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Review article

Environmental and social impacts of tidal energy developments: A review

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ABSTRACT

Marine renewable energy is gaining increased interest as an area of new developments, but little is known about its potential environmental and social impacts caused to the marine environment and the surrounding communities. While previous research around the latter focused more on offshore wind and wave technologies, there remains a gap in understanding environmental and social impacts for tidal energy and the interlinkages between them, knowing its diverse technological designs and device configuration. The associated implications on natural habitats are also uncertain. This paper fills this gap by conducting a systematic review of the environmental and social impacts of tidal energy development using Scopus and Web of Science databases, without putting any limitations on the technology used or the geographical area of study. A total of 85 peer-reviewed articles were considered and were complemented with grey literature. Overall, the review argues that potential environmental and social impacts of tidal energy projects cannot be tackled in silos as they are often interlinked. They are also location and technology-specific and vary depending on the technology used as well as the marine context in which they are present. They are influenced by the type and number of turbines, its operational characteristics, the energy extracted and the surrounding habitats. This creates uncertainty for planners, developers and communities due to their complex and interchangeable potential environmental impacts. More clarity should be provided through ecosystem-based marine planning, enhanced community awareness and more funding for research. Lessons should also be drawn from onshore and offshore wind experience.

1. Introduction

The ongoing debates on climate and energy issues reflect the urgent and pressing needs to act faster towards achieving the global decarbonization goals agreed upon in the Paris Agreement (UNFCCC, 2015). Renewable Energy (RE) technologies appear to be among the primary tools towards those goals, knowing their role in increasing energy security and affordability, along with their socioeconomic benefits. In recent years, utility-scale solar and onshore wind have become the cheapest sources of generation compared to new and existing fossil fuel plants (IEA, 2023; IRENA, 2025). Yet, and as climate challenges increase, new technologies are being considered.

In particular, the marine environment is gaining increased interest as an area of new developments, knowing its role in harnessing wind, wave, and tidal power (Díaz and Guedes Soares, 2020; Melikoglu, 2018). The development of offshore renewable energy (ORE) not only contributes to the reduction of Greenhouse Gases, but has also the ability to foster economic growth especially in coastal areas (Magagna and Uihlein, 2015). While more research has been published on offshore wind and wave energies (Bush and Hoagland, 2016; Brunbauer et al., 2023; Ferguson et al., 2019a; Henkel et al., 2013; Gonyo et al., 2021; Frid et al., 2012; Hutchison et al., 2022), there is a need for additional research on tidal energy, which is the focus of this review.

Although tidal technology was proven to be an attractive and viable one decade ago (Bernshtein, 1989; Charlier, 1982; Chowdhury et al., 2021), several challenges for its development persist. Existing research around tidal energy has widely focused on its resource assessment modelling (Fouz et al., 2022a; SEAI, 2005; Lewis et al., 2015, 2021; James et al., 2014; Buric et al., 2021; Camporeale and Magi, 2000; Cosme et al., 2023; De Dominicis et al., 2018; Falconer et al., 2009), and technological aspects, knowing the diverse configurations and designs of tidal turbines (Munaweera Thanthirige et al., 2023, 2025; Mehmood et al., 2012; Si et al., 2022; Li and Zhu, 2023a; Roberts et al., 2016; Ahmad et al., 2022; Qin et al., 2022; Wani and Polinder, 2020). It also

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includes review papers covering different aspects of tidal energy (Guillou and Thiébot, 2016; Khojasteh et al., 2023; Paredes et al., 2019; Li and Zhu, 2023b; Martinez et al., 2021; Neill et al., 2021a; Seyfried et al., 2019; Simas et al., 2010; Yahya and Satrio, 2023). While Guillou and Thiébot (Guillou and Thiébot, 2016) work focused on research around turbine optimization in the Strait off western Brittany, Khojasteh *et al (*Khojasteh et al., 2023*)*. looked at wider research on wave and tidal energy over the past 20 years. Yahya *et al (*Yahya et al., 2023*)*. also investigated the development of current energy conversion technologies and their associated numerical modelling. Other reviews focused on the technologies' life cycle assessment (Li and Zhu, 2023a; Paredes et al., 2019), their interactions with the marine environment (Neill et al., 2021b), the environmental impacts of renewable and ocean energy in general (Martinez et al., 2021; Simas et al., 2010; Clarke, 1995), and of salinity gradient energy (Seyfried et al., 2019).

Furthermore, research has highlighted that future decisions regarding project implementation should not be limited to resource and engineering aspects alone and require consideration of the wider environmental and socio-economic factors, something that this paper aims to address from a broader ecological and climate change perspective (Fouz et al., 2022a; De Dominicis et al., 2018).

Although some of the reviewed literature addresses them separately, and focuses on particular geographies, environmental and social considerations are often interlinked and should be considered together, as the former can influence people's perceptions and acceptance (O Rourke et al., 2010; Hooper et al., 2020a). This can help mitigate and manage the associated uncertainties that can result in real-world applications (Jobert et al., 2007; Bonar et al., 2015). This paper aims to address the existing gap through a systematic review of the environmental and social impacts of tidal energy development. Its novelty lies in putting no geographical or technological constraints, as previous research mostly covered specific countries and technologies, and complementing existing literature with the inclusion of grey literature and research theses published around the topic, as these sometimes cover novel work and unique approaches. This approach allows capturing the majority of the potential impacts already covered in existing literature in different regions around the world, and for different types of turbines. Through this comprehensive examination, we aim to highlight their interrelation, gain valuable insights into the challenges and opportunities accompanying these technologies, and promote informed decision-making processes.

This work builds on existing research in this area, in particular Jenkins *et al (*Jenkins et al., 2018*)*. who focused on theories for understanding and managing human dimensions of tidal energy in the United States, highlighting environmental assessments as one of its main overarching concepts; and Bonar *et al (*Bonar et al., 2015*)*. who reviewed the most significant social and ecological impacts of marine energy development (wave and tidal). Portman (Portman, 2009) also proposed a framework for public participation in EIAs. These either looked at social and environmental impacts in silos or considered them for specific countries, or combined with other technologies (e.g., thermal gradient or wave energies). Thus, studies considering both environmental and social impacts of tidal energy together were found to be limited.

It is becoming increasingly recognised that public acceptance and engagement are critical factors in the successful implementation of MRE projects. The review of the related body of literature asserts the need for thorough public engagement and consultation to increase people's awareness (Hooper et al., 2020a; Kerr et al., 2014; de Groot and Bailey, 2016; Dalton et al., 2015; Wüstenhagen et al., 2007), as little attention was given over the years to human dimensions of marine renewable energy (MRE) development (Ruano-Chamorro et al., 2018). This is not solely limited to tidal energy, but extensively covers the acceptance of offshore wind in different contexts e.g., (Laskowicz, 2021; Kim et al., 2019; Karydis, 2013; Ferguson et al., 2019b; Billing et al., 2022; Sorensen et al., 2002; Brennan and van Rensburg, 2023; Firestone et al., 2012), wave energy e.g., (Bailey et al., 2011; Stokes et al., 2014), battery storage technologiese.g., (Kear and Chapman, 2013), and other electricity generating sources e.g., (Bronfman et al., 2012; Sposato and Hampl, 2018).

At the environmental front, the paper complements findings of previous reviews conducted in this area of research, in particular Rivera *et al (*Rivera et al., 2020*)*. and Bonar *et al (*Bonar et al., 2015*)*.. While the former focused specifically on the thermal gradient and TEC technologies and applied it to an area in Mexico, the latter followed a similar approach to ours but applied it broadly to marine energy development and not only tidal. In addition, this study draws on some specific environmental areas around tidal energy, such as water quality impacts (Kadiri et al., 2012), sea level rise (Khojasteh et al., 2022), and seabird collision (Waggitt et al., 2017).

It is worthy of note that there is a diversity of existing tidal technologies, which influences the ability to predict the potential environmental and social impacts. In fact, energy is extracted from the water through two main principles: a) tidal range structures, which are man-made barrages (dams) or lagoons that concentrate the flow of water and release it through turbines, generating energy (Etemadi et al., 2011). These are fully commercial but face many challenges including their high capital expenditures and high environmental and social footprints (Hooper and Austen, 2013); b) Emerging tidal stream (sometimes called tidal current) devices that extract energy from the flowing current (Ward, 2022), and which have gained increased interest over the past years (Table 1).

Tidal range is known for their heavy infrastructures that could obstruct the entire width of an estuary or channel (Fig. 1). While tidal lagoons, although less environmentally damaging, require more construction materials than tidal barrages and higher costs (Hooper and Austen, 2013), both technologies can cause changes to sea levels, sedimentation and species distribution. They also impact other activities happening in the vicinity, including shipping, fishing and aquaculture. On the other hand, tidal stream devices are known for their diverse configurations and designs of the turbines including seabed fixed, floating, cross-flow or axial flow (horizontal axis) turbines (Fig. 2) (Munaweera Thanthirige et al., 2025; MacGillivray et al., 2013; Segura et al., 2017). These design variations aimed at prioritizing maximum energy capture while maintaining the turbines' structures, and were complemented by advancements at the level of design materials used in tidal blades (Segura et al., 2018), allowing more flexibility and optimizations options. In this paper, we use the term Tidal Energy Converter (TEC) to refer to devices that convert tidal stream into electrical energy.

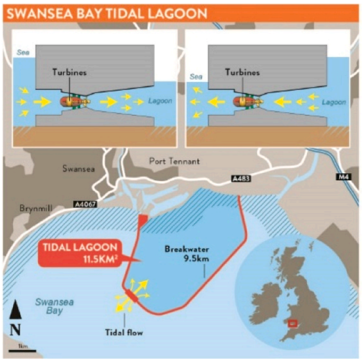
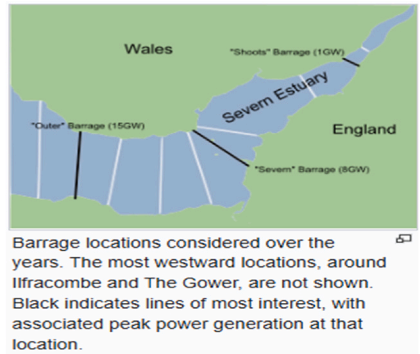
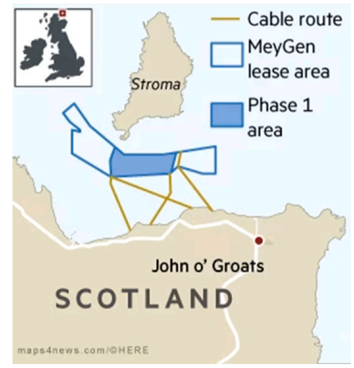
Of the different types of TECs, horizontal axis turbines have been the most widely used around the world (Munaweera Thanthirige et al., 2023; Walker and Thies, 2021), the majority of which performed well after deployment (Walker and Thies, 2021). This allowed this type of configuration to dominate yet couldn't be the only type of turbines used. A major difference between TECs' devices and configurations is often linked on one hand to the depth at which they can produce maximum energy, and on the other hand to the range of flow velocities in which they can operate. An additional challenge is related to tidal energy economics, still being an expensive technology (Borenstein, 2012; Vazquez and Iglesias, 2016; Rodrigues et al., 2021).

