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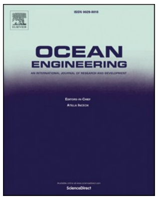

A large-scale review of wave and tidal energy research over the last 20 years

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ABSTRACT

Over the last two decades, a large body of academic scholarship has been generated on wave and tidal energy related topics. It is therefore important to assess and analyse the research direction and development through horizon scanning processes. To synthesise such large-scale literature, this review adopts a bibliometric method and scrutinises over 8000 wave/tidal energy related documents published during 2003–2021. Overall, 98 countries contributed to the literature, with the top ten mainly developed countries plus China produced nearly two-thirds of the research. A thorough analysis on documents marked the emergence of four broad research themes (dominated by wave energy subjects): (A) resource assessment, site selection, and environmental impacts/benefits; (B) wave energy converters, hybrid systems, and hydrodynamic performance; (C) vibration energy harvesting and piezoelectric nanogenerators; and (D) flow dynamics, tidal turbines, and turbine design. Further, nineteen research sub-clusters, corresponding to broader themes, were identified, highlighting the trending research topics. An interesting observation was a recent shift in research focus from solely evaluating energy resources and ideal sites to integrating wave/tidal energy schemes into wider coastal/estuarine management plans by developing multicriteria decision-making frameworks and promoting novel designs and cost-sharing practices. The method and results presented may provide insights into the evolution of wave/tidal energy science and its multiple research topics, thus helping to inform future management decisions.

1. Introduction

To meet increasing energy demand and bring about a smooth transition towards a clean energy future, global communities are diversifying their energy portfolios using a growing portion of renewable energies (EYA, 2016; Khojasteh et al., 2018a; Pacesila et al., 2016; Shmelev and van den Bergh, 2016). In this context, oceans hold huge renewable energy reserves, particularly kinetic and potential energy as the most extractable sources, produced from different ocean processes such as waves and tides. It is reported that the estimated global theoretical wave energy potential is nearly 29,500 TWh/year, and the total tidal energy potential amounted to nearly 26,000 TWh/year (Mork et al., 2010; WER, 2016). As such, extracting these energy resources can help achieve net zero emission targets by 2050. This is important as

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future global demand for electricity is estimated to rise, for example, from ~23,000 TWh in 2015 to ~49,000 TWh in 2050 (Ram et al., 2020).

There is consensus that efficiently utilising wave, tidal, and current energy could help provide reliable electricity, particularly to small islands developing states (SIDS), create socio-economic benefits, ensure a climate-friendly energy mix, and foster the emerging blue economy worldwide (IRENA, 2020; Jahanshahi et al., 2019; Khojasteh et al., 2018b). Despite several benefits and vast resources, wave/tidal energy (together) contributed only 1.6 TWh (relative to approximately 23,000 TWh of electricity consumed) globally in 2020 (IEA, 2021). This minimal contribution to the global energy mix might be attributed to several challenges in relation to (i) materials and manufacturing; (ii) hydrodynamics; (iii) survivability and reliability; (iv) environmental resources; (v) array configurations; (vi) power conversion and control systems; (vii) grid connection and infrastructure; (viii) maritime safety; (ix) socio-economic ramification; and (x) governance (Greaves and Iglesias, 2018). These underlying factors contribute to low power density, expensive structures, and low reliability, and have resulted in bankruptcy of several high-profile efforts such as Pelamis.

To cover these challenges and offer solutions, a growing and evolving volume of literature has been produced over the years to expedite the competitive deployment of wave/tidal energy devices, which is hard to synthesise using traditional review methods. However, this knowledge is critical to gain an integrative, in-depth understanding of how the wave/tidal energy field of science and its trending research topics have evolved over time. For instance, such collective and valuable information can likely help identify knowledge gaps, inform actions required to develop multicriteria frameworks, enhance financial support, boost regulatory schemes, minimise risks, maximise reliability, and increase public engagement and/or awareness (IRENA, 2020).

As an effective solution for managing and analysing vast bodies of literature, computer-based bibliometric tools are developed to provide a broad understanding of the intellectual landscape of a field of science under examination (Haghani et al., 2022b). These approaches have recently been successfully applied to different relevant fields such as renewable energy technologies with 142 documents (Bortoluzzi et al., 2021), types of renewable energy finance with 275–446 documents (Elie et al., 2021), wind energy with 841 documents (Azam et al., 2021), solar energy with 1150 documents (David et al., 2020), the implications of offshore renewable energy development for marine species with 1978 documents (Kulkarni and Edwards, 2022), and the recent progress in ocean engineering research with nearly 51,000 documents (Tavakoli et al., 2023). These studies often focused on number of documents published, and collaboration between countries, institutions, and/or authors. A recent study analysed ~3200 ocean energy articles over the last 10 years, using a general subject search (TS) strategy in the Web of Science (TS = ocean renewable energy or TS = marine renewable energy), and presented valuable results on knowledge structure of this field (Hu et al., 2022).

To complement the previous efforts, this review adopts a bibliometric method as it is impractical to synthesise such large-scale literature on wave/tidal energy using conventional review approaches. Here, over 8000 wave/tidal energy related documents published during 2003–2021 were analysed. This is achieved through carefully examining not only the number of documents produced by pioneering journals and nations and their corresponding citations, but also their growth rates over the last ~20 years. Titles, abstracts, keywords, authors, affiliations, and references of these 8000+ documents (2003–2021) were then analysed to identify the major research clusters and sub-clusters in the field of wave/tidal energy (see Section 2). The interconnections between the research sub-clusters were also investigated to provide insights into the evolution of literature, most active and inactive research streams, and how they have altered based on the varying demands. This information, in turn, can provide critical understanding about trending research topics and their evolution, as well as inform knowledge gaps and management decisions, and direct future research (including funding decisions).

To this end, Section 2 provides an introduction on the bibliometric approach taken to capture the extent of wave/tidal energy research to a new level, which was nearly impossible using typical review processes. Section 3 presents a detailed overview on the global distribution of wave/tidal energy documents as well as on pioneering journals and nations and their growth rates over the last two decades. Section 4 critically discusses the major research clusters that emerged from wave/tidal energy literature as well as their general research focus. Section 5 outlines the major wave/tidal energy research sub-clusters and how they are spatially interconnected and have temporally developed. Section 6 offers an in-depth discussion on temporal evolution of growing, emerging, and fluctuating hot topics and highlights the influential references within wave/tidal energy field of science. Finally, Section 7 presents concluding remarks.

2. Methodology

2.1. Search query

In this paper, a bibliometric approach is adopted to gain a systematic, full scope understanding of the evolution of wave/tidal energy science over the last two decades. This approach has been proven to reliably classify thousands of documents related to a field of interest (Haghani et al., 2021). To do so, a detailed, term-based search query, with minimised false positives, was developed and inserted into the Web of Science Core Collection, which provides a comprehensive coverage of scholarly research (Haunschild et al., 2016). This search query was made more specific using Boolean operators to obtain relevant search units. The date range was set from January 1, 2003 to 31st of December 2021, as over 91% of wave/tidal energy related articles indexed in the Web of Science by the end of 2021 were published during this period. The search query used is presented in the Supplementary Information. Overall, 8174 unique documents were retrieved from scientific literature, including articles, proceeding papers, reviews, book chapters, letters, etc. For these documents, information about authors, affiliations, titles, abstracts, keywords, and cited references was stored as text files and analysed (see below).

2.2. Compound annual growth rate of published documents

A compound annual growth rate (hereafter, growth rate) analysis was performed on the increasing number of documents published by the top 20 wave/tidal and renewable energy journals and contributing nations. For the latter, documents were attributed to nations based on authors' affiliations data. The growth rate analysis indicates the interest and persistence of journals or nations in publishing wave/tidal energy documents over time and regions. This metric represents the mean annual growth rate of an increasing population (here, documents) over a specified period of time, and is evaluated as below:

$$\beta = \left(\left(\frac{FV}{BV} \right)^{1/n} - 1 \right) \times 100 \tag{1}$$

where β is the growth rate (in percentage), FV is the final value (i.e., number of publications in the final year), BV is the beginning value (i.e., number of publications in the first year), and n is the number of years considered. The outcome of this analysis is discussed throughout Section 3.

