Journal of Ocean Engineering and Marine Energy (2022) 8:417–432
https://doi.org/10.1007/s40722-022-00240-3

REVIEW ARTICLE

Powering data buoys using wave energy: a review of possibilities

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Received: 11 March 2022 / Accepted: 18 May 2022 / Published online: 20 June 2022

Abstract

Data buoys are a widespread method of not only monitoring environmental parameters, but have a range of other applications: from surveillance to providing power for autonomous underwater vehicles (AUVs). The majority of data buoys currently in use are either solely powered by batteries, or they employ an array of solar panels to sporadically top up the battery power when environmental conditions are suitable. Less usual for data buoys is the use of wind power—though some successful hybrids of the two, such as the AXYS Technologies WindSentinel, also exist. As wave power technology matures, advancements in this currently underdeveloped technology could allow data buoys the option of using wave energy converters (WECs) as an alternative renewable power source. Data buoys could provide a small-scale application of WECs where many of the issues with harvesting such a stochastic and irregular energy source would be highlighted. The lessons learned in developing wave-powered data buoys could potentially be applied to larger, more costly wave energy applications such as wave farms or megawatt-level generators. This review considers data buoy projects currently in development—particularly those that look to incorporate a wave energy harvesting mechanism as either their primary or secondary power source, and their prospects, both as end-use applications in their own right, and as low-cost platforms to prove emerging wave energy technology for larger-scale use.

Keywords Review · Data buoy · Wave energy converter · Marine sensing

1 Introduction

Data buoys are one of the most useful tools available for ocean monitoring. As small-scale independent units or as part of a larger sensor network, data buoys have become a mainstay of weather forecasting and coastal surveillance. Early iterations of data buoys relied on diesel generators as their power source (Meindl 1996), but with advancements in battery technology and the reliability of photovoltaic (PV) solar panels, these technologies have replaced the diesel generators of old and become the conventional power sources for the majority of data buoys in use today. PV panels and batteries provide data buoys with a reliable supply of power which requires only infrequent maintenance and can otherwise function independently—providing either real-time or periodic packaged transmissions of the information they have gathered. This review considers the prevailing use of solar and battery power today, and looks at developments made within the wave energy sector which could disrupt this trend and pave the way for a future where wave energy converters (WECs) could either complement these as a secondary power source, or replace them entirely.

The review also examines some of the challenges posed using wave energy as a power source for data buoys. The review will also consider developments made, that may help WECs reach the same stage of advanced development as PV panels and batteries, which currently out-compete wave power in the data buoy field. Unlike the well established renewable sectors of solar and wind, where the focus of research and development is refining the existing technologies of PV panels and turbines respectively, wave energy is still a nascent technology where there is no 'go to' solution. This has led to a range of device concepts and power take off (PTO) mechanisms for harvesting wave energy: from the oscillating water column (OWC) used in Yoshio Masuda's pioneering navigation buoy (Henriques et al. 2016; Falcão and Henriques 2016); to the triboelectric nanogenera-

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tor (TENG) invented in 2012 by Zhong Lin Wang's research group (Fan et al. 2012). Section 4 of this review categorises recent developments made in wave-powered data buoys by their PTO mechanism to observe the current state of the art of wave-powered data buoys and examine the advantages of each PTO mechanism in the context of small-scale data buoys, as well as the challenges and potential drawbacks of using these as a testbed for larger devices and as a PTO for data buoys in their own right. A key aim of reviewing existing wave-powered data buoys is to highlight the novel concepts behind each development and the impact of these on advancing the use of wave energy in the field of data buoys.

Section 2 looks at the characteristics of data buoys in terms of applications, current power sources, and a discussion of their potential as testbeds for larger WECs. Significant reviews relevant to the field of wave-powered data buoys are discussed in Sect. 3. Section 4 focusses on developments in wave-powered data buoys made after 2011, as Lindroth and Leijon (2011) presents a comprehensive review of developments made in offshore wave power measurements throughout the twentieth century, and those developed in the first decade of the twenty-first, including wave-powered data buoys with a history of deployment at sea. Section 4 aims to give an overview of advancements in wave-powered data buoys since 2011, including those which refer to themselves as smart buoys, sensor buoys or nodes. Categorisation by PTO was considered most appropriate for Sect. 4 as many of the data buoys investigated are still in development, leading to a lack of detail in other categorisations considered such as deployment history, sensor type, or mooring method.

2 Characteristics of data buoys

2.1 Data buoy applications

The most widespread use of data buoys is in the field of weather forecasting and climate monitoring. Weather buoys are dotted around coastlines to provide a stream of data to meteorological offices, such as the Mobilis buoys deployed by the UK Met Office (Mobilis 2021) or the five JFC Marine buoys utilised by Met Éireann (MET Éireann 2021). These buoys record a range of parameters: from significant wave height; to atmospheric pressure; air, sea and dew point temperature; and wind velocity at key locations around their country's coastlines. Monitoring ocean parameters more generally allows effects such as desalination to be measured (ESA 2012), and through their ability to function independently, data buoys could even replace expensive manned field studies on coral reefs and other key environments where the effects of climate change are felt most harshly (Pirisi et al. 2013). Beyond monitoring the climate directly, data buoys also find a role profiling wind and waves in scouting out suitable sites for offshore wind farms (Office of Energy Efficiency and Renewable Energy 2015; Mathias et al. 2021) and wave farms (Nolan et al. 2007).

Wave powered sensing platforms are also identified in Dillon et al. (2022) as a vital component for persistent ocean observation. Dillon et al. (2022) aligns this need for ocean observation with conserving and sustainably using oceans, seas and marine resources, which was identified by the United Nations (UN) as one of their 17 goals towards sustainable development. Dillon et al. (2022) explores the constraints currently imposed on observation of deep sea areas because of a lack of available resources to supply power to these remote marine locations. Dillon et al. (2022) also specifically mentions the problem that the buoys that do pass through these deep water areas are mostly drifters, and are therefore designed for only very low power equipment, limiting the data that can be collected by these buoys. Dillon et al. (2022) highlights the need for wave energy harvesting to provide power for both long- and short-term ocean observation of remote marine areas.

Data buoy applications are almost countless, with research and development continually pushing the boundaries of where data buoys can be applied: from feeding fish (Fullerton et al. 2004) to monitoring the structural health of structures at sea (Xie et al. 2020). Data buoys, in their strictest definition, perform a sensory role, but some small-scale buoy devices on the periphery of this definition that have similar power and environmental demands are also included in this review. For example, providing power to autonomous underwater vehicles (AUVs), or remotely operated vehicles (ROVs), is a commonly listed application of data buoys. To provide AUVs and ROVs with power, the buoy essentially forms a docking station for these vessels, allowing the energy stored or harvested by the buoy to be transferred to the vehicle periodically, or the buoy provides the AUV with a continuous power supply by means of a tether. Resen Waves (Steenstrup 2015) visualise a means of transferring the energy harvested by their flywheel-based PTO via the mooring line to a battery pack or docking station on the seabed which AUVs can utilise as a charging point.

A similarly peripheral application is included in Kevin et al. (2020) where a small-scale buoy fitted with a WEC can be used to supply power to remote coastal communities in Indonesia. The scale of the PTO mechanism used in Kevin et al. (2020) allows it to be included in this review, as the challenges a device of this size this will face in its development, are likely to reflect those faced in developing PTOs for measurement buoys with a similar power demand.

The current range of applications for data buoys is multitudinous and highly varied, with new applications regularly being proposed. However, pushing the boundaries of data buoy applications furthest are the self-propelled data buoys.

First mooted in Curcio et al. (2006), self-positioning data buoy designs are driven by the belief that allowing data buoys to position themselves would be an advantageous development in the field. This proposal was not just a one-off, with Nabavi et al. (2018) further building on this idea. However, for the purposes of this review, self-propelled data buoys remain curios beyond the scope of this research. Self-propelled data buoys demonstrate the vast range of application ideas around data buoys, but adding a WEC would add further levels of complexity to an already unorthodox design.

2.2 Data buoy power sources

To allow data buoys to operate independently, a reliable means of providing power to the system is a crucial element of data buoy design. With the earliest data buoys having onboard diesel generators (and some even experimenting with nuclear reactors! (Meindl 1996)), the advent of reliable batteries and efficient PV panels has led to widespread adoption of these two technologies as the staple for providing a power source for most commercial data buoys.

The pairing of a battery which can be sporadically recharged by an array of PV panels adorns TechWorks Marine's data buoys used by the European Space Agency (ESA) (ESA 2012; TechWorks Marine 2021), and the majority of meteorological buoys, including the JFC Marine data buoys used by Met Éireann (MET Éireann 2021) and the Mobilis buoys used by the UK Met Office (Mobilis 2021).

