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REVIEW

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On the potential of ocean energy technologies to contribute to future sustainability

Jun Jie Wu[1], Varun Vijayamohan[2] and Robert W. Field[2,3*]

*Correspondence:
Robert W. Field
robert.field@northumbria.ac.uk
[1]College of Engineering and Physical Sciences, Aston University, Aston Triangle, Birmingham B4 7ET, UK
[2]Faculty of Engineering and Environment, Northumbria University, Newcastle NE1 8ST, UK
[3]Department of Engineering Science, University of Oxford, Oxford OX1 3PJ, UK

Abstract
To achieve the United Nations Framework Convention Climate Change targets and the UN Sustainable Development Goals a major switch to clean sustainable energy is required. Both solar and wind energy are already making major contributions. Great interest is being shown in other processes including a suite of renewable technology that can has been labelled "Blue Energy" otherwise known as ocean energy or marine energy technologies. This suite of technologies comprises three principal categories relating to tides, to waves and to salinity gradients that can be created between seawater and fresh water. In each of these three categories there are various technologies for the extraction of the energy, and the various processes will be briefly described. Then the three are examined in order to assess which if any, from mainly a European perspective, have good growth prospects. Especially with respect to near-horizon implementation, tidal energy, especially tidal stream devises, are considered the most promising. Notwithstanding this observation, the brief review also concludes that no Marine Energy technology has the capacity to become as ubiquitous as solar and wind and in many cases the journeys from innovation to implementation have been or could be permanently stalled.

Keywords Tidal energy, Wave energy, Salinity gradient power, Ocean energy, Blue energy

1 Introduction

The transition to sustainable energy systems is a global imperative, driven by the need to reduce reliance on finite fossil fuels and thereby mitigate climate change. As a contribution to this topical collection, which aims to examine the journey from innovation to implementation occurring in the area of sustainable energy systems, the focus herein will be on ocean energy technologies that exploit the power of tides and waves, as well as differences in salinity, to produce electricity. This area which has sometimes been labelled as 'Blue energy' is part of the spectrum of 'green' energy. The potential exploitation of differences in sea water temperatures to produce electricity is not sufficient advanced to be considered here. Now both solar and wind energy are weather dependent, and obviously solar energy is only available for part of the day. Thus alternative processes that are more predictable and can potentially operate 24/7 have an inherent attraction. In this review we assess whether ocean energy technologies are likely to contribute in a sizeable way to future sustainability. Such an assessment necessitates the provision of some context.

In a recent review on the prospects and future for the thermochemical conversion of biomass [1] by one of the co-authors it has been noted that a range of renewable energy resources have come to the fore as potential sustainable alternatives to traditional fossil fuels [2, 3] but that currently, the renewable energy processes of commercial significance are only hydroelectric, solar and wind, as illustrated by data from the UK [4]. Although as already noted both solar and wind energy depend on the weather, there has been very significant growth of both wind and solar energy in Great Britain (GB) and many other countries. For GB this growth and the demise of power production from coal, are illustrated in Fig. 1. The demise of coal in GB was complete when its last coal-fired power station ceased production on September 30th 2024.

As noted in [1], "Hydroelectric comes with its accompanying energy storage; a reservoir of water at a high elevation and the associated potential energy is the ultimate energy source from which hydroelectricity is created. Storage of fossil fuels such as coal and natural gas is also straightforward, but solar and wind energy cannot be stored in primary form." This creates a problem when there is a lack of wind because the development of energy storage is very much in its infancy. Also non-fossil-fuel-based processes, which can be ramped up during periods when supply from wind and solar is low, have not yet, apart from hydroelectricity, been developed. In many parts of the world, natural sources of hydroelectricity and consequentially the potential of pumped storage are constrained by geography.

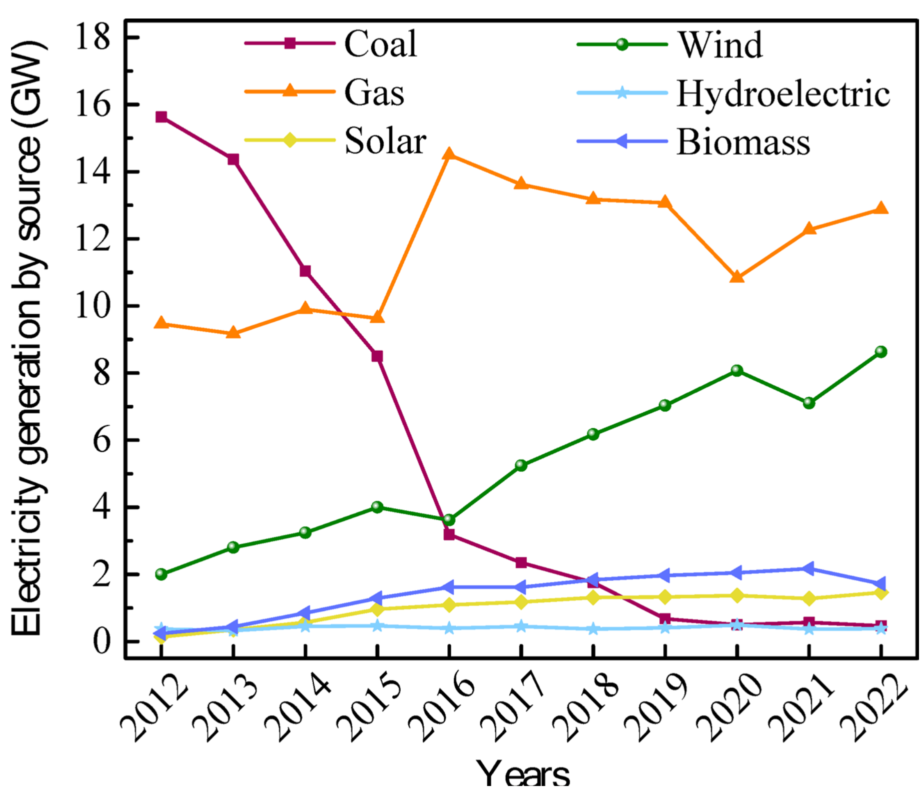

Fig. 1 Electricity generation by source in Great Britain from 2012 to 2022. Data source [4]

Consideration needs to be given to whether Ocean Energy can contribute in a sizeable way to solving either the intermittency problem or the energy storage problem that were mentioned in the previous paragraph. Unlike solar and wind energy, salinity gradient power processes have the potential to offer power on a more reliable basis because their driving force is simply the salinity gradients that can be created between seawater and fresh water. Unless a river dries up the latter offer, in principal, a continuous supply of energy. Tidal sources of energy are reliable but periodic. Whilst waves are constant, wave energy is somewhat variable as they vary by season and the variability will depend on location. The potential for Ocean Energy to address the energy storage problem is considered in Sect. 3.2, where its various processes are compared with other processes for energy generation. Technology Readiness Levels, which are defined later, are used to compare the progress (or lack thereof) of the various technologies.