This diversity in TECs creates uncertainty for planners, developers and communities due to their complex, unforeseen and interchangeable potential environmental impacts (Chowdhury et al., 2021). In consequence, these uncertainties result in significant challenges and triggers community objections, leading to project delays and increased costs. Addressing them becomes a critical issue to enable the effective deployment of tidal energy projects, ensuring alignment with environmental sustainability, and engaging communities in decision-making processes.

2. Method

Our search of peer-reviewed articles was conducted using Scopus and

Table 1
Different working principles of tidal energy technologies and examples of projects.

Tidal Lagoon	**Tidal Barrage**	**Tidal Stream**
An artificial lagoon is created and water flows in and out of lagoon generating power	An entire estuary is dammed and water flows in and out of lagoon generating power	Individual tidal turbines extracting energy from tidal stream
		
Swansea Bay Tidal Lagoon (not implemented)/Large infrastructure Inspired Pencil (2021)	The Severn Estuary tidal barrage plans (not implemented)/Large infrastructure BrighHub Engineering (n.d)	MeyGen (Phase 1, Scotland)/Modular Turbine Financial Times (2016)

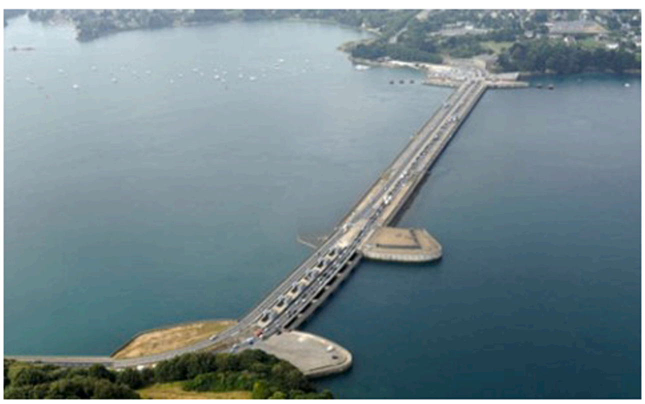


Fig. 1. Example of La Rance Tidal Barrage structure in France (The Ecologist, 2010).

Web of Science (WoS) databases, which were identified among the overlapping databases between the natural sciences and political science and sociology disciplines that we are interested in. The work followed a PRISMA flow diagram approach (Fig. 3) (Page et al., 2021), which included searches of databases and registers using specific keywords, and comprised of three consecutive steps: Identification of records, screening process and exclusion/inclusion process.

The following combination of key words were used for the search strategy in both databases. Concept 1 includes the words "Tidal Energy", "Ocean Energy", "Marine Energy"; while concept 2 comprised of the words "perception", "impact", "engage" and "environment".

A total of 1703 articles were retrieved from both databases in January 2024 (1075 articles from Scopus and 628 from WoS), which were then moved to the screening process. A technical glitch linked to the order of precedence of proximity operators was discovered in Scopus' search engine and was addressed with Scopus' support team. An FAQ note (August 2024) and a blogpost (March 2025) were added to Elsevier's website regarding the issue.

EndNote referencing tool was used for categorization, and after removing 537 duplicated articles, a total of 1166 articles remained for further investigation (Fig. 3). A visual scan of the title and abstract allowed the categorization of these articles into research themes, as follows: Social tidal (10), Environmental tidal (145), Social RE/Ocean RE (74), Environmental RE/Ocean RE (440), Economic (32), Policy (66), General RE/Ocean RE (353), Technical tidal (108) and technical report-books (10). The remaining articles were excluded. No geographical or publication date constraints were implemented throughout the systematic search, and only journals published in English were considered. Moreover, there were no exclusion of any tidal technology, as the aim was to gather the diverse impacts that might occur.

Knowing the context of this paper covering the environmental and social aspects of tidal energy, the in-depth review of those two research themes included all the articles under the "Social tidal" category (10 papers) and 75 out of the 145 articles under the "Environmental tidal" category. The latter selected set of journals were thoroughly assessed, while the remaining papers were excluded.

Additional documents from grey literature reports (n = 32), and research theses using online repositories (n = 23) (ProQuest, University of Galway's research repository and Open Access Theses and Dissertations (OATD)) were used to complement this process. While the full review of these documents was not initially planned, such literature proved to be certainly relevant for our strategic review due to their relevance to the focus of this study, particularly at the environmental front. These revolved around the following areas: Environmental impacts of MRE and tidal technologies through numerical modelling and literature review, with a focus on specific aspects such as impacts on fish, harbour seals, sea levels and flood risks, and collision risks; Resource Assessment and technological advancement (status update in Europe and beyond) as well as ocean energy trends and challenges; and social Concerns/stakeholders considerations/attitudes towards tidal energy.

3. Results

3.1. Overview of the reviewed literature

The geographical distribution and the countries covered in the environmental and social literature show that the latter is spread across the United Kingdom (UK), the United Stated (US), Japan, Indonesia, Australia, Canada and New Zealand, while the vast majority of the former case studies (21 environmental case studies) originates from the UK and Ireland, followed by France, the US, Canada and China, among others (Figs. 4a and 4b). In terms of technology focus (whenever mentioned), most studies of the social literature have investigated tidal energy in general without differentiating between technologies, while the environmental literature covered a wider range of technologies, with a majority (41 studies) focusing on tidal stream/current and TECs (Fig. 5). We refer in Fig. 5 by ORE to studies that covered MRE or marine hydrokinetic energy (MHK) in general, as well as those that didn't focus

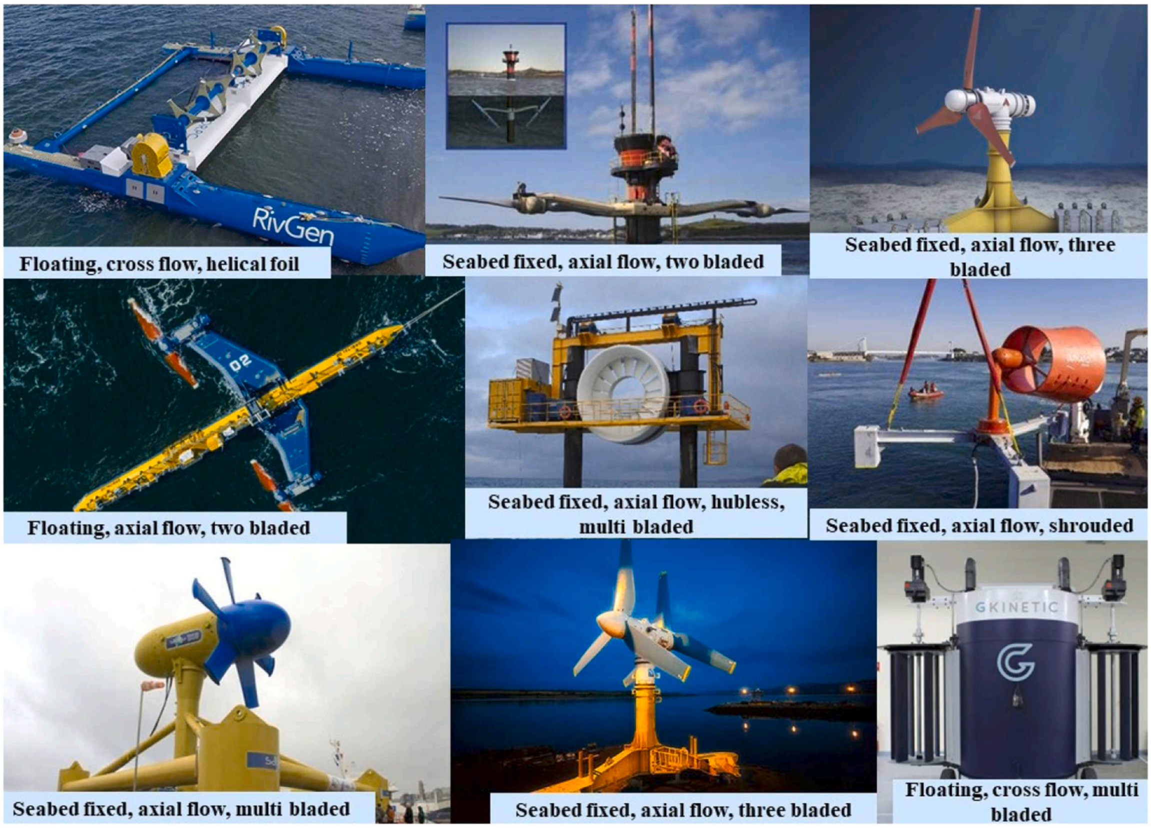


Fig. 2. Diversity of tidal stream devices' configurations (Munaweera Thanthirige et al., 2025).

on a particular technology. Only a handful of studies focused on wave energy.

The overview of the peer-reviewed literature in terms of methodology followed and geographical spread shows that half of the reviewed social literature (5 articles) are review papers, while the remaining articles are spread across a qualitative mail survey analysing people's willingness to pay and public preferences for tidal energy in Washington State, a quantitative survey examining the attitudes of communities in South West England, and three mixed-method studies including two case-study analyses in Northern Ireland and the US. On the other hand, the majority of environmental research is based on modelling, in addition to a set of review papers, and to a lesser extent, quantitative studies, environmental monitoring and desk-based case studies (Table 2).

3.2. Environmental impacts

This review has resulted with sufficient environmental studies that allowed us to identify a diverse range of potential impacts across different tidal technologies (Table 2 and Fig. 5), challenging the misconception that some REs are without environmental effects (Dacre, 2007). Chowdhury *et al (*Chowdhury et al., 2021*)*. also contended that the ecological impacts remain unclear because tidal energy technologies and ecosystems are too complex and change over time, which may result in unforeseen side-effects.

While existing MRE research has mainly focused on wind energy, technological advances in tidal energy (Qin et al., 2022; Munaweera Thanthirige et al., 2025) have not yet been associated with clear set of potential environmental impacts (Haslett et al., 2018) despite previous trials (Clarke, 1995; Watson, 1993), and still vary with respect to the technology used, the location of the project as well as the local environment.

Studies in this section have investigated the environmental impacts of tidal energy developments identified in 75 journal articles. It is also complemented by findings from around 20 research theses found through ProQuest, the University of Galway Research Repository and OATD.

Impacts were categorized according to the main receptors and stressors following Jaszczak (Jaszczak, 2023) and Martínez *et al (*Martínez et al., 2021*)*. approach, with the main receptors grouped into the water environment (water velocity and quality, sedimentation, flow dynamics), local ecology (benthic habitats, coastal birds, acoustic effects, collision risks and migration, etc.) and landscape change.