Some designs include a second renewable energy harvesting mechanism, usually a wind turbine, to allow for some redundancy in the energy sources available for recharging the battery pack. Examples of these hybrid data buoys would include AXYS Technologies' WindSentinel used by the US Government's Office for Energy Efficiency and Renewable Energy for wind profiling on potential windfarm sites (Office of Energy Efficiency and Renewable Energy 2015; AXYS Technologies 2021), and the aquaculture buoy described in Fullerton et al. (2004). Research on purely wind powered data buoys has also been ongoing since before the millennium (Meindl 1996) with papers still being published today (Yang et al. 2021), but still remains a less popular choice than batteries or solar.

Using batteries as a sole power source remains a popular option, favoured by the commonly used DataWell WaveRider buoys present at many test sites (Datawell 2021). The sole use of battery power is particularly common at the smaller end of the data buoy scale, such as the *Basic* and *Littoral* WAVY drifters by MELOA (2017).

Although the predominant trend in existing buoys is to use PV panels or batteries, a key proposal in developing data buoys further is to incorporate WECs as their PTOs. As discussed in Sect. 2.3, each method of powering data buoys has its own drawbacks. Offering data buoy developers the option of using wave energy, could open up new renewable energy solutions for data buoy applications, where using wind or solar may not be suitable. Given the marine environment in which data buoys are deployed, wave energy presents itself as a PTO solution too fitting to ignore.

2.3 Drawbacks of data buoy power sources

2.3.1 Batteries

Regardless of the energy harvesting method used, battery storage is required for most data buoys. This means the general drawbacks of batteries can be applied across the data buoy spectrum. However, where batteries are used as a rechargeable power source in conjunction with onboard energy harvesting, the decline in their capacity to hold charge was identified in Dillon et al. (2022) as being of low concern. Dillon et al. (2022) finds that even after ten years batteries fade by only 12.3–12.9% of their nominal storage capacity, with this number expected to decrease as battery technology develops in the future.

The key shortcoming specifically applicable to batteries, where they are exclusively used as the power source for a data buoy, is the limited lifespan of such a power source. In the absence of an onboard power source to recharge them, batteries can only be recharged via expensive maintenance operations. The frequency of replacement varies by model, but as an example, DataWell's WaveRider buoys have battery lives ranging from 1.6 to 3.5 years (Datawell 2021). The alternative to manned maintenance operations, which is sometimes considered for single use applications, is for the buoys to be sunk. The environmental impacts of such an action make sinking buoys with batteries on board an undesirable solution, with the potential for leaching chemicals to pollute the surrounding ocean.

2.3.2 Solar

By far the most popular method of energy harvesting for data buoys, being cheap to produce and relatively reliable, solar PV panels still have their disadvantages. Most obvious is the fact that solar power is dependent on favourable weather conditions, where sunlight is required in order for the PV cells to generate a current. The technology for manufacturing PV panels continues to evolve, generating ever higher amounts of electricity at lower and lower light levels, but this cannot overcome the fact that PV panels will never work at night or under very thick cloud cover.

Pertinent to data buoy applications is the ability to survive in a harsh environment, and it is here that the true drawbacks of PV panels lie. In an offshore environment a patina of salt, algae and other seaborne matter builds up on the flat surfaces of the panels. This layer obscures the light and over time reduces the efficiency and effectiveness of the PV panels, in essence mirroring the effect of dust build up in desert-based solar farms (Liu et al. 2021). Additionally, data buoys form floating islands attractive to resting seabirds, whose guano contributes further to the fouling of the panels. Therefore periodic maintenance operations are required to clean the surfaces of the panels, bringing with them the same financial disadvantages as replacing batteries. A compromise is to change the panel angle to reduce the risk of bird fouling, but this comes at the cost of the panels no longer being normal to the sun's rays.

Furthermore, PV panels must be placed above the water line, which can increase metacentric height and catch the wind, increasing the risk of instability in the water. The need to remain above the surface can also make PV panels an impractical choice where a low emersed profile must be kept, for example in the case of drifters.

2.3.3 Wind

Wind carries with it many of the same disadvantages as solar, namely the reliability on favourable weather conditions, and the requirement to sit significantly above the waterline. The effects on stability are even more pronounced with wind than solar, as the wind shear curve dictates that the turbines should be placed as high above the surface as possible. This instability is further increased by the turbine exerting a pitching torque on the buoy below during operation.

2.3.4 Wave

Although less susceptible to hourly variation in weather conditions, and with better forecastability than solar and wind (McArthur and Brekken 2010), WECs still require a sufficiently excited surface to operate. However, this is not the main drawback of using wave-power. Wave energy is still very much a developing field without the established range of commercial off-the-shelf technologies available for wind and solar power sources. This low technology readiness level (TRL) makes it a far more challenging PTO to implement on data buoys, although some companies such as Ocean Power Technologies (OPT) have successfully deployed wave-powered data buoys (OPT 2021). The main challenge to developing this technology is that the irregular, low frequency of ocean waves presents a challenge to conventional electricity generation methods, which have been designed for more regular, higher frequency energy sources.

Of the power sources considered for data buoys, wave power is the most susceptible to marine fouling below the water line. This build up of marine organisms, attaching themselves to the underside of the buoy, may impair the ability of the device to generate power. A traditional solution to marine biofouling is the application of an anti-fouling coating to the hull. However, despite a total ban on ecologically harmful tributyltin from 2008, modern anti-fouling coatings have also been found to release toxic biocidal agents into the surrounding ocean (Silva et al. 2021).

Besides the challenges posed by the marine environment, for data buoys in particular, wave power presents an interesting challenge, which will be referred to as the *control paradox* in this review. It refers to the dichotomy that wave-powered sensing devices face: to harvest more energy the control system increases the motion of the buoy, violating the requirement of many sensors and transmission antennae for a stable platform to operate effectively. Mathias et al. (2021) addresses this paradox directly and investigates whether it presents a prohibitive barrier in developing a wave-powered data buoy fitted with a light detection and ranging (LiDAR) array. The control paradox also has parallels to the *modelling paradox* discussed in Windt et al. (2021), where the increase in device motion caused by the control system, violates the assumption of small motion used to develop the hydrodynamic model of the WEC being controlled.

2.3.5 Hybrids

Hybrid systems combining two or more different power sources are one solution to overcoming the challenges associated with particular power sources and PTO mechanisms. Projects such as the Wavy *Ocean Atmo* and *Ocean Plus* Drifters by MELOA (MELOA 2017), and the OWC in Carolan et al. (2019) and Boland et al. (2019), believe that solar panels (which have a proven performance track record) should be used in conjunction with experimental WECs to improve reliability in performance. This allows buoys fitted with WECs to be deployed at sea without the risk of being without power. In the future, the plan for the wave activated sensor power buoy (WASP) at Dundalk Institute of Technology (Carolan et al. 2019; Boland et al. 2019) is to prioritise the WEC as a power source to gauge the feasibility of using the WEC as a primary source of power, but will retain the existing solar panels as a reliable backup over the at-sea test periods planned for this device.

Furthermore, the WindSentinel by AXYS technologies (Office of Energy Efficiency and Renewable Energy 2015; AXYS Technologies 2021), and the fish-feeding buoy described in Fullerton et al. (2004), combine wind and solar to ensure redundancy exists across power sources; demonstrating the appeal of hybrid systems even when using more established energy harvesting methods. Combining wind, wave and solar energy harvesting on a single data buoy has also been considered with the 'Tribrid' in Hegarty (2021), further discussed in Sect. 4.6.

Beyond the data buoy field, projects such as Fenu et al. (2020) demonstrate the synergy between the effects that gyroscopic WECs have on dampening pitch whilst generating electricity, and the advantage this stabilising force can have when combined with a floating wind turbine platform. This stabilising effect of gyroscopic WECs could also aid in bypassing the problems surrounding the control paradox discussed in Sect. 2.3.4, with small-scale data buoys potentially reaping the benefits of a technology developed for much larger scale applications.

Hybrid systems are, unfortunately, not a panacea to all the issues surrounding the utilisation of a single energy harvesting method. The additional complexity involved in balancing two or more power sources, as well as the additional costs of including a second power converter as a back-up, can often outweigh the benefits of the extra reliability and greater margin of redundancy that they bring. A summary of the drawbacks of hybrid wave energy converters, and further external examples of hybridising wave energy with other power sources, are discussed in Ahamed et al. (2020).

2.4 Data buoys as testbeds for large-scale WECs

One of the key aims of this review is to assess the suitability of data buoys as a low-cost testbed from which lessons learnt can be applied to larger scale WEC projects. Full-scale prototypes for large-scale WECs are often prohibitively expensive, which has led to the demise of a number of prominent wave energy companies (BBC News Scotland 2014, 2015; Deloitte 2014). Even where upfront investment costs have been met, the monetary value of full-scale prototypes means that testing is fraught with high financial risk, where mistakes can lead to disaster, as happened to Oceanlinx (ABC Radio Adelaide 2020) where the destruction of their 1:1 prototype during the deployment passage sent the company into administration (Deloitte 2014).

Being small-scale devices with an immediately useful output, data buoys are proposed as a lower risk testbed for these large-scale WECs, facing similar in-service issues, but with a much lower capital cost.

