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Examining the Potential of Marine Renewable Energy: A Net Energy Perspective

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Abstract: It is often claimed that marine renewable energy alone could meet the electricity demand of current and future human societies. However, such claims are based on highly uncertain estimations of the global potentials of marine renewable energy sources (including tidal, ocean currents, wave, offshore wind and salinity and thermal gradients), and do not take into account the embedded energy of current technologies. To better understand the effective potential of marine energy, we conducted a literature review of its gross, technical, economic and sustainable potentials, as well as the energy return on investment (EROI), and estimated the net energy potential. We found that all marine technologies could provide a maximum energy surplus of 57,000 TWh/yr. This figure goes down to $\sim$ 5000 TWh/yr when excluding offshore wind. The previous figures do not include the contribution from ocean currents, for which no reliable estimates of global potentials and EROIs could be obtained. Due to its high upfront costs and environmental impacts and low social acceptance, no additional tidal range capacity expansion is envisioned. Similarly, the combination of a low sustainable potential and the low EROI makes the large-scale exploitation of salinity gradients unlikely with current technologies. Including all technologies, the average EROI of marine energy is $\sim$ 20, but excluding offshore wind reduces the average EROI to $\sim$ 8. While we did consider sustainability constraints for some marine energy sources, our estimation of marine net energy potential primarily relied on technical factors and did not account for economic and legal constraints. Therefore, the results presented here should be interpreted as an upper bound for the actual net energy contribution of marine energy sources to the global energy mix.

Keywords: EROI; oceanic energy; offshore wind; ocean currents; OTEC; tidal; SGE; wave

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1. Introduction

Most studies agree on the fact that the global marine energy resource is considerably larger than the world's annual electricity demand [1–4], which in 2021 was 98.8 EJ/yr (27,447.4 TWh/yr) [5]. Although its theoretical potential is evident, estimates of the amount of energy that may be extracted are uncertain and the energy potential of the different technologies vary significantly depending on the source [4].

At present, just a small fraction of such a resource is currently being exploited through 30 operational ocean energy facilities around the world: fourteen for tidal energy, fourteen for wave energy, one for salinity gradient (SGE), and only one for thermal gradient (OTEC), as reported in the Ocean Energy Systems 2022 Annual Report [6]. There are currently no operational ocean current platforms. Asia (261 MW) and Europe (253 MW) account for approximately equal portions of the total installed capacity worldwide (data values for 2022 from [6]), which was between 517 MW [7] and 524 MW in the period 2019–2022, with a total power generation slightly below 1 TWh/yr (975.5 GWh/yr) [8]. In fact, the tidal barrage systems of La Rance (France) and Sihwa (the Republic of Korea) represent more than 90% of the total installed capacity worldwide, with 240 and 254 MW of the installed capacity, respectively [7,9].

Although offshore wind is not oceanic energy, it is usually included among marine technologies [10–12] since it is located in the same type of environment, and many synergies can be potentially found between the two [13,14]. Offshore wind resources are also vast. In fact, it is widely recognized that offshore wind energy has a greater potential for electricity generation than onshore wind energy, due to higher and more consistent wind speeds in offshore locations [15,16]. However, similar to the other marine resources, the offshore wind resource is mostly untapped. Indeed, of the total 830 GW of installed wind capacity in 2021, only 7% were offshore wind farms [17].

Despite the great theoretical potentials, technical [18,19], legal [20,21] and financial and economic [4,22] considerations restrict their large scale implementation [2]. Present and future environmental regulations may also severely restrict those potentials [23] as more evidence is gathered on the impacts of the energy infrastructure on marine ecosystems [24–26]. Hence, when referring to the energy potential of ocean energy systems (or any other renewable energy source) it is crucial to distinguish between theoretical, technical, economic and sustainable potentials [4,23]. The current body of literature predominantly explores the theoretical and technical potentials of marine renewable energy (MRE), which hinders the capability to conduct critical and realistic assessments of the actual techno-economic and sustainable potential for MRE.

Under the pressing need for an energy transition, accurately quantifying the potential contribution of MRE technologies to the energy mix is crucial. Such quantification is highly dependent on reliable assessments of their potentials and energy return on investment (EROI). However, the existing literature on this subject is scattered across various sources, and the reported ranges of potentials and EROIs are often wide and uncertain [4], impeding a clear and comprehensive understanding of the subject.

To address these gaps, in this work we produce the following results:

- A compilation of global energy potentials found in the literature for tidal, ocean currents, wave, offshore wind and salinity and thermal gradients, classified according to their type (theoretical, technical, economic and sustainable);
- New estimates of the EROI of the available MRE technologies, based on results from Life Cycle Assessment (LCA) studies;
- New and refined average values of the energy potentials and EROIs of the different MREs based on a critical evaluation of the literature;
- The first estimates of the maximum net energy generation potential from each MRE source by combining the energy potentials of each source with their respective EROIs;
- Identification of knowledge gaps and discussion of future industry and research directions.

After the Introduction and the Methodology (Sections 1 and 2), the first and second points are included in Sections 3 and 4, respectively. The net energy calculations (third and fourth points) are presented in Section 5, and the results, knowledge gaps and future research and industry trends for MRE are discussed in Sections 6 and 7, respectively. Finally, the conclusions of the paper are summarized in Section 8.

While acknowledging the uncertainties in the values presented in this work, our findings suggest that the potentials may not be as significant as previously reported in the literature and highlight the need for further research and investment to fully explore the opportunities and challenges associated with marine energy.

2. Materials and Methods

2.1. Energy Potentials, Energy Return on Investment (EROI) and Net Energy

By energy potential, we refer to the amount of energy that is available from a specific source within specific geographic and time (usually 1 year) boundaries. In this work, we use the concepts of theoretical, technological, economic and sustainable energy potentials, as defined by [23], which have since been widely accepted and adopted by the scientific community [27,28].

While in this work we report a few values for the global economic and sustainable potentials, we recognize that these approximations are inherently imprecise, as the viability of each marine energy project must be assessed individually based on its economic and environmental sustainability.

Marine potentials in the literature are reported in power or energy units, indistinctly. In this work, we provide both. When transforming power potentials to energy units, we consider the theoretical maximum potential (capacity factor (CF) of 100%), unless otherwise stated.

The EROI or energy gain ratio (EGR) is the ratio between the amount of usable energy delivered from a particular energy resource and the amount of exergy used to obtain it [29]. This dimensionless indicator makes it possible to compare the energy profitability of different energy production processes (provided that the same boundaries and time period are used) [30].

Depending on the boundaries considered for the analysis, the resulting EROI is given the extra qualifier of standard (EROIst), point-of-use (EROIpou) or extended (EROIext). The EROIst is obtained by dividing the energy output of a power plant by the amount of energy used to generate that output per year, including the energy used for building, operating, maintaining and decommissioning the power plant. The EROIst is calculated at the point where the fuel leaves the production facility. EROIpou extends EROIst by also including the costs associated with refining and transporting the fuel. Finally, the more comprehensive EROIext also includes the energy required to make actual use of the energy produced. For more details on the different types of EROI and their differences, the reader is referred to the original source [31].

In this work, we make the EROI estimations based on published LCA results of marine technologies. LCA is a methodology to account for the inputs and outputs of materials and energy, and the associated environmental impacts, directly attributable to a product or service throughout its life cycle, from the extraction of natural resources to final disposal (cradle-to-grave) [32]. From all published LCAs on marine technologies, only those in which the Cumulative Energy Demand (CED) was estimated could be used for the assessment of the EROI, though studies reporting Embedded Energy (EE) or Energy Payback Time (EPBT) were also reviewed.

CED measures the total amount of energy needed to produce and use a product or service throughout its entire life cycle, including the energy required for extraction, processing, manufacturing, transportation, use, and disposal. In contrast, embedded or embodied energy is a measure of the energy required to produce a product during the manufacturing stage; hence, it includes the energy required for extracting and processing raw materials, manufacturing the product, and transporting it to the point of sale [33,34].

While the concept of EPBT (or Energy Payback Period, EPP) is commonly used in the literature, its definition varies. In the majority of studies, EPBT is defined as the length of time, measured in years, required for an energy system to generate the same amount of energy (in terms of primary energy equivalent) that was consumed in its production [35,36]. However, some studies define EPBT as the period of operation needed for the energy system to recover the energy invested throughout its entire lifecycle [37–39].

Although some of the analyzed LCA studies report EROI values, in most cases they are calculated in this work using Equation (1) [40]:

$$\mathrm{EROI} = \frac{\text{Device power rating (TW)} \cdot 8760\ \mathrm{h/yr} \cdot \mathrm{CF} \cdot \text{Lifespan (yr)}}{\text{Cumulative energy demand over lifespan (TWh)}} \quad (1)$$

where CF is the capacity factor (here assumed 100%, otherwise stated), lifespan is the time duration of the technology from installation to dismantlement and cumulative energy demand is the energy needed to construct, operate and maintain the device over the lifespan.

Similarly, the EPBT is not always reported in LCA studies, in which case we obtain it using Equation (2) [37], which derives from Equation (1) by assuming the second definition of EPBT above:

$$\text{EPBT (yr)} = \frac{\text{Lifespan (yr)}}{EROI} \quad (2)$$

Although we use the term EROI interchangeably throughout this paper, it is important to note that the scope of each LCA used to calculate EROI may vary. While most of the reviewed LCAs include the energy embedded in the connecting cable up to the point of connection with the grid, the resulting EROIs may still differ from the EROIpou. To provide further clarity, we report the specific system boundaries used in the LCAs that were utilized to calculate each EROI value.

Based on the energy potentials and the EROI of the respective technologies, the net energy available to society may be estimated with the following expression [41]:

$$\text{Net energy potential (TWh/yr)} = \text{Energy potential (TWh/yr)} \times \left(1 - \frac{1}{EROI}\right) \quad (3)$$

In the previous equation, the energy potential corresponds to the technical potential of each technology, unless good estimates of the sustainable or economical potentials are available. With this approach, we obtain the maximum net energy potentials of each technology, which are not necessarily comparable to one another.

In addition, for the estimation of net energy, we exclude technologies with EROIs lower than 7, since it is considered the minimum value for a society to sustainably support its basic energy needs and maintain the social and economic structures that depend on energy [42].

Figure 1 summarizes the methodology described above to obtain the maximum (upper-bound) net energy contribution of each MRE.

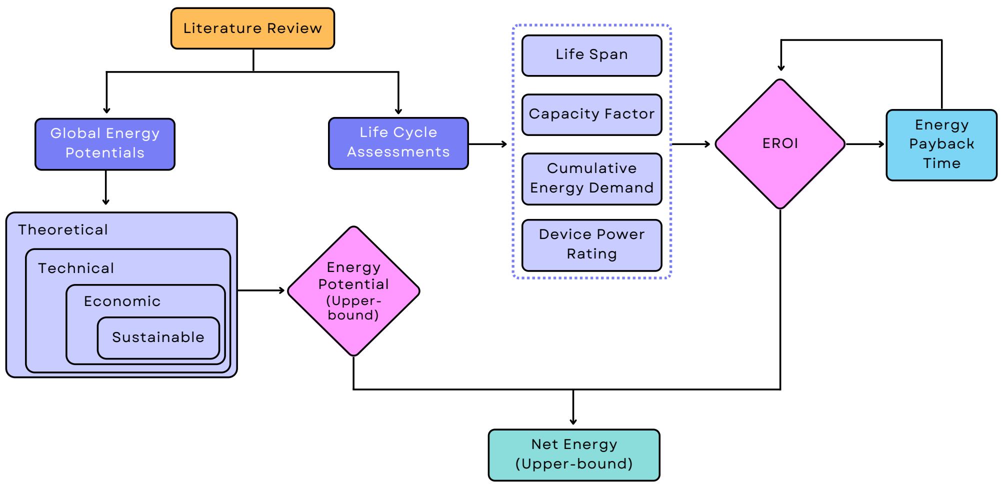

Figure 1. Summary of the methodology used to obtain the global maximum energy potential, the EROI and the maximum energy surplus (net energy) for each MRE.