The various technologies are introduced in the next section starting with wave technology, which is offshore, then moving to salinity gradient power which needs to be located close to sources of both seawater and fresh water, before considering tidal energy. In a subsequent section, data are presented to illustrate the potential contribution that the various renewable marine-based energy could contribute to the UK market. Their journeys from innovation to implementation has been far from linear and have often been stalled. To help illustrate their relative position on the path from innovation towards implementation, the concept of Technology Readiness Levels are introduced and used to assess the stage of development for each Marine Energy Technology. Prior to concluding remarks, current industrial interest in tidal and wave energy will be compared.

2 Ocean technologies

2.1 Wave technologies

Apart from the development of early devices to power navigation lights, there was little work on wave energy until the oil crisis of 1973. With government support this stimulated an examination of the potential of ocean waves to generate energy. With the oil crisis over that work went into decline in the 1980's but today there is a renewed focus upon renewable sources of energy that is independent of oil price. Whilst wave energy is considered by some to be an enormous source of renewable energy [5, 6] industrial interest is uneven, and the European Marine Energy Centre still categorise the industry as "immature" [7]. A decade ago, it was reported that "a recurring theme among wave power experts is that wave energy is where wind energy was three decades ago" [8] and this statement will be revisited later.

Many types of wave energy converters (WECs) have been designed to harness the wave power [9], such as point absorbers, oscillating water columns, overtopping devices and attenuators; a comprehensive list can be found elsewhere [7] and a slightly earlier reference lists nine forms of WECs and illustrates the operating principles of each [10]. The nine types are: (1) Oscillating Water Column, (2) Overtopping Device, (3) Heaving Buoy, (4) Submerged Pressure Differential, (5) Wave Activated Bodies, (6) Bulge Wave, (7) Oscillating Wave Surge, (8) Rotating Mass, and (9) Cycloidal Wave; see Fig. 5 in [10]. Not all of the nine types have been developed to the same extent and only the principle types are illustrated here and information on the other types are readily available in reference [10].

Integral to the exploitation of WEC's is the development of control systems to maximise energy extraction. This has seen developments from casual control [11] to non-causal control such as non-causal linear optimal control [6]. The schematic in Fig. 2 illustrates the working principle of the Point Absorber design. The waves elevate the float and as it falls the kinetic energy is captured and converted to electricity. These devices obtain energy from the wave-driven relative motion between a moving body and a stationary or immobile structure. A schematic of the system is shown in Fig. 3.

Another system involves surface attenuators which are aligned parallel to the incoming waves. They use the rise and fall of waves to create a flexing action that may be used to generate rotation or used to drive hydraulic pumps. This category can be considered to include the 1970's invention known as Salter's duck or nodding duck, although it was officially referred to as the Edinburgh Duck. Whilst the Duck's curved cam-like body can in small-scale controlled tests stop 90% of wave motion and can convert 90% of that to electricity thus giving 81% efficiency [14], this performance is not maintained at larger scale when tested under realistic conditions [15]. The efficiency of the duck often drops to around 50% in simulated rough weather (when there is more energy) and to zero under calm conditions [15].

Another device is the oscillating water column in which wave action is used to move a water column back and forth in order to pressurize air and force it through an air turbine. They have been piloted close to the beach and in deeper seas and a 2024 development will be mentioned in Sect. 4.2. As with other wave-based devises there are two obvious advantages: no fuel is consumed and there is worldwide potential as discussed latter. However, output is weather dependent and both capital cost and maintenance cost are high. The conclusion of Poullikkas a decade ago was that "Currently the major

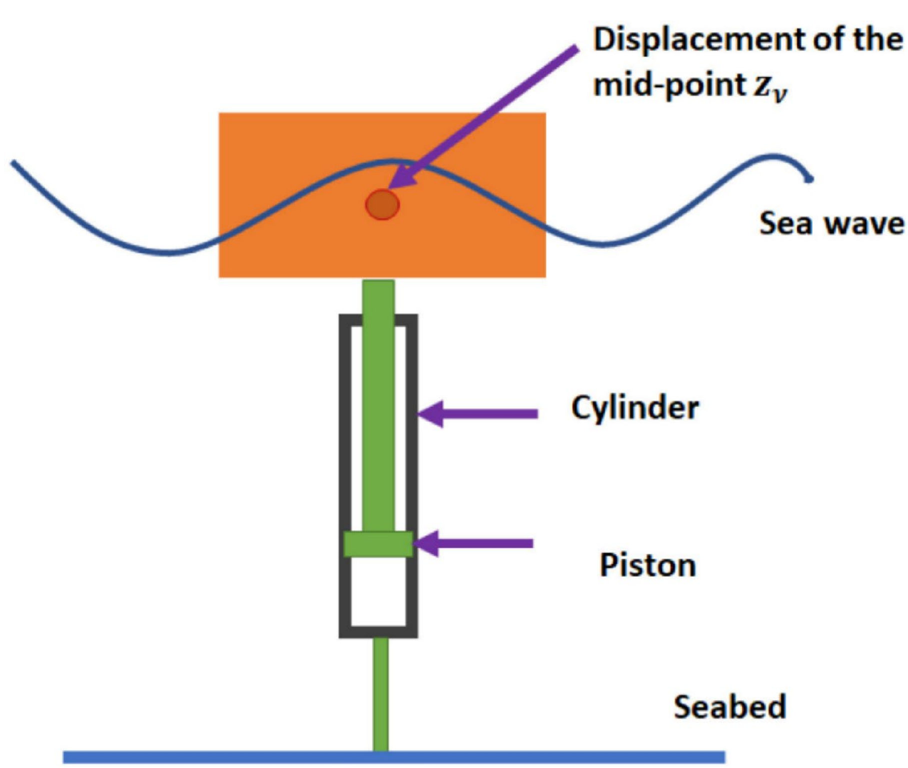

Fig. 2 Operating principle of wave technology based on a point absorber. Image courtesy of Dr Yao Zhang [12]