2.3. Titles, abstracts, and keywords

Titles, abstracts, and keywords of all retrieved documents were analysed to gain high-level insights into the major research clusters (streams) of wave/tidal energy. First, terms in the titles and abstracts were examined using Visualization of Similarities (VoS) analysing

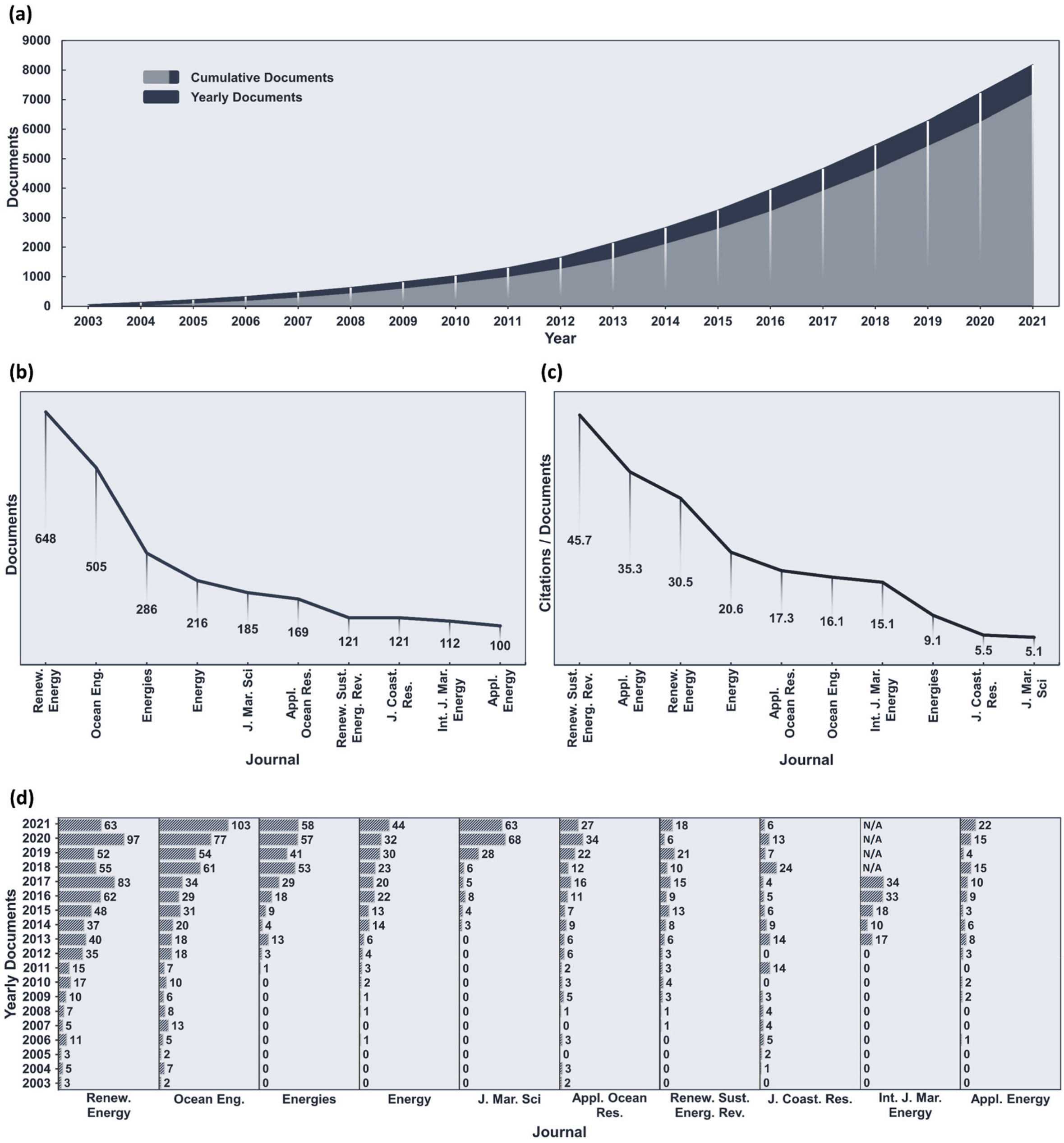

Fig. 1. (a) Cumulative and yearly wave and tidal energy related documents published from 2003 to 2021. (b) The top 10 journals with most cumulative number of wave and tidal energy documents published during 2003–2021, and (c) their corresponding ratio of citations over documents. (d) Timeseries of wave and tidal energy related documents produced by the top 10 relevant journals.

through VoSViewer software (Van Eck and Waltman, 2010). In this analysis, terms are represented by nodes and are positioned on a map such that their distance denotes similarities (i.e., a shorter distance means a stronger similarity), and the node size signifies the frequency of term appearance (for details, see Van Eck and Waltman (2010)). A cluster of similar nodes then forms a major research theme. Further, all keywords used by wave/tidal energy scholars during 2003 and 2021 were analysed to highlight the key focus of research during this period. The results of these two analyses are presented in Section 4.

2.4. Co-citation analysis, research sub-clusters, and influential references

A document co-citation analysis was performed on the retrieved documents, using CiteSpace software (Chen, 2006), to identify key research sub-clusters within the wave/tidal energy field, as well as their temporal evolution and influential references. This analysis is based on the similarity level of references cited by wave/tidal energy related documents such that frequently co-cited references likely cover an identical research theme. Therefore, the documents that jointly cited those references may form a research sub-cluster. The outcome of this analysis can be presented as a map (network) where the classified sub-clusters represent detailed research streams in wave/tidal energy literature. On the map, research sub-clusters are ranked from (1) to (*m*) (where *m* is a natural number) such that sub-cluster (1) has the highest number of cited references and sub-cluster (*m*) has the lowest number of cited references. The connecting lines between sub-clusters highlight co-citation instances with the research activities evaluated based on the yearly number of citing documents within a specific cluster and its total citations received by the references of that cluster. Key references were then identified based on their number of local citations (citations

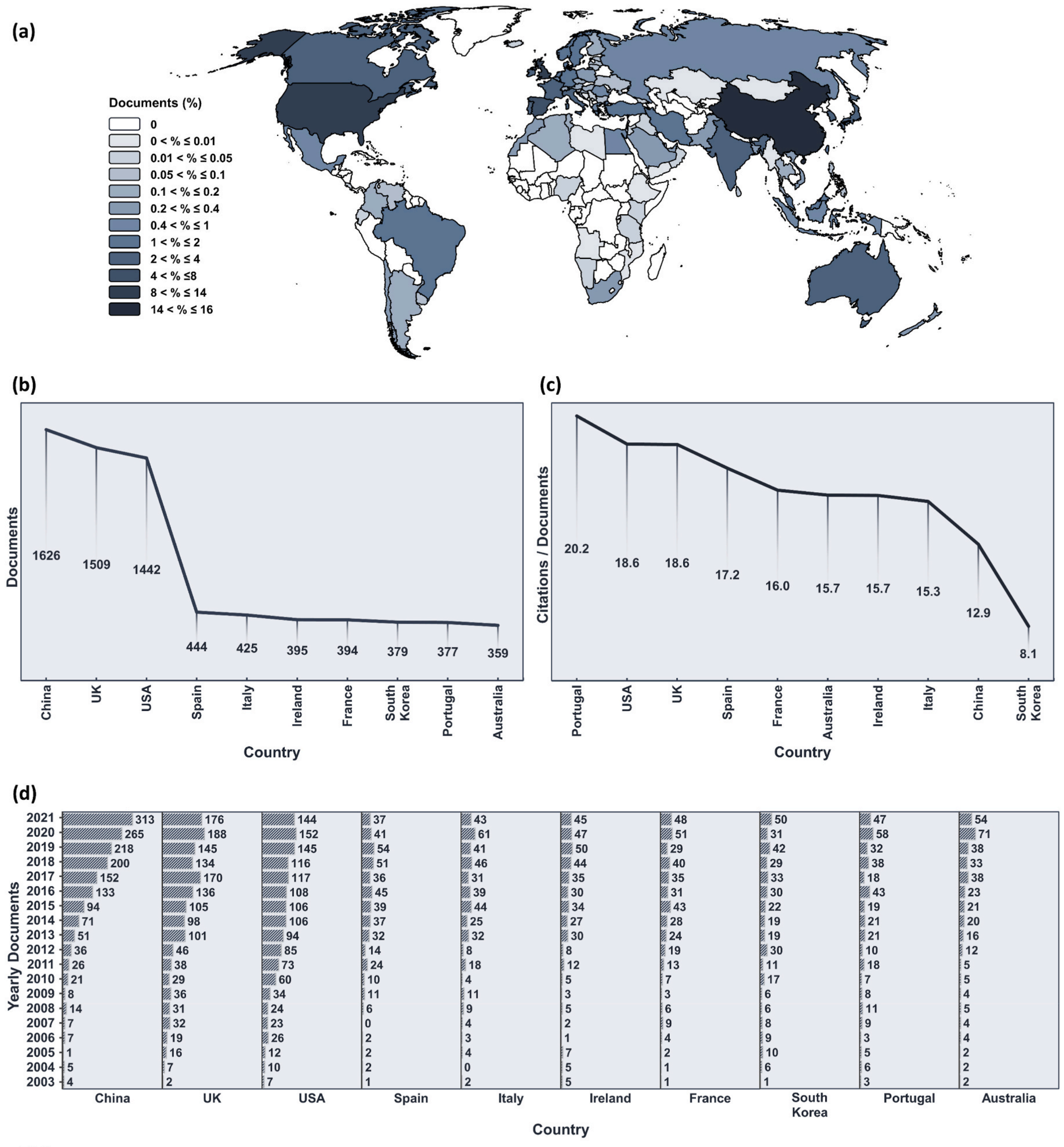

Fig. 2. (a) Global production (in percentage) of wave and tidal energy related documents published from 2003 to 2021. Documents are assigned to different nations based on all authors' affiliations data. (b) The top 10 nations with most cumulative number of wave and tidal energy related publications during 2003–2021, and (c) their corresponding ratio of citations over documents. (d) Timeseries of wave and tidal energy related documents produced by the top 10 relevant nations.

received exclusively within the field of wave/tidal energy) and burst strength (sharp increase in local citations received by a reference). The findings from this analysis are presented in Sections 5 and 6.