2.2. Literature Review

For the literature review on energy potentials of marine technologies, we made site and API (when available) searches on the main journal indexing platforms (i.e., Scopus, Web of Science, Google Scholar) by combining keywords such as *marine/oceanic*, *global*, *resource/gross/theoretical/technical/economical/sustainable*, and *potential*. We also used more specific search criteria for the respective energy forms (wave, tidal, current, OTEC, SGE, wind). The most relevant literature cited in the papers resulting from the previous searches was also reviewed.

Following a similar approach, for the review of the literature on the EROI of marine technologies, we started by looking for the few studies that specifically aimed at estimating their EROI, but then extend the search to LCA studies that had estimated their CED, EE and EPBT.

3. Energy Potentials of Marine Technologies

3.1. Tidal

From the total energy dissipated worldwide in shallow ocean and continental shelves (2.5 TW (21,915.0 TWh/yr) [43–45]), 1.71 TW (14,990 TWh/yr) are dissipated by tides [44]. Ref. [46] argued that as much as 1 TW (2365 TWh/yr, assuming a CF of 27%, as in [13]) would be technically harvestable. Ref. [47] reported a lower global tidal technical potential of 1200 TWh/yr and in more recent years, these technical potentials have been further trimmed to 500–1000 TWh/yr [48,49] and 800 TWh/yr [50].

The Ocean Energy Council estimates that the global theoretical tidal current potential is 0.5 TW [51]. According to [52], the global exploitable tidal current power with current technologies is around 75 GW (177.4 TWh/yr assuming a CF of 27%, as in [13]). Tidal stream energy harvesting is, in general, only viable at sites where flow velocities are higher than 2–2.5 m/s [4] and with water depths between 25 and 50 m [53]. A limited number of sites meet these requirements in the UK, Canada, China, the USA, Argentina, Russia, France, Australia, New Zealand, India, and South Korea [4,54].

Looking specifically at the tidal range resource, using a tidal model [55] estimated a global theoretical potential of 5792 TWh/yr near the coastal regions of only 11 countries. This figure was recently updated by the same authors, using higher resolution data, to almost twofold the initial value (9115 TWh/yr) [56]. These values correspond to 38.6% and 60.8% of the total theoretical tidal potential reported by [44] (14,990 TWh/yr), respectively. The higher value is contradictory with the accepted assumption that the theoretical potential for tidal currents is larger than for tidal range [46].

In their first work [55], the authors indicate that they expect the actual technological potential of tidal range to be much lower than the theoretical values they report, and cite a study where it was found to be 37% of the theoretical value. This would correspond to a technical potential of 2143.04 TWh/yr, which is still larger than the technical potentials reported for tidal stream and tidal range altogether (500–1000 TWh/yr [48,49]). It is also larger than the global tidal stream technical potential reported by [52] (177.4 TWh/yr), which again contradicts IRENA's assumption [46]. Hence, it seems likely that either the reported theoretical potential or the percentage of the theoretical potential suggested in [55] to obtain the technical one are overestimated.

In fact, by subtracting the theoretical potential for tidal range reported by [55] from the total theoretical tidal potential reported by [44], we should obtain a rough approximation of the actual tidal stream potential (14,990 TWh/yr–5792 TWh/yr = 9197.86 TWh/yr). If we now calculate the percentage of this theoretical tidal stream potential that is actually harvestable according to the technical potential reported by [52], it corresponds to 1.9%, which is in agreement with the 1–2% range given by [57]. If we use the same percentage for the theoretical potential of tidal range (instead of 37%), we obtain a technical potential for tidal range of 111.8 TWh/yr. These are, of course, rough assumptions, but show that the actual global theoretical potential of tidal energy likely stands in the lower range of the values reported by [47–50].

All figures discussed above are compiled in Table 1.

Table 1. Global tidal energy potentials reported in literature.

	Potentials (in TWh/yr)				
Type	**Theoretical**	**Technological**	**Economic**	**Sustainable**	**Source**
Tidal (all forms)	14,990 [1]				[43,45]
		2365 [3]			[46]
		1200			[47]
		500–1000			[48,49]
		800			[50]
		200–400 [4]			[57]
Tidal stream	4380				[51]
		177.4 [5]			[52]
Tidal range	5792 [2]				[55]
	9115 [2]				[56]

[1] In shallow ocean and continental shelves. [2] Excluding Hudson Bay due to extensive ice cover, consistent with previous studies. [3] 1 TW assuming a CF of 27%, as in [13]. [4] Assuming that 1–2% of a theoretical resource of 2.5 TW could be technically harvested. [5] 75 GW assuming a CF of 27%, as in [13].

3.2. Wave

Literature values for the global wave energy resource span from 1 to 10 TW (8766 to 87,660 TWh/yr) [4,13,50,58–60] (see Table 2). Several recent studies have tried to provide more accurate estimations for the theoretical potential of wave energy by using geospatial software [59,61,62]. The initial estimates, without taking into account the energy direction of the waves, provided theoretical potentials of 3.65 TW (32,000 TWh/yr) [61]. This value is similar to the 29,500 TWh/yr reported by [47]. Ref. [62] factored in the wave direction on the estimation of the energy potential and obtained a lower value of 18,400 TWh/yr. Ref. [59] also evaluated the effect of factoring in the wave energy direction and obtained a global wave theoretical potential (at continental level, neglecting the potential of inner seas) of 16,000 TWh/yr.

More recently, ref. [63] assessed the potential zones for the exploitation of offshore wind and wave energy at a global scale, as well as co-location opportunities, simultaneously taking into consideration aspects such as resource availability, structural survivability, logistics activities, distance to consumer centers, and extractable power. Out of the 20 countries with the highest estimated extractable power in their Exclusive Economic Zone (EEZ), Brazil, with 4500 TWh/yr, and New Zealand, with 3400 TWh/yr, stood out from the rest, and together account for roughly 9000 TWh/yr (own estimation from Figure 8 of [63]). Hence, the technical potential for the 20 countries with the highest potentials (roughly 17,000 TWh/yr) sits in the range of the theoretical potentials obtained by [59,62], and proves the need for further research on the assessment of the global potentials of wave energy.

Other studies have focused solely on the assessment of the nearshore (water depth = 10 m) resource [64], which the European Thematic Network on Wave Energy estimated to be 1.3 TW, with an associated technical potential of 100–800 TWh/yr [65]. More recent literature seems to have taken the 0.5 TW of harvestable potential, reported by [66], as the more realistic estimate to date for the technical potential. Taking the ratios used by [65] to convert the resource into a technical potential, the 0.5 TW would result in 40–300 TWh/yr. For the sake of comparison, ref. [67] estimated the Baltic Sea alone to have a technical resource in the range of 24 TWh/yr.

Table 2. Global wave energy potentials reported in the literature.

Potentials (in TWh/yr)				
Theoretical	**Technological**	**Economic**	**Sustainable**	**Source**
8000–80,000				[4,50,58] (from previous literature)
32000 [1]				[61]
29500				[47]
18400 [5]				[62]
16000 [2]				[59]
11395.8 [4]	100–800 [4]			[65]
	4380 [8]			[66]
	100–500 and 200–1000 [3]			[67]
	17000 [6,7]			[63]

[1] Not taking into account the energy direction of the waves. [2] At continental level, neglecting the potential of inner seas. [3] For 20–30 kW/m and 10–20 kW/m wave front ranges, respectively. [4] Only nearshore (water depth = 10 m). [5] Total incident wave power along the ocean-facing global coastline, neglecting certain islands and poles. [6] Own estimation using data from Figure 8 in [63]. [7] Taking into consideration aspects such as resource availability, structural survivability, logistics activities, distance to consumer centers, and extractable power. [8] 0.5 TW.

3.3. Ocean Currents

Unlike tidal currents, which are generated by the gravitational pull of the moon, large-scale ocean currents are primarily driven by wind stress and density gradients resulting from variations in temperature and salinity [68]. They flow along the western boundaries of ocean basins, further offshore and in deeper waters compared to tidal currents, and therefore require distinct technologies for harnessing their energy potential. While tidal currents are highly predictable, occurring in cycles of two high tides and two low tides per day, ocean currents are stochastic in nature, and subject to more variability. Even so, their persistence in strength and direction makes them one of the largest renewable energy resources on the planet [69–71].

Efforts to estimate the energy potential of ocean currents started in the 1970s [72,73]. Since then, most studies have focused on specific areas, known for their strong currents, including several locations along the Gulf-Stream [68,70,72–80], and the Kuroshio [81–85] and Agulhas currents [86,87].

Estimating the global potentials of ocean currents for energy generation is a complex and ongoing research topic, with few studies attempting to provide comprehensive global figures. Additionally, the terminology surrounding ocean currents can be ambiguous, with some articles using the term to refer to both tidal and ocean currents, leading to inconsistencies in the literature.

Different methodologies have been used to try to assess the global potential, from gross approximations to satellite data analysis to complex ocean circulation models. The gross approximations of the global resource potentials in the literature are highly uncertain, with values ranging from 5000 GW (43,800 TWh/yr) [88] to 450 GW (3942 TWh/yr) [70]. Regardless of the methodology used, this is somewhat expected, based on the large uncertainty on the potential values reported in the local studies listed above, some of which also using complex models.

Using results from the HYCOM global ocean circulation model, ref. [89] evaluated the power density found in global ocean current systems. The study identified eight potential locations where ocean current energy could be potentially viable (time-averaged power densities of at least 500 W/m^2). However, the study did not attempt to quantify the potential energy generation of the identified sites. In a more recent study, ref. [90] identified flow patterns of near-surface currents in the western boundaries of world oceans by analyzing velocity measurements made with satellite altimeters and Surface Velocity Program (SVP) drifters. They identified the locations of maximum velocities for the four strongest (current speeds above 1.0 m/s) western boundary currents (Agulhas Current, Gulf Stream, Mindanao Current and Kuroshio Current). The maximum available mean undisturbed power densities from the four currents were found to be 1403, 1124, 681, and 512 W/m^2, respectively. However, the previous approach does not allow taking the three-dimensional wake and velocity–depth relation of ocean currents into account [91]. Additionally, neither [89] nor [90] estimate the potential changes to the existing flow caused by the deployment of ocean turbine power plants.