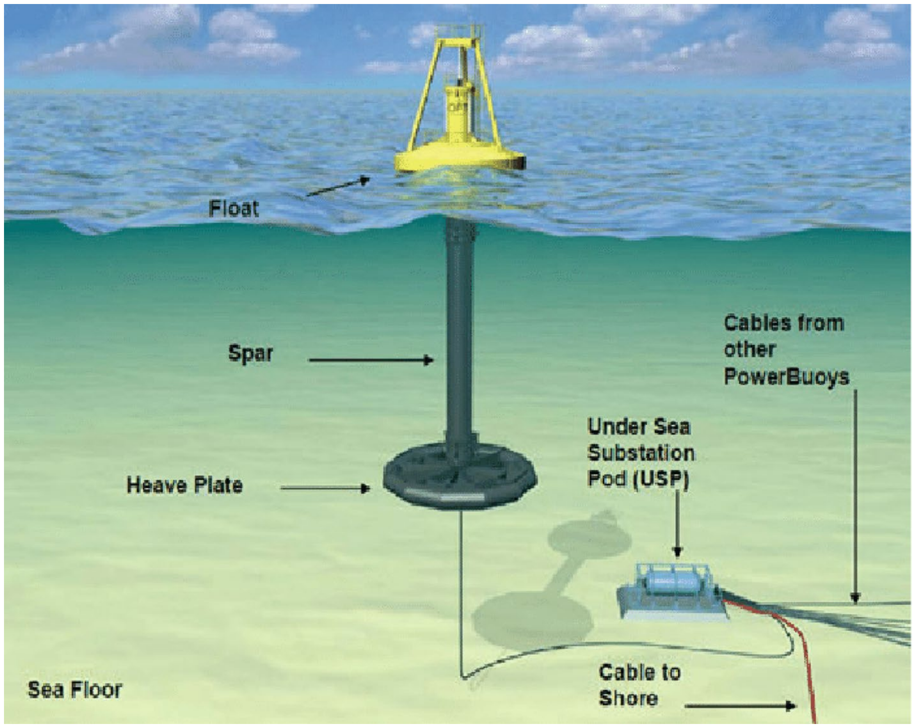

Fig. 3 Overall layout of wave harvesting system. A number of point absorbers (also called PowerBuoys) are connected to an undersea substation. Images courtesy of [13]

obstacles towards wave energy commercialization are the high capital costs of wave energy devices (translated into high electricity unit costs for power generation) and the adverse working weather conditions that these devices have to endure, requiring additional safety features which results in escalation of the capital costs" [13]. There is a balance to be struck between choosing locations that are well off-shore, which provide the highest potential for wave power, and locations that are situated near-shore, which facilitates maintenance and reduces distance to the electric grid.

Concern has also been raised about the effect upon marine life and the visual impact of the devices. As a result of this list of weaknesses few schemes have been implemented and as shown later there is less interest in wave technologies than in tidal technologies. Further comments on wave technologies will be made in Sect. 4.2 which will included levelised cost of energy data from a 2021 review.

2.2 Salinity gradient power

Two processes have been developed to extract the latent energy that is potentially available from the controlled mixing of saline and fresh water ('latent' is being used in its general sense where one means that the energy is in some sense hidden or concealed and has not been developed). One process for producing renewable energy from salinity gradients is Pressure-Retarded Osmosis (PRO), which has been evaluated in detail elsewhere [16], and Reverse Electrodialysis (RED). Regarding PRO the major Norwegian energy company Statkraft built a pilot plant around 2009 to investigate its potential but closed it in 2014 due to the low power output. At its peak the facility had produced power of just 2–4 kW which was significantly less that the design value of 10 kW. The company concluded that within the current market outlook the technology could not be sufficiently developed to become competitive “within the foreseeable future” [17]. The optimism that was there around fifteen or so years ago [18] has dissipated; the energy density is very low, and its extraction has proved to be technically more difficult than originally anticipated. With RED, the salinity gradient between seawater and fresh water is exploited via a stack of alternating cation and anion exchange membranes, and due to the chemical potential difference between salt and fresh water a voltage is generated across each membrane. To assess the technical feasibility of RED under real-life conditions a pilot plant was opened on the Afsluitdijk causeway in the Netherlands in 2014. This has established that a power density of around 1 W/m^2 is possible; the area refers to the surface area of the membrane. However this is less than half that obtainable within a PRO plant fitted with thin film composite (TFC) membranes. As the evaluation of the output from the PRO plant includes turbine efficiency and pumping losses [16], and uses less expensive membranes than RED, the commercial prospects for RED are poorer. This assessment is corroborated by the lack of positive news in the last six years [19].

Whilst both PRO and RED offer, in principal, a continuous supply of energy, they have not proven to be economically viable when the salinity gradient is the one generated between seawater and river water. As noted elsewhere [16, 19] a gradient that is twice this value is required. Such a gradient exists when one pairs reject brine from a seawater desalination plant with fresh water or treated water (i.e. water exiting a wastewater treatment plant) but this is not an ocean technology. As this paper is concerned with ocean technologies, the potential application of PRO involving reject brine from a desalination plant will not be considered herein.

2.3 Tidal energy

Tidal energy is extracted in two distinct ways. One is via barrages and lagoons which involve major civil engineering works, and the other involves tidal streams technology that is more akin to wind turbine technology. The latter extract energy from a flowing stream rather than from the release of water accumulated at high tide.

The world’s first tidal power station was the La Rance Barrage, France in 1967. It remained the world’s largest tidal power station in terms of installed capacity for 44 years. It has an annual output of 600 GWh generated by 24 turbines. The peak output is 240 MW. Today the Sihwa Lake Tidal Power Station is the world’s largest tidal power installation with a capacity to output 254 MW which is about a quarter of a typical nuclear power plant. However the plant uses a single-effect flood generation method to gather water during ‘flow’ and then generate power during ‘ebb’ phase. It produces around 550 GWh annually which is what a 65 MW plant operating for 50 weeks per annum would produce. So whilst the peak output is about a quarter of a typical nuclear power plant, the overall annual output is just one fifteenth of a nuclear typical power plant. A deeper look at future prospects of tidal range will be covered in Sect. 4.4.