3. Production of wave and tidal energy documents

Overall, 8174 documents on wave/tidal energy topics were produced during 2003–2021 (Fig. 1a). The number of documents increased significantly from 43 in 2003 to 951 in 2021 (Fig. 1a), highlighting a growth rate of 17.7% over the last two decades. The growth rate is relatively high compared to the growth rate of science studies (4.1%, Bornmann et al. (2021)), but is consistent with studies on other renewable sources such as solar energy (15%, 2006–2011, Du et al. (2014)) and hydrogen energy (18%, 1996–2005, Tsay (2008)). This is a promising finding, as the global wave energy resource alone is able to meet 15%–66% (depending on the exploitability concept used) of the total energy demand worldwide (Astariz and Iglesias, 2015b). If only 10% of shelf sea tidal energy resource is extracted worldwide, it can contribute by nearly 6% to annual mean global electricity intake (Neill et al., 2021a). This is of significance as worldwide energy consumption is anticipated to grow by 2.4% in 2022 compared to 2021 (6% increase in 2021 compared to 2020), which is consistent with its average growth rate over a 5-year period prior to the global COVID-19 pandemic (IEA, 2022). Utilising abundant wave/tidal energy resources can help decarbonise the energy mix and mitigate climate change impacts worldwide (Jin and Greaves, 2021; Khojasteh et al., 2022b). This decarbonisation, through a feedback loop, can help reduce the global electricity consumption by the end of this century, given that the future consumption is predicted to increase by 7% of current global consumption associated with 1 °C further increase in global mean surface temperature (Rode

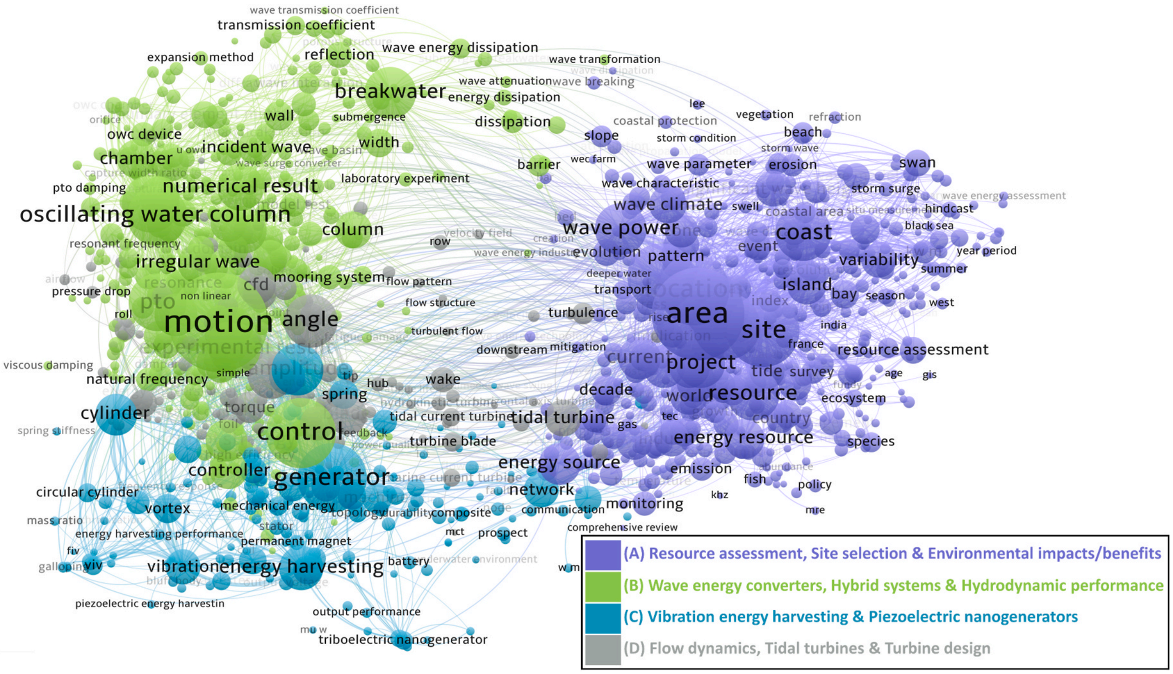

Fig. 3. Clusters of frequently co-occurred terms, highlighting four major research clusters (streams) in wave and tidal energy literature produced during 2003–2021. An interactive map is available at: https://app.vosviewer.com/?json=https://drive.google.com/uc?id=1gIDNFLAPxX7e1YbIePlCmlj3s4Demh13.

et al., 2021).

During 2003–2021, 224 different journals, conferences, and proceedings published at least 5 documents related to wave/tidal energy topics. Only 10 key journals published over 100 cumulative documents including “Renewable Energy”, “Ocean Engineering”, “Energies”, “Energy”, “Journal of Marine Science and Engineering”, “Applied Ocean Research”, “Renewable and Sustainable Energy Reviews”, “Journal of Coastal Research”, “International Journal of Marine Energy”, and “Applied Energy”, as illustrated in Fig. 1b. It is widely accepted that the ratio of citation counts over the number of documents likely indicates the quality of research published by journals (Patthi et al., 2017; Tahamtan et al., 2016). As per Fig. 1c, “Renewable and Sustainable Energy Reviews”, “Applied Energy”, and “Renewable Energy” have the largest citations per documents ratio, whereas “Journal of Marine Science and Engineering”, “Journal of Coastal Research”, and “Energies” possessed the lowest ratio. The period of time over which the top 10 journals were active and how frequent they published wave/tidal energy related documents during 2003–2021 are illustrated in Fig. 1d. It is evident that “Renewable Energy” (2003–2021; growth rate of 17.4%), “Ocean Engineering” (2003–2021; growth rate of 23.0%), “Energy” (2006–2021; growth rate of 28.7%), “Applied Ocean Research” (2003–2021; growth rate of 16.5%), “Journal of Coastal Research” (2004–2021; growth rate of 11.8%), and “Applied Energy” (2006–2021; growth rate of 26.8%) consistently published articles since 2000s (Fig. 1d). “Energies” (2011–2021; growth rate of 44.6%) and “Journal of Marine Science and Engineering” (2014–2021; growth rate of 46.3%) emerged in 2010s, and “International Journal of Marine Energy” was discontinued (2013–2017) (Fig. 1d).

Overall, 98 nations produced 8174 wave/tidal energy related documents during 2003–2021. A percentage distribution of documents produced in different nations (based on authors’ affiliations data) is depicted in Fig. 2a. Note that the total percentage equated to 100 in Fig. 2a. There were 24 nations that cumulatively produced over 100 documents during 2003–2021, with China, UK, USA, Spain, Italy, Ireland, France, South Korea, Portugal, and Australia comprising the top 10 nations (Fig. 2b). As a measure of research impact, the ratio of citations over documents for these nations were evaluated and presented in Fig. 2c. This ratio is highest for Portugal, USA, and UK, but is lowest for South Korea, China, and Italy (Fig. 2c). All top 10 nations actively produced wave/tidal energy related documents from 2003 to 2021 (Fig. 2d), although different publication growth rates were observed. These growth rates were 26.6% for UK, 25.8% for China, 22.9% for South Korea, 22.6% for France, 20.9% for Spain, 18.9% for Australia, 17.5% for Italy, 17.2% for USA, 15.6% for Portugal, and 12.3% for Ireland.

As an example, the opportunities and challenges for harnessing wave/tidal energy resources in China, South Korea, Australia, and the USA are briefly discussed below, which could be indicative of different growth rates observed in their publications. The increasing research undertaken by Chinese scholars can be attributed to the country’s national plan in prioritising the marine economy and developing marine industries and infrastructure, including marine renewables (Chang and Wang, 2017). As a pioneering initiative, the Chinese government allocated US$160 million of special funds (2010–2017) for marine renewable energy projects focused on designing new technologies and self-sufficient and self-powered islands (Wang et al., 2018). The underlying reason is the abundance of wave and tidal energy (8.3 GW and 7.7 GW, respectively) in its coastal waters (Liu et al., 2017), given China’s long coastline (18,000 km) and large continental shelf zone (4.79×10^6 km^2) with a wide range of water depths (2–100 m) suitable for deploying various energy converters (Jiang et al., 2021; Wan et al., 2020). The growing research in South Korea is likely pertinent to its ocean energy development plan (2015–2025) that reinforces research and development as well as commercial advancement to offset the country’s high energy imports (currently ~95%) (Ko et al., 2019; OES, 2015). Only extracting wave power density along the economic exclusion zones can potentially meet 15% of the annual electricity consumption in the country (Ahn and Ha, 2021). Further, South Korea has nearly 3600 islands and narrow channels with concentrated tidal energy, with its west coast (spring) tidal range reaching up to 10 m (Hwang and Jo, 2019). This is why the country has one of the highest installed tidal power capacity worldwide (OES, 2015).