However, initial research does throw up some caveats which must be noted. First, a commercial example of where data buoys were used as a proof of concept for powering a wave farm consisting of a network of buoys using the same PTO can be found in Shepard (2014). In Shepard (2014), OPT (one of the few companies to have successfully deployed wave-powered data buoys) proposed to use their wave-powered electromagnetic drive PB3 data buoys, most commonly used for surveillance (OPT 2021), as a wave farm to generate up to 62MW off the coast of Australia, in a project partnered with Lockheed Martin (Shepard 2014). Unfortunately, even with the PB3's proven track record as a data buoy, the project soon collapsed with the developers deciding it was not commercially viable (Parkinson 2014). This highlights the power industry's lack of confidence in scaling the performance of individual data buoys to large-scale applications.

Furthermore, the findings of a recent review on TENGs (Rodrigues et al. 2020) state that the reason small-scale wave power projects have previously failed is precisely because they have tried to scale down a solution for a much larger device. One key issue with scaling PTO mechanisms is that the magnified effects of friction at a small scale may significantly change the effectiveness of a particular PTO mechanism. Hence, Rodrigues et al. (2020) insists that, for small-scale projects, the solutions must also be small-scale, in their belief: TENGs. This sentiment is echoed by another recent review (Xu et al. 2022), which finds that the typical requirements of data buoys are generally at odds with the typical specifications of an electromagnetic generator. Xu et al. (2022) advocates the use of TENGs as a promising solution to small-scale wave energy applications, as TENGs can turn wave induced motion directly into electricity, without the need for a secondary transmission system, as found in more conventional WECs.

3 Existing reviews

To set the parameters for this review, and to assess the surrounding research landscape, a search for other reviews covering relevant subjects was carried out. These are explored in the Sects. 3.1–3.3.

3.1 Wave power measurements

Of existing reviews, one of the most comprehensive is Lindroth and Leijon (2011), which is a review of wave power measurements. Lindroth and Leijon (2011) covers a wide range of wave power measurement applications; a broad scope which also encompasses wave-powered data buoys. The focus of Lindroth and Leijon (2011) is on devices which have an at-sea deployment history, demonstrating which projects made it to this advanced stage of development. Lindroth and Leijon (2011) includes data buoys all the way back to Yoshio Masuda's navigation buoy, and all data buoy devices deployed at sea up to the year of publication.

A clear trend that can be observed in Lindroth and Leijon (2011) is the almost exclusive use of OWCs as the PTO for wave-powered data buoys: from the IPS Buoy and the N2 Buoy in 1980 and 1981, respectively, and even in the case of the Ocean Energy Buoy. The Ocean Energy Buoy was a 1:4 scale commercial device for electricity generation first tested at Galway Bay in 2006, but had a measurement system fitted in 2008 (Lindroth and Leijon 2011). However, a key takeaway from Lindroth and Leijon (2011) is that from this significant number of OWC powered data buoys, a recurring impediment to their further development was the low power that they generated in a real ocean environment.

3.2 Wireless sensor networks

Ocean-based wireless sensor networks (WSNs) are a key application area for data buoys, and are, therefore, included in this review. Three reviews were found concerning ocean-based WSNs—two focussing on aerial wireless sensor networks (AWSNs) (Albaladejo et al. 2010; Xu et al. 2014) and one concerning underwater wireless sensor networks (UWSNs) (Felemban et al. 2015).

Albaladejo et al. (2010) specifically excludes solitary data buoys, but does find 12 unique applications of WSNs at sea. However, the focus of Albaladejo et al. (2010) is more on the architecture of building ad-hoc networks from existing sensor buoys, and the challenges that this presents, rather than highlighting the progress of wave-powered data buoys in the field of WSNs. Conversely, although Xu et al. (2014) proposes itself as a continuation of Albaladejo et al. (2010), it does include a solitary wave-powered data buoy—specifically the one described in Pirisi et al. (2013), which is a prototype for a reef monitoring buoy, further discussed in Sect. 4.4.

Whilst the UWSNs considered in Felemban et al. (2015) are mostly unrelated to data buoys, there are underwater sensor nodes which are of a similar size to data buoys and could provide rich ground for cross pollination of ideas and lessons learned in their development. One such example is CalWave's xNode (Lehmann 2021), which utilises a WEC as its PTO system, to power onboard underwater sensors. The xNode is also small-scale and is designed to be incorporated into UWSNs. However, being a commercial product, available details about the xNode's design are scarce, but monitoring its success once deployed could highlight issues that similarly sized wave-powered data buoys will also have to overcome at sea.

3.3 Tribolelectric nanogenerators

In the field of small-scale wave-powered devices, a technology impossible to overlook is the triboelectric nanogenerator, or TENG for short. Developed in 2012 by a group headed by material scientist, Zhong Lin Wang, this PTO mechanism is an adroit solution to the problems posed in harvesting a low frequency, stochastic energy source such as a person's body motion—or in the case of data buoys: the ocean's waves.

TENGs are clearly currently topical with developers refining the mechanism and constantly exploring potential new applications. Three reviews were found concerning ocean-based applications of this nascent technology. The reviews of Wang et al. (2017) and Zhao et al. (2021) are general and apply to all notable ocean-based TENG developments since their invention in 2012, exploring the myriad ideas in this incipient field.

However, most apposite to this review is the approach taken in Rodrigues et al. (2020), which specifically considers TENGs in relation to their application aboard data buoys. Rodrigues et al. (2020) only includes TENGs which have been developed to at least the physical prototype stage, disregarding some of the exploratory 'blue sky' ideas included in Wang et al. (2017) and Zhao et al. (2021). Using this approach Rodrigues et al. (2020) observed that no TENGs had been tested in realistic sea conditions (only in idealised set ups). This observation formed the basis for the lead author's of Rodrigues et al. (2020) to publish a follow-up paper on testing TENGs in realistic sea conditions (Rodrigues et al. 2021). The group's focus on TENGs in relation to data buoys, is a product of developing their own TENG powered data buoy in Portugal. Their review (Rodrigues et al. 2020) is presented as an argument for using TENGs in small-scale wave power applications and, as discussed in Sect. 2.4, as a counter-argument against the scalability of TENGs and other PTOs.

Zhao et al. (2021) and Wang et al. (2017) also promote the use of TENGs, presenting them as the most power dense of ocean energy harvesting mechanisms at a small-scale. Whilst Wang et al. (2017) considers all TENG developments, the focus of Zhao et al. (2021) is on TENG applications as distributed ocean sensors, particularly where they can act as part of a WSN, such as those discussed in Sect. 3.2. However, also included in Zhao et al. (2021) are some examples of other more unusual PTOs that could be used in sensor buoys, categorised as electromagnetic harvesters (EMHs), electroactive polymer harvesters (EAHs), triboelectric nanogenerators (TENGs), and hybrid harvesters (HHs). Although the majority of these examples are very theoretical, and not specific towards developing a particular device, included amongst them is a wave-induction turbine which has undergone sea testing (Joe et al. 2017), and a double backwards bent duct OWC for fish farms (Chowdhury et al. 2015), both of which are further discussed in Sect. 4.2. Also included in Zhao et al. (2021) is Li et al. (2019), which is a pendulum-based WEC drifter included in Sect. 4.6.2.

With TENGs being such a new technology the three reviews covering their uses at sea (Wang et al. 2017; Rodrigues et al. 2020; Zhao et al. 2021) are quite comprehensive, with this review considering further TENG developments made after the publication of Zhao et al. (2021). In addition, Xu et al. (2022), a recently published review discussed in Sect. 3.4, has a considerable focus on TENGs, so effort has been made to avoid overlap between the devices considered in Xu et al. (2022) and this review.

3.4 Applications of wave energy marine buoys

Xu et al. (2022) presents a review of wave energy marine buoys with a focus on the applications of marine energy buoys at sea. The Introduction of Xu et al. (2022) finds some commonality with this review, acknowledging the predominance of solar power within the field, and touching on some of the drawbacks that wind and solar encounter in an offshore environment, including the reduction in effectiveness of solar panels in a dynamic environment. Xu et al. (2022) follows the Introduction with an overview of common PTOs related to wave power in general, and categorises the common PTOs in wave energy as overtopping devices, OWCs and oscillating bodies. However, finding no overtopping devices in the field of marine buoys, Xu et al. (2022) instead looks at the other two classifications and discusses the applications of these PTO types in general, and with respect to large-scale wave energy production, as well as relating some examples of smaller scale buoys which utilise these PTOs. A particularly interesting finding from Xu et al. (2022) in relation to this review is that for oscillating body WECs, the requirements for buoys are "fundamentally different from large floating platforms", with buoys requiring:

- Smaller size
- Structure simplicity
- Axisymmetry

According to Xu et al. (2022), these requirements put data buoys at odds with electromagnetic generators typically used in wave energy, which require complex structures and often achieve inefficient performance in mild sea states. The review goes on to suggest that TENGs are a more suitable choice for small-scale applications. However, one aspect overlooked by Xu et al. (2022) in this statement, is the role that having a control system can play in improving the performance of small-scale WECs in milder sea states, for example, as is planned for future development on the MBARI WEC in Hamilton et al. (2021). Indeed, the lack of control in TENG devices is later listed specifically by Xu et al. (2022) as an advantage of TENG-based devices over conventional WECs, due to the added simplicity this brings to the system.