As the lagoon planned for Swansea Bay (UK) has been shelved, the authors are not aware of any plans to add to the inventory of large plants (i.e. those over 200 MW). The plan that had been proposed for Swansea Bay was for a tidal lagoon costing £1.3bn. Tidal lagoons are said to have less of an impact on the ecosystem than tidal barrages but need to involve the deployment of ultra-low-head technology. Whilst in June 2015, the UK government awarded planning permission for the scheme, it declined (when asked three years later) to give financial support in the form of a guaranteed price for the electricity

Table 1 Tidal power plants worldwide (main sources [23, 24])

Tidal power plant	Country	Generating power (mw)
Sihwa Lake	South Korea	254
La Rance	France	240
MeyGen	Scotland	86
Annapolis Royal	Canada	20
Kislaya Guba	Russia	0.4
Jiangxia	China	3.9

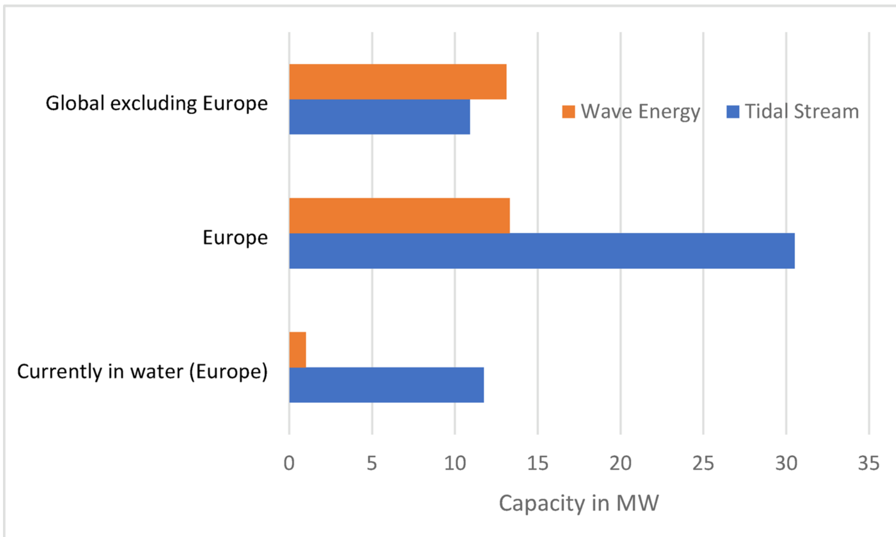

Fig. 4 Accumulative production capacity in MW for Europe and globally. Tidal (blue) and Wave Energy (orange). Source of data [25]

that the lagoon would produce. At the present time the British Hydropower Association states that "the main barrier to the deployment of tidal range is the lack of a price stabilisation mechanism to provide investor confidence" [20].

Illustrations of the three schemes, tidal barrage, tidal lagoon and tidal stream can be found in numerous placed e.g. [21] and [22]. The double lagoon design could be designed to contribute to baseload. Regarding installed capacity an overview of the current position for large installations is given in Table 1.

3 Potential of ocean energy technologies

The first subsection gives an overview of current capacity, then the contribution that Ocean Energy might make to the energy storage challenge is addressed, ahead of Sect. 4 on the future prospects of the various ocean technologies. These will be assessed in terms of Technology Readiness Levels that are introduced and defined in Sect. 4.1.

3.1 Current capacity

According to Dupont [25] the accumulative capacity of tidal and wave stream generation that has been installed globally up to end 2023 is 41.4 MW for tidal steam and 26.4 wave energy. Figure 4 provides a breakdown. To put this in context, the national grid in the UK generates around 30 GW. The Figure also shows the capacity that is currently 'in water' in Europe and this is almost 40% for tidal stream but less than 10% for wave energy. The expression 'in water' in essence refers to a device being duly located and deployed for operation. Progress in 2020 towards wider deployment is reported in Table 2 and it is clearly very modest [26] whilst the activity in 2023 was at a slightly higher level [25]. Nevertheless the European Union (EU) ocean energy target for 2025 which is 100 MW [26] will not be met because the sum of 'in water' of both tidal stream and wave is less than 15 MW—see Fig. 4.

Tidal power is also produced by exploiting the tidal range. Now the cost of electricity generation for 'La Rance' and 'Sihwa Dam' are reported to be EUR 0.04 per kilowatt-hour and EUR 0.02 per kilowatt-hour respectively. These prices are for two barrage systems and presumably do not include an allowance for the capital cost. Total costs for such schemes will vary greatly depending on location. For tidal technologies an estimate range of a levelised cost (LCOE) is EUR 0.25–0.47 per kilowatt-hour range [28] corroborated by a more recent estimate being within this range [29].

3.1.1 Potential for ocean technologies to contribute to the challenge of energy storage

It is important to consider the potential for Ocean Technologies to contribute to the challenge of energy storage because as John Browne who was head of BP from 1995 to 2007, and a former a former president of the Royal Academy of Engineering (2006 to July 2011) made clear recently, storage is vital. So when considering the energy transition, storage must not be overlooked [30]. In commenting upon the UK's future energy mix, on the day the UK's last coal-fired power station at Ratcliffe-on-Soar in Nottinghamshire ceased production, (thereby ending the UK's 142-year history of burning coal

Table 2 Progress in 2020 as reported by ocean energy [26]

Month	Tidal energy	Wave energy
January	60 kW tidal turbine installed by Design Pro in Scotland	
February		2 GWh electrical production reached by Basque wave plant Mutriku
March	Europe hits 50 GWh power generation using tidal stream	
April	China's SIMEC Atlantls Energy deploys tidal project with 50 kW power	
May	Ocean energy receives strong public support according to UK government	
June	Lease for 12 MW tidal project in Raz Blanchord, France has been secured by SIMEC Atlants Energy	
July		Core Power ocean announces factory in Portugal for wave energy and secured equity fund worth € 9 million
September	Tidal kite factory opened by Minesto in Wales. By 2025 US commits an investment worth USD 600 million in ocean energy. License for 4 MW tidal project is granted to Bid Moon Power	
October	New York's City east rivers get 105 kW power from 3 tidal turbines installed by Verdant Power	China's GIEC installs Sharp Eagle device with capacity of 500 kW [27]
November	A 10 year marine license for CorPower wave project is awarded by Portugal. Record investment CAN$28.5million for SME's tidal stream pilot farm generating 9 MW	
December	Sabella unveils tidal turbine blade which are 30% cheaper than current turbines	Wave piston in Spain's Canary islands deploys wave device

for electricity) he made some incisive points and referred directly to 'renewables with storage' as one category that needed further development. Owing to the time it takes to get investment in place, he was of the opinion that with respect to both renewables with storage and nuclear, the UK and the rest of the world are a quarter of century behind where they need to be. He also added that carbon capture and storage (CCS) was an interim solution only, adding that ultimately alternatives would be needed.