Finally, in what is the most comprehensive study on the estimation of the global ocean currents' potential to date, ref. [69] identify 42 sites where the installation of turbine power plants (TPP) may be favorable using a global eddy-resolving ocean model. According to the authors, TPP should occupy a 10 km-wide section of a western boundary current at depths between 20 and 46 m to harvest a Theoretical Available Power (TAP) that ranges from 100 to more than 1200 MW for all 42 sites. However, by virtually implementing the TPPs in 16 of the preselected 42 locations, they found the harnessable power (HP) to be significantly smaller (reduction between 29 and 89% from the original TAP for all 16 sites) due to the change of trajectory of the current and, to a lesser extent, the weakening of the current.

The HP as described in [69] may be assimilated to the upper bound of the technical potential. However, it was only estimated in 16 of the 42 locations, hence the global technical potential cannot be estimated from their results. Furthermore, it should be noted that some of the identified sites are located as far as 35 km away from the coast, which presents a significant technical challenge [92]. This distance may render several of the identified sites unviable when economic costs and environmental impacts are taken into consideration.

Based on all the above, we conclude that there are currently no reliable estimates of the potential energy that can be derived from global ocean currents. Further research is required to accurately assess this potential. In this regard, we believe that the work of [69] provides an excellent starting point for further investigation. Their research found that there is no robust empirical relationship between the TAP and the HP. Therefore, their approach of modeling virtual TPPs is seen as the most effective method for assessing the energy potential without affecting the currents or causing any harm to the environment. We recommend that future studies build upon their findings and explore the potential of TPPs in greater detail.

3.4. OTEC

The global OTEC resource is limited by the intensity of the vertical thermal gradient of the stratified ocean. Oceanic stratification is the result of a triple process: heating of the ocean surface by the sun, density differences produced by geographic differences in evaporation and precipitation rates, and the greater stability of a fluid in a gravitational field when the more dense fluid is placed below the less dense. Assuming an average temperature difference of 20 K between the surface and deep ocean water, ref. [45] estimates that about 100 TW (876,000 TWh/yr) is globally available.

Ref. [93] combined a one-dimensional steady-state model of the vertical structure of oceanic temperature with an equation to estimate OTECs net electrical power generated per unit area (as the product of the evaporator heat load and the gross OTEC conversion efficiency (estimated to be 2.85%)) over an ocean surface equivalent to 10×10^{14} m^2. By also subtracting the energy used by the pumps, the author reports a potential of 2.7 TW (23,652 TWh/yr). By applying several refinements to the original model, in a subsequent study, the same author updated the initial estimation to a range between 2.7 (secular scale) and 5 TW (43,800 TWh/yr) (short term) if 16 Sv of intermediate water was pumped to the surface [94]. However, this flow has the same order of magnitude as the Overturning Circulation and could produce unacceptable impacts on marine ecosystems and climate. Ref. [95] estimated that degasification of such flow of CO_2-rich intermediate water could add 253 t/s of CO_2 to the atmosphere, which is 24% of the anthropogenic CO_2 input of 2011.

In a later work, ref. [58] reported a smaller technical potential of 10,000 TWh/yr, while [96] report a global OTEC supply delivered to shore for Grid Connected and Energy Carrier OTEC plants of 37,000 TWh/yr.

Continuing the work initiated by [93,94,97], the net power that could potentially be extracted by covering all ocean areas suitable for OTEC (temperature gradients between surface and deep water exceeding 18 °C, c.a. 30% of the ocean surface) with this technology, without affecting the vertical oceanic thermal structure, was assessed. To that end, the authors incorporated OTEC operations (represented with fluid sources and sinks of prescribed strength) on an 4° by 4° resolution ocean general circulation model (OGCM). Using a simple formula, derived from previous works [93,94], they obtained a net power (subtracting energy used by pumps) of 30 TW (262,800 TWh/yr). Later in the same year, the same authors published the results of a similar exercise, but using a higher resolution (1° by 1°) and more vertical layers. This new assessment resulted in a much lower value of 14 TW (122,640 TWh/yr). However, in both studies, persistent environmental effects were identified, such as surface cooling in the tropics balanced by surface warming elsewhere, with a net transient heat input into the oceanic water column, as well as a boost in the deep oceanic circulation [98]. Based on that fact, the authors suggest 7 TW as a safe threshold to minimize the impacts on the oceanic temperature field.

On their 2018 article, ref. [98] improved the approach used by [97] by allowing some atmospheric feedback to the same OGCM. These updates resulted in 8–10.2 TW (70,080–89,352 TWh/yr) for global OTEC scenarios, and 7.2–9.3 TW (63,072–81,468 TWh/yr) for OTEC implementation within 100 km of coastlines. However, in the same article, the authors argue that an overall OTEC power production of about 2 TW (17,520 TWh/yr) would not have large-scale environmental effects, and that 6–7 TW might be produced provided that the associated effects remain acceptable.

Using a similar approach to [97–99], but with a different OGCM and simulation strategy, ref. [100] estimated a time-mean global OTEC power potential during the 1955–2021 period of 8.55 TW (74,898 TWh/yr). Using measured global long-term ocean heat content (OHC), the authors also estimated the time-mean global OTEC power potential to be 9.36 TW (81,994 TWh/yr). They also estimated the OTEC power potential in the same time-frame, but only within the exclusive economic zone (EEZ), which the authors argue would be more practical and cost-effective, and found them to be 4.69 TW (41,084 TWh/yr) and 4.87 TW (42,661 TWh/yr) for the simulated and observed cases, respectively.

Although the technical and environmental constrains still apply, the technical potentials reported above were obtained using the low thermal efficiencies of pure OTEC systems. However, much higher overall thermal efficiencies may be achieved by coupling OTEC with other systems able to reuse the excess heat from the first (integrated OTEC). By integrating OTEC with a membrane distillation desalination plant, ref. [101] obtained a thermal efficiency of 25.38% as compared to the 2.19% of the OTEC system operating on its own. Similarly, ref. [102] proposed a system combining cooling, desalination and power generation and obtained an energy saving rate of 33.72% and thermal efficiency of 29.33%. In addition to improving thermal efficiency, these integrated systems may bring other benefits such as fresh water, hydrogen or ammonia generation, to provide air conditioning and also to create a controlled environment for aquaculture.

It is also relevant to mention that [100] made projections under the RCP8.5 emissions scenario, and found that the OTEC potential may increase by 45.5% by the end of the century (time-mean during 2071–2100 of 12.88 TW), compared to their estimated present-day level (8.55 TW).

All values discussed above are summarised in Table 3.

Table 3. Global OTEC energy potentials reported in the literature.

Potentials (in TWh/yr)				
Theoretical	**Technological**	**Economic**	**Sustainable**	**Source**
876,000				[45]
	37,000			[96]
	23,652 to 43,800			[93,94] [1,2]
	10,000			[58]
	122,640 to 262,800			[97,99] [1,2]
	63,072 to 81,468 [2]		<17,520	[98] [1,3]
	74,898 (81,994)	41,084 (42,661) [5]		[100] [1,4]

[1] Subtracting the energy consumed by pumps. [2] Assuming non-negligible effects on the oceanic temperature field. [3] Considering a maximum distance of 100 km of coastlines for OTEC implementation. [4] Simulated and measured (within parenthesis) potentials. [5] Within the EEZ only.

3.5. Salinity Gradient

The first estimations of the globally available power in the form of salinity gradients at river mouths were made in the 1970s, and ranged between 1.4 and 2.6 TW (12,305–22,776 TWh/yr) [103,104] (see Table 4).

Ref. [105] estimate the Gibbs free energy (ΔG_{mix}) released by the mixing of river water (35 g/L NaCl) and seawater (88 mg/L NaCl) in two different proportions: a) assuming that river water mixes into an infinite volume of seawater, and b) using the ratio of volumes of the two types of water that maximizes ΔG_{mix} of the total solution volume. Then, they multiply the global river discharge (37×10^3–46×10^3 km^3/yr) by the two values of ΔG_{mix} to obtain theoretical salinity gradient potential ranges of 28.1×10^3–35.0×10^3 TWh/yr and 16.2×10^3–20.1×10^3 TWh/yr for cases a and b, respectively.

Ref. [106] estimated the global theoretical and technical potentials for salinity gradient power to be 1.724 and 0.983 TW (15,102 and 8611 TWh/yr), respectively. The same values are reported in [107].

Ref. [108] reports a global theoretical potential of 3.16 TW (27,667 TWh/yr) technical potential of 5200 TWh/yr and an ecological potential (to sustain the ecological stability of the river) of 520 TWh/yr. These potentials were also reported in [109].

Based on previous (undisclosed) assessments, ref. [110] reported the global power production potential to be 0.23 TW (2000 TWh/yr). The same value was reported by [111], assuming that only 20% of the global river discharge can be used for salinity gradient energy generation.

Using a similar approach, ref. [112] claimed that if one tenth of the global river discharge was used for power production (with PRO) from the mixing with seawater, 1370 TWh/yr (0.16 TW) could be generated. A similar technical potential (1650 TWh/yr) was reported by [113,114].

Finally, ref. [115] estimated the value of the global extractable salinity gradient potential to be 625 TWh/yr (2.25 EJ/yr), including 49% of all river mouths, an environmental flow of 30% of the mean river discharge, an extraction factor of 0.2, and an average CF of 84%.

Table 4. Global Salinity Gradient energy potentials reported in the literature.

Potentials (in TWh/yr)				
Theoretical	**Technological**	**Economic**	**Sustainable**	**Source**
12,305 to 22,776				[103,104]
	2000 [1]			[110,111]
	1650			[113]
15,102	8617			[106,107]
27,667	5200		520	[108,109]
	1370 [2]			[112,116]
			625	[115]
16,200 to 35,000				[105]

[1] Assuming that only 20% of the global river discharge can be used for salinity gradient energy generation.
[2] Assuming that one tenth of the global river discharge could be used for power production (with PRO).

3.6. *Offshore Wind*

When compared to other ocean energies, the offshore wind sector is considered to be in a relatively mature state [4]. The first platform was established in Denmark in 1991 [117,118], and Statoil-Hydro and Siemens installed the first large scale grid connected floating wind turbine in 2009 on the Norwegian coast, at Karmøy [119].

The estimates of the potential for global offshore wind differ greatly depending on the study and its associated assumptions and constraints [120]. The defined water depth, the power density, and the capacity factor are the key contributors to these discrepancies [121].

Ref. [40] estimated the kinetic energy generation rates onshore and offshore from the global kinetic energy dissipated in the atmospheric boundary layer. Assuming that this power is distributed over each cell proportionally to the mean wind speed squared, the resultant potential for available energy over suitable offshore areas (exclusive economic zone up to 50 m deep) is 8.35 TW (73,146 TWh/yr).

The first estimations of offshore wind energy resources were typically constrained by close proximity to land and shallow water depths, allowing for bottom-fixed foundations. Refs. [122,123] used similar methodologies and obtained 157,000 TWh/yr and 192,800 TWh/yr, respectively. The studies interpolated between the vertical layers of the GEOS-5 database pressure fields, assuming 100 m hub heights. The turbine power density was the only difference between the two cases, at 5.84 MW/km^2 and 5 MW/km^2, respectively.

Projections of several Atmospheric general circulation models (AGCMs) on the modification of the large-scale wind field after the installation of large wind farms, reviewed by [124], show that power production tends to saturate at 1 W/m^2 of surface for wind farms larger than many hundreds of km^2 and a surface coverage tending to infinity, even though scattered wind farms may produce a mean electrical power larger than this. The potentially extractable electrical power was studied by [95] in three scenarios of increasing occupation of the ice-free global continental shelves. In these scenarios, wind turbines occupy 10%, 25% and 50% of continental shelves surface up to 225 m deep, respectively. Using the asymptotic value of 1 W/m^2 reported by [124], the extractable power obtained was 1.8, 4.5 and 8.9 TW, respectively).