3.2.1. Impact on velocities and flow dynamics

The impacts of installing arrays of TECs or building tidal barrages have the potential to significantly alter tidal currents and water levels within the area of implementation and even beyond. Tidal streams are highly dynamic environments, but their hydrodynamic characteristics could vary from few meters to many kilometres in scale, depending on the device used and the surroundings habitats (Lieber et al., 2018). Modifications to tidal currents' velocities and dynamics has appeared in several journals (Frid et al., 2012; Bonar et al., 2015; Rivera et al., 2020; El-Geziry et al., 2009; Baker et al., 2020; Ma et al., 2023; Haverson, 2017).

When modelling the hydro-environmental impacts of a tidal range project in the UK's Bristol Channel and Severn Estuary, Angeloudis and Falconer (Angeloudis and Falconer, 2017) noted that the devices' impacts were linked to its operational characteristics, and increase as the project scale increases, while altering the ecology and morphology of the area, and increasing turbidity. The authors showed that modelled tidal lagoons in the area have a lower environmental impact than tidal range structures, but also produce less energy than the latter.

Another study in the UK's Inner Sound Channel conducted by Chatzirodou *et al (*Chatzirodou et al., 2019*)*. mentioned that TECs can have an impact on mobile sea bed areas, and cause morphological changes to hydrodynamics, but this depends on the amount of extracted

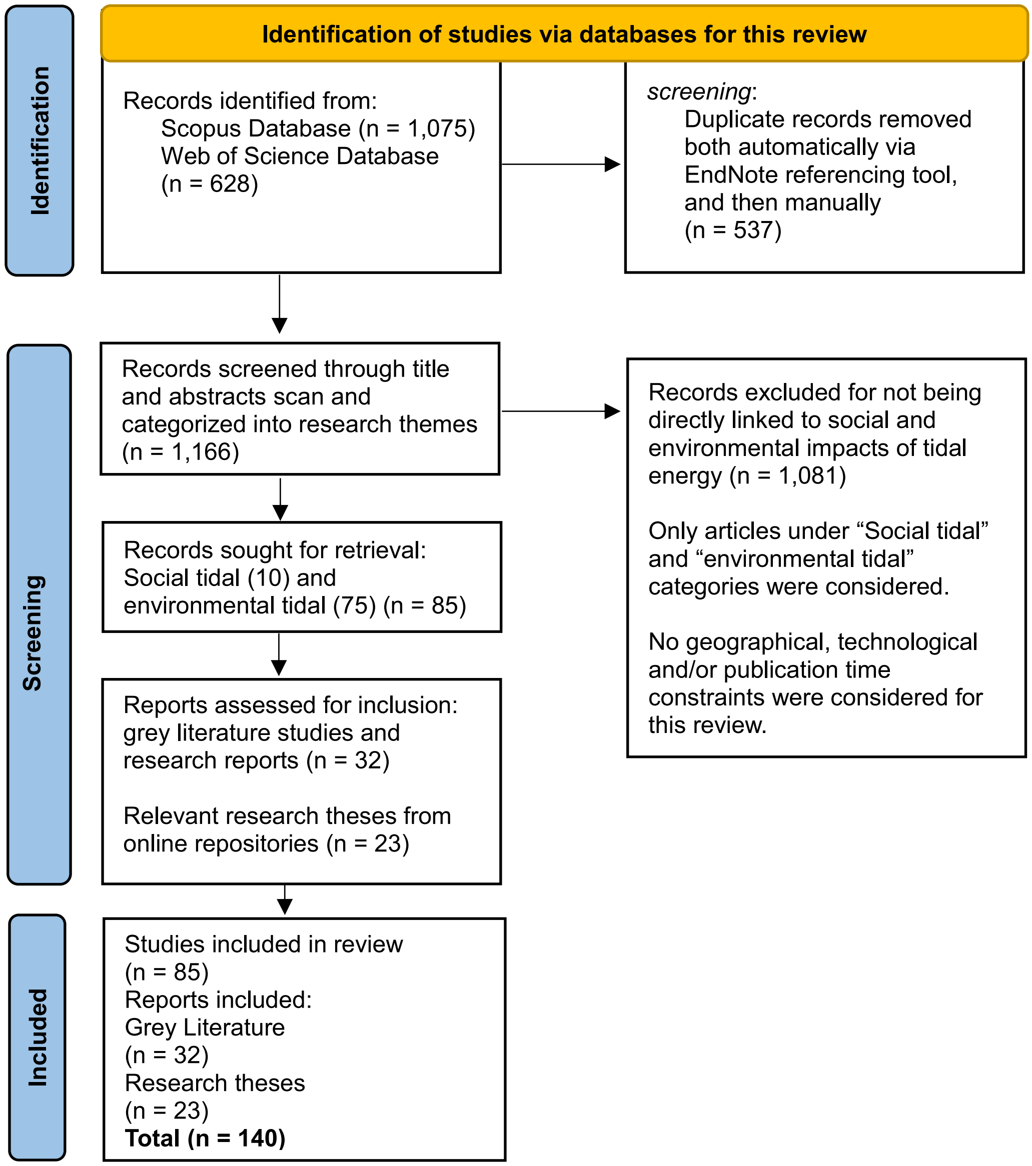


Fig. 3. Systematic Review methodological chart reflecting the number of studies considered for this article, adapted from Page et al (Page et al., 2021).

energy as well as on the proximity of TECs. This complements Haverson's *et al (*Haverson's et al., 2018*).* findings in South Wales's Ramsey Sound where proposed TECs caused changes to velocity not only in the proximity of the project but up to 24 km from it, while in the case of the Alderney Race in France, changes to velocities and hydrodynamic flow were encountered at a distance up to 10 km from the proposed TEC arrays, and particularly during spring tides (Neill et al., 2012). In the Pentland Firth, large flow regime changes were also observed for up to 10 km away from TECs, while minor ones occurred at 120 km (du Feu, 2018).

Moreover, El-Geziry *et al (*El-Geziry et al., 2009*).* suggested that the supporting structure of the TECs' rotor influences local flow dynamics by reducing the speed of the current, while others stress that the extraction of kinetic energy using tidal stream farms or tidal barrages will decrease tidal range, velocity of the current and potentially affect local hydrography (Frid et al., 2012; Baker et al., 2020; Fallon and S, 2012). Currents are usually attenuated due to energy extraction while flow accelerates around the array of TECs (Fallon and S, 2012).

3.2.2. Sedimentation

Altering the local hydrodynamics in the vicinity of the tidal energy project can influence the surrounding sedimentation processes, as water velocity controls the latter and might cause changes to sediment transportation pathways, erosion, deposition and concentration (turbidity) (Bonar et al., 2015; Rivera et al., 2020; Baker et al., 2020; Robins et al., 2014; Hill, 2015). Rivera *et al (*Rivera et al., 2020*).* stressed that an increase in the velocity around the installed devices could also lead to a resuspension of sediments, and modifications to benthic habitats and coastal ecosystems (Auguste et al., 2019), or nearby offshore sandbanks, even if devices are positioned above bedrock (Robins et al., 2014).

Several case studies have covered sedimentation challenges resulting from the use of TECs (Chatzirodou et al., 2019; Haverson's et al., 2018; Neill et al., 2012; Robins et al., 2014; Martin-Short et al., 2015; O'Laughlin et al., 2014; Ross et al., 2021) and tidal barrage (Baker et al., 2020; Angeloudis and Falconer, 2017), as the potential impact is highly dependent on the technology used, project size and energy extracted. Looking at impacts of a large array of TECs on the sediment dynamics and sandbanks morphology of the UK's Inner Sound Channel, Chatzirodou *et al (*Chatzirodou et al., 2019*).* found that changes caused to those sandbanks as a result of TECs exceeded changes caused by the natural hydrodynamic regime, and might create a new flow environment for the benthic ecology in deep sea sandbanks, impacting habitats and breeding

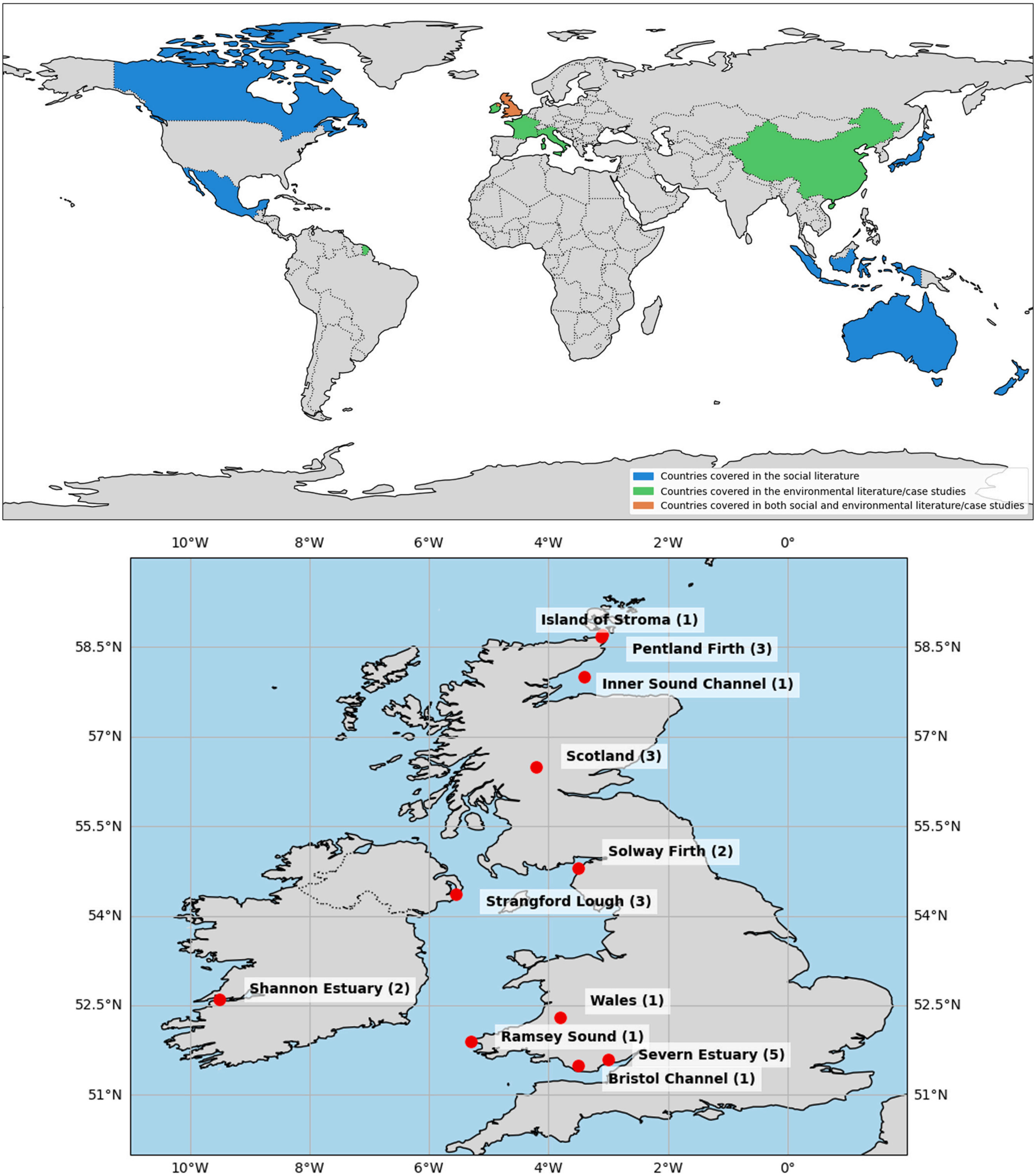


Fig. 4. a: Geographical coverage/locations of the peer-reviewed social (in blue) and environmental (in green) literature. Locations highlighted in orange represent countries covered in both social and environmental literature. b: Cases studies in the UK and Ireland covered in the environmental literature.