Table 3 sets the various components of Ocean Energy within the context of current energy sources that are used for power production and for completeness includes Pressure Retarded Osmosis. The potential (or lack thereof) for Ocean Energy to address the energy storage problem, which is the particular focus of this section, also emerges from Table 3. Now as noted elsewhere hydroelectricity comes with its accompanying energy storage, namely a reservoir of water at a high elevation [1]. Furthermore, nuclear energy simply needs fuel rods and the storage of fossil fuels such as coal and natural gas is straightforward whereas solar and wind energy obviously cannot be stored in primary form. Currently storage of electricity *at scale* is not possible, for example, the battery systems with an output of 320 MW only store a total amount of energy of 640 MWh [31] which amounts only to just two hours of operation at full power. So given the variability inherent in the deployment of solar and wind energy, it is constructive to assess whether any of the Ocean Energy processes can be operated in the manner of hydroelectric

Table 3 Setting ocean energy in context

Energy source and group[1]	TRL	Reliability of power production	Flexibility of power production	Comment[2]
A. Fossil Fuels	9	Excellent	Gas fired power stations—excellent Others e.g. coal– good	Combined cycle gas turbines (CCGT) plants have a global average energetic conversion efficiency of 55 ± 2% [32]
B. Biomass	9	Excellent	Technically same as coal	In UK, used as contributor to baseload to reduce average emission of net CO_2
B. Nuclear	9	Excellent	Used mainly for baseload	Construction phase is long
C. Hydroelectric	9	Excellent	Often used to meet peak demand	Highly limited by geography
C. Solar	9	Diurnal cycle, the seasons and weather dependency restrict output	None (and only available for part of the day)	Cost efficient storage is highly needed to enable a combined system to output during night-time
C. Wind	9	The seasons and weather dependency limit reliability	Limited	Wind drought discussed and illustrated in Wang and Wu [1]. Cost efficient storage is needed
D. Pressure Retarded Osmosis	4	Technically high but long-term trials would be required	Theoretically there is an operational option that can provide flexibility	After basic trial (*circa* TRL 4 to 5), further work beyond academe not pursued [1]
D. Tidal Barrage	8	Excellent	Limited by semidiurnal cycle. Design can smooth output	Justification for TRL 8 (actual technology completed and qualified through test and demonstration) in Sect. 4.4
D. Tidal Stream	6	Good. Longer term trials desirable	Limited by semidiurnal cycle	Technology prototype demonstration in an operational environment (TRL 7) limited
D. Wave	5 or 6	The seasons and weather dependency limit reliability	Design dependent—probably limited	Many designs have not reached beyond TRL 5 but Pelamis (see Sect 4.2) close to achieving TRL 7

[1]The first three groups are those defined by Kate Morley at National Grid Live: Fossil Fuels, Other Sources and Renewables. The Group D are those being classified as Ocean Energy. [2]Technology Readiness Levels (TRL) are introduced in Sect. 4.1

power stations or CCGT plants which are available 24/7 all year round and can readily be used at both full and reduced levels of power production.

A recent review of the thermochemical conversion of biomass foresaw one potential route for its exploitation, namely that one can produce solid material for power generation and thus augment the current practice of burning wood chips for power production [1]. Burning wood chips currently contributes 7.1% to Great Britain's annual electricity generation [4] but at present there is no renewable source (except hydroelectric power) which includes an element of storage. The wood chips just referred to are in the category of 'other' rather than 'renewable' [4] because the associated carbon footprint is modest rather than low.

It is instructive to ask if the arrival of Ocean Energy would aid the energy transition by providing a source that came with inherent storage. An advantage of tidal power is the reliability of its semidiurnal cycle but by its very nature this is not a source that can be switched on and off. In so far as one can conceive of tidal barrage as having inherent storage, it is equivalent to the energy obtained in one half-day cycle. Wave power would have inherent variability and no associated storage. Stepping back one can see that these potential sources of power, like solar and wind processes, are ultimately linked to the sun's current heating of the Earth and its revolution around the sun (and the moon's revolution around the earth). By contrast fossil fuel sources and nuclear fuel rods provide a source of chemical energy that is released when these substances undergo a reaction which are respectively combustion and nuclear fission and there is associated storage at the place of energy generation or in linked infrastructure. The only Ocean Energy process that can be operated continuously, and upon demand at variable load, are those based upon the controlled mixing of seawater and fresh water which are Pressure Retarded Osmosis and Reverse Electrodialysis (RED) [17]. Now when waters with different salinities are mixed there is a change in the overall Gibbs free energy, and this can theoretically be exploited continuously where there is a ready source of both seawater and fresh water. The controlled mixing 1 m.^{3}/s of seawater with an equal amount of fresh water can theoretically produce *circa* 1 MW. This might initially sound impressive, but it is equivalent to warming the mixed waters by only circa 0.1 ^{o}C and neither process is close to being technologically ready. As discussed elsewhere there is no reason to expect this to change [16, 19]

4 Future prospects for ocean technologies

Section 4.1 introduces the scale used for Technology Readiness Levels (TRL) and then the following three sub-section assesses the TRL levels for the various classes of Ocean Technology.

4.1 Technology readiness levels

Technology readiness levels (TRL) are used to assess the maturity of a particular technology. A technology project or class of technology can be evaluated against the parameters for each technology level and then assigned a TRL rating. There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest. Funding bodies use TRL to help determine whether a project or proposal is suitable for a specific funding opportunity, but they are also a useful framework by which to assess how far a technology has progressed towards implementation. The TRL levels and definitions are given in Table 4.