Xu et al. (2022) comes from the Dalian Maritime University's Marine Micro-/Nano-Energy and Self-Powered Systems Lab, who specialise in small-scale marine energy, particularly focussed on TENGs. The laboratory at Dalian Maritime University are responsible for the 7 s-shaped TENG array in Wang et al. (2021c), further detailed in Sect. 4.5. It is, therefore, unsurprising that the section on TENGs in Xu et al. (2022) is particularly detailed, and that the paper establishes an argument that promotes TENGs as the most promising solution for small-scale wave energy applications. Table 2 in Xu et al. (2022) lists the power outputs of example TENGs as power densities, which although a good method by which to compare TENGs to one another, can make TENGs look particularly favourable as a PTO choice for WECs when compared with other PTOs, due to the small volume that a typical TENG occupies. However, Xu et al. (2022) does address some of the engineering problems currently surrounding TENGs. Namely, these are listed as load matching, system integration and output stability.

Xu et al. (2022) presents a contemporary complement to this review, focussing primarily on applications, and includes a number of useful figures that establish a basis for many of the concepts discussed in both Xu et al. (2022) and in this review. Xu et al. (2022) also contains a discussion of two examples of hybridising TENGs with a secondary PTO (Chandrasekhar et al. 2020; Chen et al. 2020), which present a particularly interesting development in the field. Interested readers are encouraged to consider Xu et al. (2022) in conjunction with this paper, as the two differing approaches, considering similar subject matter, combine to give a comprehensive picture of the current wave-powered data buoy research landscape.

4 Wave-powered data buoy prototypes since 2011: by PTO mechanism

In Sect. 1, the categorisations considered for this review are briefly mentioned. Table 1 includes all the categorisations considered, with dashes where certain information was not available or not explicitly stated. This section contains a discussion of wave-powered data buoy prototypes that have had research published between 2011 (when Lindroth and Leijon 2011 was published) and 2021, as well as selected commercial ventures within the field, where companies have made active progress in this same time frame. Section 2.1 provides justification for the inclusion of some peripheral examples of small-scale buoys that are not data buoys, but are of a scale where the challenges they face, and the lessons learnt in overcoming these challenges, can be applied to data buoys. The review of PTO methods in Ahamed et al. (2020) is a summary of the various mechanisms by which wave energy is currently harvested, and given the comprehensive coverage of available PTOs included in Ahamed et al. (2020), the same bin names were used for the PTO categorisations in Sects. 4.1–4.6.

4.1 Hydraulic motor system

Identified by Ahamed et al. (2020) as the most suitable PTO device for generating usable electricity from wave energy, one of the identified wave-powered data buoys in development uses this form of energy harvesting to recharge its

Table 1 Wave-powered data buoy prototypes since 2011: by PTO mechanism

PTO mechanism	Leading institution/company	Citation	Development status	PTO control used?	Mooring	DoFs harnessed	PTO power output	Novelty
Hydraulic motor system	MBARI (USA)	Hamilton et al. (2021)	Deployed at sea	No*	Heave cone or single-point	Heave	100’s of W	Extensive deployment history (*Planned soon)
Turbine transfer system/OWCs	Uni. de Lisboa (Portugal)	Henriques et al. (2016) Oikonomou et al. (2021)	Wave tank testing	Yes	4-point in tests but TBD	Heave	100’s of W	Biradial turbine for latching control
	Uni. do Porto (Portugal)	Mathias et al. (2021)	Rig testing	Yes	Single-point catenary	Heave	10’s of W	LiDAR application, addresses control paradox
	Uni. de Lisboa (Portugal)	de Almeida Duarte (2018)	Computer sim.	Yes	Yes—type not specified	Surge	kW-scale	Backwards bent duct shape
	Sunchon National Uni. (Rep. of Korea)	Zhao et al. (2021) Chowdhury et al. (2015)	Computer sim.	No	–	Surge	100’s of W	Double backwards bent duct shape
	DkIT (Ireland)	Boland et al. (2019) Carolan et al. (2019)	Deployed at sea (no PTO**)	None	Single-point	Heave	0 W**	Planned dual-use of OWC sensor and PTO (**PV panels used)
	Uni. of Indonesia (Indonesia)	Kevin et al. (2020)	Computer sim.	–	Yes - type not specified	Heave	mW-scale	Piezoelectric generator instead of turbine
	Pohang Uni. of Science and Technology (Rep. of Korea)	Zhao et al. (2021) Joe et al. (2017)	Deployed at sea	–	None	Heave	10’s of W	Mooring free PTO for deep sea deployment
	Beihang Uni. (PRC)	Xiao et al. (2021)	Rig testing	Yes	Yes - type not specified	Heave	mW-scale	Dual turbine PTO with belt power transmission
Direct mechanical drive	Resen Waves (Denmark)	Steenstrup (2015)	Wave tank testing	–	Single-point	Heave	100’s of W	Commercial project hoping to offer off-the-shelf “Smart Buoy”
	Southwest Jiaotong Uni. (PRC)	Xie et al. (2020)	Wave tank testing	None	None	Heave	1’s of W	Double-x shaped mechanism for unidirectional rotation

Table 1 continued

PTO mechanism	Leading institution/company	Citation	Development status	PTO control used?	Mooring	DoFs harnessed	PTO power output	Novelty
	Shanghai Maritime Uni. (PRC)	Wang et al. (2021b)	Rig testing	–	–	Pitch	Not specified***	Magnetic lead screw PTO (*** 40V peak output)
	Uni. of Hawai'i at Manoa (USA)	Nolte et al. (2013) Nolte and Ertekin (2014)	Deployed at sea	–	Drogue or single-point	Heave	10's of W	Testing drogued vs. moored device, found drogue design unimportant in deep seas
Direct electrical drive	OPT (USA)	OPT (2021)	Available commercially	Yes	Single-point or 3-point	Heave	kW-scale	Commercially available data buoy
	Politecnico di Milano (Italy)	Pirisi et al. (2013)	Rig testing	Yes	–	Heave	100's of W	Genetic swarm algorithm used in control
TENGS[1]	Uni. do Porto (Portugal)	Rodrigues et al. (2021)	Wave tank testing	–	Single-point	Surge, heave and pitch	mW-scale	First TENG test in realistic sea conditions
	Dalian Maritime Uni. (PRC)	Wang et al. (2021a)	Wave tank testing	–	Double-point	Mostly pitch	10's of W	Array of 7-TENGs with rectifier to align AC frequencies
Hybrid	Uni. of Limerick (Ireland)	Hegarty (2021)	Computer sim.	Yes	3-point	Heave	100's of W	Proposes 'Tribrid' wave, wind and solar buoy
Piezoelectric	Ferdowsi Uni. of Mashhad (Iran)	Nabavi et al. (2018)	Rig testing	Yes****	–	Heave	mW-scale	Harvests buoy vibrations (****in self-tuning mode)
Gyroscopic	MELOA (EU)	MELOA (2017)	Available commercially	–	None	Pitch	mW-scale	Commercially available, low-cost, wave-solar hybrid drifters
	Uni. Politecnico de Catalunya (Spain)	Carandell et al. (2019)	Wave tank testing	–	Yes - type not specified	Pitch	mW-scale	Testing MELOA gyroscope in anchored buoy
	Soochow Uni. (PRC)	Zhao et al. (2021) Li et al. (2019)	Deployed at sea	None	None	Pitch	mW-scale	Gyroscope only drifter

[1]: Also see existing reviews: Xu et al. (2022), Zhao et al. (2021), Rodrigues et al. (2020), Wang et al. (2017)

onboard batteries. This is the data buoy being developed by a team from the Monterey Bay Aquarium Research Institute (MBARI) and Sandia National Labs, named the MBARI-WEC in Hamilton et al. (2021). Although started in 2009, it is an active project with new papers surrounding its development still being published (Hamilton et al. 2021). The goal of the MBARI-WEC is to avoid dependence on batteries, which are the industry standard for marine monitoring buoys.

The MBARI-WEC uses a point absorber design, adapted from an off-the-shelf hydraulic motor converted to be used as a generator. This data buoy is one of the few wave-powered data buoys identified which has withstood numerous full-scale trials within the ocean, including overwintering in 2015 for a total of 131 days at sea. Indeed, in Hamilton et al. (2021), it is stated that this data buoy is the very first of its kind with an extended deployment history, and the project to develop the buoy further is still ongoing. The plans outlined in Hamilton et al. (2021) are to include a control system (currently absent from the design) with which to optimise the power capture of the device and thereby improve its efficiency.