grounds of marine species. Furthermore, in the case of Ireland's Shannon Estuary, modelling by Hartnett *et al (*Hartnett et al., 2013*)*. has shown that a significant spread of mudflats (slobs or coastal wetlands that are of environmental importance) are exposed due to reductions in tidal range for a distance of up to 6 m. Potentially, this could also lead to a contrasting positive impact of minimizing flood risks (Hartnett et al., 2013; García-Oliva et al., 2017). Moreover, O'Laughlin *et al (*O'Laughlin et al., 2014*)*. found that the reduction of tidal amplitude minimized the channel's sediment export capacity in Canada's Minas Basin.

On the other hand, Angeloudis and Falconer (Angeloudis and Falconer, 2017) showed that flow stagnation in the UK's Severn Barrage area can drive sediments' settlement causing morphological changes, while Baker *et al (*Baker et al., 2020*)*. shed light on the changes in sediments' accumulation, and thus species habitats, due to a tidal

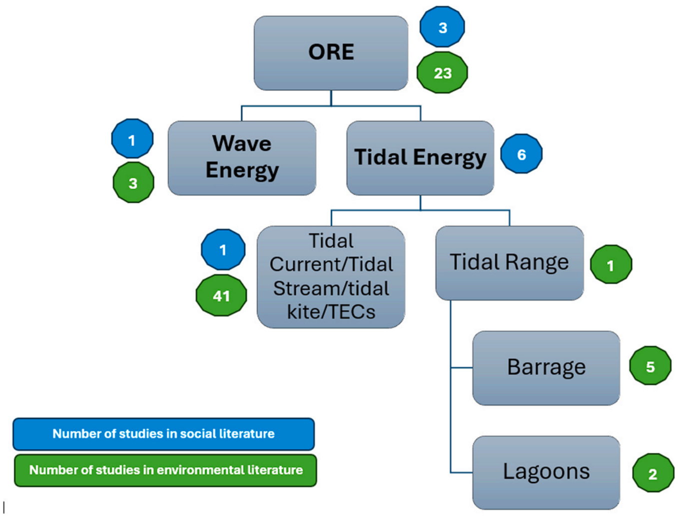


Fig. 5. Technological focus of the environmental and social literature.

barrage in an estuarine context.

The number of turbines used in modelling tidal arrays plays an important role in quantifying the environmental impacts. Martin *et al* (Martin et al., 2012). observed sediment migration from the edges of the Inner Sound to its centre, but this does not happen with arrays less than 85 turbines and might stretch for kilometres away from the project. In addition, Robins *et al* (Robins et al., 2014). found that the sedimentary impacts of arrays below 50 MW capacity would still be within the acceptable ranges, while Neill *et al* (Neill et al., 2012). simulation around a headland concluded that a 300 MW full scale TEC array could considerably alter the surrounding sandbanks.

3.2.3. Landscape change

Landscape change around tidal energy developments' sites is linked to any alteration experienced to the terrestrial landscape surrounding the location. Although under-researched, this area is critical to consider as an influencing factor to turbines' siting (Jaszczak, 2023).

Ma *et al* (Ma et al., 2023). outlined that tidal barrages will have an impact on both marine and offshore environments through the production of construction waste which not only will pollute seawater and air, but also sandy beaches which can affect the survival of animals. In the Inner Sound of Stroma (UK), Martin-Short *et al* (Martin-Short et al., 2015). simulations indicated that siting an array of TECs (increasing number from 0 to 400 devices) will lead to significant changes to the hydrodynamics, leading to escalated rates of erosion in the coastal zone. The 400 turbines scenario had the potential to reshape the local landscape during the flood tide (Martin-Short et al., 2015), while the 8 GW scenario modelled in Van Der Molen *et al* (Van Der Molen et al., 2015). also showed that effects would be observed at longer distances, particularly to tidal and ecosystem variables. In addition, a 300 MW scenario TEC array could lead to changes in the headland sandbanks (Neill et al., 2012),something that developers are advised to further investigate prior to any implementation.

3.2.4. Water level rise and surface water quality

Water level rise and water quality alteration are also among the environmental impacts identified in the literature and are sometimes considered as knock-on effects on the hydro-environment (Kadiri et al., 2012). In some cases, sea level rise caused by tidal energy projects might influence tidal currents to strengthen or lessen (Khojasteh et al., 2022), but this is also dependent on the marine context of interest (estuary, sea or ocean, coastlines, etc.), its shape as well as the tidal technology used (Kadiri et al., 2012). In the case of barrages, for example, they have the potential to impact the tidal range by influencing the sea level of the basin, and thus reducing the water levels upstream of the barrage (Rivera et al., 2020; Kadiri et al., 2012; Hooper and Austen, 2013; Falconer et al., 2010; Kirby and Retière, 2009), and reducing the risk of flooding (Pelling, 2014).

For estuaries, García-Oliva *et al* (García-Oliva et al., 2017). asserted that the impact on water levels is influenced by the amount of energy extracted from TECs rather than by their numbers as in the case of sedimentation, something that was established by Wang *et al* (Wang et al., 2015).. Water levels are also influenced by the channel

Table 2
Overview of the social and environmental peer-reviewed literature summarizing their type (methodology), technology focus, year of publication, geographical distribution and identified impacts.

Category	Year of Publication	Study Type/ Methodology	Geographical Distribution	Topics covered in existing reviews	Overview of identified impacts
Social Literature (10)	2006–2023	Review (5) Mixed methods (3) Quantitative (1) Qualitative (1)	UK US Japan Indonesia Australia Canada New Zealand	Social and ecological issues associated with wave and tidal current energy generation Review of theories and frameworks around human dimensions of tidal energy Environmental and Social Impacts of Thermal Gradient and Tidal Currents in Mexico Blue economy Impacts of tidal energy from an ecosystem services perspective	*Technology focus: Tidal Energy in general* Impacts: Public Acceptance and stakeholders' engagement. Procedural and distributive justice. Decision-making and local ownership. Fisheries. Marine recreation and tourism. Place attachment. Economic impact.
Environmental Literature (75)	2009–2023	Modelling (40) Review (8) Qualitative (8) Quantitative (3) Environmental Monitoring (3) Guidance document (3) Desk-based case study (3)	UK & Ireland (21 case studies) France US Canada China	Collision risks of tidal stream turbines Effects of tidal stream devices on seabirds Water quality impacts of tidal energy Sea level rise Environmental impact of ocean energy devices Environmental impact of renewable energy sources	*Common impacts for TECs and tidal range:* Sedimentation Landscape change Local hydrodynamics (velocity change) impacts on species abundance *TECs only:* impacts on coastal birds Acoustic effects Collision risks *Barrages only*: Alteration to sea levels

geometry (Oliva, 2016). Sea level rise will generate nonlinear effects in estuaries which will vary depending on their configuration and marine context (Khojasteh et al., 2022; Kresning, 2016). Authors also noted that such changes to tidal dynamics will have future repercussions on existing tidal resources.

In addition, tidal barrages have the potential to affect surface water quality by introducing harmful chemicals as well as changing local salinity levels which have implications for certain marine species (Bonar et al., 2015; Kadiri et al., 2012; Hooper and Austen, 2013; Kirby and Retière, 2009). Kirby and Retière (Kirby and Retière, 2009) investigated the environmental effects of the La Rance tidal barrage construction and noted reductions in salinity that impacted species' local abundance, contrarily to the case of the Severn Estuary barrage where an increase in salinity is predicted (Kadiri et al., 2012). Authors stressed that this is not likely the case with TECs and no change to salinity levels is expected. Furthermore, Fenrich *et al (*Fenrich et al., 2013*).* looked at water quality parameters such as available nutrients and physio-chemical parameters and developed a model to reduce the negative effects on surrounding habitats, while Kadiri *et al (*Kadiri et al., 2012*).* noted changes in salinity, dissolved oxygen levels and metal concentrations in the water column. Yet, these also varied with the technology used.

Further modelling results conducted by Wang *et al (*Wang et al., 2015*).* outlined that energy extraction decreased flushing rates in the channel and increased vertical mixing in the bay, influencing water quality responses. Thus, it is important to consider these alterations in tidally dominated environments (Guillou et al., 2019).

3.2.5. Benthic habitats alteration

3.2.5.1. Species Abundance and distribution of fauna. Introducing TECs into a certain marine environment might cause changes to the surrounding habitats, particularly during the installation and decommissioning phases (Haverson, 2017). Disturbance to benthic habitats and displacement or disappearance of local fauna and animals from preferred habitats were broadly highlighted in the reviewed literature (Bonar et al., 2015; Rivera et al., 2020; Williamson et al., 2019), and there was an overall consensus that the interactions between such devices and the benthic dynamics are poorly understood and need further investigation. The lack of baseline data on marine species and habitats was also recognized (Kregting et al., 2016; Shields et al., 2009; Fox et al., 2018). Findings and results on alteration of benthic habitats and ecological impacts were different and sometimes contradictory depending on device type, array size and location of the project (Shields et al., 2009). This was referred to by Broadhurst (Broadhurst, 2013) as species-specific interactions with potential TECs.

In the case of the UK's Severn estuary, Baker *et al (*Baker et al., 2020*).* observed increases in suitable habitats for species following the construction of a tidal barrage, while the development of a similar barrage off the coast of Normandy in France became an artificial reef for species, despite causing some disturbance at its early stages (Sheehan et al., 2013). In the UK's Ramsey Sound, Haverson (Haverson, 2017) modelling showed minimal impacts on the benthic environment.