Table 4 Technology readiness levels as used by UK Research and Innovation [33]

TRL 1	Basic principles observed and reported
TRL 2	technology concept or application formulated
TRL 3	analytical and experimental critical function or characteristic proof-of-concept
TRL 4	technology basic validation in a laboratory environment
TRL 5	technology basic validation in a relevant environment
TRL 6	technology model or prototype demonstration in a relevant environment
TRL 7	technology prototype demonstration in an operational environment
TRL 8	actual technology completed and qualified through test and demonstration
TRL 9	actual technology qualified through successful mission operations

4.2 Wave energy

From Table 2 it seems that the industrial interest in tidal power, particularly tidal stream, is growing at a far faster rate than the interest in wave power but wave energy converters continue to be improved e.g. the GIEC Sharp Eagle device developed in China (mentioned in Table 2) and the OE35 from Ocean Energy which is a new floating wave energy device. Floating on the ocean's surface, the OE25 incorporates a trapped volume of air, with the lower part of the enclosure partly filled with seawater and open to the sea. Passing waves cause the water to oscillate and drive trapped air through a turbine to generate electricity. In September 2024, a €19.6 million project based around the OE 25 and co-funded by the EU Horizon Europe Programme and by Innovate UK, the UK's innovation agency, received the go-ahead [34]. The aim of the project, which will be based at the European Marine Energy Centre (EMEC) in Orkney, Scotland, will be the completion of a rigorous technical and environmental demonstration over a two-year period at the scale of 1 MW. If successful then this would be at the TRL 7 level, which is "technology prototype demonstration in an operational environment." However the trials are yet to begin and whether this will be able to displace a previous leading WEC, namely the Pelamis, has yet to be established.

Interestingly, a recent review on the trends and economic potential of global wave power suggested that the WEC Pelamis, which the new OE25 has superseded, was at a TRL of 8 or 9 [35]. However a reading of a report on the development of Pelamis suggests that there were technical issues [36] which stands in contrast to the claims that this devise had reached the stage of "actual technology completed and qualified through test and demonstration" (TRL 8) or even the stage of "actual technology qualified through successful mission operations" (TRL 9). Beyond the pre-production prototypes there seems to have been three small farms with Pelamis WECs [36]. Firstly three Pelamis P-750 WEC machines were used in the Agucadoura Wave Farm 5 km off the Agucadoura coast of Portugal and the farm initially delivered 2.25 MW of electricity as planned. However the system was towed back to the port after four months due to technical problems. Finance for the re-installation of the generators was not obtained and the wave farm was shut down [36]. Subsequently a second-generation device, P2-001, was bought and tested by E.ON UK (2009). Then Scottish Power bought a P2 unit in 2012 but the company went into administration and ceased trading in 2014 [36]. This reflects the economic reality of wave power which is at least four times more expensive than wind and solar [29]. As for the technology readiness itself it has been reported that the P2 test programme operating in seas off the Orkneys and accumulated 7500 grid connected operating hours and exported 160MWh of electricity to the national grid

Table 5 Electricity generation, annual basis

Country	Electricity generation (TWh)	Exploited hydropower (TWh)	Theoretical wave power potential (TWh)	Current percentage hydroelectric	Wave potential as percentage of current generation
Australia	265.1	14.3	224.9	5.4	85
Brazil	625.6	399.3	32.9	64	5.3
Canada	660.4	382	47.9	58	7.3
Chile	83.9	20.9	122.6	25	146
China	7503.4	1269.7	6.1	17	0.08
Denmark	30.5	0.0	0.7	0	2.3
France	555.4	58.5	48	10.5	8.6
Germany	612.4	20.2	0.2	3.3	0.03
India	1558.7	161.8	33.1	10.4	2.1
Ireland	30.7	0.9	15.4	2.9	50
Japan	1036.3	73.9	17.5	7.1	1.7
Mexico	364	23.8	52.7	6.5	14
New Zealand	44.6	25.6	73	57	164
Norway	134.8	125.3	5.6	93	4.2
Portugal	53.7	8.7	7.6	16	14
Russia	1118.1	194.4	34.1	17	3.0
South Africa	230	5.7	49.8	2.5	22
Spain	275.8	25.2	12.7	9.1	4.6
UK	323.7	6.0	26.2	1.9	8.1
USA	4401.3	271.2	122.8	6.2	2.8
Overall	19,908	3087	934	15.5	4.7

Comparison of exploited hydropower and theoretical wave power potential for selected countries. Theoretical wave power sourced from [35]. Electricity generation and exploited hydropower are sourced from existing datasets [38–40] and identical to data used by Shao et al. [35]

[14]. The full history suggests that the Pelamis achieved TRL 7, "technology prototype demonstration in an operational environment".

Probably Pelamis P2 achieved TRL 7 but is no longer the leading WEC and is not being taken forward for further development. In general, the TRL rating for Wave Power would seem to be a TRL of 5, namely "technology [with] basic validation in a relevant environment". The lack of a consensus as to which WEC, or sub-set of WECs, to use is indicative of an "immature" industry and if paraphrasing Levitan's [9] observation that "wave energy is three decades behind wind energy", then the potential contribution will not be until 2040 (if at all). Not only is the path from innovation to implementation non-linear but there is no guarantee that TRL 9 will be reached because either the capital costs inhibit the financing of development at the higher TRL levels, or the technical challenges such as overcoming the adverse working weather conditions are insurmountable. This observation is consistent with both the fact that the Wave Hub project sited approximately 16 km off Hayle, on the north coast of Cornwall, UK, was originally developed for wave power, but following limited interest is being developed for floating offshore wind [37] and secondly the evolution of levelised cost of energy by renewable source between 2010 and 2018 (Fig. 2 of [27] indicates that the cost of wave energy is higher than that from any other source; the difference compared to wind and solar is around a factor of 4.

Finally it is interesting to assess whether wave power, cost and reliability permitting, could ever rival solar and wind energy. Table 5, which has been developed from the prior work of others [35, 38–40], indicates that countries with long west coastlines have high level of wave power potential with the prime examples being Australia, Chile, Ireland, New Zealand, Portugal and South Africa but no other countries in the list have a potential wave power production that is greater than 10% of current electricity generation.