Ref. [125] made a similar analysis of the offshore power extractability, but for different periods. The first one, using the current technology (up to 50 m deep), and the following ones, using floating turbines (assuming depths up to 1000 m deep). Then, they determined one scenario of low use, where 4% of the surface of the accessible shelf between 0 and 10 km, 10% between 10–50 km and 25% between 50–200 km were used; and a high use scenario, where 5% (0–10 km), 40% (10–50 km) and 80% (50–200 km) of the surface were used. Their estimation of extractable power for both scenarios was 189 EJ/yr (52,500 TWh/yr) and 624 EJ/yr (173,000 TWh/yr) for the first period and 197 EJ/yr (54,722 TWh/yr) and 652 EJ/yr (181,111 TWh/yr) for the next periods.

Other recent studies estimated the global technical potential for floating wind turbines up to 1000 m deep at 329,600 TWh/yr, of which 230,004 TWh/yr are generated in deep waters (more than 60 m) [121]. Moreover, the International Energy Agency (IEA) has provided estimates of a global potential of more than 420,878 TWh/yr, including ocean depths up to 2000 m [15].

A summary of the energy potentials reported for offshore wind is shown in Table 5.

Table 5. Global offshore wind energy potentials reported in the literature.

Potentials (in TWh/yr)				
Theoretical	**Technological**	**Economic**	**Sustainable**	**Source**
731,46 [1]				[40]
	157,000 [2]			[122]
	192,800 [3]			[123]
15,768, 39,420 and 77,964 [4]				[95]
	52,500 and 173,000 [5]			[125]
	54,722 and 181,111 [6]			[125]
	329,600 [7]			[121]
	420,878 [8]			[15]

[1] Exclusive economic zones up to 50 m deep. [2] Up to 200 m, assumes loss of 10% of potential power caused by interturbine interference. [3] Up to 200 m, 10% array losses and 20% averaged CF. [4] Turbines occupying 10%, 25% and 50% of continental shelves surface up to 225 m deep. [5] For low- and high-use scenarios using the current technology (up to 50 m deep). [6] For low- and high-use scenarios using floating turbine technology (up to 1000 m deep). [7] Up to 1000 m deep, 12.5% array losses and 20% averaged CF. [8] Turbines founded up to 2000 m deep on the continental shelves.

4. EROI of Marine Technologies and Devices

4.1. Tidal

Ref. [126] modeled the embedded energy of a tidal stream array of 200 marine turbines sited in the Kaipara Harbor north of Auckland, with a total predicted output over an assumed 100-year lifespan of 67.5 TWh (CF of 37%). The EE was found to be 2.85×10^9 MJ. Not taking into account the energy used during the O&M and decommissioning phases, this would lead to an EROI of 85.3, with an EPBT of 1.18 years.

Ref. [127] performed a cradle-to-grave LCA of the Seagen marine current turbine, and obtained an energy intensity of 214 kJ/KWh, considering a potential annual energy production from the turbine of 4736 MWh (CF of 48%) and a lifespan of 20 years. Using these data, the authors reported an energy payback period of approximately 14 months. Based on these data, we estimate the EROI of this system to be 16.8.

On the other hand, ref. [128] carried out a cradle-to-grave LCA of four tidal stream energy devices: those from OpenHydro (Open-Centre Turbine, rated at 2 MW, lifespan 20 years), Tidal Generation Ltd. (Deepgen, rated at 1 MW, with 25 years lifespan), ScotRenewables (SR2000, rated at 2 MW, lifespan 20 years) and Flumill (Flumill, rated at 2 MW, lifespan 20 years). They were studied based on a functional unit, defined as an 10 MW array installed for 100 years and implemented in a hypothetical site with specific tidal and climate conditions. Over their lifespan, the functional units of Open-Centre Turbine generated 7,500,000 GJ, Flumill and SR2000 generated 6,500,000 GJ and Deepgen produced 5,800,000 GJ. Based on the energy debt and credit reported by [128] (in Table 2), we estimated the EROI to be 14, 11.8, 14.31 and 9 for the Open-Centre Turbine, SR2000, Flumill and Deepgen, respectively. The EPBTs estimated in the paper were 7.3, 8.7, 7.2 and 11.2 years, respectively.

In the framework of the H2020 PowerKite project, ref. [129] performed a cradle-to-grave LCA of Minesto's initial plans of a Deep Green Utility (DGU) tidal current power plant in Holyhead (Wales), with two configurations. The first consisted of an array of twenty four 500 kW kites (12 MW in total), with a CF between 23% and 46%. The second configuration, which according to the authors reflects a more favorable tidal site, consisted of eighteen 750 kW kites (13.5 MW in total) and a CF of 46%. The EROIs at the Holyhead site were found to be between 4.6 to 8.7, which corresponds to EPBTs of 3 to 6 years.

The values of the EROI for tidal range technologies (Table 6), including tidal barrage and tidal lagoon systems, are more uncertain.

With the second-largest tide range in the world ($\sim$ 14 m) [36,130], the Severn Estuary, located in the southwest of the United Kingdom, has long been considered a potential site for tidal power generation. As a result, several proposals for tidal range power plants have been made in the area over the years. The Cardiff–Weston barrage proposal is the most well-known, and has been subjected to several LCA studies [36,131,132]. In [132], emissions and embedded energy were analyzed over the expected lifespan of the barrage (120 years), but excluding the decommissioning stage (hence not a full or cradle-to-grave LCA). Based on previous assessments, the energy output was assumed to be 16.8 TWh/yr (with ebb generation and flood pumping) and the CED (without decommissioning) was 1,958,700 TJ. The authors report an energy gain ratio (EROI) of 3.7, with an energy payback period of 33 years. A previous study in the same site had obtained an EROI of 14.2 [131]. Ref. [132] justify the lower value obtained in their study by the fact that they made a more accurate approximation of the operation energy. Ref. [132] also assessed the case excluding flood pumping (ebb generation only) which resulted in a much higher EROI value of 24.2 and an EPBT of 5 years.

In the most recent analysis of the same project proposal, ref. [36] obtained an energy gain ratio of 22.2, considering ebb generation and flood pumping. However, this value may be overestimated because neither the energy required to build the barrage nor that used in the decommission phase were accounted for. They report an EPBT of 8.6 years, which corresponds to the moment in time in which the energy produced matches the CED until then. To obtain to this figure, the authors considered 50% power generation capacity in year 1 and a construction period of 6 years. With a lifespan of 120 years and the value of EROI reported by the authors (22.2), we estimate a shorter EPBT of 5.4 years with Equation (2).

Hammond and coauthors had previously performed the same analysis for the Shoots Barrage proposal [133], which is a smaller tidal range system upstream of the Cardiff–Weston barrage proposal, and obtained very similar values (EROI = 22.31, EPBT = 9.16 years). The EPBT in this study also considered 50% power generation capacity in the first year, but in this case the construction period was 5 years.

Similarly, ref. [134] made an assessment of the EE and carbon emissions of the Swansea Bay Tidal Lagoon project, also located in the Bristol Channel, from a Life Cycle perspective. In their LCA, the authors considered the following stages: material production, transport, construction and operation, while decommissioning was excluded from the study. They report an EE of 7800 TJ (2167 GWh) with a net annual energy output of 400 GWh over its 120 years lifecycle. Based on these data, we obtain an EROI of 22.15, with an EPBT of 5.5 years. Unfortunately, to our knowledge, the previous findings were never published in a peer reviewed journal and so the EROI estimated here must be taken with caution.

The estimated EROIs for tidal stream and tidal range systems are summarized in Tables 6 and 7.

Table 6. Summary of literature values of EROIs for tidal range technologies.

Device, Technology (Manufacturer) or Case Study	LCA Boundaries	EROI Value (Energy Payback Time)	Reference
Cardiff–Weston tidal barrage proposal, UK	construction and O&M	3.7 (33 years) [1] and 24.2 (5 years) [2]	[132]
Cardiff–Weston tidal barrage proposal, UK	energy accounting for construction and O&M	14.2 (8.3 years) [1]	[131]
Swansea Bay Tidal Lagoon project	cradle to gate and O&M	22 (5.5 years) [2]	EROI was estimated using energy intensity and energy output estimations made in [134] [3]
Shoots barrage proposal, UK	cradle to site and O&M	22.31 (9.16 years [4]) [1]	[133]
Cardiff–Weston tidal barrage proposal, UK	cradle to site and O&M	22.2 (8.6 years [4]) [1]	[36]

[1] Ebb generation and flood pumping. [2] Ebb generation only. [3] Non-peer reviewed. [4] See assumptions made for the calculation of the EPBT in the text.

Table 7. Summary of the literature values of EROIs for tidal stream technologies.

Device, Technology (Manufacturer) or Case Study	LCA Boundaries	EROI Value (Energy Payback Time)	Reference
200 marine turbines sited in the Kaipara Harbor, New Zealand	cradle to gate	85.26 (1.18 years) [1]	Both EROI and EPBT are estimated using energy intensity and energy output over lifespan [126]
Seagen (Marine Current Turbines Ltd.)	cradle to grave	16.8 (1.2 years) [2]	Estimated using data from [127]
Open Centre Turbine (OpenHydro)	cradle to grave	14 (7.3 years)	EROI estimated using energy intensity and energy output over lifespan from [128]
Deepgen (Tidal Generation Ltd.)	cradle to grave	9 (11.2 years)	EROI estimated using energy intensity and energy output over lifespan from [128]
SR2000 (ScotRenewables)	cradle to grave	11.8 (8.7 years)	EROI estimated using energy intensity and energy output over lifespan from [128]
Flumill (Flumill)	cradle to grave	14.31 (7.2 years)	EROI estimated using energy intensity and energy output over lifespan from [128]
Deep Green utility in Holyhead, Wales (Minesto)	cradle to grave	4.6 (6 years) to 8.7 (3 years)	[129]

[1] Lifespan of 100 years, as opposed to the 20–25 years considered in the other studies. [2] The EPBT reported by the authors was estimated using the lifetime energy input.

4.2. Wave

Ref. [38] performed a cradle-to-grave LCA of the first generation Pelamis Wave Energy Converter (WEC), rated at 750 kW. With an estimated power output of 2.97 GWh/yr and a lifecycle of 20 years, they report an energy intensity of 293 kJ/KWh and an EPBT of 20 months (1.6 years). With these figures, we estimate an EROI of 12.3.

Ref. [135] performed a cradle-to-grave LCA to a WEC concept project from Uppsala University, which is based on a system utilizing the heaving (up-and-down) movement of the waves. The wave power plants analyzed in their study consist of 1000 such WEC devices, which have an estimated lifespan of 20 years. They consider two case studies:

Case NO reproduces the operating conditions 400 km from the coast of Norway (20 kW/m wavefront), and Case SE corresponds to operation conditions with an average power flow of 5 kW/m wavefront. Case NO delivers 1.33 TWh, whereas Case SE delivers 0.395 TWh over their lifespan. The energy intensity of Case NO is 0.57 MJ/KWh, while that of Case SE is 1.76 MJ/KWh. From these data, the EROI can be estimated to be 6.3 and 2.04 for the NO and SE case studies, with EPBTs of 3.2 and 9.8 years, respectively.