On the other hand, in the Strangford Lough Narrows (Northern Ireland) (Kregting et al., 2016), no changes to benthic communities were noted when the SeaGen device was put in waters, as these showed an opportunistic nature in high flow environments. O'Carroll *et al (*O'Carroll et al., 2017*).* also studied SeaGen and noted minimal influence of local fauna in the area. Van Der Molen *et al (*Van Der Molen et al., 2015*).* modelled large arrays of TECs in Scotland's Pentland Firth and noted changes for up to 10% occurring to ecosystem variables several kilometres away from their location, similarly to du Feu (du Feu, 2018) modelling in the same area which shows minimal changes for up to 8% of habitats. Also, Fox *et al (*Fox et al., 2018*).* reported the potential impacts tidal devices could have on marine vertebrates and the need for more stringent monitoring programs for these receptors to understand the device-animal interactions (Wiesebron et al., 2016).

Several reviewed journals have solely focused on the potential changes to fish density and abundance (fish quotas) as a result of tidal currents' change, and the risk of displacement to neighbouring fisheries (Breen, 2014; Fraser, 2017). Fish schools and schools' area (distribution, height) usually increase around a turbine structure (Williamson et al., 2019) and schooling characteristics were influenced by daylight and tidal phase (Fraser, 2017). Scherelis *et al (*Scherelis et al., 2020*).* observed variations of up to 25% in fish aggregations at a tidal site in Australia, calling for an early-stage environmental monitoring, while the overlap of fish schools with potential kite operations were shown to be more predictable, and major negative impacts could be avoided (Whitton et al., 2020). This adds to Zangiabadi *et al (*Zangiabadi et al., 2017*).* findings that changes in pressure and turbulence might not directly cause mortality of fish unless collision takes place.

3.2.5.2. Coastal birds. Four articles from the literature gave particular importance to the impacts of potential TECs developments on seabirds (García-Oliva et al., 2017; Couto et al., 2022; Isaksson et al., 2020; Waggitt and Scott, 2014), as these might be affected by changes in spatial and temporal distributions of intertidal habitats (Hooper and Austen, 2013; García-Oliva et al., 2017). Waggitt and Scott (Waggitt and Scott, 2014) called for more survey activities and environmental impacts assessments (EIA) at potential tidal sites, as species' vulnerability can different according to the location.

Looking at seabirds' interaction and distribution before and after the implementation of a tidal array in the Scottish island of Stroma, Couto *et al (*Couto et al., 2022*).* argued that predators could be benefiting from faster water currents resulting from TECs to target their prays easily in preferential locations. The change in distribution and presence of fish habitats (depth, aggregation) will induce changes to seabirds' benthic foraging, but authors stress that these impacts may vary with seabirds' categories (Couto et al., 2022).

On the other hand, no direct impact was observed in the Solway Firth estuary (on the border of England and Scotland) and waterbirds' habitat loss was minor (García-Oliva et al., 2017). Yet, TEC arrays in general will cause minimal losses compared to the barrage technology with a similar installed capacity, and the technology and location change will cause alterations to the habitats and therefore to the scale of the impacts on birds. This shows again how variable and interchangeable impacts could be in different locations and contexts, and for that reason, Isaksson *et al (*Isaksson et al., 2020*).* proposed a conceptual framework to predict and assess the impacts of tidal energy on seabirds to look beyond the impacts on individual groups of species but rather on the overall populations living around the areas of implementation.

3.2.5.3. Acoustic effects. Another aspect that is still uncertain when it comes to tidal devices is the level of acoustic impact these turbines could have on the surroundings habitats as well as fauna. Six articles covered this issue (Martin et al., 2012; Lossent et al., 2018; Pine et al., 2019; Willis et al., 2013; Xu et al., 2011, 2012) focusing on TECs, in addition to grey literature (Fraser, 2017), while Copping *et al (*Copping et al., 2019*).*, (Copping et al., 2020, 2021) tackled the issue from a risk retirement perspective.

Underwater noise could be emitted from the devices' moving components and may affect marine life or alter their behaviour (Frid et al., 2012; Hooper and Austen, 2013). This falls under the potential environmental impacts that need to be further understood (Martin et al., 2012), as they can inform Marine Spatial Planning (MSP) and future design of arrays (Pine et al., 2019). Lossent *et al (*Lossent et al., 2018*).* explored the acoustic impact of an operating TEC in Paimpol-Bréhat, France on marine fauna, and revealed that the noise emitted from the turbine was comparable to a 19-metre boat travelling at 10 knots speed (~11.5 miles/hour), and therefore little impact (in terms of injuries on the hearing apparatus) on invertebrates, marine mammals, and fish was observed. This corresponds to a radius of around 1.5 kilometres. Yet, behavioural disturbances may occur up to one kilometre around the device, particularly for harbour porpoises, grey seals and bottlenose dolphins (Lossent et al., 2018). In addition, the assessment corresponded to the potential noise impact of a single turbine, and not to the one involving full-scale arrays (Lossent et al., 2018; Pine et al., 2019).

In Strangford Lough, Pine *et al (*Pine et al., 2019*).* investigated the Listening Space Reduction (LSR) on marine mammals caused by two different TECs in both winter and summer, and concluded that LSR are species- and device-dependent and also variable through the seasons. Results showed an excess of LSRs of 80% for harbour seals and of 55% for harbour porpoises (Pine et al., 2019). Additional noise types were studied with particular focus on background noise (Willis et al., 2013; Xu et al., 2011, 2012), which can affect any potential TEC, and increases with increasing tidal flow. Willis *et al (*Willis et al., 2013*).* highlighted that background noise in Ramsey Sound (West Wales) was influenced by tidal considerations and the traffic of local boats.

Therefore, authors stress the need to consider noise data and noise modelling in the EIAs processes prior to any development scenario.

3.2.5.4. Collision risks and migration. While impacts of TECs vary between locations, species and seasons, there is a need for greater understanding of their potential risks of collision and migration of species in the surrounding habitats. The issue has been covered more widely than other environmental impacts, with 13 articles in our review specifically focusing on the collision impacts of TECs on marine mammals and fish. Yet, there is still a need to investigate and assess how they behave in proximity of such devices on the longer term and their coexistence opportunities (Hastie et al., 2018). Turbines should be compliant with the Marine Mammal Protection Act and avoid causing harm to marine mammals (Grear, 2018).

Concerns revolved around collision with TECs, changes in migratory or preying behaviour, and even displacement from preferred habitats (Williamson et al., 2019). The rates of collision are influenced by a set of other environmental factors such as flow rate, visibility, background noise as well as the device’s location and orientation in the water (Bonar et al., 2015), and thus it was noted that most of the species tend to avoid the devices rather than colliding with it. Yet, the risk of collision remains in place as a decision-making barrier to its consenting process if it was proven that any potential device will affect species’ movement and/or routes of migration (Rivera et al., 2020; Horne et al., 2021). Frid *et al (*Frid et al., 2012*).* suggested that fish mortality associated with TECs can be high and collision may result in disorientation, while Lieber *et al (*Lieber et al., 2018*).* explored the probability of harbour seals and grey seals colliding with TECs in the tidal channel of Strangford Lough and revealed that on average, seals avoided areas of intense acoustic backscatter, consequently avoiding the turbines. Therefore, the lethal effect of TECs was noted to be “over-conservative” (Onoufriou, 2020), and that not all seal collisions are fatal. This complements Hastie *et al (*Hastie et al., 2018*).* findings which showed that seals will undergo behavioural changes to avoid physical injury. Authors note a localised impact extending to around 500 m of the turbine signal which resulted in avoidance of such areas, which was also highlighted when looking at the SeaGen TEC (Sparling et al., 2018), where avoidance occurred, but was not a barrier to the transit of seals past the device. Behavioural changes were observed with decreasing frequency of transits during turbine operating times.

Horne *et al (*Horne et al., 2021*).* conducted some modelling work focused on collision risks with TECs, proposing a framework that could be applied for any type of device, configuration and setting to better understand this type of interaction. Authors estimated mortality rates considering the speed and location of the receptors (animals) when collision happens, and propose that these simulations could be confidently used in future EIAs in potential tidal sites.

Small cetaceans, particularly porpoises, have also avoided the rotors of the devices even while being inactive, due to their capacity to acoustically detect their presence (Gillespie et al., 2021). As a result, the risk of collisions with these species remained low, since most of them continue to pass close to the TECs, but at distances over 35 m. On the other hand, Auks and Cormorants could face higher risks as a result of changes to their foraging areas and prey preferences where devices are installed (Waggitt and Scott, 2014), raising particular attention to the micro-habitats created and occupied around TECs.

When it comes to fish, a major concern is also the potential physical injury caused by striking with the TEC, and the uncertainty around their avoidance behaviour (Hastie et al., 2014; Peraza and Horne, 2023; Gadd, 2023), highlighting the need to conduct environmental monitoring and risk assessments (Peraza and Horne, 2023). Fish schools were proven to increase around the turbine in Williamson *et al (*Williamson et al., 2019*).* analysis of the ecological effects of TECs, increasing the risk of collision, but those approaching it show signs of avoidance (Viehman, 2016). A laboratory-scale water tank monitoring conducted by Yoshida *et al (*Yoshida et al., 2022*).* showed a difference in avoidance levels of fish to the TEC between bright and dark conditions (71–92% respectively). This indicates an increased alertness in darker conditions, overall avoiding strikes, injuries or mortality. Water pressure and turbulence may not directly lead in general to increased fish mortality rates (Zangiabadi et al., 2017), but it might provide top predators with hotpots for foraging of fish aggregations (Gadd, 2023). Migratory fish could also be threatened by potential injuries and collision in the presence of barrages (Baker et al., 2020).

3.3. Social impacts

Environmental considerations of MRE developments can hardly be dissociated from the social impacts of such projects, as they largely contribute to people’s perceptions to possible effects and sometimes pose a barrier and influence their acceptance (O Rourke et al., 2010; Hooper et al., 2020a). Several studies have highlighted the lack of information around the environmental effects of MRE development (Rivera et al., 2020; Dacre, 2007; Kazimierczuk et al., 2023) with a particular focus on the surrounding communities, and the need for more research to ease stakeholders’ concerns, uncertainties and perceptions (Jenkins et al., 2018; Ruano-Chamorro et al., 2018).

Despite this growing body of literature around tidal energy in recent years (Ross et al., 2021; Couto et al., 2022; Fouz et al., 2022b; Coles et al., 2023), to date, relatively little is known about its social effects when deployed in marine ecosystems, and many uncertainties remain in place, particularly in local communities (Kazimierczuk et al., 2023; Leslie and Palmer, 2014; McTiernan, 2018). Limited information is also available on the factors that shape people’s perceptions towards MRE projects, and the general expression of support cannot be assumed as acceptance (Hooper et al., 2020a; de Groot and Bailey, 2016; Wüstenhagen et al., 2007; Walker, 1995). Therefore, perceived risks or benefits, understanding scale and spatial position (Carlson, 2022), and collaborating with many disciplines shall be considered (McTiernan, 2018).