It is noteworthy that the five countries that generate the greatest amount of electricity (China, India, Japan, Russia and USA) have, as a group, a potential annual wave energy output of electricity that is only 1.4% of their current total annual production (namely 214 TWh *cf* 15,618 TWh). By contrast their hydroelectricity production currently totals 1971 TWh which is nine times more than their *potential* wave energy output. Given that hydroelectric power is hugely outperforming not only actual but even the potential contribution of wave energy, its future as a global contributor seems to be limited. Whilst proponents of wave energy devises may indicate that global models do not capture non-linear dynamics, which are important for detailed assessment of local wave energy potential, the fact remains that globally wave energy *potential* is far less than current hydroelectric energy production. Moreover the predicted potentials for wave energy along, for example, Western Europe's western facing coast are based upon use of a multi-year wave hindcast database and performance data of various WEC power systems obtained previously under different conditions. Now such modelling investigations frequently neglect practical and environmental issues including the moorings of devices and the ability of WEC structures to survive extreme storm events. However some studies have undertaken a holistic study taking into account wave resource, stability, risk plus installation and maintenance costs. For example, in a study of the wave energy resource off the northwest Iberian Peninsula coast, Ribeiro et al. [41] examined the temporal and monthly variability of the wave power and included the influence of risk, water depth and distance to the coast. They also stated that the wave energy will worsen by the end of the century due to the decrease in wave energy's mean value coupled with an increase in its variability and an increase in the risk factor due to an increase in the frequency of extreme ocean waves [41]. Additionally, the whole structure will need to withstand chemical and biochemical degradation. So whilst the models may indicate enhanced potential in the areas of high waves, the ability of a WEC to withstand the enhanced challenges has yet to be tested.

Another thorough study [42] noted in its conclusions that "a significant disparity exists between the available wave energy resource and the actual wave energy that can be effectively harnessed in a given location. The critical factor in this regard is the technology associated with WEC devices, as it delineates the proportion of wave energy that can be efficiently converted into electricity. The primary reason for the lower TRL of wave energy, which currently stands at approximately 6, in comparison to other marine energy sources, is the absence of a standardized WEC device, in contrast to, for example, offshore wind technology." The assessment that TRL stands at approximately 6 accords with our statements in Table 3, which seeks to set Ocean Energy in context.

Western Europe's potential for wave power with its long western facing coastlines is, in a global context, relatively large. Now although the EU has set new ocean energy targets of 100 MW by 2025, 10 GW by 2030 and 40 GW by 2050 ([25] p3), Ocean Energy recently reported that companies developing wave power are targeting off-grid applications [22]. These companies foresee a future in developing WECs to decarbonise offshore oil and gas platforms, to decarbonise all ranges of ocean data monitoring activities and to power isolated communities dependent on expensive diesel consumption. Other work [43] also discusses the potential for using wave energy converters in nearshore and offshore niche markets where these converters are part of hybridised synergetic technologies. The hope that such developments will bring new perspectives to improve the chances of a successful deployment and operation of future WECs is explicitly expressed together with the observation that "wave energy has yet to reach a level of commercial viability that enables it to become competitive with alternative energy sources, both renewable and non-renewable." These potential strategic directions and observations indicates that wave energy will not make any significant contribution to the power grid for at least the next 15 years.

4.3 Salinity gradient power

A few remarks will be made about PRO but further remarks regard Reverse Electrodialysis (RED) are essentially superfluous given the negative assessment in Sect. 2.2. It is salutary to examine the decades long journey of PRO because other Ocean Energy technologies may follow the same path. The conceptual simplicity of PRO was recognised as early as the 1970's [44] but concern about costs has always been recognised as a problem [45–47]. Thus in the twentieth century the concept of PRO remained just that—a concept—whereas RO rose to become by 2000 the main desalination technology of the world (see Fig. 1 of [48]).

With the advance of membrane technology and increasing concern about sustainability at the beginning of the twenty-first century, attempts were made to advance PRO beyond TRL 1 and 2. This work was bolstered by very appealing estimates of its global potential. One estimate from 2009 was that osmotic technology would soon produce 1,600TWh a year globally [17], which is around 13 times the annual hydropower generation of Norway and similar in magnitude to the annual amount of hydropower produced globally; the sum of the values listed in Table 5 is 3087 TWh.

Disappointingly, as an overall process PRO was never able to develop beyond TRL 4 or 5. Whilst the Statkraft facility was referred to in Sect. 2.2 as a pilot plant, the peak power production was only a few kW and at best this was a "basic validation in a relevant environment" i.e. TRL 5. The facility was closed in 2014 because the power density (power per unit of membrane area) of the prototypes was insufficient and the development of PRO for the pairing of seawater and fresh water has ceased.

4.4 Tidal energy: tidal stream and tidal range

Firstly the prospects of tidal stream are considered. A report for the UK government [49] indicated that tidal stream could, in the opinion of the authors, become significant and had the potential to reach LCOE of £150 per MWh once 100 MW had been installed, reducing to £90 per MWh by 1GW and £80 per MWh by 2GW. Reasonably they were anticipating a learning curve for the technology, but the journey has yet to begin and the current LCOE in Jin and Greaves [29] for tidal stream equates to £285 per MWh. Catapult [49] added that further reductions are possible with additional focus on innovation and added that there is the possibility of cost approaching levels now current for offshore wind. It was estimated that UK tidal stream industry could generate a cumulative benefit to the UK by 2030 of £1.4bn and support a total of almost 4000 jobs. It is now six years since the report was published and as Fig. 4 indicates only 40 MW of tidal energy has ever been installed globally.

The UK has one of the largest tidal stream generation capacity in the world, with the majority of its capacity being in Scotland. The UK's tidal power resource is close to 10 GW, which is about 50% of Europe's tidal stream energy capacity. Currently there are seven operational tidal stream projects in operation with a capacity of 9.1 MW with 2.3 MW under construction. On paper far more could come on-stream. RenewableUK have reported that a further 390 MW has been approved for development [50]. One of the foremost companies in this space is the Orkney-based Orbital Marine Power. In 2011 they were the first company in the world to successfully connect a floating tidal turbine to the grid and currently their latest device, the O2 machine is deployed in the waters off Orkney where it has been exporting electricity into the UK grid since July 2021 [51].