Ref. [136] performed an LCA on the Oyster 1 device (Oscillating Wave Surge Converter (OWSC)), from Aquamarine Power. The CED over the lifespan of 15 years was estimated to be 5 347 619 MJ (1 485 449.72 KWh), with an EPBT of 12 months. The Oyster 1 device is rated at 315 kW with an estimated CF of 51%. This results in an EROI of 15.3.

Ref. [137] carried out a full life cycle assessment of the (315 kW) Oyster 1 and the (800 kW) Oyster 800 surge wave energy converters. The authors considered a lifespan of 15 years and an annual output of 1.52 GWh for the Oyster 1, while the lifespan of Oyster 800 was set at 20 years and the annual output to 3.85 GWh. The CF used for the two devices was 55%. The CED of Oyster 1 was estimated to be 891 kJ/KWh, while that of the Oyster 800 was 634 kJ/KWh. Accordingly, the EROI of the Oyster 1 and Oyster 800 devices are 4.04 and 5.67, with EPBTs of 3.7 and 3.5 years, respectively (note that lifetimes are different for the two devices). The CED for the Oyster 1 obtained in this study (20 314 800 MJ) was almost 4 times that estimated by [136] (5 347 619 MJ), which also results in a EROI c.a. four times smaller than that obtained by [137].

Ref. [138] performed a cradle-to-grave LCA on a Buoy–Rope–Drum (BRD) WEC. The BRD WEC was developed by a research group at Shandong University (Weihai, China) and has a designed rated power capacity of 10 kW. The energy intensities and EPBTs reported in the study ranged between 387 kJ/KWh–968 kJ/KWh and 26–64 months (2.2–5.4 years), with CFs of 50% and 20%, respectively. With a 20-year lifespan, this corresponds to EROIs of 9.1 and 3.7, respectively.

Ref. [139] carried out an LCA of the Wave Dragon WEC (overtopping) following the EDIP methodology [140]. They obtained the data from a 1:4.5 scale prototype, tested for 21 months in sea conditions at a less-energetic site. They considered all phases in the lifecycle of the device (manufacturing, transport, O&M and decommissioning) and anticipated a lifetime of 50 years. The authors report the energy return (EROI) of the device to be 20, with an EPBT of 2.42 years.

Ref. [141] also analyzed the 7 MW Wave Dragon overtopping WEC, but in this case only taking into account the energy embedded in the materials required to build it. Its annual power generation when placed in Wales Coast would be 20 GWh with a lifespan of 50 years. Using the energy intensities of [142,143], the embedded energies are 39.09 GWh and 32.69 GWh. According to the previous values, their EROI and EPBTs are 25.6 and 30.6, and 2 and 1.6 years, respectively.

In the same article, ref. [141] also performed a LCA on the 750 kW Pelamis WEC (attenuator), which only considered the energy embedded in the construction materials. The annual energy output was estimated at 2.5 GWh, if placed in Irish coasts. The lifetime of the device was assumed to be 20 years. Two data sources were used for the energy intensities of the required materials, [142,143]. Considering the two sources of information, the EEs were 3.03 GWh (EROI is 16.5) and 2.97 GWh (EROI is 16.83), respectively. The EPBT was roughly 1.2 years for the two cases.

Ref. [144] carried out a cradle-to-grave LCA of the Pelamis 1 WEC. The case study was for a typical wave farm located off the north-west coast of Scotland, with a lifespan of 20 years. The authors report an EROI of 7.3, with an EPBT of 33 months (2.8 years).

Ref. [145] made a cradle-to-grave LCA of the MegaRoller WEC, which is an OWSC based on the existing design implemented and commercialized as WaveRoller. The authors report a CED of 432 kJ/KWh, and a total energy production of 53 GWh over a lifespan of 20 years. Based on these data, we obtain an EROI of 8.3 and an EPBT of 2.4 years (authors report 2.5 years).

In their recent work, ref. [146] carried out a cradle-to-grave LCA on the 350 kW CorPower Ocean AB point absorber WEC, as part of a 10 MW array (of 28 units) placed in

Aguçadora, Portugal, and under three O&M scenarios. They report mean CED ranges of 0.38 MJ/KWh–0.60 MJ/KWh. With a lifespan of 20 years and an annual energy production of 33 GWh/yr (CF of 38%), we estimate an EROI range of 5.3–9.5 and EPBTs (considering the CED of the total lifespan) of 2.1–3.6 years.

Another relevant work is in this area is that of [147], who performed LCAs of ocean energy devices using detailed technical information on the components and structure of around 180 of them from the Joint Research Centre (JRC) ocean energy database. Though the LCA is very comprehensive, it does not estimate the CED, hence their EROI cannot be obtained.

A summary of the EROIs of wave energy devices found in the literature is presented in Table 8.

Table 8. Summary of literature values for EROIs by device/technology for WEC.

Device, Technology (Manufacturer) or Case Study	LCA Boundaries	EROI Value (Energy Payback Time)	Reference
P-750 Pelamis (Ocean Power Delivery Ltd., now Pelamis Wave Power)	cradle to grave	12.3 (1.6 years)	EROI estimated using energy intensity and energy output over lifespan from [38]
WEC concept project from Uppsala University	cradle to grave	6.3 (3.2 years) for case NO; 2.0 (9.8 years) for case SE	[135] (non peer-reviewed)
Oyster 1 (Aquamarine Power)	cradle to grave	15.3 (1 year)	Estimated using data from [136]
Oyster 1 and Oyster 800 (Aquamarine Power)	cradle to grave	4.0 (3.7 years) for Oyster 1; 5.7 (3.5 years) for Oyster 800	Estimated using data from [137]
Buoy-Rope-Drum (BRD) Wave Energy Converter (Shandong University)	cradle to grave	9.1 (2.2 years) with CF = 50%; 3.7 (5.4 years) with CF = 20%	EROI estimated using data from [138]
Wave Dragon WEC (Wave Dragon Aps)	cradle to grave	20 (2.42 years)	[139]
Wave Dragon WEC (Wave Dragon Aps) placed in Wales Coast	energy embedded in the construction materials	25.6 (2 years) with energy intensities from [142]; 30.6 (1.6 years) with energy intensities from [143]	EROI and EPBT estimated using data from [141]
P-750 Pelamis WEC (Pelamis Wave Power) placed in the Irish coast	energy embedded in the construction materials	16.5 (1.2 years) with energy intensities from [142]; 16.8 (1.2 years) with energy intensities from [143]	Estimated using data from [141]
Pelamis P1 WEC (Pelamis Wave Power) wave farm located off the north-west coast of Scotland	cradle to grave	7.3 (2.8 years)	[144]
MegaRoller OWSC	cradle to grave	8.3 (2.4 years)	EROI estimated using data from [145]
10 MW array of 28 350 kW CorPower Ocean AB point absorber WEC	cradle to grave	5.3 (3.6 years) to 9.5 (2.1 years)	EROI and EPBT estimated using mean CED range given in [146]

4.3. Ocean Currents

Literature on LCAs of ocean currents as a source of energy is notably scarce. To date, only one LCA study has been conducted on an ocean current technology, the Deep Green Utility developed by Minesto, which employs a turbine coupled to a wing that utilizes tidal or ocean currents to generate electricity [148]. Ref. [129] estimated the EROI and EPBT for a tidal current case study, hence the results are reported in Table 7 from the Section 4.1.

According to the study, the technology has the potential to operate at a CF ranging from 70 to 95% in a continuous ocean current [129].

There exists an open-sea test site for ocean current energy in Florida: the Southeast National Renewable (Energy Center—Ocean Current Test Facility) [6], but no LCA studies are found from their platform. Additionally, the IHI corporation and NEDO Organization have developed a 100 kW class ocean current turbine system called "Kairyu" and have conducted a demonstration test for the Kuroshio current [149]. In the mooring test, it generated an approximately 30 kW output at the current velocity of about 1 m/s [150].

4.4. OTEC

Very few LCA studies report the CED of OTEC technologies (see Table 9). Ref. [151] performed an LCA of a 10 MW OTEC system at Curaçao, in the Caribbean Sea, based on information of the feasibility report of ocean thermal energy conversion by Bluerise. The total annual energy output was estimated to be 252 288 000 MJ/yr (considering a CF of 80%) and the CED over the lifespan was at 948 699 241 MJ, which results in an EPBT of 3.76 years. In addition, with the lifespan of the plant considered in that work (30 years), we estimate an EROI of 8.

Ref. [152] carried out a LCA for an OTEC plant operating for 20 and 40 years offshore Oahu, Hawaii, with CFs of 85%, 95%, and 100%. For a 20-year operational OTEC plant, the CED, EROI, and EPBT ranged from 0.68 to 0.80 MJ/KWh, 4.5 to 5.3, and 3.7 to 4.4 years, respectively. For a 40-year operational OTEC plant, CED, EROI, and EPBT ranged from 0.53 to 0.62 MJ h/kW, 5.8 to 6.8, and 5.9 to 6.9 years, respectively.

Ref. [141] estimated the EE in the materials for construction of a 100 MW closed cycle OTEC system. The annual power production was estimated to be 191.7 GWh, considering a CF of 30%, a 25% of self-consumption and a lifespan of 30 years. Taking the material intensities from [142,143], the EE in the materials are 455.8 GWh (EROI of 12.6) and 390.2 GWh (EROI of 14.7), with EPBTs of 3.1 and 2.4 years, respectively.

Table 9. Summary of literature values for EROIs by device/technology for OTEC.

Device, Technology (Manufacturer) or Case Study	LCA Boundaries	EROI Value (Energy Payback Time)	Reference
10 MW OTEC system at Curaçao, in the Caribbean Sea (Bluerise)	based on information of the feasibility report of ocean thermal energy conversion by Bluerise	8 (3.8 years)	Estimated using data from [151]
10 MW OTEC pilot plant offshore Oahu, Hawaii	cradle-to-grave	4.5 to 5.3 (3.8 to 4.4 years) for 20 years of operation with CF of 85% and 100%, respectively; 5.9 to 6.8 (5.9 to 6.9 years) for 40 years of operation with CF 85% and 100%, respectively.	[152]
Closed cycle 100 MW OTEC system	energy embedded in the construction materials plus 25% of self-consumption during operation	12.6 (3.1 years) with energy intensities from [142]; 14.7 (2.4 years) with energy intensities from [143]	Estimated using data from [141]

4.5. Salinity Gradient

The literature on SGE technologies is scarce and good quality studies are lacking [39]. When focusing on LCA studies applied to SGE technologies, the knowledge gap is even larger (see Table 10). Though the environmental impacts of SGE had been previously studied [153,154], only in 2020 did [155] perform what they claim was the first comprehensive LCA of a SGE system (reverse electrodialysis (RED)). In another recent LCA study of a RED system, ref. [156] argued that the lack of environmental studies may be related to the very few pilot projects built and operated for long periods. Even more recently, ref. [157] published an environmental impact assessment of a hypothetical 50 kW RED plant installed in La Carbonera Lagoon, Yucatán, Mexico. In a modeling exercise (not an LCA), ref. [158] estimated the net energy produced during the operation phase of a 1 MW SGE plant in the Strymon River (Greece). However, neither [155,157] reported the CED or energy intensity of the studied systems, hence their EROI cannot be estimated. Similarly, in [158], only the energy required during operation is reported, while the energy embedded in the construction and decommissioning phases are not taken into account. According to this, the EROI cannot be reliably estimated.

