.S Life Cycle Inventory Database (Clemons et al., 2021) and Ecoinvent database (Hayibo et al., 2022; Parascanu et al., 2025) were considered.

LCIA: A range of LCIA methodologies was employed in the gathered studies. The LCIA were conducted by using Recipe (Clemons et al., 2021), Environmental Footprint (EF) (Parascanu et al., 2025), CED (Hayibo et al., 2022).

Interpretation: The environmental hotspots of floating PV are mainly related to the raw material extraction and manufacturing of the PV panels & other components for the most of the environmental impact categories considered (Clemons et al., 2021; Hayibo et al., 2022; Parascanu et al., 2025), while EoL phase is dominant for some others (Clemons et al., 2021).

Limitations and Challenges: The output of the studies is geographically specific, and the emission data could vary based on the travel distance and PV profile. There is a lack of technical insights in PV performance, and further work to better address the challenges in design and operations is required (Clemons et al., 2021). Also, it is important to explore the lifespan of the system's components (Hayibo et al., 2022). In addition, it is important to state that some environmental impacts of floating PV panels are not assessed through LCA (i.e. corrosion, temperature variations, interaction with marine ecosystems), which requires further evaluation using other methodologies (Parascanu et al., 2025).

3.5 LCA of Hydrogen Energy

Looking into the budget for global carbon, it is important that decarbonisation decisions count on a precise and comprehensive assessment of GHG emissions for effective validity (Davies & Hastings, 2023). For the energy transition, hydrogen plays a key role due to its adaptable energy and storage capacity. The production of hydrogen can be made through several feedstocks and generation processes, providing a separate colour which is the indication of the carried out process (Mio et al., 2024). Hydrogen possesses an eco-friendly nature for replacing fossil fuels;

however, its storage on a larger scale and transporting far from production is challenging. In this manner, hydrogen supply chains are under consideration for their deployment; however, it has environmental concerns that require further consideration (Noh et al., 2023).

Selected papers for this review cover the LCA studies on various hydrogen energy production systems as alkaline electrolysis (AEL), polymer electrolyte membrane electrolysis (PEM) and solid oxide electrolysis (SOEC) powered by onshore/offshore wind power (Zhang et al., 2023), proton exchange membrane (PEM) water electrolysis (Noh et al., 2023), electrolysis of water powered by a FPV (Mio et al., 2024), offshore wind-driven green hydrogen generation system (Guven, 2024), FPV-powered green hydrogen generation system (Guven, 2025), and green hydrogen production using Steam Methane Reforming (SMR) and Autothermal Reforming (ATR) methodologies powered by offshore wind turbines (Davies & Hastings, 2023). A brief summary of selected studies focusing on the main phases of the LCA study is presented as follows:

Goal and Scope Definition: In the selected studies, the cradle-to-gate (Noh et al., 2023; Zhang et al., 2023; Mio et al., 2024; Guven, 2025) and cradle-to-grave system boundaries (Guven, 2024) were applied. The lifetime of the systems varies between 20 to 30 years. The functional unit for all the studies was one kilogram of hydrogen produced, Davies & Hastings (2023), who used producing 0.5MtH_2 per year while calculating total GHG emissions and resultant carbon footprint.

LCI: Several sources for the LCI were used to gather the data. As background data, solely Ecoinvent (Mio et al., 2024; Zhang et al., 2023), Korea National LCI database and Ecoinvent (Noh et al., 2023), and databases from GREET 2022 and 2023 (Guven, 2024, 2025) were considered. Davies & Hastings (2023) used local databases for primary sources of information, such as: UK Health & Safety Executive, the Department for Business, Energy and Industrial Strategy, and the North Sea Transition Authority.

LCIA: A range of LCIA methodologies was employed in the gathered studies as follows: CML 2001 (Zhang et al., 2023); CML-IA baseline (Noh et al., 2023), Recipe 2016 (Guven, 2024; Mio et al., 2024; Guven 2025).

Interpretation: The environmental hotspots of the hydrogen energy system are mainly related to raw material extraction, component manufacturing, and system operation up to the production of hydrogen (due to electricity consumption, transport routes, etc.) in different environmental impact categories (Davies & Hastings, 2023; Zhang et al., 2023; Mio et al., 2024; Guven 2024; Guven, 2025).

Limitations and challenges: With the limited carbon budget to deal with climate change, a major significant output without error is required, which means that changes in energy infrastructure should be sound in the preliminary attempt (Davies & Hastings, 2023). The main limitation of the considered studies is usage of limited number of global climate models for climate forecasting and the lack of data or data uncertainty related to the considered systems (including lifetime and average power generation data assumptions), their disposal at EoL stage but also downstream emissions (Davies et al., 2023; Noh et al., 2023; Zhang et al., 2023; Guven, 2024; Mio et al., 2024; Guven, 2025). Besides, environmental impact categories other than GWP should be further investigated for improvements (Mio et al., 2024).

3.6 General Evaluation

A general evaluation of the collected data on the main characteristics of the LCA studies and also environmental hotspots and limitation & challenges in those studies are presented in Table 1 & Table 2, respectively.