Australia has arguably the largest wave energy potential globally (Hemer et al., 2017) and a considerable proportion of universal tidal (range) energy dissipation occurs on Australia’s northwest of the country (Egbert and Ray, 2000; Neill et al., 2021b). Australia represents

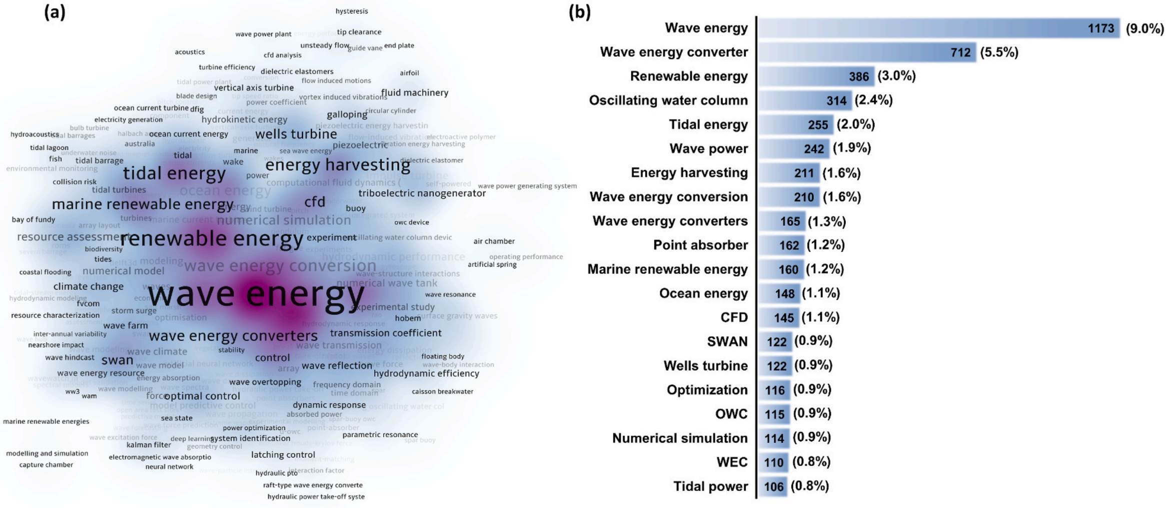

Fig. 4. (a) A heatmap (density map) of wave and tidal energy keywords used during 2003–2021, with darker purple colour highlighting central keywords (research focuses) and larger font size indicating higher number of times a keyword appeared in wave and tidal energy related documents. An interactive map for (a) is available at: https://app.vosviewer.com/?json=https://drive.google.com/uc?id=1q9q6ocJc3tZyiRa9lbiXWBWRLLW5YW6v. (b) The top 20 keywords emerged in wave and tidal energy literature and their corresponding occurrences and overall percentage (in brackets) amongst all keywords used during 2003–2021.

a country where ocean energy resources far exceed the nation’s current electricity demand. Although wave/tidal energy conversion could contribute to both further growth of Australia’s blue economy, and meeting its decarbonisation targets, the country faced several interdisciplinary challenges related to (i) technological advancement ensuring low cost of energy conversion/supply with least environmental impacts, (ii) raising public awareness and training educated workforce, (iii) supportive political and regulatory frameworks, (iv) insufficient investment, and (v) great distances between resource locations and population centres and/or electricity infrastructure (Hemer et al., 2018; Manasseh et al., 2017). The USA possesses considerable wave (e.g., on the west coast and Hawaii) and tidal (e.g., Cook Inlet and Alaska) energy resources with a huge potential to contribute to a surge in carbon-neutral installed electricity generating capacity (Kilcher et al., 2021; Lehmann et al., 2017). However, several challenges first need to be addressed to provide sustainable and cost-competitive electricity from wave/tidal energy. For instance, the USA federal and state governments should facilitate industrial development, introduce and extend (carbon) tax credits, and offer low interest loans to private firms to overcome technological, environmental, geographic, and socioeconomic complexities of employing wave/tidal energy (Lehmann et al., 2017; PMI, 2022).

4. Research clusters of wave and tidal energy literature

The co-occurrence term analysis was undertaken to identify major research clusters (streams) that have emerged in wave/tidal energy literature. The outcome of this analysis is depicted in Fig. 3, where terms that co-occurred frequently in a set of documents formed a distinct cluster (see Section 2.3). As per Fig. 3, four distinct, broad clusters emerged representing (A) resource assessment, site selection, and environmental impacts/benefits; (B) wave energy converters, hybrid systems, and hydrodynamic performance; (C) vibration energy harvesting and piezoelectric nanogenerators; and (D) flow dynamics, tidal turbines, and turbine design.

Overall, cluster (A) highlights the fact that wave/tidal energy development should be based on multicriteria decision-making frameworks that consider prioritisation and selection of available resources, ocean climatology, distance to critical infrastructure, water depth, environmental considerations, and potential conflict of interests between stake holders and users (Flocard et al., 2016; Kamranzad and Hadadpour, 2020; Neill et al., 2014; Shao et al., 2020; Veigas et al., 2014). The most frequent terms in cluster (A) included “area”, “assessment”, “location”, “resource”, “site”, “region”, “wave power”, “coast”, “energy resource”, and “variability”.

Cluster (B) generally indicates the recent interest towards integrating breakwaters and wave energy converters such as oscillating water columns (OWCs), overtopping devices, and oscillating buoys. This concept has several important advantages such as simultaneously protecting coastal areas (e.g., from frequent flooding under climate change and sea-level rise (Di Lauro et al., 2020; Khojasteh et al., 2022a; Vicinanza et al., 2011)) and generating electricity, reduced investment in construction, maintenance, and survivability, and withstanding harsh climate conditions (Ashlin et al., 2018; Cheng et al., 2022; Trivedi and Koley, 2021; Zhang et al., 2020). This cluster also covers the significance of power take-off systems and their controllers in ensuring efficient (and maximised) energy extraction during different operating conditions (e.g., low to high loadings) and regulating load transmission (Henriques et al., 2016; Hillis et al., 2020; Xu et al., 2020). A few of the most frequently used terms in cluster (B) included “motion”, “breakwater”, “OWC”, “control”, “experimental result”, “PTO”, “numerical result”, “hydrodynamic performance”, “chamber”, and “damping”.

Cluster (C) signifies a novel approach in extracting energy from oceanic or river currents which is based on flow induced oscillations. These are naturally occurring and typically catastrophic instabilities that can be enhanced to convert horizontal marine hydrokinetic energy at high power density (Bernitsas, 2016; Bernitsas et al., 2008). The converters depend on vortex-induced vibration (VIV) and galloping phenomena, where the former is based on nonlinear resonance occurring in a fluid structure interaction, and the latter can be triggered by a geometric or flow asymmetry (Bernitsas et al., 2006; Kim and Bernitsas, 2016). These no-rotor, no-blade converters have the hydrodynamic conversion efficiency of up to 88% of the Betz limit over a broad range of velocities (Kim et al., 2021; Lv et al., 2021; Rostami and Armandei, 2017). This cluster also highlights triboelectric nanogenerators and piezoelectric energy harvesters as promising tools to extract mechanical energy of ocean due to their low cost, high efficiency, large power density, and lightweight features (Shen et al., 2021; Wang et al., 2015; Xu et al., 2021; Zou et al., 2021). Terms that frequently appeared in this cluster included “generator”, “amplitude”, “cylinder”, “energy harvesting”, “oscillation”, “vibration”, “power density”, “network”, “vortex”, and “excitation”.

Table 1
Wave and tidal energy research sub-clusters emerged during 2003–2021.