4.2 Turbine transfer system and OWCs

From the plethora of OWC powered data buoys in Lindroth and Leijon (2011) discussed in Sect. 3.1, OWCs seem to be the closest that wave-powered data buoys have as a somewhat standard PTO. However, as pointed out in Lindroth and Leijon (2011), the low amount of power captured by OWCs in real sea conditions presents a challenge to the widespread adoption of this PTO system. In spite of this, OWCs are still one of the most widespread PTO methods documented by wave-powered data buoy projects since 2011, with Portuguese universities leading the way.

In Henriques et al. (2016), from a group at the Instituto Superior Técnico (IST), at the Universidade de Lisboa, Portugal, the performance of two oceanographic buoys is compared: one a spar buoy based on the shape of Yoshio Masuda's navigation buoy, and the other a coaxial-duct OWC based on a design by Takahashi Takashi from the 1980s. Henriques et al. (2016) updates both buoy designs by optimising their hydrodynamic shape and adding a biradial turbine. The use of a biradial turbine in Henriques et al. (2016) is the key novelty behind these buoys, as a biradial turbine enables latching control on an OWC, something not previously possible with the more common Wells turbine. Further justification for using a biradial turbine is explained in Henriques et al. (2017), and in the group's review of OWCs and turbines (Falcão and Henriques 2016). A wealth of other papers support the spar buoy project at IST, with the most recent, (Oikonomou et al. 2021), describing 1:10th Froude-scale testing of the spar buoy in a wave tank, simulating the effects of the biradial turbine with an orifice plate. These experiments found an average power generation of 1 kW can be expected for Portuguese open Atlantic climate and 0.4 kW for Mediterranean conditions, concluding that the design would be appropriate for powering the planned onboard sensory equipment in the open Atlantic but not the Mediterranean.

Building on the spar buoy design in Henriques et al. (2016) and Oikonomou et al. (2021), Mathias et al. (2021) presents a spar buoy project from the Universidade do Porto that adapts the designs in Henriques et al. (2016) and Oikonomou et al. (2021) for the novel application of LiDAR monitoring of offshore wind farms. Through its application of wind characterisation using LiDAR, which requires a stable platform, Mathias et al. (2021) tackles the control paradox, discussed in Sect. 2.3.4, head on, investigating the compromise between limiting the OWC's resonance motion and generating enough energy to power the LiDAR on a 1:16th scale device. Despite concluding that it is currently not possible to achieve the required power for a LiDAR within the restrictions posed by ensuring a stable enough platform for its operation, Mathias et al. (2021) remains hopeful that, as LiDARs become more energy efficient, OWCs could be used to power them in the future. Additionally, Mathias et al. (2021) concludes that for buoys fitted with sensors that demand less power than LiDARs, yet still require a stable platform, OWCs could be used successfully as the PTO mechanism.

Also from the Universidade de Lisboa, de Almeida Duarte (2018) describes optimising the shape of a backward bent duct OWC for deep water marine sensing. This purely theoretical design has not undergone any experimental testing, but simulations find that a 1 metre extension to the duct allows power capture to be increased by more than 1 kW. Similarly, Chowdhury et al. (2015) is a backward bent duct OWC being developed at Suncheon National University of Korea, included as an example of an OWC in Zhao et al. (2021). Chowdhury et al. (2015) is further pushing the design of backward bent duct OWCs, by proposing a design which couples two ducts facing opposite directions to a single turbine, allowing surge motion in both directions to be captured.

Outside of Portugal, the WASP OWC project described in Boland et al. (2019) and Carolan et al. (2019), at Dundalk Institute of Technology, currently uses the OWC chamber purely as a pressure sensor for wave profiling, with PV panels providing onboard power. However, plans are outlined in Boland et al. (2019) and Carolan et al. (2019) to include a turbine in the OWC chamber from which to harvest energy, while maintaining the pressure sensor function. Initial plans are to couple harnessed wave energy with the existing solar panels for deployment reliability, but with the power output of the OWC prioritised to assess its feasibility as a main power source. The Dundalk OWC has undergone deployments at the SmartBay 1:4 test site in Galway Bay, and plans are to continue testing there as the project develops.

Kevin et al. (2020) is an Indonesian study that aims to tackle the problem of low access to electricity faced by much of the country's population. In Indonesia 20% of the population have no access to electricity and this buoy is proposed as a solution for providing a small-scale power source for remote coastal communities facing this problem. The novelty in Kevin et al. (2020), is that it proposes a piezoelectric generator in place of the more usual air turbine, to convert the changes in pressure within the OWC chamber to useful electricity. Although not a data buoy as such, (Kevin et al. 2020) is still a small-scale wave-powered buoy and the unusual approach of using a piezoelectric generator in place of a turbine is an interesting consideration for similarly sized OWC-based data buoys.

Beyond the OWC, other PTOs which use turbines as their fundamental component also exist in the field of data buoys. The review of TENGs and other small-scale PTOs, (Zhao et al. 2021), includes (Joe et al. 2017), which is a design where a dual water turbine suspended below the buoy is used to generate power. Initially developed in Joe et al. (2017), to allow wave-powered data buoys to be deployed in deep sea environments by removing the need for a mooring, the successful testing of this buoy at sea (generating a peak power of 38 W) puts it among the few that have successfully carried out deployment at sea. Xiao et al. (2021) proposes a very similar design, but where a belt drive transmission system is used to absorb load fluctuations and vibrations due to the waves. Rig testing of a scale prototype achieved power capture of 26 mW. Future plans for Xiao et al. (2021) are to hybridize the turbine WEC with a second PTO (a two-body point absorber). However, with no mention of a specific application, sensory or otherwise, Xiao et al. (2021) remains a small-scale buoy on the periphery of this review.

4.3 Direct mechanical drive

Resen Waves' Smart Power Buoy (Steenstrup 2015) is mentioned in Ahamed et al. (2020) as an example of devices using a direct mechanical drive PTO. It uses a flywheel-based direct mechanical drive PTO, where a tether to the seabed turns the flywheel which is in turn connected to a generator. The mooring line for the buoy forms a power cable to a fixed point on the seabed where it can be used to power a range of underwater sensors or AUVs. The Resen Waves device has been in development since 2015 and claims to be the first wave-powered "Smart Buoy". 1:20 scale 2D wave tank testing was concluded in 2021, with 300 runs used to validate the company's numerical model (Steenstrup 2021). Resen Waves was formed as a spin-out from the Technical University of Denmark (DTU), and being a commercial venture has its focus on protecting its Intellectual Property (IP) via the use of patents (patent number: 3513058, in all EU countries and Norway; pending approval elsewhere). However, Resen Waves have stated that Daniel Enevoldsen from the DTU will be publishing a write-up of wave tank tests in his forthcoming MSc thesis.

Other direct mechanical drive data buoys include Xie et al. (2020), which proposes a novel double-X-shaped mechanism for directly turning heave motion into unidirectional rotation. Not only is the mechanism in Xie et al. (2020) novel in itself, but the proposed application of monitoring the structural health of sea bridges is also unusual. Monitoring ageing of material, overload operations, etc. is usually done by battery powered sensors, the replacement of which is labour intensive and time consuming. Other energy harvesting solutions have been proposed elsewhere, which harness the vibration of the bridge itself, but the device in Xie et al. (2020) is claimed to have higher energy conversion efficiency at a lower cost than the bridge vibration harvesting devices it seeks to out-compete. The device has undergone testing in experimental rigs, but is yet to be deployed in realistic sea conditions.

Wang et al. (2021b) is a feasibility study to prove the magnetic lead screw WEC as a suitable PTO for data buoys. The magnetic lead screw mechanism uses the pitching motion of a data buoy to cause the onboard power generation unit (in this case a modified DC motor) to slide along the magnetic lead screw beneath, resulting in a rotational speed of up to 4700 rpm within the generator. Wang et al. (2021b) describes both the computational fluid dynamics (CFD), and the experimental testing of the WEC using a rocking rig to simulate the pitching motion generated by waves striking a data buoy, allowing a range of tilt angles and their resultant voltage to be investigated. A peak voltage of 40 V is recorded for a wave with a height of 1.4 m and a period of 4.5 s, but no explicit power outputs are given.

In Hawai'i Nolte et al. (2013) presents a summary of in-ocean experiments carried out on both a moored-, and a drogued heaving point source WEC, equipped with sensors measure the external sea-state. The device in Nolte et al. (2013) builds on previous work detailed in Davis et al. (2009) and Symonds et al. (2010), but brings the device to the important development milestone of at sea testing. This project shares many similarities with the MBARI WEC in Hamilton et al. (2021), with both having been deployed at sea, although the device in Nolte et al. (2013) is of a smaller scale than that in Hamilton et al. (2021). However, both the MBARI WEC and the device in Nolte et al. (2013) have the option of using either a single point mooring or a drogue/heave cone, allowing them to be deployed without the need to secure them to the seabed. The ability to produce power without a mooring line to the ocean floor is a key stepping stone towards the deep-ocean sensing capabilities, proffered by Dillon et al. (2022), as an advantage of wave-powered data buoys over the more common PV panels and batteries currently used, as discussed in Sect. 2.1. However, unlike the MBARI WEC, which achieved around 300 W of power from the heave cone configuration, Nolte et al. (2013) found the drogued configuration of their WEC to have significantly lower power capture, when compared with the single-point mooring configuration. However, despite the single-point mooring outperforming the drogued WEC in Nolte et al. (2013), the authors conclude the paper by saying that a redesign of the drogue (specifically the drogue depth and sizing) could allow the drogued version to obtain similar power output to the moored WEC configuration. This hypothesis is tested by Nolte and Ertekin (2014), which numerically predicts and compares the power generated by two different drogue designs attached to the device. Nolte and Ertekin (2014) finds that although a redesigned drogue can capture more energy in shallow waters (10.6 m long drogue in 18 m ocean depth), the size of the drogue becomes unimportant if the drogue is deeply submerged (100 m long drogue in 2000 m ocean depth). This is an important conclusion, which has direct ramifications for designing deep water drogued data buoys for the applications suggested in Dillon et al. (2022). A final conclusion of Nolte and Ertekin (2014) is that although control theory could be implemented on the moored device, to apply control theory to the drogued version a second generator would be required to allow the device to produce power throughout the entire wave cycle.