Surprisingly, the only LCA on a SGE technology that we could find in our review that actually measured the CED was that performed by students from the University of Surrey in a Multi-Disciplinary Design Project [159]. In this work, the authors carried out a feasibility study of the PRO technology to generate 10 MW constantly in a lagoon located at the mouth of the River Avon in the Severn Estuary, in the UK. In their study, they took into account the energy invested in the construction, running, maintaining and decommissioning of the plant. With a design life of 30 years, they obtained an EROI of 0.6, which served them to prove the unfeasibility of the project. Unfortunately, to the best of our knowledge, this work was never published in a peer-reviewed journal.

Looking specifically at the literature reporting EROI values, ref. [160] report EROIs of 7 and 6–7 for RED and PRO technologies, respectively, and based on previous literature. However, looking into those articles, we could not find how the values reported by [160] were obtained. Ref. [161] adds that even though RED is among the highest energy efficiency techniques, it also has a low EROI, without providing any further clues.

Table 10. Summary of literature values for EROIs by device/technology for Salinity gradient.

Device, Technology (Manufacturer) or Case Study	LCA Boundaries	EROI Value (Energy Payback Time)	Reference
Reverse Electrodialysis (RED)	–	7	[160] based on previous studies.
Pressure Retarded Osmosis (PRO)	–	6-7	[160] based on previous studies.
Feasibility study of a 10 MW PRO system in a lagoon located at the mouth of the River Avon in the Severn Estuary, in the UK	cradle to grave	0.6	[159] [1]

[1] Non-peer reviewed.

4.6. Offshore Wind

Several LCA studies have been carried out on offshore wind systems, and values of EROI and EPBT were either reported or can be extracted from the data.

A meta-analysis of the EROI for onshore and offshore turbines installed from 1977 to 2007 was conducted by [162]. The offshore stations reported (placed in wind fields of 17, 16 , and 9.2 m/s) had EROIs of 33.3, 51.3, and 14.8, respectively.

The first LCA study for floating offshore wind was performed by [163]. They conducted a preliminary LCA for a Norwegian company project (Sway Company) of a floating offshore wind farm located 50 km away from the shore, constituted by 40 floating wind power plants. The study obtained an EPBT of 13 months with a lifetime of 20 years, which corresponds to an EROI of 18.45. This high result is probably due to the fact that they do not take into account the marine ecotoxicity or emissions linked to the installation and maintenance of the farm.

The research of floating technologies was followed by [164], who reviewed six LCAs for six conceptual offshore farms: one with bottom-fixed and five with floating turbines of 90 m hub height located 200 km off the British coast. The EROI obtained was 12.4 for the bottom-fixed case, and 7.5–12.9 for the floating systems.

Ref. [165] conducted another LCA for two case studies of floating offshore wind farms, but using a detailed O&M model to better estimate its impacts. The first case study was based on the Hywind Scotland deployment and the second on the Kincardine deployment at the south-east of Aberdeen, Scotland. This study finds values in similar ranges to the previous one, but slightly lower; they obtain EPBTs from 3.3 to 4.3 years for the Hywind and 2.8 to 3.7 years for the Kincardine, which implies EROIs of 5.81–7.57 and 6.5–8.9 with 25 years of lifetime expected in both projects.

A LCA study for conceptual offshore farms was conducted by [166]. They proposed two turbines of 4 and 6 MW turbines of 2015 state-of-the-art technology and 30 and 50 km from the coast. The calculated EPBT was 11.1 and 10 months, respectively, which with 20 and 25 years of expected lifetime implies an EROI of 21.6 and 30, respectively.

A theoretical LCA of different energy generation technologies was carried out by [167] and obtained an average EROI of 13.5 for offshore wind plants. However, it omitted technical details regarding the type of farm under consideration. Ref. [40] analyzed two offshore wind farms with a CF of 39%, one anchored at a depth of 15 m and the other one floating, the LCAs provided EROIs of 12 and 10.4, respectively.

The Company Siemens-Gamesa made a LCA estimation of an offshore power plant consisting of 80 turbines SG 8.0-167 DD of 8 MW placed 50 km from shore and 22 km from shore to grid, with an expected average wind speed of 10 m/s, and with steel foundation [168]. They estimate an EPBT of 7.4 months for an expected lifetime of 25 years, which implies an EROI of 40.5. This figure can be considered representative of a modern wind farm, with large turbines and placed in an optimal wind region such as the North Sea. The payback period is in the range estimated by the LCA of Vestas of a V117-4.2 MW wind power plant, which obtain a payback time of 5 and 8 months for strong and low winds, respectively [169].

Ref. [170] conducted a LCA on the Alpha Ventus Farm, located in the North Sea at a depth of 30 m and 16 km from the German coast. In this study, they estimate different EPBT values for 6 scenarios. In the first one—the standard scenario—they obtain 8.8 months with 20 years of lifetime, which implies an EROI of 27.3. The second one has the same boundaries as the first one, but the cable has 40 years of lifetime (20 years for the other components), which results in an EROI of 39.3 with 6.1 months of EPBT. The third and fourth scenarios are identical to the standard but have different full load hours; they obtain 9.5 months (EROI 25.3) for 3600 h/a and 8.1 months (EROI 29.6) for 4200 h/a, compared to 3900 h/a, in the first scenario. For the next scenario, they lower the wind farm maintenance by half and obtain 8.7 months of EPBT (27.6 EROI). Finally, the last scenario assumes that the offshore wind farm has 40 WEC instead of 12; they obtain 7.4 months of EPBT, which implies an EROI of 32.4.

The energy performance of different power stations deployed in the United Kingdom was examined by [171], which obtained an EROI (electricity-equivalent) of 18 for offshore wind stations with a range of variability between 16 and 30. An increased blade size and better wind field tend to improve the turbine EROI due to enhanced CF. This is probably the cause for the large values reported by [172] for wind farms installed in New Zealand: a mean value of 34.3. [173] estimates the EROI of an offshore farm in the Taiwan Strait with and without an offshore substation located 8–15 km from the coast. They obtain an EROI of 18.7 without the substation and 16.7 installing the offshore substation. If they considered the recycling of waste materials, the EROIs increased to 26.7 and 23.2, respectively.

Ref. [174] estimated an EROI of 8.7 for the standard offshore wind technologies. This low number could be the result of pessimistic assumptions that need to be tested, including the assumption that "indirect investments of Renewable Energy Systems constitute at least 100% of the total direct energy investments estimated" by typical LCA analyses.

Table 11 summarizes the EROI values and EPBTs reported in the present section.

Table 11. Summary of literature values for EROIs for offshore wind technologies.

Device, Technology (Manufacturer) or Case Study	LCA Boundaries	EROI Value (Energy Payback Time)	Reference
Review of 119 wind turbines (onshore and offshore) [1]	Input-Output and Process Analysis	33.3 (7.2 months), 51.3 (5 months) and 14.3 (4 months)	[162]
Floating offshore wind farm 50 km away from the shore based on the Sway Company project	production and end-of-life	18.45 (13 months)	Estimated using data from [163]
6 conceptual offshore farms 200 km off the British Coast, at Doggerbank	cradle to grave	12.4 (19.2 months) for the bottom-fixed concept; 7.5–12.9 (19.2–32.4 months) for the floating systems	[164]
Two floating offshore wind farms case studies	cradle to grave	5.81–7.57 for the Hywind Scotland (39.6 to 51.6 months) and 6.5–8.92 for the Kincardine Aberdeen (33.6 to 44.4 months)	Estimated using data from [165]
Two conceptual offshore farms, with 4 and 6 MW turbines	cradle to grave	30 (10 months) and 21.6 (11.1 months)	Estimated using data from [166]
Theoretical LCA of different electricity generation technologies (undisclosed offshore wind farm)	cradle to grave	13.5 (22.2 months)	[167]
Bottom-fixed and floating offshore wind farms with 39% CF	cradle to grave	12 (25 months) for the turbines founded at 15 m depth; 10.4 (28.8 months) for the floating system	[40]
Siemens-Gamesa LCA of 80 turbines SG 8.0-167 DD of 8 MW	cradle to grave	40.5 (7.4 months)	Estimated using data from [168]
6 scenarios for the Alpha Ventus farm in the North Sea	cradle to grave	27.3 (8.8 months), 39.3 (6.1 months), 25.3 (9.5 months), 29.6 (8.1 months), 27.6 (8.7 months), and 32.4 (7.4 months)	Estimated using data from [170]
Different power stations deployed in the United Kingdom	cradle to grave	18 (13.3 months)	[171]
Wind farms installed in New Zealand	cradle to grave	34.3 (7 months)	[172]
Offshore farm simulation in the Taiwan Strait, near the coast of Fangyuan Township	hybrid analysis (input-output and process analysis)	16.7 (14.4 months) with an offshore substation (26.7 if recycling waste materials) and 18.7 (12.8 months) without it (23.2 recycling waste materials)	[173]
Global assessment	cradle to gate and O&M	8.7 (34.5 months)	[174]

[1] Only values for offshore wind are reported here.

5. Net Energy

In this section, we discuss the energy potentials and EROIs of the different forms of MRE collated in Tables 1, 2, 3, 4, 5 and Tables 6, 7, 8, 9, 10, 11, respectively, and use the most reliable figures to obtain their respective potential net energy contribution. A summary with the results obtained in this section is shown in Table 12.

5.1. Tidal

Studying the same site (Cardiff–Weston proposal in the Severn Estuary), ref. [36,131,132] obtained values of EROI slightly above 20 using different hypothesis (see Table 6). Ref. [134] also report an EROI above 20 for the Swansea Bay Tidal Lagoon project. However, all these studies neglect the energy consumption of different stages of the lifecycle of these barrages, hence in this work we settle on a value of 20. Despite the high energy return, the large environmental impacts and upfront economic costs of building large dams and creating artificial impoundments [10,46,175–177], combined with the small number of sites with large tidal ranges that could be dammed, are hindering the development of new tidal range capacity, and may result in a low global sustainable potential for this type of technology. Compared to conventional barrage schemes, tidal lagoon power plants impound a smaller body of water and should therefore be less intrusive [55]. However, it is not yet possible to give a factual assessment of the full life-cycle of environmental consequences of tidal lagoons, since there are no full-scale systems of this type in operation to date [178]. Taking all the previous into account, we reckon that further adoption of tidal range technologies is unlikely.

Excluding [126] (not cradle to grave LCA), the mean of all EROIs for tidal stream collated in this study is 11.16 (the median is 11.5) (see Table 12). For the estimation of net energy, we will use the median (11.5).

For the tidal stream technical potential (see Table 1), we use the 177.4 TWh/yr reported by [52], noting that it is the only value for the potential of this form of energy that we found in the literature. This value is likely in the lower range of the literature, considering the combined technological potentials of tidal stream and tidal range reported in this work, but it is also likely that when taking into account economic and sustainable aspects, the actual potential becomes even smaller.

According to this, the net energy that may be obtained from tides on an annual basis (besides the 0.12 TWh/yr generated by La Rance and Sihwa altogether), based only on technical considerations, would be 162 TWh/yr ($177.4 \cdot (1 - 1/11.5)$).