Sub-cluster Number	Sub-cluster Label
(1)	Wave energy conversion devices
(2)	Tidal energy resources
(3)	Wave energy resources
(4)	Chamber-turbine systems
(5)	Floating and wave surge energy devices
(6)	Hydrodynamic performance and optimisation
(7)	Flow and vortex induced vibration energy
(8)	Coastal protection
(9)	Environmental impacts
(10)	Triboelectric nanogenerators
(11)	Flapping foils and horizontal-axis turbines
(12)	Oscillating water columns
(13)	Breakwaters and plate wave energy converters
(14)	Raft-type wave energy converters
(15)	Vertical-axis turbines
(16)	Tidal lagoons and barrages
(17)	Fluid dynamics
(18)	Hybrid energy systems
(19)	Numerical approaches

Cluster (D) represents the challenges of designing cost-competitive, efficient, optimised, and survivable energy converters and turbines, as well as the practical application of numerical models prior to physical experimentation and/or deployment (López et al., 2014; Windt et al., 2018). Gaining knowledge of fundamental fluids dynamics using numerical models can help fabricate scalable arrays of turbines (and blades), with low complexity and high power output, that can survive harsh environments and impact loads (Adcock et al., 2021; Halder et al., 2017; Kaufmann et al., 2019). The widely used terms in cluster (D) comprised "tidal turbine", "blade", "numerical analysis", "angle", "CFD", "wells turbine", "rotor", "wake", "turbulence", and "flow field". It is worth noting that cluster (D) sits in the centre of other peripheral clusters (i.e., clusters (A), (B), and (C)) and overlaps with them (Fig. 3). This central position highlights the multidisciplinary role of cluster (D) in all research topics related to wave/tidal energy, given that numerical examination of energy resources and conversion devices can help identify optimal sites (e.g., in present-day and under future climate change impacts), run several tests and scenarios at different scales, and improve design and efficiency (Khojasteh and Kamali, 2016; Khojasteh et al., 2022b).

An analysis on all keywords (13,043 in total) used during 2003–2021 indicated that the major research focus was on wave energy related topics (Fig. 4a). The top 20 keywords formed nearly 40% of all keywords used over the last two decades, with "wave energy", "wave energy converter", "renewable energy", "oscillating water column", and "tidal energy" emerging as the top five keywords (Fig. 4b). Amongst the top 20 keywords, 50% were focused on wave energy, 40% were general terms, and 10% were related to tidal energy (Fig. 4b). This is an interesting observation as the tidal energy knowledge dated back to nearly 2000 years ago (Boretti, 2020), whereas the first wave energy device was patented in 1799 (Mayon et al., 2022). Despite the challenges in wave/tidal energy technology development (e.g., manufacturability, reliability, affordability), tidal energy is often perceived as a more promising renewable energy source, as it is more predictable and less intermittent, and has less land requirement, reasonably established technology, and reasonable cost of investment and maintenance (Díaz et al., 2020; Garcia-Oliva et al., 2017; Mestres et al., 2019; Mueller et al., 2010; Neill and Hashemi, 2018). As such, it seems that the research on tidal energy has been underrepresented thus far. This is potentially due to the fact that economically viable tidal energy occurs in hotspots which generally exist in a limited number of countries, as opposed to wave energy which is much wider spread worldwide.

5. Research sub-clusters of wave and tidal energy literature

A document co-citation analysis was performed on all wave/tidal energy documents published during 2003–2021. In this analysis, documents with analogous research focus were classified into distinct sub-clusters based on the similarity of their references (i.e., documents with similar research focus often cite a similar set of references, forming a standalone sub-cluster – see Section 2.4) (Haghani et al., 2022a). Overall, 19 sub-clusters were identified and ranked from (1) to (19) based on the higher number of influential references and number of documents embodied within them. These sub-clusters are presented in Table 1. Note that the 19 labels presented in Table 1 were specified such that they best represent the articles and the general theme of research within each sub-cluster. Extra sub-clusters with less than 25 documents within them were also disregarded.

Generally, sub-clusters that are positioned in the centre of the network and are interconnected to multiple sub-clusters are of interdisciplinary research significance and a research component when exploring other research disciplines (Fig. 5a). For instance, sub-cluster (6) hydrodynamic performance and optimisation is interlinked to several other sub-clusters focused on resource assessment, energy conversion devices, coastal protection services, and turbine systems (Fig. 5a). On the contrary, isolated, often fringing, sub-clusters are likely focused on specific research topics with new application to wave/tidal energy science, such as sub-clusters (7) flow and vortex induced vibration energy and (10) triboelectric nanogenerators (Fig. 5a).

It is worth noting that a recent review of ocean energy science found 17 research sub-clusters primarily related to wave energy converters and resource assessment, tidal energy and turbines, wind energy, and triboelectric nanogenerators (Hu et al., 2022). However, the thorough analysis performed herein solely on wave/tidal energy discipline provided 19 detailed research sub-clusters, together with their evolution, including different types of energy converters, design optimisation processes, coastal protection, environmental impacts and considerations, hybrid schemes, and application of numerical modelling approaches (Table 1).

The extent of citations received by references of sub-clusters can provide a broad understanding on which research sub-clusters have been active or inactive over the last two decades, with connectors between them highlighting interactions between sub-clusters (Fig. 5b–e). In 2005, sub-clusters (1) wave energy conversion, (3) wave energy resources, (4), chamber-turbine systems, and (12) oscillating water columns were most active as the key focus of research (Fig. 5b). In 2010, further research activities and interactions were observed amongst more sub-clusters, in addition to those detected in 2005, including (2) tidal energy, (5) floating and wave surge energy devices, (6) hydrodynamic performance and optimisation, (8) coastal protection, (9) environmental impacts, (11) flapping foils and horizontal-axis turbines, and (17) fluid dynamics (Fig. 5c). Research sub-clusters (7) flow and vortex induced vibration energy, (10) triboelectric nanogenerators, (13) breakwaters and plate wave energy converters, (14) raft-type wave energy converters, (15) vertical-axis turbines, (16) tidal lagoons and barrages, (18) hybrid energy systems, and (19) numerical approaches only exhibited noticeable activities in 2015 (Fig. 5d) and 2020 (Fig. 5e) snapshots.

6. Growing, emerging, and fluctuating research topics and influential references

Generally, the number of documents within each sub-cluster and their associated citation counts can provide insights into steadily growing, emerging, fluctuating, and declining research topics related to wave/tidal energy. As per Fig. 6a, research on sub-clusters (1) wave energy conversion devices, (5) floating and wave surge energy devices, and (6) hydrodynamic performance and optimisation persistently grew from early 2000s to 2021. Research sub-clusters (10) triboelectric nanogenerators and (14) raft-type wave energy converters emerged as

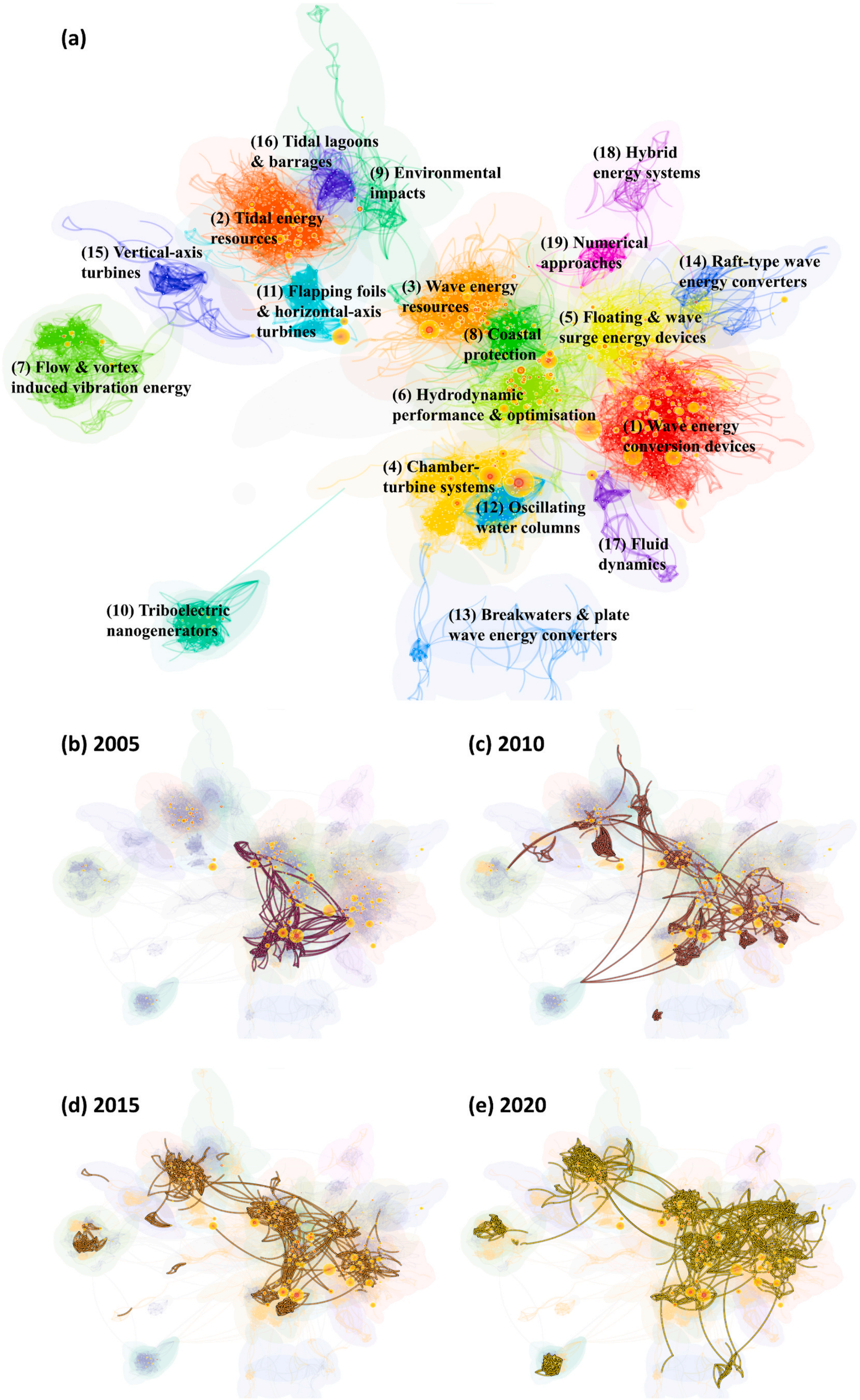

Fig. 5. (a) A network of research (document co-citation) sub-clusters emerged in wave and tidal energy literature during 2003–2021. The level of research activities for sub-clusters of wave and tidal energy literature in (b) 2005, (c) 2010, (d) 2015, and (e) 2020.