Studies in this section have investigated the social impacts of tidal energy developments identified in 10 journal articles, in addition to grey literature covering this topic.

3.3.1. Public acceptance and stakeholder engagement

Social acceptance, an attitudinal construct that refers to projects that have been already deployed or are in place (Dreyer et al., 2017), plays a crucial role in the successful implementation of tidal energy projects. It has appeared in several articles as a key factor in achieving RE targets (Díaz and Guedes Soares, 2020; Melikoglu, 2018; Carlson, 2022) while avoiding social conflicts, and particularly in six out of the ten reviewed articles. Jenkins *et al (*Jenkins et al., 2018*).* propose, based on Wüstenhagen *et al (*Wüstenhagen et al., 2007*).* conceptualization, three levels for social acceptance categorization of RE technologies:

"socio-political acceptance, community acceptance, and market acceptance". While some research, such as Karytsas and Theodoropoulou (Karytsas and Theodoropoulou, 2014)'s study, claimed positive support and encouraging attitudes toward RE, opposition remains most strident at the local and regional levels, and this might arise due lack on engagement on one aspect of the project rather than on the project as a whole (Bonar et al., 2015).

The reviewed literature promoted the role of early stakeholder involvement as a key pillar for public acceptance (Bonar et al., 2015), despite the latter's dependency on various location-specific considerations (e.g., sense of identity or belonging, traditional practices, cultural and heritage values, etc.) (Díaz and Guedes Soares, 2020; Melikoglu, 2018), perceived risks and barriers at the local community level as well as individual impacts resulting from the proposed TECs (Shyam Kularathna and Takagi, 2018). When exploring the potential impacts of the SeaGen underwater TEC in Northern Ireland, Haslett *et al (*Haslett et al., 2018*).* found that the views of the stakeholders involved converged around the device's impact on marine biodiversity, ecosystem services and human wellbeing. This is line with the results from Hooper *et al (*Hooper et al., 2020b*).* who surveyed three communities in England where hypothetical TEC projects were planned, and found that perceptions were driven by environmental factors, impacted coastal activities and place attachment, and not by demographic considerations.

Bonar *et al (*Bonar et al., 2015*).* also refer to the concept of "Not in My Backyard" (NIMBYism), which plays a significant role in community acceptance of tidal energy projects. NIMBYism is the phenomenon where individuals and communities express opposition to the implementation of projects in their immediate vicinity, despite supporting the broader goals of RE (Devine-Wright, 2009, 2005; Chad et al., 2014). Yet, this concept has been criticized for its simplification and invalid explanation for local opposition, neglecting complex motivations and perceptions (Devine-Wright, 2005; Burningham, 2000; Wolsink, 2006, 2007; Devine-Wright, 2013; Rand and Hoen, 2017; Dugstad et al., 2023).

On the other hand, the role of effective and open communication and stakeholder engagement mechanisms was addressed in all six studies (Hooper et al., 2020a; Bonar et al., 2015; Jenkins et al., 2018; Haslett et al., 2018; Kazimierczuk et al., 2023; Polis et al., 2017). More positive perceptions, increased public acceptance of tidal energy projects and adherence to the biodiversity protection were raised by Bonar *et al (*Bonar et al., 2015*).*, Haslett *et al (*Haslett et al., 2018*).*, while Jenkins *et al (*Jenkins et al., 2018*).* highlighted the role engagement efforts can have in addressing concerns and uncertainties. This would result in increased willingness to pay (WTP), reduced levels of conflicts, and more trust (Hooper et al., 2020a; Kazimierczuk et al., 2023; Polis et al., 2017). By engaging with communities, developers can foster a sense of ownership among community members.

3.3.2. Procedural and distributive justice

An important aspect among the social impacts of tidal energy developments, and which was not fully covered in the reviewed literature is the role of procedural and distributive justice in navigating community acceptance and promoting the successful development of RE initiatives. *Procedural justice* is concerned with fair decision-making processes and the extent to which affected residents are involved in these processes (Gross, 2007). *Distributive justice,* on the other hand, focuses on achieving an equitable distribution of outcomes, addressing concerns arising from the unequal distribution of costs and benefits within local communities (Gross, 2007).

This concept has only appeared in Jenkins *et al (*Jenkins et al., 2018*).*, who linked the acceptance of MRE projects with issues related to trust, risk and rewards, worldviews, as well as procedural and distributive justice. By addressing those aspects, RE projects can enhance community engagement, foster social acceptance, and ensure the well-being and involvement of local communities.

3.3.3. Decision-making and local ownership

The sense of ownership and the participatory approach has been brought up in four of the reviewed studies, and has been identified as a crucial factor for informed decision-making and sustainable development (Bonar et al., 2015; Rivera et al., 2020; Haslett et al., 2018; Lyons et al., 2023). Involving local communities in decision-making processes not only ensures their voices are heard, but also enhances the overall project outcomes, leads up to a greater support, and unpacks potential uncertainties, conflicts and opposition around different aspects of the projects (Bonar et al., 2015; Rivera et al., 2020; Haslett et al., 2018). Despite the lengthy nature of this engagement process, it addresses local people's concerns and increases their ownership of the project by highlighting potential benefits at the local level (Bonar et al., 2015). This becomes more important when the developer is an outsider to the community and its integration into the community generates scepticism.

In the case of Northern Ireland's SeaGen (Haslett et al., 2018), community concerns around the decision-making process focused on the aspects of biodiversity in particular, while in the case of Australia (Lyons et al., 2023), it revealed lack of indigenous community trust in state policies. On the other hand, Wiersma and Devine-Wright (Wiersma and Devine-Wright, 2014) identify additional areas of concern revolving around visual impacts and spatial context, and find that these engagement processes are dynamic, complex and variable by nature, but are also indispensable when applied transparently in different sets of decision-making areas.

3.3.4. Impact on fisheries

Potential impacts of tidal energy development on fisheries were covered by several reviewed articles as well as in grey literature (Hooper et al., 2020a; Bonar et al., 2015; Ruano-Chamorro et al., 2018; Rivera et al., 2020; Leslie and Palmer, 2014; Shyam Kularathna and Takagi, 2018; Smits et al., 2006). Fisheries are usually concerned with both the socio-economic and environmental adverse impacts of tidal energy devices, especially when these are installed close to local settlements, and in spaces potentially occupied by marine users, leading to opposition for such developments (Bonar et al., 2015; Leslie and Palmer, 2014). Environmental considerations were briefly reported by Rivera *et al (*Rivera et al., 2020*).*, Breen (Breen, 2014) when tackling the effects of tidal devices on hydrodynamics, thus impacting the distribution of fish, seabirds and mammals.

On the social front, conducted surveys by Hooper *et al (*Hooper et al., 2020a*).* and Shyam Kularathna and Takagi (Shyam Kularathna and Takagi, 2018) have stated the importance of fisheries industry and the need to protect them from any potential impacts and identify ways for co-locations strategies. Shyam Kularathna and Takagi (Shyam Kularathna and Takagi, 2018) go further by analysing the reasons behind the fisheries' community rejection, where 19% of respondents have indicated that MRE technologies will have negative impacts on commercial fishing. Fishing methods, locating projects in potential fishing grounds, and concerns about the noise and vibration these devices might cause were highlighted as the main reasons. The latter could result in economic losses affecting the fisheries interests, thus its economic value (Smits et al., 2006).

3.3.5. Marine recreation and tourism

Some of the issues that are frequently overlooked when thinking about ORE projects' implementation are the impacts on the individuals rather than on the community as a whole, in particular when it comes to marine users and coastal activities (Shyam Kularathna and Takagi, 2018). This includes tourism and navigation, recreational activities, among others (Leslie and Palmer, 2014). These subjects closely linked to the marine environment were covered under different contexts (Hooper et al., 2020a; Bonar et al., 2015; Ruano-Chamorro et al., 2018; Haslett et al., 2018; Shyam Kularathna and Takagi, 2018).

Outdoor recreational opportunities were outlined among the environmental concerns in the case of the SeaGen (Haslett et al., 2018), while marine recreation and alteration to local surfing environment were reported in Bonar *et al (*Bonar et al., 2015*).* giving the UK's Cornwall Wave Hub as an example. In the case of Japan (Shyam Kularathna and Takagi, 2018), 32% of surveyed respondents indicated their concern of MRE's impacts on aesthetics while 28% brought up the issue recreational fishing, while surveyed communities in England (Hooper et al., 2020a) were asked to rate a set of features, including recreational activities.

Grey literature, particularly Sommer (Sommer, 2023), found that recreation and tourism can be negatively impacted by "access restrictions, noise and visual disturbance, safety and navigation risks or decreased accommodation availability during construction" [p. 47]. These findings were based on an-depth look into Ruano-Chamorro *et al (*Ruano-Chamorro et al., 2018*).* work that listed recreation as one of the negative effects of tidal energy (Mendoza et al., 2019; Dreyer et al., 2019; Richardson et al., 2022).

3.3.6. Place attachment and property values

Place attachment, which influences community acceptance, represents the strong emotional bond and value that local residents form with their community, homes, and surrounding areas (Devine-Wright, 2009; Vorkinn and Riese, 2001). The disruption of familiar landscapes, changes to the seascape, and potential loss of cultural and historical connections can trigger cultural concerns and resistance among local communities. Areas with strong place attachment may exhibit more opposition to development, as the project can be seen as disrupting the natural beauty of the region and threatening the emotional bond between people and place (Dugstad et al., 2023; Devine-Wright and Howes, 2010). The same technology might be perceived or opposed differently when proposed at two different locations (Stokes et al., 2014), especially when marine and coastal environments are involved in specific local contexts (de Groot, 2015).

Place attachment has appeared in both peer-reviewed and grey literature (Hooper et al., 2020a; Jenkins et al., 2018; Lyons et al., 2023; Sommer, 2023). The "emotional connection" to particular places leading to place attachment was mainly highlighted by Hooper *et al (*Hooper et al., 2020a*).* as a reflection to bonding with the natural environmental and social attachments. The authors differentiate between two types of place attachments, one linked to family and friends while the other is a connection to the natural environment, and conclude that perceptions and opposition to developments in coastal areas are not influenced by demographic factors, but rather by place attachment considerations and environmental concerns. This further highlights the interlinkage between social and environmental aspects. The latter influence place attachment characteristics of natural landscapes, the presence of wildlife, and opportunities for outdoor recreation, which might be all potentially impacted by tidal energy developments (Hooper et al., 2020b).

Place attachment was also reported among the four concepts for understanding human dimensions of tidal energy covered by Jenkins *et al (*Jenkins et al., 2018*).*, along with acceptance, justice and economics. While looking at theories and frameworks for understanding human dimensions as a new and under-applied area of research, the authors claimed that place attachment, alone, do not offer mechanisms for managing human dimensions.