4.4 Direct electrical drive

Ocean Power Technologies (OPT) are one of the few companies to have successfully deployed wave-powered data buoys through their POWERBUOY (PB) range, of which the PB3 is the flagship. The PB3 buoy utilises direct electrical drive as its onboard power supply (OPT 2021). With its proven success as a surveillance device, extensively deployed by the US Navy in American coastal waters, it was proposed that an array of PB3 buoys would be combined to act as a wave farm (Parkinson 2014 being a real-world example of using data buoys as a proof of concept for a large-scale project) but unfortunately, as discussed in Sect. 2.4, this project did not come into fruition.

Experimental testing of a reef monitoring buoy which uses a tubular permanent magnet linear generator is described in Pirisi et al. (2013). The unique concept behind this buoy is the optimisation used in its control system, which is based on a hybrid of particle swarm optimisation and the genetic algorithm, concatenated by the authors to ’Genetic Swarm Optimisation’. The buoy is proposed as alternative to expensive manned field studies, by providing key water parameter data in a reef area (normally gathered by divers), through building up a UWSN powered by these buoys.

4.5 Triboelectric nanogenerators

As discussed in Sect. 3.3, reviews of TENGs (Rodrigues et al. 2020; Wang et al. 2017; Zhao et al. 2021), concerning their application as WECs, are comprehensive. Therefore, there is little merit in recreating these reviews, as Rodrigues et al. (2020) in particular covers all aspects of TENG applications in the data buoy field. However, it is worth reiterating that the key conclusion of Rodrigues et al. (2020) is the distinct lack of any tests of TENGs in realistic sea conditions. TENGs are repeatedly described by their proponents as having appealing characteristics such as their light-weight and low cost, high power density, high efficiency and the ability to operate at low frequencies. However, with this hypothesis only proven in simplified experimental setups under ideal sea conditions, the authors of Rodrigues et al. (2020) went on to publish the first paper detailing TENG testing under realistic sea conditions in Rodrigues et al. (2021). In Rodrigues et al. (2021), the focus is on testing 3 different TENG prototypes at 1:8 scale in a 28 × 12 × 1.2 m wave basin, under conditions designed to represent conditions off the Portuguese west coast. The three 3D-printed prototypes each used a different design of TENG to determine the most effective type for harnessing wave energy, in a set-up designed to simulate realistic conditions. The three types tested are

- Anisotropic circular TENG
- Unidirectional flat-based TENG
- Unidirectional lateral-based TENG

These prototypes were separately fitted to a model of a commercial navigation buoy, with Bluetooth used for wirelessly transmitting results. The tests found that, although TENGs theoretically capture all 6 degrees of freedom (DOFs), in realistic sea conditions surge, heave and pitch were found to be most relevant to harvesting energy from the wave motion. Other findings were that the TENGs electrical power outputs tend to rise with increasing pitch amplitudes and decreasing period due to the increase in the sphere velocity. Overall the unidirectional lateral-based TENG was found to be most efficient under the imposed experimental conditions.

The other recent paper regarding TENGs for use as PTOs in data buoys, also published in 2021 and, therefore, also not included in Rodrigues et al. (2020), is the array described in Wang et al. (2021a). In Wang et al. (2021a), 7 s-shaped TENGs are stacked to form a single array designed as a PTO for a data buoy. Wang et al. (2021a) proposes the use of a rectifier bridge to align the AC frequencies of the 7 TENGs on board with one another. Published in the same issue of *Nano Energy* as Rodrigues et al. (2021), the prototype in Wang et al. (2021a) was also tested in a wave basin, measuring 50 × 3 × 1 m, to study the TENG’s performance over a variety of wave directions. The buoy was shown to have a maximum power density of 34.65 W/m^2 in tests, enough to directly light a 12W LED. The ability to stack TENGs on top of one another is a major advantage of this type of PTO, and Wang et al. (2021a) proposes a solution for combining their outputs into a usable AC signal.

4.6 Hybrid and others

This heading is used in Ahamed et al. (2020) primarily for hybrid systems where an additional method of energy harvesting, such as PV panels or wind turbines, is used in conjunction with a WEC to add some redundancy to the power supply, as touched on in Sect. 2.3.5. In this review, the only true hybrids by this definition, are the PTOs used by the MELOA Wavy *Ocean Atmo* and *Ocean Plus* Drifters (MELOA 2017) which combine gyroscopic energy harvesting with solar power, and the 'Tribrid' buoy in Hegarty (2021) which proposes adding wind, wave and solar energy harvesting to a Mobilis DB 8000 buoy.

The 'Tribrid' buoy detailed in Hegarty (2021), is a feasibility study on a surface buoy designed to provide power to an ROV at an offshore testing facility. The modelling of the 'Tribrid' was carried out by Exceedence Ltd., collaborating with researchers at the Science Foundation Ireland Research Centre for Energy, Climate and Marine (MaREI), to compare the performance of two different PTOs. First, an OWC-based WEC was modelled, followed by a model using the *Gator* spring pump and hydroelectric turbine (Pelagic Innovation Ltd. 2021). The study concluded that the *Gator* had the greater energy output, and that combining it with an onboard wind turbine and PV panels, would allow the buoy to provide sufficient year-round power to operate an ROV for 1 hour every day. However, Hegarty (2021) acknowledges that this modelling is hypothetical and that full-scale testing would be needed to verify that sufficient power output could be achieved.

Other devices that could be considered hybrids in a broader definition would be the WASP OWC from Dundalk Institute of Technology (Carolan et al. 2019; Boland et al. 2019), where PV panels are planned as a back-up power supply once the OWC is converted to a WEC, and the Indonesian buoy which proposes the use of a piezoelectric generator in place of the usual air turbine. However, with the PV panels proposed as a stepping stone to a fully wave-powered device in the WASP, and the piezoelectric generator being a redesign of an OWC rather than a second PTO system, it was deemed appropriate to include these buoys in Sect. 4.2 instead.

With the MELOA drifters being closely linked to the other gyroscope projects (in particular Carandell et al. 2019) it was chosen to categorise them in Sect. 4.6.2, with the remainder of this section being an exploration of the more unusual 'Other' PTOs used by data buoys.

4.6.1 Piezoelectric

Unlike (Kevin et al. 2020), where a piezoelectric generator replaces the turbine in an OWC design, Nabavi et al. (2018) uses a piezoelectric beam as a direct method of harnessing the vibrations of a buoy at sea. Two different designs (one self-tuning and one not) are proposed and an experimental test rig is set up. The experimental testing uses real world wave excitation data from buoys in two locations, one in San Francisco Bay and one off the coast of Boston, to drive the motions of the rig in a realistic manner. Using this method, power is captured on the mW-scale, making it appropriate only for very low power applications. The work in Nabavi et al. (2018) directly builds on that of Zurkinden et al. (2007), in which a number of different piezoelectric-based WEC ideas are proposed.

4.6.2 Gyroscopic

The gyroscopic energy harvesters, developed by MELOA and used in their Wavy Drifter line, combine gyroscopic energy harvesting with solar power. The PTOs within these drifters utilise the pitching motion of the buoy to drive a gyroscope inside. However, being such small-scale devices (even by data buoy standards), the exaggerated frictional effects allow energy capture only in the the largest models of the series, namely the *Ocean Atmo* and *Ocean Plus* (MELOA 2017). A detailed design of the gyroscope PTO system created in the development of these drifters, and the concomitant testing in an anchored buoy, is described in Carandell et al. (2019), where a power output 0.22 mW was achieved.

Described in the review of TENGs and other small-scale PTOs (Zhao et al. 2021), the drifter in Li et al. (2019) also uses a pendulum mechanism, to drive the WEC on board. Published in 2019, the same year as Carandell et al. (2019), the drifter in Li et al. (2019) achieved a power output of 0.13 W during at-sea testing.