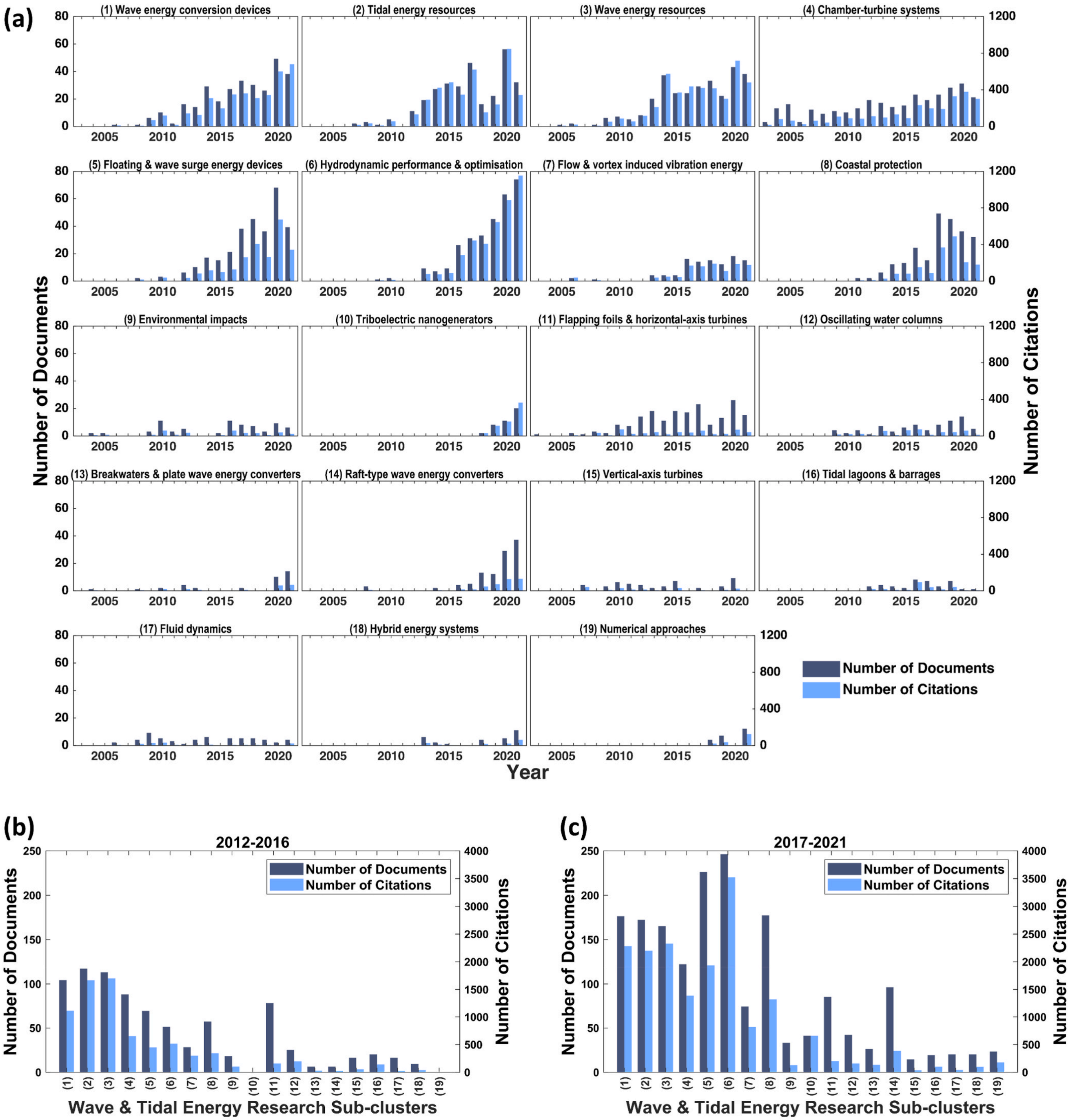

Fig. 6. (a) Temporal development of wave and tidal energy research sub-clusters including their published documents and the associated citations during 2003–2021. Cumulative number of documents and their corresponding citations for different research sub-clusters during two different periods of (b) 2012–2016 and (c) 2017–2021, highlighting the changes in research focus and trending topics over the last 10 years.

hot topics, primarily over the last 10 years. However, research on sub-clusters (2) tidal energy resources, (3) wave energy resources, (4) chamber-turbine systems, (7) flow and vortex induced vibration energy, (8) coastal protection, (9) environmental impacts, (11) flapping foils and horizontal-axis turbines, (12) oscillating water columns, (13) breakwaters and plate wave energy converters, (15) vertical-axis turbines, (16) tidal lagoons and barrages, (17) fluid dynamics, (18) hybrid energy systems, and (19) numerical approaches often fluctuated (i.e., decreased and increased sporadically) during 2003–2021.

The variations in recent research interests and trending topics over the last 10 years are further explored by summing up the number of documents and their corresponding citations for two different timespans of 2012–2016 and 2017–2021 (Fig. 6b-c). The top 3 research sub-clusters with the largest number of published documents during 2012–2016 included (2) tidal energy resources, (3) wave energy resources, and (1) wave energy conversion devices (Fig. 6b). However, these sub-clusters shifted to (6) hydrodynamic performance and optimisation, (5) floating and wave surge energy devices, and (8) coastal protection during 2017–2021 (Fig. 6c).

Recent variations in wave/tidal energy hot topics reflect the fact that

Table 2
A summary of key research clusters and sub-clusters of wave and tidal energy literature during 2003–2021, together with the influential references and examples of documents with highest coverage of influential references as well as the primary research focus of each sub-cluster.