However, it is important to recognise that areas with strong place attachments also present an opportunity for developers to engage with communities and address their concerns. This inclusive approach allows developers to frame their proposals in a way that highlights how the project will enhance, rather than threaten, the various components of place attachment. Therefore, de Groot (de Groot, 2015) calls for a place-based approach rather than a technology-based approach that considers community priorities, local socio-historical preferences and local values.

Concerns may also arise regarding potential negative impacts of tidal energy projects on property prices in the surrounding coastal area of energy infrastructure development (Chad et al., 2014; Vyn and McCullough, 2014). The literature reflected this aspect from different perspectives (Bonar et al., 2015; Ruano-Chamorro et al., 2018; Shyam Kularathna and Takagi, 2018). While negative effects on property values were considered among the social impacts of tidal energy (Bonar et al., 2015; Ruano-Chamorro et al., 2018), 46% of respondents in Shyam Kularathna and Takagi (Shyam Kularathna and Takagi, 2018) study thought MRE projects will have positive impacts.

3.3.7. Economic impact

What matters the most for stakeholders is the cost of energy and the associated economic benefits that RE developments could bring. This could materialize in reduced electricity prices for households, job creation for the surrounding communities as well as the impact on the regional economy. Although tidal energy's levelized cost of energy (LCOE) is still not competitive compared to solar and wind, it still has an important economic role to play in terms of providing an efficient portfolio mix in the energy system (Allan et al., 2011), impact on the regional economy (Allan et al., 2014; Fanning et al., 2014; Quirapas and Taeihagh, 2021), and in mitigating intermittent power supply and reducing energy system costs (Lamy and Azevedo, 2018; Harcourt et al., 2019; Lian et al., 2023).

In fact, this was clearly revealed in our reviewed literature (Coles et al., 2023; Shyam Kularathna and Takagi, 2018; Lyons et al., 2023; Dreyer et al., 2019). Despite most respondents to Shyam Kularathna and Takagi (Shyam Kularathna and Takagi, 2018) survey showing great support for MRE projects, their final acceptance was linked to issues related to job creation and economic impacts. While 30% of respondents have thought MRE projects will have a negative impact on electricity rates, 37% have indicated, on the contrary, that these kinds of projects will have positive impacts on electricity rates with 78% mentioning job creation too (Shyam Kularathna and Takagi, 2018). These same economic concerns regarding electricity prices were highlighted as well by Dreyer *et al (*Dreyer et al., 2019*)..*

On the other hand, Coles' *et al (*Coles et al., 2023*).* analysis concluded that the economic benefits of tidal stream energy can only be seen with projects at gigawatt scale, and with lower LCOEs. Yet, questions remain around the distribution of such benefits and how to ensure good governance and resource ownership within communities (Lyons et al., 2023). The latter balance in the distribution of costs and benefits was also raised by Jenkins *et al (*Jenkins et al., 2018*).*, Shyam Kularathna and Takagi (Shyam Kularathna and Takagi, 2018), knowing its influence on the final public acceptance decision. In the case of small-scale RE projects, and tidal energy in particular, local communities usually hold the burden of the direct costs, while benefits are showcased more at the regional level, which highlights the critical role of such balance.

4. Discussion

This review has examined the potential environmental and social impacts of tidal energy technologies, and has shown that such developments and processes are dynamic, complex, and depend on several interrelated factors. This is in lines with Wiersma and Devine-Wright (Wiersma and Devine-Wright, 2014)'s findings around the nature of ORE developments. Our approach and methodological work have applied neither a geographical (country or region) or a technological constraint, with the aim to systematically capture many of the potential impacts that might occur. It brings novelty to existing previous reviews by considering those impacts together and not independently, and by focusing on tidal energy rather MRE developments. An additional characteristic is the inclusion of more than 20 published research theses around the topic that were accessed from online repositories along with grey literature, allowing to draw a more holistic picture of such impacts.

For tidal energy, a new industry is shaping up, and the geographical spread of the environmental and social studies covered in this review reflect the technological and skills' advancements in countries that have paved the way for developers to install devices in waters, or have plans underway to do so (BBC, 2021; Offshore Energy, 2024a, 2024b, 2021). Despite a higher number of environmental studies included in this review, a wider geographical spread was shown in the social literature covering countries from North America to Australia passing through the UK. This was noteworthy, considering the low number of social articles (10) the review has resulted in, as well as the limited number of real-world case studies and tidal energy applications that address stakeholders' concerns. As for the environmental literature, it showed a concentration of case studies in the UK and Ireland with few additional ones in France, US and Canada, the majority of which (40 articles) were predominated by desk-based modelling studies.

In fact, this geographical distribution reflects the efforts done by governments, academia and developers to advance tidal energy development, and mirrors a representation of where most of the funding and research are taking place (Ocean Energy Europe, 2025), mostly in developed countries. On one hand, Governments are realizing the importance of ORE resources (and tidal in particular as a reliable and predictable source of energy) in the energy transition, and are issuing the necessary regulatory policies and funding schemes, including for Research & Development (R&D), skills development, and cross-border cooperation e.g., (Ocean Energy Europe, 2025; Nova, 2023; Now, 2020; Innovation News Network, 2023; UK Government, 2021; Offshore Energy, 2024c, 2024d; US Department of Energy, 2023; The Engineer, 2023). On the other hand, developers are continuously working to secure all the licensing and planning requirements to have their devices in water including the needed EIAs e.g., (Offshore Energy, 2023; UK Government, 2015), collaborating with academia and engaging with communities as an tool to address their concerns. The high number of modelling literature reflects the importance of rigorous research prior to any deployment and shows that software-based modelling has become an integral part of both resource and environmental assessments to quantify resource potential on one hand, and identify, avoid and mitigate potential impacts on the other. It is important to highlight the need to ensure shared knowledge and expertise between developed to developing countries, allowing technological transfer to the latter once the environment for such developments is enabled.

4.1. Diversity and challenges of tidal technologies

The literature has also shown the diversity of tidal technologies used (Figs. 1, 2 and 5), and thus the different types of impacts each could generate. Over the years, developers have come up with different design approaches and diverse configurations to capture tidal energy, resulting in a range of complex shapes and designs (Munaweera Thanthirige et al., 2023, 2025, 2024). The technology which appears to have the biggest impact on the water environment seems to be tidal barrage being a fully mature technology that has been applied for decades, something that was also highlighted by Jaszczak (Jaszczak, 2023). Extracting tidal range energy with tidal barrages or lagoons is generally more environmentally harmful, the projects are typically extremely large one-off structures, and they are only possible in areas with high tidal range and certain geographic constraints. In contrast, tidal stream energy is less environmentally harmful, the turbines are modular and they have potential for use in more locations, however they are not a fully mature technology. Despite that, many environmental impacts are common for both technologies, particularly in the literature around sedimentation, landscape change, local hydrodynamics (velocity change) and impacts on species abundance. Alteration to sea levels was identified more in the case of the barrages, while impacts on coastal birds, acoustic effects and collision risks were mostly observed for TECs.

This diversity of existing tidal technologies is a double-edged sword, as it implies high-risk technological profiles that confront investors (Segura et al., 2017). This results in more difficult commercialization pathways, and little design consensus when compared to other RE technologies such as solar and wind. Another major challenge is the economics of tidal energy as an expensive technology that still cannot compete with dominant and established RE sources (e.g., onshore wind) based on standard LCOE criteria (Borenstein, 2012; Vazquez and Iglesias, 2016; Rodrigues et al., 2021; Bhuiyan et al., 2022; Catalano et al., 2024; Yang et al., 2022). For example, the UK has been including a strike price for tidal energy in its Contracts for Difference (CfD) renewable auctions, with its latest round in 2024 resulting in a rate of 172 £ /MWh, following a 198 £ /MWh in 2023 (Offshore Energy, 2024c; Lubbock, 2023; UK Government, 2024). In comparison, strike prices of both solar and onshore wind ranges around the 50 £ /MWh (UK Government, 2024).

Despite having a higher LCOE, tidal energy offers consistent and predictable power generation that can mitigate the issues associated with solar and wind intermittency (Allan et al., 2011; Harcourt et al., 2019). Moreover, it brings numerous benefits including enhanced grid stability, a well-balanced energy portfolio, reduced power shortages and decreased energy storage requirements (Fouz et al., 2022a). By combining the strengths of wind/solar and tidal energy, a resilient and sustainable energy mix can be reached.

The technology proves to be highly beneficial, competitive and financially viable in remote and islandic communities (Si et al., 2022; Jenkins and Beaver, 2025; Almoghayer et al., 2022), where fossil fuels dominate and where grids have limited access, enhancing energy security. In such contexts, it can contribute to economic growth, infrastructure development and job creation. Research suggests that if the revenue from a development was retained locally, the employment impacts could be up to eight times higher than that of a traditional commercially owned project (Okkonen and Lehtonen, 2016) Yet, tidal energy technology still lacks sufficient R&D funding to overcome deficiencies and risks (Segura et al., 2017; Zhang et al., 2025). As a consequence, no generalized conclusions could be drawn regarding the gravity and intensity of such impacts (Sommer, 2023), knowing the dependency on the marine environment and the location-specific considerations.

4.2. On environmental impacts

To summarise the environmental impacts resulting from this review, the natural division of the information according to the different receptors and stressors (Jaszczak, 2023; Martínez et al., 2021) has allowed a comprehensive investigation of almost all possible impacts on the water environment, local ecology and landscape change. These revolved around changes to velocities and hydrodynamics, sedimentation, water quality, benthic habitats and species, coastal birds, acoustic effects, and collision risks and migration. Yet, these impacts remain majorly dependent on the different types of technologies and device configuration, as well as on the characteristics of the location (García-Oliva et al., 2017).

Research has shown that appropriate management, design and siting of a TEC, alone or in arrays, could protect coastal environments (Inger et al., 2009). It has also shown that modelling exercises and simulations can be useful tools to assess, investigate and mitigate potential impacts (Kadiri et al., 2012; Wang et al., 2015). Developers are thus required to consider the identified impacts as part of their project planning, and to carry out an early-stage environmental impact assessment and monitoring of the location in order to collect all relevant information of the fauna and flora of the proposed area (Scherelis et al., 2020; Zangiabadi et al., 2017). This should not be a one-time assessment, but rather a continuous process of evaluation of the environmental conditions before, during, or after project development. Finally, the scale of any potential array of TECs plays a significant role in the resulting impacts, something that developers should further investigate prior to any implementation. As technological advancements continue to evolve towards more efficient and more environmental-friendly TECs, changing means of design and management could help in reducing potential environmental impacts (Ma et al., 2023).