5.2. Wave

The technical potential for wave energy estimated in this work from data reported by [63] is higher than the lower bound theoretical potentials collated in Table 2. Therefore, we will discard this value for the calculation. The value reported by [66] is a rough estimate of 0.5 TW, and from the remaining values (considering technical and economic potentials), no robust statistical analysis can be performed. However, when factoring in sustainability constraints, the technical potential is likely to go well below 1000 TWh/yr. Here, we use an optimistic value of 1000 TWh/yr.

Regarding the EROI of wave energy technologies, the mean of all collated values is 11.2, and the median is 8. This results from the fact that there are many low EROIs and only a few higher ones (see Table 8). Technologies with higher EROIs are more likely to become commercially available. Therefore, here we first calculate the average EROI by device (only those with an EROI > 7), and then select only the technology with the highest EROI. This approach, will most likely result in an overestimation of the future global average EROI, since it is likely that several technologies with different EROI ranges will coexist (and also less optimal sites). Using this approach, we find that the highest EROI is that of the Wave Dragon WEC, with an average value of 20.

With a technical potential of 1000 TWh/yr and an average EROI of 20, the mean annual net energy that could be extracted from waves, based only on technical considerations and in the very best case scenario, would be 950 TWh/yr.

5.3. OTEC

OTEC is the energy source with the highest potential, which is also the one with the highest uncertainty of all. Therefore, this will have a large impact on the final net energy potential of ocean energy altogether.

The global technical OTEC potentials in the most recent literature are in the 7–9 TW range (see Table 3). However, Nihous and colleagues have reported on several occasions that no more than 7 TW may be exploited without significant large-scale environmental effects. Ref. [100] obtained slightly higher technical potentials, but when considering only the potential in EEZ, the potential (more economically viable) goes down by 45%. Ref. [98] went even further and cut the potential to 2 TW to prevent potential negative environmental effects. Considering the EEZ only, this potential would decrease to 1 TW (8760 TWh/yr, considering the theoretical maximum potential). According to our discussion in Section 3.4, this latter figure would imply a potential flow of CO_2 to the atmosphere of 5% of the anthropogenic input of 2011. While it may still be seen as a considerable amount, it would be much less disruptive than larger powers.

From the very few studies that are available from which EROIs can be estimated for OTEC (see Table 9), it is apparent that with current technology it is unlikely that the average EROI for the whole technical potential remains above 7. Here, using what we consider a very optimistic exercise, we assume that only 50% of all the techno-economic potential (4380 TWh/yr) of OTEC would be exploitable with an average EROI of 7. This leaves us with a very rough estimate for the annual OTEC net energy production of 3750 TWh/yr.

Here, we estimate the current marine energy potentials, hence we did not take into account the 45% increase in the global OTEC potential due to climate change projected by [100] by 2100. If this was taken into account (assuming that the 45% applies equally to EEZ and outside of it), the techno-economic potential (in EEZ) would be 1.45 TW, and the net energy production would go up to 5440 TWh/yr (that is without taking into account potential technological improvements that would likely translate into higher EROIs).

5.4. Salinity Gradient

The average of all technical potentials for SGE is 3767 TWh/yr (median is 2000 TWh/yr) (see Table 4). However, some authors have also estimated what they argue would be a sustainable potential for SGE [108,115]. The average value for the sustainable potential is 570 TWh/yr.

Despite the lack of studies available on the energy intensity of SGE, the prospects for the EROI of this technology are not very high (see Table 10). According to this, and the expected relatively low sustainable energy potential, here we will assume a null annual contribution from SGE to the energy mix.

5.5. Offshore Wind

There is a fair amount of literature on the energy potential and LCA analyses for offshore wind systems, but the estimates vary greatly depending on the study. Since most of the potentials we report are technological, the value varies widely depending on its constraints (water depth, distance from the coast, available area, turbine density, capacity factor, etc.). We did not find offshore wind studies that reported economic or sustainable global energy potentials.

Here, we consider the potential values of [125], as the study includes both anchored and floating technologies for low-use and high-use scenarios. In addition, their calculations exclude areas with low average wind speeds. The range varies between 52,500 and 181,111 TWh/yr (see Table 5), the average of which is 116,805 TWh/yr. However, the realization of the high-use scenario (5% (0 km–10 km), 40% (10 km–50 km) and 80% (50 km–200 km)) is improbable, since both marine life and fisheries would be severely impacted. Although the low-use scenario also occupies a large portion of marine areas (4% (0 km–10 km), 10% (10 km–50 km) and 25% (50 km–200 km)), we consider it a top boundary for the exploitable potential. Factoring in site-specific sustainability and legal constraints will undoubtedly limit even further the effective potential. Therefore, 54,722 TWh/yr is the most reasonable value for global offshore wind energy potential.

Reported values of offshore wind EROIs range from 6 to 51 and the average EROI among all the analyzed studies is 22.6 (median 21.6) (see Table 11). The wide range of uncertainty is caused by the specific assumptions established in the different studies. Recycling waste materials also has an important positive impact on EROIs [173,179]. Ref. [165] emphasizes the need for a more thorough investigation of how O&M strategies impact marine ecosystems, as the selection of vessels and the volume of maintenance activities in LCA studies are generally based on broad assumptions. Indeed, research on the impacts of offshore wind farms on marine ecosystems is still in its early stages (e.g., biodiversity loss, seabed destruction, pollution, acoustic noise, electromagnetic field enhancement by underwater transmission cables, etc.) [25,179,180]. Moreover, some recent studies find that large clustered offshore wind farms can impact sea surface fluxes, which is on the magnitude of a climate change impact [26]. Thus, changes in atmospheric climate caused by offshore wind platforms must also be taken into consideration.

Table 12. Average energy potentials and EROIs used in this work for the estimation of the annual net energy production.

Energy Form	Technical Potential (in TWh/yr)	Economic Potential (in TWh/yr)	Sustainable Potential (in TWh/yr)	Average EROI	Net Energy (in TWh/yr)
Tidal range			0	20	1.1 [1]
Tidal stream	177.4			11.5	162
Waves	1000			20 [2]	950
OTEC			4380 [3]	7	3750
SGE	0 [4]			<7	0
Offshore wind	54,722			21.6	52,188
TOTAL					57,051

[1] Current energy generation of La Rance (600 GWh/yr) and Sihwa (550 GWh/yr) tidal barrage systems, applying an EROI of 20. [2] Average value for the Wave Dragon WEC. [3] We assume that only half of the current techno-sustainable potential for OTEC will be exploitable with an EROI of ∼7. [4] Assumed to be unexploitable due to low EROI.

6. Discussion

Reliable estimates of the potentials and EROIs for various renewable energy technologies are crucial in strategic planning for future renewable energy portfolios. By combining the technical potential with the EROI, we can estimate the overall net energy that marine technologies could potentially contribute to meet the energy demands of our current societies. Integrated Assessment Models (IAMs) and energy system models are often used to make this mid- to long-term energy planning, and as such, the potentials and EROIs are also crucial inputs to these models [181].

It is important to emphasize that the objective of this study is not to discredit any MRE sources or technologies. Rather, the focus is on identifying and highlighting those with the highest potential to contribute to the future energy mix. By prioritizing the most promising resources and technologies, policymakers and stakeholders can more effectively allocate resources and promote the development and deployment of MRE on a larger scale.

In line with this objective, it is also important to consider the technical and regional suitability of different MRE resources when evaluating their overall potential. While certain MRE resources may have limited potential or exhibit high regionality, they may still be well-suited for specific geographic locations. For instance, although tidal energy may not be exploitable at a global scale, it could be particularly viable in regions such as the UK or Canada. Thus, careful consideration of both technical potential and regional suitability (including environmental impact assessments) is crucial to effectively harness the benefits of MRE resources.

6.1. Literature Review

The literature on marine energy potentials is characterized by a significant degree of uncertainty [4]. This uncertainty can be attributed to several factors, the most important being the inherent complexity of the subject, which arises from the heterogeneity of environmental conditions across different regions and in time [182]. On the methodological side, factors responsible for the large uncertainty include the use of different methodologies (from sophisticated models to simplistic assumptions or basic rules of thumb), the number and complexity of variables included in each analysis (e.g., technical, economic and environmental aspects) and their spatial resolution (e.g., spatially explicit vs. global averages). Finally, the diversity of technologies considered in different studies and the fact that many of them are in the pilot phase make it difficult to provide reliable estimations of energy potentials.

The methodological challenges outlined above are compounded by the lack of clear boundaries between the different types of potentials reported in the literature [4]. Consequently, the reported technical potentials may, in some cases, be closer to theoretical potentials, while ecological potentials may be presented without proper consideration of their economic viability.

In addition, while in most cases theoretical and technical potentials of marine energy resources are relatively easier to approximate, reliable assessments of global economic and ecological potentials can only be achieved through a bottom-up approach, which involves analyzing each combination of site and technology individually. As a result, the majority of potentials collated in this work correspond to theoretical and technical potentials.

This work also highlights the significant discrepancy in quantitative assessments of technological potential between wave, tidal, and offshore wind technologies compared to SGE and OTEC and ocean currents. Specifically, the majority of available studies have focused on the former, while the latter have received far less attention [175]. In fact, the present study reveals that the current literature does not provide sufficient evidence to provide reliable values for the energy potential of ocean currents.

While the EROIs of other energy technologies and fuels have been thoroughly evaluated in numerous publications [31,162,174,183–185], the number of studies on marine RE technologies is relatively scarce. This makes the present work a significant contribution to the field, as it is the first comprehensive attempt at compiling the EROI of various MRE technologies.

Obtaining reliable estimates of the EROI of marine technologies is particularly challenging due to their diversity and the range of conditions of the different locations, their low maturity and the overall lack of operational experience [39,186]. Most technologies analyzed in LCA studies are in pilot phases or are full-scale prototypes [39], and as such, the obtained results may differ significantly when scaled-up. The lack of operational experience leads to large uncertainties in the estimations made during the O&M and decommissioning phases, and even their lifespan, which are generally based on expert judgments [39]. Moreover, the lack of standardization in LCA methodologies [35,144,187] and the scarcity of data on energy inputs and outputs are further challenges to estimating the EROI of marine technologies [138].

Similar to what was found in the literature of energy potentials, OTEC, SGE and ocean current technologies are underrepresented in the LCA studies of marine technologies, and good quality studies are lacking [39,187].

6.2. Potentials, EROI and Net Energy

The technical potentials obtained in this work for offshore wind, wave and tidal stream are 55,000, 1000 and 180 TWh/yr, respectively. The sustainable potentials for OTEC and SGE are 4380 and 570 TWh/yr, respectively, while that of tidal range is negligible due to high environmental impacts [10,46,175–177].

Although many efforts have been dedicated to the assessment of the potential of ocean currents, there are still uncertainties and knowledge gaps that need to be addressed before accurate figures can be reported. Despite this, when considering the numerous challenges associated with harvesting ocean currents in deep water and at long distances from shore, as well as the weakening effects that turbine power plants can have on the currents [69], it seems relatively safe to say that ocean current energy will not make a significant contribution to the future energy mix.