Research Clusters	Research Sub-clusters	Influential Cited References		Citing Documents	
		Highest Local Citation Count	Strongest Citation Burst	Highest Coverage	Key Focus
(A) Resource assessment, Site selection & Environmental impacts/benefits	(2) Tidal energy resources	1. Bahaj et al. (2007) (143) 2. Khan et al. (2009) (108) 3. Rourke et al. (2010b) (104) 4. Garrett and Cummins (2007) (99) 5. Neill et al. (2009) (98)	1. Bryden and Couch (2006) (13.46) 2. Blunden and Bahaj (2006) (12.77) 3. Carballo et al. (2009) (12.36) 4. Blanchfield et al. (2008) (11.15) 5. Ahmadian et al. (2012) (10.7)	1. Iglesias and Carballo (2014) (52) 2. Ng et al. (2013) (48) 3. Adcock et al. (2015) (41) 4. Roche et al. (2016) (34) 5. Ramos and Iglesias (2013) (32)	• Resource assessment • Tidal power generation • Hydro-environmental impacts • Arrays of turbines • Tidal dynamics
	(3) Wave energy resources	1. Booij et al. (1999) (321) 2. Gunn and Stock-Williams (2012) (194) 3. Bahaj (2011) (110) 4. Liberti et al. (2013) (106) 5. Arinaga and Cheung (2012) (106)	1. Iglesias and Carballo (2010b) (19.94) 2. Waters et al. (2009) (18.77) 3. Booij et al. (1999) (18.36) 4. Rusu and Guedes Soares (2009) (15.87) 5. Iglesias and Carballo (2010a) (15.21)	1. Morim et al. (2016) (54) 2. Rodriguez-Delgado et al. (2019a) (51) 3. Guillou et al. (2020) (48) 4. Iglesias and Carballo (2014) (43) 5. Patel et al. (2020) (39)	• Resource assessment • Wave farms • Multi-criteria approaches • Commercialisation
	(8) Coastal protection	1. Falcão (2007) (162) 2. Astariz and Iglesias (2015a) (135) 3. Margheritini et al. (2009) (81) 4. Pérez-Collazo et al. (2015) (78) 5. Vicinanza et al. (2014) (69)	1. Iglesias and Carballo (2011) (11.08) 2. Contestabile et al. (2017) (10.56) 3. Falcão (2007) (10.19) 4. Millar et al. (2007) (8.24) 5. Iuppa et al. (2016) (7.87)	1. Bergillos et al. (2019b) (53) 2. Bergillos et al. (2019a) (52) 3. Bergillos et al. (2019c) (48) 4. Rodriguez-Delgado et al. (2019a) (47) 5. Rodriguez-Delgado et al. (2019b) (39)	• Flood mitigation • Climate change impacts • Beach erosion • Dual wave farms
	(9) Environmental impacts	1. Boehlert and Gill (2010) (48) 2. Inger et al. (2009) (46) 3. Esteban and Leary (2012) (39) 4. Shields et al. (2011) (38) 5. Frid et al. (2012) (30)	1. Shields et al. (2011) (8.34) 2. Gill (2005) (6.74) 3. Langhamer et al. (2010) (4.93) 4. Inger et al. (2009) (4.46) 5. Kerr (2007) (3.12)	1. Roche et al. (2016) (17) 2. Grecian et al. (2010) (12) 3. Witt et al. (2012) (11) 4. Langhamer et al. (2010) (10) 5. Isaksson et al. (2020) (10)	• Future research priorities • Marine birds • Fish distribution • Biodiversity
	(16) Tidal lagoons & barrages	1. Xia et al. (2010b) (32) 2. Neill et al. (2018) (29) 3. Waters and Aggidis (2016) (27) 4. Xia et al. (2010c) (26) 5. Bae et al. (2010) (26)	1. Xia et al. (2010a) (8.08) 2. Xia et al. (2010c) (7.98) 3. Xia et al. (2010b) (6.63) 4. Burrows et al. (2009) (6.25) 5. Bae et al. (2010) (5.37)	1. Angeloudis et al. (2016b) (20) 2. Angeloudis et al. (2016a) (20) 3. Angeloudis and Falconer (2016) (15) 4.Roche et al. (2016) (11) 5. Bray et al. (2016) (10)	• Tidal energy impoundments • Numerical modelling • Potential impacts • Optimal site selection
(B) Wave energy converters, Hybrid systems & Hydrodynamic performance	(1) Wave energy conversion devices	1. Falcão (2010) (985) 2. Drew et al. (2009) (426) 3. Babarit et al. (2012) (296) 4. Henderson (2006) (261) 5. López et al. (2013) (236)	1. Leijon et al. (2005) (27.36) 2. Shek et al. (2007) (15.97) 3. Rhinefrank et al. (2006) (13.76) 4. Leijon et al. (2006) (12.73) 5. Mueller (2002) (12.73)	1. Guo and Ringwood (2021a) (125) 2. Guo and Ringwood (2021b) (91) 3. Falcão and Henriques (2016)(54) 4. Al Shami et al. (2019) (45) 5. Göteman et al. (2020) (44)	• Wave energy technologies • Geometric/configuration optimisation • Control strategies • Performance assessment
	(4) Chamber-turbine systems	1. Falnes and Perlin (2003)(730) 2. Clément et al. (2002) (434) 3. Raghunathan (1995) (143) 4. Falcão and Justino (1999) (139) 5. Setoguchi and Takao (2006) (128)	1. Falnes and Perlin (2003) (32.39) 2. Sarmento and Falcão (1985) (28.12) 3. Evans (1982) (27.34) 4. Setoguchi et al. (2001) (14.51) 5. Raghunathan (1995) (14.11)	1. Falcão and Henriques (2016)(47) 2. Guo and Ringwood (2021a) (42) 3. Gomes et al. (2020) (32) 4. Cui et al. (2019) (32) 5. Cambuli et al. (2019) (31)	• Air chamber/turbine • Self-rectifying turbine • Wells turbine • CFD modelling

(continued on next page)

Table 2 (*continued*)

Research Clusters	Research Sub-clusters	Influential Cited References		Citing Documents	
		Highest Local Citation Count	Strongest Citation Burst	Highest Coverage	Key Focus
	(5) Floating & wave surge energy devices	1. Cruz (2008)(273) 2. Li and Yu (2012) (119) 3. Borgarino et al. (2012) (89) 4. Whittaker and Folley (2012) (89) 5. Yu and Li (2013) (87)	1. Cruz (2008)(17.56) 2. McCormick (2007) (10.87) 3. Hulme (1982) (8.84) 4. Kagemoto and Yue (1986) (8.18) 5.Whittaker et al. (2007) (8.06)	1. Guo and Ringwood (2021a) (37) 2. Davidson and Costello (2020) (33) 3. Gomes et al. (2020) (29) 4. Nguyen et al. (2020) (26) 5. Chen et al. (2021) (26)	• Geometric optimisation • Floating oscillating water column • Mooring systems • Scaling strategies
	(6) Hydrodynamic performance & optimisation	1. Falcão and Henriques (2016) (281) 2. Evans and Porter (1995) (145) 3. Heath (2012) (136) 4. López et al. (2014) (121) 5. Mustapa et al. (2017) (118)	1. López et al. (2014) (10.32) 2. Josset and Clément (2007) (8.65) 3. Elhanafi et al. (2017) (8.39) 4. Vyzikas et al. (2017) (8.05) 5. Ozkop and Altas (2017) (8)	1. Zhao et al. (2019) (40) 2. Cui et al. (2021) (37) 3. Wang and Zhang (2021) (33) 4. Rezanejad et al. (2021) (32) 5. Guo et al. (2021) (29)	• Hybrid systems • Numerical modelling • Experimental investigation • Efficiency assessment • Interacting forces
	(12) Oscillating water columns	1. Torre-Enciso et al. (2009) (102) 2. El Marjani et al. (2008) (71) 3. Jayashankar et al. (2009) (46) 4. Amundarain et al. (2011) (43) 5. Garrido et al. (2012) (24)	1. El Marjani et al. (2008) (6.94) 2. Polinder and Scuotto (2005) (6.02) 3. Jayashankar et al. (2000) (5.77) 4. Garrido et al. (2015) (5.31) 5. Chadwick et al. (2004) (4.76)	1. Garrido et al. (2013b) (18) 2. Garrido et al. (2013a) (17) 3. Otaola et al. (2015) (17) 4. Garrido et al. (2016a) (17) 5. Garrido et al. (2016b) (17)	• Hydrodynamic response and optimisation • Experimental tests • Numerical and mathematical modelling • Power control system
	(13) Breakwaters & plate wave energy converters	1. Huang et al. (2011) (32) 2. Yu (1995) (24) 3. Losada et al. (1996) (24) 4. Dalrymple et al. (1991) (18) 5. Liu and Li (2011) (15)	1. Isaacson et al. (1999) (4.27) 2. van der Meer et al. (2005) (3.33)	1. Chen and Jiang (2009) (8) 2. Selvan and Behera (2020) (8) 3. Chen et al. (2010) (8) 4. Zhao et al. (2021c) (7) 5. Vijay et al. (2020) (7)	• Submerged breakwater • Numerical, analytical, and experimental studies • Water waves scattering
	(14) Raft-type wave energy converters	1. Babarit (2015) (121) 2. Yemm et al. (2012) (87) 3. Pecher and Kofoed (2017) (43) 4. Zheng et al. (2015) (41) 5. Newman (1994) (36)	1. Zheng et al. (2015) (3.55)	1. Nguyen et al. (2019b) (12) 2. Nguyen et al. (2019a) (12) 3. Zhang et al. (2019) (11) 4. Nguyen et al. (2020) (11) 5. Nguyen and Wang (2020) (10)	• Multi-mode converters • Hydraulic power take-off • Floating platform • Performance improvement • Hydrodynamic analysis
	(18) Hybrid energy systems	1. Muliawan et al. (2013b) (38) 2. Muliawan et al. (2013a) (23) 3. Wan et al. (2015) (22) 4. Jonkman et al. (2009) (19) 5. Hu et al. (2020) (14)	1. Jaya Muliawan et al. (2013) (3.86) 2. Michailides et al. (2016) (3.52)	1. Si et al. (2021) (12) 2. Li et al. (2021) (9) 3. Zhao et al. (2021a) (7) 4. Muliawan et al. (2013a) (6) 5. Gkaraklova et al. (2021) (6)	• Wave-wind energy converters • Hydrodynamic performance • Combined wave energy devices
	(19) Numerical approaches	1. Crespo et al. (2017) (32) 2. Brito et al. (2020) (18) 3. Monaghan (1994) (16) 4. Babarit (2017) (15) 5. Crespo et al. (2015) (14)	1. Crespo et al. (2017) (6.08) 2. Monaghan (1994) (6)	1. Domínguez et al. (2021) (16) 2. Luo et al. (2021) (16) 3. Quartier et al. (2021b) (15) 4. Quartier et al. (2021a) (14) 5. Ropero-Giralda et al. (2021) (12)	• Particle method • Smoothed particle hydrodynamics • Improved turbulent models
(C) Vibration energy harvesting & Piezoelectric nanogenerators	(7) Flow & vortex induced vibration energy	1. Bernitsas et al. (2008) (108) 2. Williamson and Govardhan (2004) (100) 3. Sarpkaya (2004) (61) 4. Taylor et al. (2001) (59) 5. Xiao and Zhu (2014) (55)	1. Erturk and Inman (2008) (7.23) 2. Anton and Sodano (2007) (7.02) 3. Bearman (1984) (7.01) 4. Xiao et al. (2012) (6.7) 5. Barrero-Gil et al. (2012) (6.62)	1. Zhao et al. (2021b) (43) 2. Sun et al. (2018) (19) 3. Antoine et al. (2016) (18) 4. Bernitsas et al. (2006) (18) 5. Zhu et al. (2018) (18)	• Hydrokinetic power • Fluid induced vibration • Piezoelectric energy harvester