As it may be seen from Table 1, both cradle-to-gate & cradle-to-grave system boundaries are used; especially cradle-to-grave studies are more common for all marine renewables except the hydrogen energy production. For the functional unit, unit amount of electricity is the common usage. Background data for the LCI is provided from various global and local databases and the main information source is the Ecoinvent database, which is common for all types of marine renewable energy LCA studies. A range of series of LCIA methodologies are used and Recipe method is used at least one of LCA studies considered for all.

Table 1. A common evaluation of covered LCA studies in terms of LCA methodology

	Floating Offshore Wind Turbines	**WECs**	**Tidal Turbines**	**Floating PV**	**Hydrogen Energy**
System Boundaries					
cradle-to-gate	×	×	✓	×	✓
cradle-to-grave	✓	✓	✓	✓	×
Functional Unit					
unit amount of electricity/hydrogen production	✓	✓	✓	✓	✓
energy production device	×	✓	✓	✓	×
operation of the system for a defined period	✓	×	✓	✓	×
Used databases for background data					
Ecoinvent (*different versions*)	✓	✓	✓	✓	✓
PE International	✓	×	×	×	×
JRC Emissions Database	✓	×	×	×	×
Gemis 5	✓	×	×	×	×
Chinese Core Life Cycle Database (CLCD)	✓	×	×	×	×
Australian emission database	×	✓	×	×	×
U.S LCI Database	×	×	×	✓	×
Literature / industry reports / product category rules / meteorological data	×	✓	✓	✓	×
GaBi Professional	×	×	✓	×	×
World Steel Association LCI	×	×	✓	×	×
University of Bath ICE	×	×	✓	×	×
ELCD	×	×	✓	×	×

USLCI	×	×	✓	×	×
Korea National LCI	×	×	×	×	✓
GREET 2022 & 2023	×	×	×	×	✓
UK Health & Safety Executive Database	×	×	×	×	✓
LCIA methodology					
EPD	✓	×	×	×	×
CED	✓	×	×	✓	×
CML (*different versions)*	✓	✓	×	×	✓
Recipe (*different versons)*	✓	✓	✓	✓	✓
ILCD 2011	✓	×	×	×	×
IPCC 2013	✓	×	×	×	×
AWAI	✓	×	×	×	×
Australian Indicator Set v2.01	×	✓	×	×	×
TRACI v2.1	×	✓	×	×	×
LCEA	×	×	×	✓	×
EF	×	×	×	✓	×
GREET 2022	×	×	×	×	✓

** CED: Cumulative Energy Demand; LCEA: Life Cycle Energy Analysis; EF: Environmental Footprint*

As it may be seen from Table 2, environmental hotspots for all type of marine renewable energy systems is similar; raw material extraction, manufacturing and installation phase is the most prominent life cycle phase due to the high steel content of the structures and EoL phase also prominent due to the assumed recycling rates of used materials. In terms of limitations and challenges, data related issues (availability, uncertainty, transparency, geographical & temporal variability), missing environmental impacts of the systems and focusing on environmental impacts of single devices but missing the evaluation of array of devices are the common points addressed. It is important to state that this table is prepared based on the literature review and the limitations & challenges are included only when they are mentioned in the included studies.

Table 2. A common evaluation of covered LCA studies in terms of their results

	Floating Offshore Wind Turbines	**WECs**	**Tidal Turbines**	**Floating Solar**	**Hydrogen Energy**
Environmental Hotspots					
Raw material extraction, manufacturing and installation	✓	✓	✓	✓	✓
Operation	×	×	×	×	✓
EoL	×	✓	✓	✓	×
Limitations and Challenges					
Data related issues (availability, uncertainty, transparency, geographical &	✓	✓	✓	✓	✓

temporal variability)					
Limited number of environmental impacts covered	✓	✓	✓	✓	✓
Lack of evaluation of impacts for array of devices	×	✓	×	×	×

4. Conclusion

In this study, an overview of existing literature on the LCA of possible components of FMEIs is presented. Comparing the number of studies, offshore wind energy has been the most frequently studied, while there are only a limited number of studies on LCA of floating hydrogen energy systems. Most of the studies apply cradle-to-grave system boundaries, use unit production of electricity as the functional unit, different databases for background data provision for the LCI and a wide range of LCIA methodologies. Except for the offshore wind energy systems, most of the studies focus on single devices rather than offshore energy farms. Lack, transparency and uncertainty of data, uncertain EoL applications and geographical & temporal variations of the systems and the LCI data are the main limitations identified in the evaluated studies. It should also be remembered that there are certain environmental impacts that cannot be identified using LCA methodology yet, such as underwater noise, electromagnetic fields, etc.

Considering those highlighted points, key areas for advancement in LCA of marine renewable energy systems may be listed as follows: Expanding the covered environmental impact categories both in terms of covering the considered environmental impact categories – not only focusing on GWP- but also developing methodologies to include different environmental impact categories such as impact of underwater noise, electromagnetic fields, etc. in the LCA methodology would be leading a more holistic representation of environmental burdens. In addition, increasing data existence on those systems, reduce uncertainty of the conducted studies and providing the transparency of the data & study results are crucial for the robustness of the evaluations which will guide the decision-making process of the related industry stakeholders and policy makers. In addition, development of a dedicated LCA application procedure for FMEIs would be beneficial for the sector, as integrating multiple components results in a more complex system in terms of materials involved, installation methods, diverse O&M applications & schedules and EoL applications. Besides, possible synergistic & antagonistic relations between the components & environmental impacts should be considered, needing further future evaluation.

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