Clearly economics are fundamental to adoption of tidal energy technology. Now according to USA reports, a 2019 study on commercial-scale tidal energy estimated its production cost to be \$130–\$280 per MWh [52] compared to \$20 per megawatt-hour for wind [53]. The tidal power industry has supply-chain challenges due to the lack of established and routine production as well as the challenge of designing machines for a very corrosive environment [54]. The cost range given for the USA crosschecks with a UK report that the cost of generating power from tidal streams has fallen by 40% since 2018 [55]. Now 60% of £285 per MWh (a UK figure given above for 2018) is £171 per MWh, but whether the reported forecast of Offshore Renewable Energy Catapult [55] that prices could fall below nuclear energy in little over a decade, with 1 MWh of power costing as little as £78 by 2035 compared with £92.50 for the new Hinkley Point C power plant is both debatable as well as being not germane to a discussion of major energy sources. The aforementioned Scottish renewable energy company Orbital Marine Power is the technology partner for Orcas Power & Light Cooperative's proposed site off Blakely Island in Rosario Strait, Washington State [56]. Both this site and the location in the Orkneys indicate that tidal energy has potential for remote locations, rather than locations in general. For remote locations, the interest in tidal stream is fairly widespread. As noted by [57], "tidal energy resource is usually abundant close to… remote islands along China's coastline,…. Another advantage is that tides, either diurnal or semi-diurnal, can be forecast more accurately compared with offshore wind and ocean waves, making it a reliable and predictable renewable resource." A number of prototypes have demonstrated successful operation in an operational environment and thereby reached TRL 7. The focus has generally been upon testing full-scale prototypes rather than a set of machines, i.e. a "farm", for large scale deployment. The world's first offshore tidal array was installed by Nova in 2016 in Bluemull Sound, Shetland which is a remote location [58]. So as a reliable source tidal stream will probably have a niche place in the renewable energy portfolio of future decades delivering energy security for those living afar from the main centres of population.

Having considered the prospects of tidal stream which exploits the kinetic energy generated by strong flows, consideration is now given to the future prospects of tidal range which exploits the potential energy generated by the rise and fall in estuarial waters. Only in certain geographic locations is the rise and fall of commercial significance. Not only are such power stations site specific but since the construction of La Rance Barrage, the world's first tidal power station in 1967, only one other comparable station has been constructed; see Table 1. This immediately indicated that the prospects for this technology are not promising. The actual technology has certainly been completed and qualified through test and demonstration making it at TRL 8. However due to environmental concerns it is probably no longer correct to advocate a rating of TRL 9 which is "actual technology qualified through successful mission operations". In a world looking at a triple bottom line approach, the technology can be seen as no longer meeting all parts of the mission. Generally the location has to be in estuarial waters, and this is the Achilles heel of this technology because of the negative influence on marine life.

The environmental impact of tidal barrages is significant causing changes in salinity and sediment levels and thereby disrupting coastal ecology resulting in a decrease in biodiversity—a loss of flora and fauna. In the UK such concerns have contributed to the demise of plans to construct the Severn Barrage, a proposed tidal barrage in the Severn Estuary of the UK. This site has a very large tidal range and many potential advantages including a projected project life of around 120 years which is around three times that of nuclear power plants. Nevertheless it is most unlikely to be built because today's "missions" need to incorporate successful measures to mitigate ecological harm and plant construction costs are high.

Plans for the Swansea Lagoon scheme mentioned in Sect. 2.3 seem to be in 'deep storage' which for the UK leaves just one scheme under active consideration. This is the Centre Port scheme [59]. This project involves a container terminal, flood defence, plus rail and road links in addition to a tidal power station. Also it would involve construction across a bay rather than a river mouth. This combination of differences compared with past UK proposals means that this scheme may possibly flourish. Meanwhile a recent EU report noted that there is only one tidal barrage scheme in the pipeline and that is the one that may be located at Brouwersdam in the Netherlands [60]. The Dutch authorities are currently exploring the possibility of converting an existing dam into a tidal power plant that would generate around 20 MW and also bring some environmental benefits. That this is the only one being considered within the EU, and as it would only have a capacity that is less than 10% of La Rance (see Table 1), it is clear that barrage schemes will not be contributing to the energy transition to more renewable sources.

5 Concluding remarks

Ocean Energy pushes a number of psychological buttons in a world looking for solutions to our environmental problems and until recently it seems that many have been reluctant to conclude that its potential contribution to the portfolio of renewable energy technologies will be limited. Certainly there seems to be no prospect that salinity gradient power will have any role to play in extracting energy from the oceans, be it at small or larger scale. Also, the prospects for tidal barrage schemes are also weak because of the large capital cost, environmental concerns and the limited number of geographical locations due to the need for a minimum tidal range. Nevertheless one scheme that is not estuarial, and which would produce around 1% of the UK energy needs, was identified in the previous section. Interestingly the energy company Centrica has backed the Centre Port proposal [61].

In displays of investment in a technology against time, it is common for there to be a minimum corresponding to TRLs 4 through to 7 and this minimum has been labelled the 'Valley of Death'. It corresponds to a period where neither academia nor the private sector prioritise investment of time and other resources. In some cases technologies that could have reached maturity are not developed. However we posit that this is not the case for either salinity gradient power or tidal range. Firstly, for reasons intrinsic to the technology salinity gradient power cannot achieve the energy density that would be required (see for example [62]) and the pioneer in this area REDstack BV in the Netherlands has pivoted away from energy production; they now advocate that their world-leading ElectroMembrane Stacks are a technology enabling carbon capture, sustainable water use and resource recovery [63]. Secondly the deployment of tidal range is constrained for the reasons given in Sect. 4.4. These two technologies have TRL levels either side of the remaining Ocean Energy technologies which are wave and tidal stream.

As tidal energy is produced by the rise and fall of tides, which has high power density and strong predictability, interest in this area is likely to continue particularly as it can contribute to energy security. However when wave and tidal stream companies state that they have strong project pipelines, currently they are referring to projects of a few megawatts to a few tens of megawatts in both tidal stream and wave energy. Whilst this is very small compared with overall demand from the energy grid it shows that there is still momentum for localised deployment in both areas. As a reliable source, it will probably have a limited place in the renewable energy portfolio of the future. Whilst the order of magnitude of that level will depend upon future developments, the clear indications are that Ocean Energy will not make any significant contribution to the power grid for at least the next 15 years.

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J.J.W and R.W.F were jointly responsible for conceptualization, formal analysis, and writing & editing of the manuscript text. V.V. provided initial drafts of Sect. 2.1, 2.3 and 3.1.

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