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Table 2 (*continued*)

Research Clusters	Research Sub-clusters	Influential Cited References		Citing Documents	
		Highest Local Citation Count	Strongest Citation Burst	Highest Coverage	Key Focus
	(10) Triboelectric nanogenerators	1. Fan et al. (2012) (55) 2. Chen et al. (2015) (48) 3. Wang et al. (2017) (46) 4. Wang (2017) (42) 5. Scruggs and Jacob (2009) (35)	1. Scruggs and Jacob (2009) (5.99) 2. Zhu et al. (2014) (5.52) 3. Zi et al. (2016) (4.45)	1. Shen et al. (2021) (41) 2. Zhao et al. (2021b) (35) 3. Liu et al. (2021) (29) 4. Chen et al. (2020) (25) 5. Wang et al. (2021) (24)	• Blue energy harvesting • Hybrid nanogenerators • Performance assessment • Low-frequency wave energy
(D) Flow dynamics, Tidal turbines & Turbine design	(11) Flapping foils & horizontal-axis turbines	1. Falnes (2007) (406) 2. Pelc and Fujita (2002) (135) 3. Uihlein and Magagna (2016) (91) 4. Batten et al. (2007) (51) 5. Boyle (2004)(20)	1. Grabbe et al. (2009) (8.99) 2. Boyle (2004)(8.74) 3. Bryden et al. (2004) (7.96) 4. Uihlein and Magagna (2016) (6.62) 5. VanZwieten et al. (2006) (6.56)	1. Rourke et al. (2010a) (27) 2. Rourke et al. (2010b) (24) 3. Simpson et al. (2008b) (16) 4. Simpson et al. (2008a) (15) 5. Park (2017) (9)	• Hydrodynamic response • Techno-economic challenges • Efficiency assessment
	(15) Vertical-axis turbines	1. Menter (1994) (95) 2. Batten et al. (2006) (40) 3. Hwang et al. (2009) (12) 4. Antheaume et al. (2008) (10) 5. Camporeale and Magi (2000) (9)	1. Batten et al. (2006) (6.01) 2. Camporeale and Magi (2000) (5.61) 3. Hwang et al. (2009) (4.38) 4. Li and Çalişal (2010) (3.59) 5. Li and Calisal (2007a) (3.31)	1. Li and Calisal (2007a) (13) 2. Li and Çalişal (2010) (9) 3. Li and Calisal (2007b) (9) 4. Marsh et al. (2015a) (7) 5. Marsh et al. (2015b) (7)	• CFD modelling • Blade design • Power output estimation • Hydrodynamic optimisation
	(17) Fluid dynamics	1. Kofoed et al. (2006) (191) 2. Hirt and Nichols (1981) (12) 3. Lin and Liu (1998) (9) 4. Kuik et al. (1988) (8) 5. Evans (1980) (7)	1. Kofoed et al. (2006) (11.51) 2. Hirt and Nichols (1981) (7.57) 3. Evans (1980) (4.35) 4. Venugopal and Smith (2007) (3.39)	1. Luo et al. (2021) (17) 2. Beels et al. (2010a) (12) 3. Beels et al. (2010b) (11) 4. Bhinder et al. (2009) (8) 5. Liu et al. (2008) (7)	• Wake effects • Numerical prediction • Non-linear effects • Design and reliability performance

energy conversion devices have not yet reached commercial maturity due to their high levelised cost and a requirement for further technological advancement, structural integrity, and effective governance. As such, scholars have slightly shifted the focus of their research from solely assessing resources and identifying appropriate sites to optimising energy conversion devices and associated infrastructure as well as exploring novel design strategies (Gaudin et al., 2021). Further, recent research also deals with utilising wave/tidal energy resources in the context of better managing coastal/estuarine erosion and inundation, which are likely increasing under widespread climate change impacts (Bergillos et al., 2018, 2019b). This cost-sharing scheme (i.e., energy conversion plus boosting broader coastal/estuarine management benefits), in turn, can stimulate faster commercialisation and sustainable coastal development (Xu and Huang, 2018).

Further details regarding wave/tidal energy research sub-clusters and how they are associated with major clusters are summarised in Table 2. For each research sub-cluster, influential references with the highest local citation counts and strongest citation burst, as well as documents with the highest coverage of influential references and key focus of the sub-clusters are presented (Table 2). Here, by way of example, only one sub-cluster (i.e., sub-cluster (1)) is scrutinised to provide insights into its influential entities. The readers are referred to Table 2 for further information regarding additional sub-clusters of interest.

As per Tables 2 and in sub-cluster (1) from major cluster (B), seminal review papers on wave energy converter technologies received the highest local citations (e.g., Drew et al. (2009) and Falcão (2010)), whereas technical articles focused on novel approaches for generating electricity from ocean waves experienced a sudden spike in their citation counts (e.g., Leijon et al. (2005) and Shek et al. (2007)). Citing documents with the highest coverage of influential references often examined geometry and array configuration optimisation of wave energy converters (e.g., Guo and Ringwood (2021a)), or reviewed wave energy technologies from research and/or commercial perspectives (e.g., Guo and Ringwood (2021b)).

7. Conclusions

Oceanic waves and tides contain vast reserves of clean energy. Yet, these energy resources are some of the least utilised renewables due to several existing challenges. As such, a large and growing volume of academic literature on wave/tidal energy topics has evolved over the years covering a wide range of subjects such as diminishing global dependence on fossil fuels and meeting increased energy demand, addressing design and governance challenges, generating reliable electricity, offering socio-economic and environmental benefits, and ensuring a climate-friendly energy portfolio worldwide. Synthesising such a large-scale body of literature, although valuable, is nearly impossible using traditional review processes. As such, this review adopted a bibliometric, big-data approach to analyse over 8000 wave/tidal energy articles published between 2003 and 2021, providing insights into the space-time evolution of this field of science. The findings indicated that, overall, 67% of literature was produced by ten mainly developed countries, plus China, with nearly one-third of all documents published in ten specific journals (six energy-focused journals and four broad scope ocean/coastal journals). Four major research clusters arose, including (A) resource assessment, site selection, and environmental impacts/benefits; (B) wave energy converters, hybrid systems, and hydrodynamic performance; (C) vibration energy harvesting and piezoelectric nanogenerators; and (D) flow dynamics, tidal turbines, and turbine design.

Nineteen research sub-clusters, associated with the major clusters, emerged (see Tables 1 and 2) highlighting that research on “wave energy conversion devices”, “floating and wave surge energy devices”, and “hydrodynamic performance and optimisation” persistently grew from early 2000s to 2021, whereas research on “triboelectric nanogenerators” and “raft-type wave energy converters” appeared as emerging topics in 2010s. Over the last decade, a shift in the research focus amongst scholars was observed, reflecting the goal of providing sustainable and cost-competitive wave/tidal energy in the global market. This shifting focus highlights a need to not only accurately assess the energy resources and identify optimal sites, but also to further optimise energy converters and explore novel designs as well as to integrate marine renewable plans with broader coastal and estuarine management schemes. The approach implemented in this review is a reproducible method that could be repeated in the next 5–10 years to better understand the trajectory of wave/tidal energy science evolution and compare the research themes and trends with those presented herein. Such a detailed analysis may provide an understanding about knowledge, investment, and management strategies required to successfully direct the future efforts on wave/tidal energy topics.

CRediT authorship contribution statement

Danial Khojasteh: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing - original draft, Writing - review & editing, Project administration. Abbas Shamsipour: Data curation, Formal analysis, Investigation, Visualization, Writing - original draft. Luofeng Huang: Formal analysis, Investigation, Writing - original draft. Sasan Tavakoli: Conceptualization, Formal analysis, Investigation, Writing - original draft. Milad Haghani: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing - review & editing. Francois Flocard: Investigation, Writing - review & editing. Maryam Farzadkhoo: Formal analysis, Investigation, Visualization, Writing - original draft. Gregorio Iglesias: Conceptualization, Investigation, Writing - review & editing. Mark Hemer: Investigation, Writing - review & editing. Matthew Lewis: Investigation, Writing - review & editing. Simon Neill: Investigation, Writing - review & editing. Michael Bernitsas: Investigation, Writing - review & editing. William Glamore: Conceptualization, Investigation, Supervision, Writing - review & editing.

Declaration of competing interest

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

Data availability

The data supporting the findings of this study is available within the article and its supplementary material.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.oceaneng.2023.114995.

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