Based on all the previous, in this work, we challenge the claims that ocean energy alone (hence excluding offshore wind) may have the potential to cover the current global electricity demand (27,447.4 TWh/yr [5]). In fact, with the potentials estimated in this work, in the best case scenario and excluding most economic and environmental restrictions (hence including the tidal barrage technical potential), ocean energy alone would cover less than a fourth of the global electricity demand ($\sim$ 6000 TWh/yr).

Of all the technologies analyzed in this work, offshore wind, wave energy, and tidal range have the highest average EROIs (around 20). The EROI of tidal stream is slightly above 10, while OTEC's EROI is around 7. The EROI of SGE remains uncertain, and current evidence suggests that it may be lower than 7. Given the limited research available, further LCA studies are necessary to provide reliable estimates of the EROI of ocean current technologies.

According to the estimations made in this work, the total maximum annual net energy that may be extracted from marine energy sources would be 57,051 TWh/yr (Table 12) with an average EROI close to 20. From this total, >90% comes from offshore wind, and 77% of the remaining percentage is covered by OTEC. Wave energy may produce a maximum energy surplus of 950 TWh/yr, while tidal energy may contribute less than 200 TWh/yr. Due to the low technical potentials and EROIs, in this work the contribution of SGE with current technologies is considered negligible. Finally, it must be noted that the average EROI of 20 is highly influenced by that of offshore wind. Indeed, if offshore wind is excluded, the average EROI becomes 8.

A summary of the results discussed in this section is presented in Figure 2.

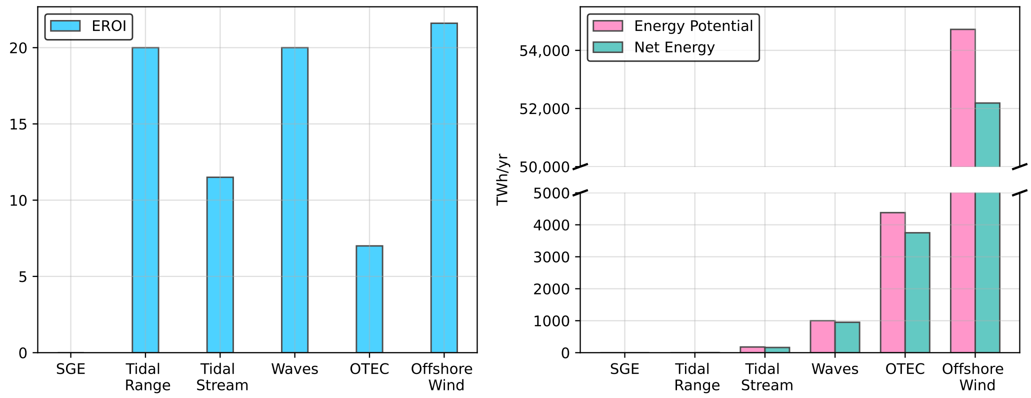

Figure 2. Estimated average EROIs (left), and maximum (upper bounds) global energy potentials and net energy potentials (right) for each MRE (see Table 12 for the actual values). NOTE 1: the EROI of SGE is not represented in the figure, as it is below the threshold considered in this work (EROI < 7). NOTE 2: although the values of the energy potentials (and net energy potentials) shown in this figure are indicative of the scale of the respective potentials, they are not comparable to one another, as different technical, economic and sustainability criteria were considered to obtain each of them. The values for offshore wind, waves and tidal stream may be assimilated to technical potentials, while those of OTEC, SGE and tidal range are closer to their sustainable potentials (see Section 2 for further details). NOTE 3: this figure does not include the values for ocean currents, as neither their energy potentials nor the EROI of the available technologies could be reliably estimated based on the available literature (see Sections 3.3 and 4.3).

6.3. Limitations of the Present Study

The findings reported in this study provide an initial estimate of the potentials and EROIs of various marine technologies. However, it should be noted that the results are subject to a high degree of uncertainty, partly due to limitations in the available literature, as previously discussed. This uncertainty is significant for less-extensively studied technologies, such as OTEC and SGE, and particularly for ocean currents. As further research and development progress in these areas, more reliable estimates of their potentials and EROIs can be expected, potentially affecting the overall conclusions of this study.

The current study also acknowledges a potential limitation that could lead to an overestimation of current potentials and net energy. Specifically, the consideration of economic and environmental restrictions for the various technologies is incomplete [39,144]. As such, the net energy estimations primarily rely on technological potentials, with economic and environmental constraints included only if adequately documented in the literature. Therefore, the net energy potentials obtained in this work for each type of energy are not comparable to one another, but they all represent the maximum energy surplus that each could potentially contribute. This limitation also highlights the need for periodic updates as additional economic assessments and environmental impact assessments become available.

In this study's approach for estimating net energy, we utilized average EROI values for each marine energy source, computed as the mean of all technologies harnessing the respective resource type. Moreover, a uniform application of EROI was adopted for the entire resource, except for OTEC. Given its vast potential and an EROI close to the viability threshold of 7 used in this study, it was assumed that only half of OTEC's sustainable potential may be harnessed with an EROI of 7. This assumption is highly uncertain, as estimates of the minimum societal EROI vary significantly in the literature [30].

Spatial overlapping of MRE resources, as well as co-location opportunities or hybrid solutions, were not explored in this work. This represents a potential avenue for further investigation, as the integration of different renewable energy sources in a shared location could lead to improved efficiency and reduced costs and environmental impacts [7,14,188–191].

Additionally, the results presented here correspond to a point-in-time image of the current situation, as both the marine energy resources and particularly the EROIs of marine technologies are continuously evolving. Indeed, a growing body of literature has started analyzing how marine resources may be affected by climate change in the future [100,192–195]. Resource potentials may also be affected by more restrictive environmental future legislations, such as the recent UN pledge to protect 30 percent of the planet's lands and inland waters, as well as of marine and coastal areas, by 2030. Climate change may also shorten the lifespan of marine devices and increase maintenance costs [196], potentially reducing their energy return. The EROI of renewable energy systems are also dependent on the pace of technological innovation, the gains in operation experience, and the need for increased back-up generation and storage [186].

7. Future Industry and Research Directions

The marine energy landscape is diverse, with ongoing efforts to improve existing technologies and develop new devices and processes to reduce the levelized cost of energy (LCOE) and enable commercial exploitation of marine energy resources [14,71,197].

Despite numerous pilot systems being tested worldwide, the number of connected grid systems remains limited [6], highlighting the need for further development and investment [175].

Clear legal frameworks defining potential areas for development are crucial to facilitate the exploitation of marine energy resources [198]. Spain's recent approval of the Maritime Space Management Plans (POEM) Royal Decree 150/2023 on 28 February 2023, which outlines specific offshore areas for wind energy exploitation, marks significant progress in this regard [199].

However, for such legal frameworks to be truly effective, they must be based on the most recent scientific evidence, especially with regard to sustainability. Despite the growing number of oceanic energy technologies, there has been relatively little research on the assessment of their environmental impacts, largely due to the fact that many of the currently available devices have not yet been deployed or tested [200,201]. Moreover, the vast marine areas and ecosystems where these technologies could be implemented make it difficult to identify all potential impacts [10]. Baseline data on biodiversity in sea waters are also limited, further complicating efforts to evaluate the impacts of marine energy technologies after installation [46].

According to the previous, and to ensure the sustainable exploitation of marine energy resources, future research should prioritize the assessment of environmental impacts, particularly on biodiversity and ecosystem health. A common framework for evaluating the environmental impacts of marine energy technologies should be developed upon common consensus of industry stakeholders, scientific experts and policymakers. Additionally, monitoring systems that track the environmental impacts of marine energy technologies over time should be established, and the collected information should be integrated into decision-making processes related to energy development. Most importantly, industry leaders should adopt a precautionary approach to the deployment of new marine energy technologies, which involves careful risk assessment and management to minimize environmental damages.

Furthermore, as with all other forms of renewable energy, marine energy is anticipated to be impacted by climate change. Indeed, climate change will modify the resource, will reduce the durability of infrastructures/devices and increase O&M costs [100,192–195]. Research in the field is currently focused on developing more resilient marine energy technologies that can withstand harsher ocean conditions resulting from climate change, while industry leaders are investing in adaptation strategies and renewable energy storage solutions to ensure the sustainability of marine energy resources in the long term.

8. Conclusions

In this work, we review the existing literature on the global potentials of marine energy sources, and the EROIs of currently available marine energy technologies. These values are used to estimate the net energy potential of marine technologies, as well as the average EROI of marine energy.

The technical potentials obtained in this work for offshore wind, wave and tidal stream are 55,000, 1000 and 180 TWh/yr, respectively. The available literature allowed obtaining what might be considered approximations to the actual sustainable potentials for OTEC, SGE and tidal range. For OTEC and SGE, the sustainable potentials are 4380 and 570 TWh/yr, respectively, while that of tidal range is negligible due to its high environmental impact.

The average EROIs are $\sim$ 20 for offshore wind, waves and tidal range, 12 for tidal stream, 7 for OTEC and <7 for SGE. Based on their low EROIs, SGE is not considered a viable technology currently, while for OTEC we assume that only half of its sustainable potential will be exploitable with an EROI of 7.

The available evidence in the literature is insufficient to provide reliable estimates of the energy potential of ocean currents, nor the EROI of available ocean current technologies.

Crossing the estimated potentials and EROIs, we find that marine technologies (excluding ocean currents) could provide a maximum energy surplus of 57,000 TWh/yr. Excluding offshore wind, the net energy from the oceans goes down to a maximum of $\sim$ 5000 TWh/yr, with OTEC being the major contributor (>77%).

Finally, the average EROI for the whole potential of all marine energy types combined is close to 20, while it goes down to $\sim$ 8 when excluding offshore wind.

The estimations made in this work generally take optimistic views and do not take into account all economic and environmental restrictions. As such, we anticipate that subsequent studies will produce even narrower ranges. Therefore, we view this work as a contribution to a broader and ongoing dialogue on marine energy potentials, and an invitation for further research.

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writing—original draft preparation, R.S. and J.C.; writing—review and editing, J.S, J.C. and A.G.-O.; funding acquisition, J.S. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

AGCM	Atmospheric General Circulation Models
API	Application Programming Interface
BRD	Buoy-Rope-Drum
CapMix	Capacitive Mixing
CED	Cumulative Energy Demand
CF	Capacity Factor
EE	Embedded Energy
EEZ	Exclusive Economic Zone
EGR	Energy Gain Ratio
EPBT	Energy Payback Time
EROI	Energy Return on Investment
EROIst	standard EROI
EROIpou	point-of-use EROI
EROIext	extended EROI
GHG	Greenhouse gas
HP	Harnessable Power
IAM	Integrated Assessment Models
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCOE	Levelized Cost of Energy
MRE	Marine Renewable Energy
OGCM	Ocean General Circulation Model
OHC	Ocean Heat Content
OTEC	Ocean Thermal Energy Conversion
OWSC	Oscillating Wave Surge Converter
O&M	Operation and Maintenance
PRO	Pressure Retarded Osmosis
RCP	Representative Concentration Pathways
RED	Reverse Electrodialysis
SGE	Salinity Gradient Energy
SGP	Salinity Gradient Power
SVP	Surface Velocity Program
THC	thermohaline circulation
TPP	Turbine Power Plants
VRE	Variable Renewable Energy
WEC	Wave Energy Converter
WED	Wave Energy Devices

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