Despite the low power output of the gyroscopic WEC in Carandell et al. (2019), MELOA (2017) and Li et al. (2019), gyroscopic WECs have been scaled up successfully for large wave power devices such as the ISWEC—which has been taken from a small-scale prototype (Bracco 2010) to testing at full scale, generating 100 kW (Jin and Greaves 2021). The ISWEC is a great example of scaling up a small device to the kW scale and is proof that doing so is possible.

Furthermore, gyroscopic WECs in general have the advantage of potentially deriving benefit from the stabilising effects of this method of harvesting energy, as discussed in more detail in Sect. 2.3.5.

5 Conclusion

From the array of small-scale wave-powered data buoys investigated since 2011, some observations about the state of the art can be made. It is clear that OWCs remain the most popular solution as a PTO mechanism for small-scale data buoy prototypes. However, this is a position they have held since the 20th century (Lindroth and Leijon 2011), so given the paucity of successfully deployed OWC data buoys, this lack of success over such a long period could be viewed as concerning. On the other hand, this experience gained does mean that more recently developed OWC-based buoys can be more targeted in their research; for example, the projects at IST integrating latching control via the use of a biradial turbine to improve energy capture (Henriques et al. 2016, 2017; Falcão and Henriques 2016; Oikonomou et al. 2021), or exploring options to avoid the use of turbines altogether (Kevin et al. 2020).

Interestingly, the second most popular PTO mechanism documented over the past decade is the TENG, which has the opposite problem to the OWC. Having never been deployed at sea (and only very recently in realistic sea conditions) there is not the same history of unsuccessful deployments associated with TENGs as with OWCs, but there also is no conclusive evidence that these devices will function effectively when exposed to the harsh environmental conditions associated with offshore deployment.

A lack of real deployment history is not a drawback unique to TENGs. While this review documents a wealth of prototypes which have made it to simulation, rig testing and even wave tank testing, the associated costs, both temporal and financial, means few of the prototypes of the past decade have a proven track record at sea (drifters, with their low construction cost and ease of deployment are the exception to this rule). Of the larger devices, the MBARI-WEC (Hamilton et al. 2021), with its 131 day overwintering in 2015, and the commercially available OPT PB3 (OPT 2021), are the only data buoys to have extensive at sea deployments where wave energy has been successfully harnessed as a primary power source.

Another noteworthy trend that can be observed is the under-representation of hybrid systems. Although Carolan et al. (2019) and Kevin et al. (2020) deserve an honourable mention, the ‘Tribrid’ buoy in Hegarty (2021) and the larger MELOA drifters (MELOA 2017) are the only true hybrid wave-powered data buoys found during this research. With data buoys outside of wave power utilising a combination of power sources (Fullerton et al. 2004; AXYS Technologies 2021), it could be expected for more data buoys to follow along the lines of Carolan et al. (2019) and MELOA (2017), using reliable solar panels as a back-up energy supply. A broader interpretation of a hybrid data buoy would be to use two different WECs on the same device. Of the devices considered within the scope of this review, (Xiao et al. 2021) is the only one to mention hybridising a second WEC (a two-body point absorber) with its dual turbine PTO, as well as the TENG-electromagnetic generator hybrids, Chandrasekhar et al. (2020) and Chen et al. (2020), included in Xu et al. (2022). It would be interesting to see more future developments couple PTOs harnessing different DOFs in the data buoy field. Rodrigues et al. (2020) found TENGs to primarily capture surge, heave and pitch, so including a second PTO mechanism to harness, for example, the rolling motion of a TENG powered drifter, could be an interesting area of research.

In addition to establishing the state of the art of research surrounding wave-powered data buoys, another aim of this review was to establish the potential of small-scale wave-powered data buoys to act as testbeds for larger-scale WECs. While the hypothesis that data buoys can make useful testbed’s for larger scale devices has not been disproven, there is a clear indication that there is an important debate going on as to the usefulness of wave-powered data buoys and other small-scale WECs as such testbeds due to scaling issues, particularly given the magnified effects of friction at a small scale. This goes some way towards justifying the popularity of TENGs amongst researchers, as a solution to small-scale wave energy problems, and why OWCs on the smaller scale have struggled.

Acknowledgements The authors are thankful for discussions with Thomas Kelly, Matias Carandell, Daniel Clemente, and Marco Rosati.

Author Contributions IM: writing—original draft preparation, literature search and analysis. JR: review and editing, supervision, conceptualization, funding acquisition, and project administration.

Funding Open Access funding provided by the IReL Consortium Open Access funding provided by the IReL Consortium. This project (Grant Aid Agreement no. ES/20/003) is carried out with the support of a Marine Institute Eoin Sweeney Scholarship and funded under the Marine Research Programme by the Irish Government.

Declarations

Conflict of interest The authors have no conflicts of interest to declare.

References

ABC Radio Adelaide (2020) Wrecked Oceanlinx wave generator 'saga' at Carrickalinga continues with further delays. Online. https://www.abc.net.au/news/2020-04-28/oceanlinx-generator-still-stranded-at-carrickalinga/12190502. Accessed 31 Aug 2021

Ahamed R, McKee K, Howard I (2020) Advancements of wave energy converters based on power take off (PTO) systems: a review. Ocean Eng 204(107):248

Albaladejo C, Sánchez P, Iborra A et al (2010) Wireless sensor networks for oceanographic monitoring: a systematic review. Sensors 10(7):6948–6968

AXYS Technologies (2021) FLiDAR WindSentinels. Online. https://axystechnologies.com/products/flidar-windsentinel/. Accessed 1 Sept 2021

BBC News Scotland (2014) Wave power firm Pelamis calls in administrators. Online. https://www.bbc.com/news/uk-scotland-scotland-business-30151276. Accessed 31 Aug 2021

BBC News Scotland (2015) Aquamarine power calls in administrators. Online. https://www.bbc.com/news/uk-scotland-scotland-business-34659324. Accessed 31 Aug 2021

Boland M, Kelly T, Carolan R et al (2019) Scale model testing of the WASP—a novel wave measuring buoy. In: Proceedings of 13th European wave and tidal energy conference, Napoli, Italy, pp 1531-1–1531-9

Bracco G (2010) ISWEC: a gyroscopic wave energy converter. Ph.D. thesis, Scuola di Dottorato, Politecnico di Torino

Carandell M, Toma DM, Carbonell M et al (2019) Design and development of a kinetic energy harvester device for oceanic drifter applications. In: Proceedings of IEEE international instrumentation and measurement technology conference, Auckland, New Zealand, pp 1–6

Carolan R, Walsh B, Boland M et al (2019) The design and construction of a prototype WASP - a novel wave measuring buoy. In: Proceedings of 13th European wave and tidal energy conference, Napoli, Italy, pp 1594-1–1594-8

Chandrasekhar A, Vivekananthan V, Kim SJ (2020) A fully packed spheroidal hybrid generator for water wave energy harvesting and self-powered position tracking. Nano Energy 69(104):439

Chen X, Gao L, Chen J et al (2020) A chaotic pendulum triboelectric-electromagnetic hybridized nanogenerator for wave energy scavenging and self-powered wireless sensing system. Nano Energy 69(104):440

Chowdhury OR, Kim H, Park D et al (2015) Development of a simple and innovative wave energy harvester suitable for ocean sensor network application. Int J Smart Home 9(11):197–210

Curcio J, McGillivary P, Fall K et al (2006) Self-positioning smart buoys, the un-buoy solution: logistic considerations using autonomous surface craft technology and improved communications infrastructure. In: Proceedings IEEE OCEANS conference, Boston, USA, pp 1–5

Datawell (2021) Product list. Online. https://www.datawell.nl/products/buoys.aspx. Accessed 31 Aug 2021

Davis E, Ertekin RC, Riggs R (2009) A buoy-based WEC device to provide low power to sensors. In: Proceedings of 28th ASME international conference on offshore mechanics and arctic engineering, Honolulu, Hawai'i, USA, pp 1109–1118

de Almeida Duarte AP (2018) Modelling and analysis of a backward bent duct buoy WEC for oceanographic applications. Online. https://www.semanticscholar.org/paper/Modelling-and-analysis-of-a-backward-bent-duct-buoy-Duarte-Duarte/4003a34914a470c2ee9f70373727d23d55cf9467. Accessed 31 Aug 2021

Deloitte (2014) Report to Creditors pursuant to Section 439A of the Corporations Act 2001. Online. https://www2.deloitte.com/content/dam/Deloitte/au/Documents/finance/insolvency/oceanlinx/deloitte-au-fas-439a-report-271014.pdf. Accessed 31 Aug 2021

Dillon T, Maurer B, Lawson M et al (2022) Cost-optimal wave-powered persistent oceanographic observation. Renew Energy 181:504–521

ESA (2012) Sea and space meet for business in Ireland. Online. https://www.esa.int/Space_in_Member_States/Ireland/Sea_and_space_meet_for_business_in_Ireland. Accessed 1 Oct 2021

Falcão AFO, Henriques JCC (2016) Oscillating-water-column wave energy converters and air turbines: a review. Renew Energy 85:1391–1424

Fan F, Tian Z, Wang Z (2012) Flexible triboelectric generator. Nano Energy 1:328–334