4.3. On social impacts

Considering social impacts, the social literature did not differentiate between the different technologies and designs, but categorized them all under the umbrella of tidal energy, highlighting a lack of awareness of their diversity as well as on socio-economic impacts each could generate. This gap in the literature reflects the need to re-centre social sciences as a bridge between engineering and modelling assessments, environmental impacts and real-world applications, and to highlight the interlinkages between the social and environmental components of each technology as one influences the other. Tidal energy projects are characterized by more location-specific considerations, which might trigger public opposition due to specific aspects of the project rather than the project as a whole (Bonar et al., 2015). Therefore, public acceptability becomes critically important for project success (Kerr et al., 2014). Concerns are often linked to people's sense of identity or belonging to the area, and are intertwined with the history and traditions of local communities (Díaz and Guedes Soares, 2020; Melikoglu, 2018). Opposition could emanate as a result of NIMBYism considerations, where people prefer not to see projects being implemented in their vicinity, despite broader support for RE (Devine-Wright, 2009, 2005; Chad et al., 2014), and could also arise from potential negative impacts on property prices in the surrounding area of energy infrastructure (Chad et al., 2014; Vyn and McCullough, 2014). As an alternative to NIMBYism, community responses have been linked to place-based theory or place attachment, as RE projects may impact cultural heritage sites, historical familiar landscapes and seascapes, and cause the loss of traditional practices and historical connections (Dugstad et al., 2023; Vorkinn and Riese, 2001; Devine-Wright and Howes, 2010). Additional social impacts identified in this study were linked to decision-making and local ownership, fisheries, marine recreation and tourism, economic considerations such as job creation, and issues related to trust and justice in distribution of benefits.

Social acceptance through early stakeholders' engagement and open communication are key in such developments linked to MSP. To understand communities' sense of ownership, developers, regulators and planners are advised to follow participatory approaches and dynamic processes when it comes to potential tidal energy projects. It is important to understand people's perceptions in different locations and contexts, and at different scales to ensure project success and community support (Jenkins and Beaver, 2025). These processes should take into account people's "emotional connections" (Hooper et al., 2020a) and place attachment considerations to the location of interest (Jenkins et al., 2018; Lyons et al., 2023; Sommer, 2023). They should also address their concerns as well as highlight potential project's benefits for individuals and the community at large (cleaner and cheaper electricity, access to jobs, etc.). In addition, issues of justice and risks, fair decision-making and equitable distribution of costs and benefits should not be neglected (Jenkins et al., 2018).

Future engagement processes should ensure better awareness and more clarity around the type of tidal technology used, as each will pose its own acceptance challenges. These regulatory issues should be addressed and included in the permitting, planning and licensing processes in order to ensure increased public engagement and social acceptance, and facilitate the involvement of local communities (Wiersma and Devine-Wright, 2014). Permitting processes are sometimes lengthy and costly. Streamlining them and creating a one-stop shop for all ORE permitting requirements, including tidal energy, would therefore reduce lead-in times. Clarity around those processes as well as on the regulatory framework will provide certainty for investors, allow faster potential deployments and ensure decarbonization goals. MSP is not only a social process (Ehler et al., 2019), but primarily a political process in which stakeholders negotiate their understanding of shared marine space in order to achieve economic, social and ecological objectives (Brent et al., 2020; Cote and Nightingale, 2012; Flannery et al., 2019; Qiu and Jones, 2013). Their fulfilment can pave the way for environmentally sustainable developments that are supported by strong regulatory and planning regimes. Therefore, it becomes important to develop an ecosystem-based MSP that is not limited to sector-by-sector management (Foley et al., 2010). Establishing an appropriate planning framework will also need to be empowered by sufficient R&D funding that tackles not only technological advances, but also issues of justice, and community engagement approaches through guidelines and frameworks.

4.4. Extracting lessons from other technologies

This review has also shown that lessons could be extracted from other RE and ORE technologies, particularly onshore and offshore wind and to some extent wave energy (Bailey et al., 2011), in the context that more research was done in these areas. Bonar *et al (*Bonar et al., 2015*)*. highlighted that although RE are thought to be more acceptable when placed away from coastlines, this does not guarantee public support due to their perceived social and environmental effects and their commercial and technological viability (de Groot and Bailey, 2016; Bailey et al., 2011; Jones and Richard Eiser, 2010; Haggett, 2011; Kaldellis et al., 2016). This highlights again the interlinkages between environmental and social aspects of such technologies. Despite that the majority of the reviewed literature focuses on understanding public perception (Bailey et al., 2011; Warren et al., 2005), attitudes (Krohn and Damborg, 1999), stakeholder consultation (Gray et al., 2005) and local opposition (Jones and Richard Eiser, 2010), these cannot be tackled away from fisheries (ten Brink and Dalton, 2018), recreation and tourism areas, wind turbines' noise and cumulative ecological threats.

Experience from offshore wind has shown that aesthetic perceptions influenced public responses, and visual impacts remain among the main concerns (Wiersma and Devine-Wright, 2014; Warren et al., 2005; Depellegrin et al., 2014). It also highlighted the conflicting visions among communities towards their perception of the sea usage and ownership (Wiersma and Devine-Wright, 2014), as well as the important role awareness and education can have in influencing acceptance (Bush and Hoagland, 2016; Gonyo et al., 2021). Moreover, perceived recreational impact of offshore wind projects, along with their economic benefits, were among the strongest predictors of support (Ferguson et al., 2019a; Gonyo et al., 2021). Reviewed literature suggests that offshore wind farm development would be better accepted with extensive stakeholders consultation and higher clarity on decision-making (Brunbauer et al., 2023; Portman, 2009; Gray et al., 2005), including with fisheries, marine users and environmental groups (Inger et al., 2009; Machado and de Andrés, 2023).

On the other hand, experience of onshore wind energy proved that the choice of location and community participation are crucial to the success of such developments (Jobert et al., 2007). For these projects, stronger land-based connections exist than the ones that could unfold offshore, due to the fact that the visual impact of wind turbines could be linked to place attachment considerations (Bonar et al., 2015). Communities who oppose onshore wind turbines consider them noisier and more visually intrusive than other technologies (Warren et al., 2005; Krohn and Damborg, 1999; Wolsink and Sprengers, 1993), reflecting individuals' own values and beliefs, and confirming the need for community ownership characteristics as effective means for RE support (Haggett, 2011). Visual impact, ownership, information and participation were the main elements of onshore wind social acceptance in the literature, along with procedural and distributive justice concerns (Jobert et al., 2007; Wiersma and Devine-Wright, 2014).

On the latter justice issue, it is important to underscore the significance of context-specific approaches to community engagement, and to consider the effectiveness of different engagement mechanisms in achieving procedural justice. Greater engagement with local residents can take various forms, ranging from providing information to active local participation in development allowing community members to have a voice and actively shape the project's outcomes (Ek and Persson, 2014; Brennan and Van Rensburg, 2016; Brennan and van Rensburg, 2020; Dimitropoulos and Kontoleon, 2009). Some studies, such as Devine-Wright (Devine-Wright, 2011), suggest that using public meetings as a mechanism of engagement may be less efficacious due to pre-existing negative beliefs about this form of engagement. Instead, the use of leaflets and articles in local media to disseminate findings may be more effective in engaging the community and promoting transparency. With regards to promoting distributive justice, measures such as creating employment opportunities (Caporale and De Lucia, 2015; Vazquez and Iglesias, 2015), facilitating local ownership of the development (Lienhoop, 2018), providing financial compensation to the local authorities (Lamy and Azevedo, 2018; Ek and Persson, 2014; Vazquez and Iglesias, 2015) are crucial. These measures ensure that the benefits generated by RE projects are shared equitably among community members. Distributive justice also includes considerations such as the provision of recreational facilities (García et al., 2016) and the allocation of funds for local sustainability programs (Ek and Persson, 2014; Caporale and De Lucia, 2015; Kermagoret et al., 2016).

4.5. Limitations of the reviewed literature

Tidal range energy extraction via lagoons or barrages is fundamentally different from TECs as highlighted earlier. This distinction is not always clearly stated in the reviewed literature and the terminology can sometimes be non-specific, particularly in the social literature. The systematic review results did not come up with particular studies around the environmental impacts of tidal barrages and lagoons. Therefore, it would be important in the future to further investigate their impacts to have empirical knowledge when compared with TECs. Another aspect which was not directly covered in our review are the different ways in which TECs are installed (such as floating or sea-bed fixed), along with related anchoring systems. These aspects can have different and diverse impacts on the environment and would need further investigation as well, with the aim of identifying potential priority areas for empirical studies around the impacts of different TECs configurations and installation methods.

The diversity of tidal technologies and devices did not allow any generalization of their potential social and environmental impacts like the one identified in the literature around offshore wind. Most of the existing literature has focused on the operational phase of tidal devices, but more empirical research and emphasis is needed to cover the construction and decommissioning phases, where several environmental impacts could occur in the location. Moreover, a wider consideration of the cumulative impacts of tidal technologies before and after installation in the marine environment is thus essential, while also looking at patent data and patent-based prospective Life Cycle Assessment (LCA) such as the framework proposed by Spreafico (Spreafico, 2025).

More research and case studies of real-time, non-modelling applications would be able to give better clarity around these environmental issues, their potential mitigations measures, community concerns, as well as including the economic aspect of the technology. It is becoming crucial that future research would consider both environmental and social impacts together and for each tidal technology alone.

5. Conclusion

Tidal energy is becoming a highly attractive RE resource due to its predictability and potential contributions to grid stability, reliability, and decarbonization goals. However, alongside its promise, this technology is still an expensive solution, and comes with direct and indirect impacts on both environmental and social levels, and a set of barriers are often overlooked. The findings of this paper constitute a starting point for developers, policymakers and regulators to consider before implementing any project, as environmental and social impact considerations are very often interlinked.

The review has shown the importance of thorough public engagement and consultation processes to investigate the social acceptance of MRE projects, as a key pillar for ecosystem-based MSP. By understanding public perceptions, beliefs, risks, cultural concerns and their connections with the marine environment, concepts like place attachment, procedural and distributive justice can be better addressed and managed. In addition, there is a need for better awareness and clarity around the potential social impacts of different tidal technologies. While the social literature explored tidal energy in general, the environmental literature reflected the diversity of existing technologies, and the impacts of various TEC designs and configurations. This highlights the need to consider social sciences as a tool to bridge the gap between engineering assessments and environmental considerations.

Environmental literature emphasizes the need for comprehensive EIA that goes beyond technical feasibility to understand the marine context in which devices are put, as well as the surrounding habitats and species. It calls policymakers for more clarity around regulatory and planning processes as well as enhanced R&D, to address location and technology considerations and quantify the gravity and intensity of the potential impacts.

CRediT authorship contribution statement

Marc Ayoub: Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization. **Flanagan Michael:** Writing – review & editing, Project administration, Validation, Visualization. **Gesche Kindermann:** Writing – review & editing, Supervision, Conceptualization, Validation.

Declaration of Competing Interest

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

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Data availability

No data was used for the research described in the article.

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