Felemban E, Shaikh FK, Qureshi UM et al (2015) Underwater sensor network applications: a comprehensive survey. Int J Distrib Sens Netw 11:896832

Fenu B, Attanasio V, Casalone P et al (2020) Analysis of a gyroscopic-stabilized floating offshore hybrid wind-wave platform. J Mar Sci Eng 8(6):439

Fullerton B, Swift M, Boduch S et al (2004) Design and analysis of an automated feed-buoy for submerged cages. Aquacult Eng 32(1):95–111

Hamilton A, Cazenave F, Forbush D et al (2021) The MBARI-WEC: a power source for ocean sensing. Ocean Eng Mar Energy 7:189–200

Hegarty A (2021) Broadening out the working footprint of a cabled seabed observatory using an interconnected surface buoy, and examining the potential to achieve similar utility from a stand-alone buoyed platform. Ph.D. thesis, Centre for Robotics and Intelligent Systems, University of Limerick

Henriques JCC, Portillo JCC, Gato LMC et al (2016) Design of oscillating-water-column wave energy converters with an application to self-powered sensor buoys. Energy 112:852–867

Henriques JCC, Sheng W, Falcão AFO et al (2017) A comparison of biradial and Wells air turbines on the Mutriku Breakwater OWC wave power plant. In: Proceedings of ASME 36th international conference on ocean, offshore and arctic engineering, Trondheim, Norway, pp 62651-1–62651-12

Jin S, Greaves D (2021) Wave energy in the UK: status review and future perspectives. Renew Sustain Energy Rev 143(110):932

Joe H, Roh H, Cho H et al (2017) Development of a flap-type mooring-less wave energy harvesting system for sensor buoy. Energy 133:851–863

Kevin K, Simanjuntak EF, Utomo AR et al (2020) Study on micro-scale ocean wave power generator using oscillating water column system with piezoelectric. In: Proceedings of 8th international electrical engineering congress, Chiang Mai, Thailand, pp 1–4

Lehmann M (2021) CalWave xNode. Online. https://calwave.energy/solutions/. Accessed 8 Sept 2021

Li Y, Guo Q, Huang M et al (2019) Study of an electromagnetic ocean wave energy harvester driven by an efficient swing body toward the self-powered ocean buoy application. IEEE Access 7:129758–129769

Lindroth S, Leijon M (2011) Offshore wave power measurements-a review. Renew Sustain Energy Rev 15(9):4274–4285

Liu X, Yue S, Lu L et al (2021) Investigation of the dust scaling behaviour on solar photovoltaic panels. J Clean Prod 295(126):391

Mathias N, Marini RN, Morais T et al (2021) Response of a self-powered offshore floating support structure with an OWC for powering a LIDAR device. Ocean Eng 220(108):366

McArthur S, Brekken TKA (2010) Ocean wave power data generation for grid integration studies. In: Proceedings of IEEE power and energy society general meeting, Minneapolis, USA, pp 1–6

Meindl A (1996) Guide to moored bouys and other ocean data acquisition systems. Intergovernmental Oceanographic Commission of UNESCO, Paris, pp 21–22

MELOA (2017) WAVY drifters. Online. https://www.ec-meloa.eu/pages/wavy-drifters. Accessed 29 Aug 2021

MET Éireann (2021) Happy birthday buoys. Online. https://www.met.ie/happy-birthday-buoys. Accessed 31 Aug 2021

Mobilis (2021) Data acquisition buoys. Online. https://mobilis-sa.com/en/products/data-acquisition-buoys/. Accessed 30 Aug 2021

Nabavi SF, Farshidianfar A, Afsharfard A (2018) Novel piezoelectric-based ocean wave energy harvesting from offshore buoys. Appl Ocean Res 76:174–183

Nolan G, Ringwood J, Holmes B (2007) Short term wave energy variability off the west coast of Ireland. In: Proceedings of the 7th European wave and tidal energy conference, Porto, Portugal, pp 1–10

Nolte J, Ertekin RC (2014) Wave power calculations for a wave energy conversion device connected to a drogue. J Renew Sustain Energy 6:013117–1

Nolte J, Ertekin RC, Davis E (2013) In-ocean experiments of a wave energy conversion device moored to an anchor and to a drogue. J Ocean Technol 8:72–85

Office of Energy Efficiency and Renewable Energy (2015) Wind measurement buoy advances offshore wind energy. Online. https://www.energy.gov/eere/articles/wind-measurement-buoy-advances-offshore-wind-energy. Accessed 1 Sept 2021

Oikonomou CL, Gomes RP, Gato LM (2021) Unveiling the potential of using a spar-buoy oscillating-water-column wave energy converter for low-power stand-alone applications. Appl Energy 292(116):835

OPT (2021) PB3 PowerBuoy. Online. https://oceanpowertechnologies.com/pb3-powerbuoy/. Accessed 30 Aug 2021

Parkinson G (2014) Renew economy: World's biggest wave energy project sinks without trace. Online. https://reneweconomy.com.au/worlds-biggest-wave-energy-project-sinks-without-trace-30448/. Accessed 31 Aug 2021

Pelagic Innovation Ltd. (2021) tfi—Gator. Online. http://pelagicinnovation.com/tfi-gator/. Accessed 29 Nov 2021

Pirisi A, Grimaccia F, Mussetta M et al (2013) Optimization of an energy harvesting buoy for coral reef monitoring. In: IEEE congress on evolutionary computation, Mexico

Rodrigues C, Nunes D, Clemente D et al (2020) Emerging triboelectric nanogenerators for ocean wave energy harvesting: state of the art and future perspectives. Energy Environ Sci 13:2657–2683

Rodrigues C, Ramos M, Esteves R et al (2021) Integrated study of triboelectric nanogenerator for ocean wave energy harvesting: performance assessment in realistic sea conditions. Nano Energy 84(105):890

Shepard J (2014) EE Power: Lockheed Martin and Victorian Wave partner on 62MW wave energy project. Online. https://eepower.com/news/lockheed-martin-and-victorian-wave-partner-on-62mw-wave-energy-project/. Accessed 31 Aug 2021

Silva ER, Tulcidas AV, Ferreira O et al (2021) Assessment of the environmental compatibility and antifouling performance of an innovative biocidal and foul-release multifunctional marine coating. Environ Res 198(111):219

Steenstrup PR (2015) Resenwaves. Online. https://www.resenwaves.com/. Accessed 10 Aug 2021

Steenstrup PR (2021) Tank testing and numerical modeling. Online. https://www.resenwaves.com/wave-energy-data-communications/tank-testing-and-numerical-modelling/. Accessed 22 Oct 2021

Symonds D, Davis EP, Ertekin RC (2010) Low-power autonomous wave energy capture device for remote sensing and communications applications. In: Proceedings of IEEE energy conversion congress and exposition, Atlanta, GA, USA, pp 2392–2396

TechWorks Marine (2021) What we do: data buoys. Online. https://techworks.ie/en/what-we-do/data-buoys/. Accessed 10 Aug 2021

Wang H, Fan Z, Zhao T et al (2021a) Sandwich-like triboelectric nanogenerators integrated self-powered buoy for navigation safety. Nano Energy 84(105):920

Wang H, Wu W, Zhu L et al (2021b) Design and experiment of a new wave power conversion device for self-powered sensor buoy. In: Proceedings of IECON 2021—47th annual conference of the IEEE Industrial Electronics Society, pp 1–5

Wang MJ, Kazyak E, Dasgupta NP et al (2021) Transitioning solid-state batteries from lab to market: linking electro-chemo-mechanics with practical considerations. Joule 5(6):1371–1390

Wang ZL, Jianga T, Xu L (2017) Toward the blue energy dream by triboelectric nanogenerator networks. Nano Energy 39:9–23

Windt C, Faedo N, Penalba M et al (2021) Reactive control of wave energy devices—the modelling paradox. Appl Ocean Res 109(102):574

Xiao H, Liu Z, Zhang R et al (2021) Study of a novel rotational speed amplified dual turbine wheel wave energy converter. Appl Energy 301(117):423

Xie Q, Zhang T, Pan Y et al (2020) A novel oscillating buoy wave energy harvester based on a spatial double X-shaped mechanism for self-powered sensors in sea-crossing bridges. Energy Convers Manag 204(112):286

Xu G, Shen W, Wang X (2014) Applications of wireless sensor networks in marine environment monitoring: a survey. Sensors 14(9):16932–16954

Xu R, Wang H, Xi Z et al (2022) Recent progress on wave energy marine buoys. J Mar Sci Eng 10:566

Yang K, Abdelkefi A, Li X et al (2021) Stochastic analysis of a galloping-random wind energy harvesting performance on a buoy platform. Energy Convers Manag 238(114):174

Zhao T, Xu M, Xiao X et al (2021) Recent progress in blue energy harvesting for powering distributed sensors in ocean. Nano Energy 88(106):199

Zurkinden A, Campanile F, Martinelli L (2007) Wave energy converter through piezoelectric polymers. In: Proceedings of COMSOL users conference, Grenoble, France